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INVESTIGATING EFFECTIVE WAYFINDING IN AIRPORTS: A BAYESIAN NETWORK APPROACH

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Abstract. Effective wayfinding is the successful interplay of human and environmental factors resulting in a person successfully moving from their current position to a desired location in a timely manner. To date this process has not been modelled to reflect this interplay. This paper proposes a complex modelling system approach of wayfinding by using Bayesian Networks to model this process, and applies the model to airports. The model suggests that human factors have a greater impact on effective wayfinding in airports than environmental factors. The greatest influences on human factors are found to be the level of spatial anxiety experienced by travellers and their cognitive and spatial skills. The model also predicted that the navigation pathway that a traveller must traverse has a larger impact on the effectiveness of an airport's environment in promoting effective wayfinding than the terminal design.

Keywords: Bayesian network, graphical model, wayfinding, airport.

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Introduction

Wayfinding is the 'consistent use and organisation of sensory cues from the external environment in order to reach a desired destination' (Lynch 1960). This can be broken down into three specific, but interrelated, processes: decision making (and the development of a plan of action), decision execution (transforming the plan into appropriate behaviour at the right time and place), and information processing (comprised of environmental perception and cognition, which are responsible for the information basis of the two decision related processes) (Arthur, Passini 1992). In other words, wayfinding is the result of the interplay between human factors such as spatial orientation, cognitive mapping abilities, language, culture, gender and biology and environmental factors such as paths, nodes, landmarks, layout complexity and signs (Farr *et al.* 2012).

This interplay between human and environmental factors has led to a multifaceted interest in wayfinding. Research by cognitive and behavioural psychologists has helped to define issues such as memory, cognitive mapping, spatial recognition and information processing (Kuipers 1978; Passini 1981, 1984; Garling *et al.* 1984; Peponis *et al.* 1990; Timpf *et al.* 1992). Computer scientists have made cognitively based computation models that simulate learning and problem solving in spatial networks. Other mathematically based research has lead to the development of index measures such as the Visibility Index (VI) (Braaksma, Cook 1980; Tošić, Babić 1984; Dada, Wirasinghe 1999) and Inter-Connection Density (ICD) (O'Neill 1991) that provide a quantification measure of the ease of wayfinding in a built environment. Despite this research, there has not been a model of wayfinding that reflects the complexity of the interplay between human and environmental factors for effective wayfinding.

This paper proposes the use of Bayesian Networks (BN) to combine the human and environmental aspects of wayfinding. BN are probabilistic graphical models used for reasoning under uncertainty (Pearl 1985, 1986; Cowell *et al.* 2007; Jensen, Nielsen 2007). This model will be applied to airports, and will find the factors that contribute to effective wayfinding.

Effective wayfinding is the successful outcome of the interplay between human and environmental fac-

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tors resulting in a person successfully moving from their current position to a desired location in a timely manner. This is important in a wide range of systems from hospitals to city centres. An exemplar system is transportation hubs such as airports, where its benefits are tangible. These benefits include a reduction in clutter and unnecessary information, improved traveller flow and reduced airport crowding, which enables travellers to reach their destination quickly and easily thereby allowing them time to explore their environment. It also allows passengers to get to their flights on time, and leads to a reduction in enquiries to airport staff, decreased traveller frustration and confusion, and ultimately leads to increased traveller satisfaction (De Barros *et al.* 2007; Churchill *et al.* 2008; Correia *et al.* 2008; Farr *et al.* 2012). The Wayfinding BN model proposed in this paper explores the effects that human or environmental factors have on effective wayfinding in airports and highlights the main influences on the human and environmental factors. The model identifies the most important elements of communication, the built environment in an airport; and what effect if any, do gender, airport familiarity and anxiety have on effective wayfinding in airports.

1. Background

1.1. Wayfinding

Wayfinding is the process of finding your way to a destination in a familiar or unfamiliar setting, can be broken down into a four-step process of orientation (when a person finds out where they are with respect to the required destination), route selection (choosing a route that will lead to the desired destination), route control (the constant control and confirmation that a person is following the selected route) and recognition of destination (the individuals ability to realize that they have reached their desired destination) (Downs, Stea 1973). These processes make use of a person's cognitive mapping and spatial orientation skills, and environmental cues (Farr *et al.* 2012).

A person's cognitive mapping skills is dependent on their ability to process and consolidate their internalised reflection of space, and their awareness of the environment (Tolman 1948; Downs, Stea 1973; Arthur, Passini 1992; De Jesus 1994). This skill is used to form a cognitive map, which is a person's internal representation of the external world (Downs, Stea 1973). By successfully forming a cognitive map, a person is able to establish their position and is able to achieve successful spatial orientation. This is used in conjunction with environmental cues to undertake successful wayfinding.

The cues taken from the environment can include signs, maps, landmarks and paths. In a built environment, the effectiveness of these cues can be assessed using a framework proposed by (Downs, Stea 1973). In this framework, a successful wayfinding system is one that allows a person to recognize their correct location at the start of a journey as well as establish their successful arrival at their destination. The system strengthens a person's belief that they are travelling in the correct direction and allows the person to recognise their location and orient himself or herself within the relevant space, and aids in the effective wayfinding in an environment.

1.2. Wayfinding in Airports

In the context of a transportation hub like an airport, a wayfinding system that facilitates effective wayfinding is important for a number of reasons. A system that directs the flow of people through the terminal quickly and efficiently, particularly during peak travel times, will allow for minimum confusion and disorientation for travellers. This can result in a decrease in passenger frustration and an increase in passenger satisfaction, which will improve passenger experience. Passenger experience is an emerging issue for airports as it plays an important role in a passenger's opinions of an airport (De Barros *et al.* 2007; Churchill *et al.* 2008).

A wayfinding system can also be used by airport management to address other strategies. It can be employed to direct passengers to revenue generating activities such as retail outlets (Farr *et al.* 2012). It can also be used to reduce operating costs by lessening the amount of staff time lost due to providing directions to passengers. As well, it can help negate potential lawsuits by ensuring that legislative or operational targets such as inbound or outbound passenger processing times are met; it can ensure that the correct evacuation directions and placement of signs can mitigate injury or death during an emergency situation.

Due to the uniqueness of the environment of an airport, there are many potential influencing factors that impact effective wayfinding. Additionally, the multiple perspectives of passengers, operators and management make it important to have models that include these perspectives as well as the human and environmental factors involved in wayfinding.

1.3. Wayfinding Models

Previous wayfinding models specifically designed for airports by Braaksma and Cook (1980), Tošić and Babić (1984), and Dada and Wirasinghe (1999) have used the VI. This index relates the ease of wayfinding to the value of available sight lines in an environment. By equating ease of wayfinding as a function of the existence of sight lines, the VI constructed as the ratio of the number of sight lines, or links, between nodes in a terminal and the total number of sight lines that should exist within the terminal. However the VI does not provide any insight into the factors that influence effective wayfinding in airports.

This paper proposes a complex system modelling approach that recognises wayfinding as a complex system. BN, which are an appropriate complex systems modelling tool, will be used to determine which factors, human or environmental, have a greater impact on effective wayfinding in airports. Other questions that the model will answer are:

- what are the main influences on these human and environmental factors;

- what elements of communication are the most important;
- which built environment elements are the most important in an airport;
- what effect, if any, do gender, airport familiarity and anxiety have on effective wayfinding in airports.

1.4. Bayesian Networks

BNs are a graphical modelling method used for reasoning under uncertainty (Pearl 1985, 1986; Cowell *et al.* 2007; Jensen, Nielsen 2007; Korb, Nicholson 2011). They have been used in many applications including health, ecology and forensic science to better understand and model complex issues (Kuikka, Varis 1997; Taroni *et al.* 2004; Kjærulff, Madsen 2012; Riesen, Serpen 2008; Johnson *et al.* 2010). A BN represent variables as nodes and arcs as the direct dependencies between variables (Pearl 1986). In many BNs, nodes are discrete variables either by nature or constructed to be so for ease of computation however continuous nodes can also be used (Korb, Nicholson 2011). Common discrete nodes are Boolean nodes (e.g. true or false), ordered values (e.g. low, medium, high) and integral values (e.g. 1–50).

The Directed Acyclic Graph (DAG) that results after the construction of a BN is quantified through a series of conditional probabilities based on data or information available about the system or problem (Jensen, Nielsen 2007; Korb, Nicholson 2011) and defines a factorisation of a joint probability distribution over the variables represented in the DAG. The factorisation is represented by the directed links in the DAG (Jensen, Nielsen 2007; Kjærulff, Madsen 2012).

Each conditional probability distribution given by $P\left(X_V \mid X_{pa(v)}\right)$, where V is the set of nodes in the DAG; $P\left(X_V\right)$ the joint probability distribution over the set of variables X_V and $X_{pa(v)}$ the set of parent variables of variable X_V. The conditional probability represents a set of rules, where each rule, or conditional probability, which takes the form:

$$P\left(X_V = x_V \mid X_{pa(v)} = x_{pa(v)}\right) = z,$$

or, more simply,

$$P\left(x_V \mid x_{pa(v)}\right) = z.$$

The probability distributions of a BN is the product of the conditional probabilities of all the variables of a BN, conditioned only on its parents (Pearl 1985).

There are several advantages in using BNs to investigate the factors that influence effective wayfinding in airports. They are a useful tool as they can provide support for decision analysis and can collate, organise and formalise information such as empirical data, model outputs and expert knowledge about the issue of concern (Uusitalo 2007; Johnson *et al.* 2010). This is useful for the Wayfinding BN model especially as data relating to human factors and survey results may be sparse and so each piece of available information can be utilised. Combining different sources of knowledge is possible because BNs are able to, in a mathematically coherent manner, incorporate data with different accuracies and from different sources, allowing the combination of data measured on different levels of accuracy to be undertaken (Marcot *et al.* 2001; Uusitalo 2007). This means that for the Wayfinding BN model, we are able to combine survey data, expert elicited data and data from the literature to quantify the resulting BN. Variables that encode managerial decisions, costs, and utilities can be added to BNs to allow management to see the relationships that occur between actions, knowledge and uncertainty. These augmented BNs, commonly referred to as Influence Diagrams, can also show the impact of decisions and the risks of highly undesirable outcomes (Uusitalo 2007). Kuikka *et al.* (1999) used BNs to identify management measures to reduce the risk of overfishing of the Baltic cod. In an airport, the Wayfinding BN model can be used to investigate the impact of changing aspects of the wayfinding system, such as signs, colour and light, and employ strategies that would encourage favourable human factors in an airport.

2. Methods

The construction of the Wayfinding BN model is a three-step process: conceptual model structure, defining the model states and quantifying the model. The conceptual model, which shows the important factors, represented by nodes, and the interactions between the nodes, represented by directed arrows, is developed. For a BN composed of discrete nodes, each node is categorised into a small number of states. These states are chosen to be meaningful in the context of the problem as well as the node in which they are put. These states are generally discrete values and must be mutually exclusive. The nodes and states are quantified by assigning probabilities to the states. The probabilities assigned are conditional on the states of the nodes that directly affect it. Finally, the quantification of the nodes can be undertaken using information from a number of sources including experimental data, simulation models, statistical or mathematical models, results from previous studies and expert knowledge (Johnson *et al.* 2010; Korb, Nicholson 2011).

2.1. Conceptual Model

The conceptual model, which forms the basis of the Wayfinding BN model was developed in a three step process. It was originally developed based on the air travel, airport and wayfinding experiences of a focus group which was composed of a multi-disciplinary team with differing levels of air travel and airport experience. Following this, a thorough review of wayfinding research was completed and the information from this review (Farr *et al.* 2012) was used to further refine the conceptual model. Finally, the conceptual model was presented to a wider audience of airport operators and BN modellers for feedback on the structure of the model.

2.2. Categorisation of Nodes

Following the finalisation of the structure of the Wayfinding BN, the nodes were assigned states and definitions. The three step process from the conceptual model was continued with information from the focus group, the literature review and the wider audience being used to inform the assignment of states and definitions for the nodes. Due to the nature of the available information, the nodes were given binary states where possible, allowing for a robust BN model to be constructed. The nodes, their states and definitions can be seen in Table 1.

Table 1. Nodes and states of the Wayfinding Bayesian network model

Node	Description	States
Airport Familiarity	A passenger's familiarity with an airport	Familiar, Unfamiliar
Air Travel Familiarity	A passenger's level of familiarity with air travel	Familiar, Unfamiliar
Ambassador	A passenger's use of an airport ambassador service, if it is provided	Use, Don't use
Audibility	The audibility of an airport's public address system	Audible, Inaudible
Between Activity Centres	The presence of sight lines between the activity centres of an airport	Present, Absent
Between Signs	The presence of sight lines between signs in an airport	Present, Absent
Built Environment Elements	The effective use of built environment elements such as paths, districts, edges, landmarks and nodes	Effective, Ineffective
Clarity	The clarity of the signage in the airport	Clear, Unclear
Cognitive and Spatial Skills	A passenger's cognitive abilities	Good, Bad
Colour	The tone of the colours used in the airport terminal	Cool, Warm
Communication	The effectiveness of communication in the airport terminal	Effective, Ineffective
Discretionary Time	The amount of discretionary time that a passenger has in the airport terminal	Ample, Meager
Districts	Sections of an environment that have a recognisable, common character. They are generally internally recognised by an individual and are sometimes used as external reference points as a person passes or travels towards them	Distinct, Indistinct
Distance to Travel	The distance that the passenger has to travel in the airport terminal	Long, Short
Edges	The presence of boundaries between two areas in the airport terminal. Edges are important elements of the built environment and play an important role in organising a built environment. In an airport terminal, examples include walls and barricades. Edges are an important organising feature, particularly in the role of holding together generalised areas	Present, Absent
Environmental Factors	The level of the environmental factors such as terminal design and navigation pathway complexity that contribute to effective wayfinding in airport terminals	Good, Bad
Frequency	The frequency with which visual elements of communication such as signs and maps occur in the airport terminal	High, Low
Gender	The gender of the passenger	Female, Male
Human Factors	The level of the human factors such as spatial anxiety and cognitive and spatial skills that contribute to effective wayfinding in airport terminals.	Good, Bad
Landmarks	External reference points. Examples in airports include large signs or art installations. These points are generally local and only visible to restricted areas	Present, Absent
Language	The suitability of the language used in the airport terminal with the passenger	Suitable, Unsuitable
Level Changes	Are level changes required in order for the passenger to make their way to their desired destination	Yes, No
Light	The brightness of the lights in the airport terminal	Bright, Dim
Location	The suitability of the placement of the visual elements of communication such as signs and maps occur in the airport terminal	Well placed, Poorly placed
Maps	The clarity of the maps provided in the airport terminal	Clear, Unclear
Navigation Pathway	The complexity of the navigation pathway that a passenger must traverse in order to reach a desired destination in the airport terminal	Simple, Complex

End of Table 1

Node	Description	States
Navigation Urgency	The urgency with which a passenger needs to find their way to a desired destination in the airport terminal	Urgent, Not urgent
Nodes	Strategic points where an individual can enter an environment and are generally a junction or convergence of paths	Present, Absent
Nomenclature	The universality of the symbols used in the visual elements of communication in the airport terminal	Common, Uncommon
Other Passengers	A passenger's use of other passengers in the airport to ask directions in order to reach a desired destination	Ask directions, Don't as directions
Paths	The passages along which an individual moves for example walkways. Paths are the most predominant feature of a built environment due to their functional necessity to allow people to move from one location to another	Present, Absent
Person to Person	The usefulness of the communication that a passenger has with other people in the airport	Good, Bad
Personnel	A passenger's use of airport personal to ask directions in order to reach a desired destination	Ask, Don't ask
Physical Changes	Is a terminal or level change required in order to reach a desired destination in the airport terminal	Required, Not required
Previous Experience	A passenger's level of experience with air travel, the airport and the processes involved in air travel	Experienced, Inexperienced
Process Experience	A passenger's experience with the processes involved in the airport. These processes include check-in, security and customs	Experienced, Inexperienced
Public Address System	The quality of the public address system in the airport terminal	Good, Bad
Purpose	A purpose of a passenger's movement throughout the airport terminal	Evacuation, Business as usual
Sight Line	The presence of sight lines between activity centres and signs in the airport terminal	Present, Absent
Signage	The quality of the signage in the airport terminal to facilitate effective wayfinding	Good, Bad
Spatial Anxiety	The level of spatial anxiety that a passenger experiences in the airport.	Nervous, Not nervous
Terminal Change	Is a terminal chafe required in order for a passenger to reach a desired destination in the airport terminal	Yes, No
Terminal Design	The effectiveness with which the terminal design is able to allow effective wayfinding	Effective, Ineffective
Transit or Transfer Required	Is a transit or transfer required for the passenger?	Yes, No
Travel Purpose	The purpose for a passenger's travel	Business, Personal
Terminal Visual Elements	The effectiveness of the airport terminal's visual elements. These include signs, light and colour	Effective, Ineffective
Visual Elements of Communication	The quality of the visual elements of communication in the airport terminal	Good, Bad
Visual Pollution	The level of visual pollution in the airport terminal	High, Low
Wayfinding	The effectiveness of wayfinding in the airport terminal	Effective, Ineffective
Web	The quality of the information on an airport's website relating to wayfinding in the airport terminal	Informative, Uninformative

2.3. Quantification

In order to use different sources of information, the quantification of the nodes and the BN were undertaken in three ways: using a synthesis of human judgement via the Dephi method, using information from an online survey, and using information from the literature review. The quantification using a modified Delphi method was done with a small group of participants. The Delphi method is a group technique aimed to obtain the most reliable consensus of opinion of a group of experts (Dalkey, Helmer 1963). The method has been refined and developed so that it is now a social research technique that aims to obtain a reliable group opinion using an expert group and is a valid instrument for forecasting and supporting decision-making (Landeta 2006; Linstone, Turoff 1975). It is a method that can structure communication between groups, or between people in order to resolve a complex problem. The characteristics of the Delphi method (Landeta 2006) are that it is a repetitive process so experts are consulted at least twice so that they can reconsider their answer aided by the information they receive from the other experts. The method maintains the anonymity of the participants as the responses go directly to the group coordinator, thereby allowing the process to be undertaken with experts who cannot meet at the same time and place.

This allows for the elimination of irrelevant information flowing between experts. The Delphi method allows for a group response, which means that all opinions form part of the final answer.

In the quantification of the Wayfinding BN model constructed in this study, five participants with differing background, experience and familiarity with airports and air travel were interviewed and asked their beliefs for the states in the nodes of the model. The first author met with each respondent separately and they were given background to the project. Participants were asked to complete the conditional probability tables associated with the BN based on their experience. The responses were then examined and a response range for all states was compiled. A second meeting was held with each of the participants. The response range for the states in the nodes were displayed and the individuals were again asked to consider the ranges and revise the conditional probability tables for the BN. Following this second consultation, the result of the responses were compiled and an average of the result for each state, based on the responses from the participants was calculated. These probabilities were then used to populate the conditional probability tables in the Wayfinding BN model.

An online survey was then designed and deployed. 33 respondents to the survey provided data that was used to quantify the Wayfinding BN model. This survey asked participants to think about their wayfinding experience in airports and required them to provide their opinion on issues such as the impact of the complexity terminal design, communication and their mood on this experience. Again, the responses were compiled and the average of each of the new probabilities along with the data from the initial quantification was calculated and used to populate the Wayfinding BN conditional probability tables.

Finally, the nodes of the BN that were unable to be quantified through the Delphi and survey processes were quantified by using data from the literature on wayfinding research.

The nodes of the final Wayfinding BN model were interrogated to answer the questions posed in this paper; namely which factors, (human or environmental) have a greater impact on effective wayfinding in airports; what the main influences on these human and environmental factors are; what elements of communication are the most important; which built environment elements are the most important in an airport; and what effect, if any, do gender, airport familiarity and anxiety have on effective wayfinding in airports.

3. Results

The Wayfinding BN model can be seen in Figure 1 and is comprised of 49 nodes and 58 connections. Two internal nodes, 'Human Factors' and 'Environmental Factors feed directly into the outcome node, 'Wayfinding'. This is in accordance with the literature, which states that wayfinding is an interplay between human and environmental factors, and in this instance wayfinding is in the context of an airport. Although the structure of the model is based on the general experiences of the fo-

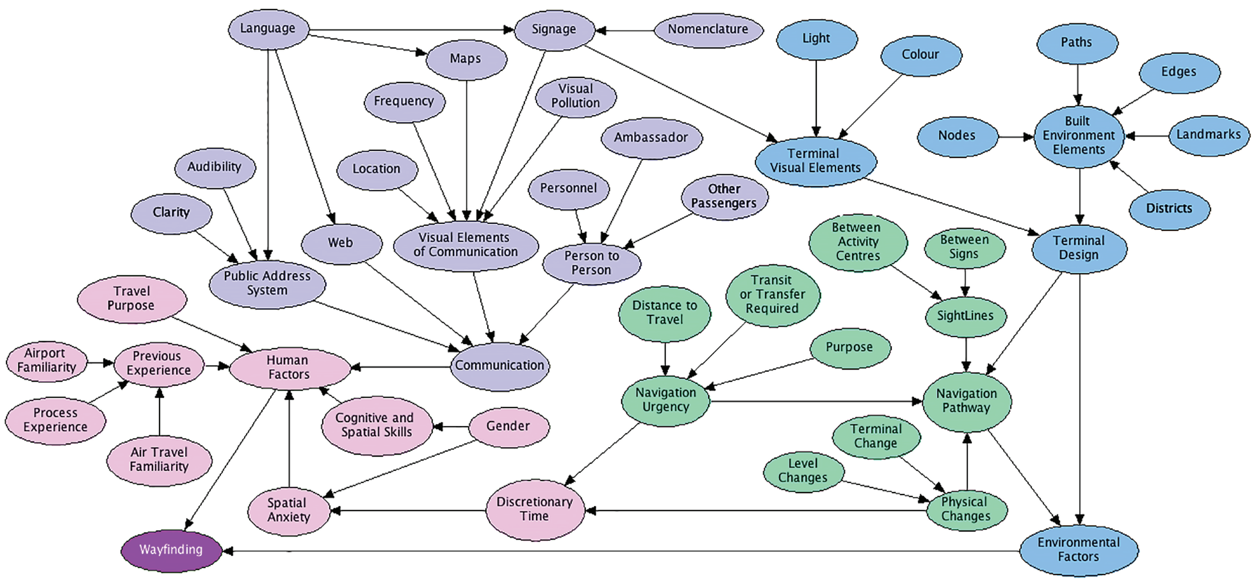

Fig. 1. The Wayfinding Bayesian Network (variables of interest are represented as nodes, and arcs show the direction of the dependencies between the variables; variables related to 'Human Factors' are shown in pink; light blue represent variables pertaining to the built environment in the airport; green represents the variables relevant to navigation pathway; variables pertinent to communication are in light purple; and the node of interest 'Wayfinding' can be seen in dark purple)

cus group and respondents, it can be easily adapted to a particular airport by adding specific information for that airport to the nodes. For example, the nodes that influence 'Terminal Visual Elements', 'Terminal Design' and 'Navigation Pathway', can be updated with information from a specific airport to assess the effectiveness of wayfinding in that airport.

The Wayfinding BN model can be used to answer the questions posed earlier, namely, what effects do human or environmental factors have on effective wayfinding in airports; what are the main influences on these factors; what are the most important elements of communication, the built environment in an airport; and what effect if any, do gender, airport familiarity and anxiety have on effective wayfinding in airports.

The overall probability of Wayfinding in this study is shown in Table 2. It shows that Effective Wayfinding, Good Human Factors and Good Environmental Factors have a probability of 80.18%, 79.81% and 76.93% respectively.

Table 2. The overall probability of wayfinding in this study, showing the probabilities of the internal nodes 'Human Factors' and 'Environmental Factors'

Environmental Factors	Human Factors	Wayfinding
Good: 76.93%	Good: 79.81%	Effective: 80.18%
Bad: 23.07%	Bad: 20.91%	Ineffective: 19/82%

3.1. Main Influencing Factors

The relative influence of the direct internal nodes on wayfinding can be investigated by using the Wayfinding BN model. We are able to predict the affect on Effective Wayfinding when one or more of the factors have been deemed to impact on a traveller's ability to navigate their way through an airport, are changed. We start this by setting the states of these factors to extremes, we see the effect on the probability of effective wayfinding. If we set both Human and Environmental Factors to being 'Good', (we do this by setting the probability of 'Good' to 100%, which means the node is definitely in this state) effective wayfinding has a probability of 96.8%. By setting both the Human and Environmental Factors in a state of 100% 'Bad', the model shows that Effective Wayfinding is reduced to a probability of 4.4%. The fact that a large change occurs in the probability of effective wayfinding when human and environmental factors are set to the extremes of having both 'Good' or both 'Bad' is not surprising since wayfinding requires the interplay of human and environmental factors. Setting Human and Environmental Factors to opposite extremes results in an effective wayfinding probablity of 89.6% when Human Factors is 'Good' and Environmental Factors is 'Bad'; and 74% when Human Factors is 'Bad' and Environmental Factors is 'Good'.

The influence of the two internal nodes, Human Factors and Environmental Factors, on Wayfinding finds that the state of the Human Factors node has a large influence on Wayfinding it can change the effectiveness of Wayfinding from 95.14% effective, with 'Good' set to 100%, to 21.02% effective with 'Bad' set to 100%. The impact of Environmental Factors on Wayfinding effectiveness is less dramatic, with a 100% Effective Airport System resulting in 82.51% Effective Wayfinding, and a 100% Ineffective Airport System resulting in 72.40% Effective Wayfinding. The implication of this result is that Human Factors have a greater influence than Environmental Factors on effective wayfinding in an airport setting.

If an airport was to try to ensure that 100% effective wayfinding was in place, it would require that human factors be 'Good' 94.17% of the time, with 'Good' environmental factors in place 79.17% of the time. This result is shown in (Table 3). Such a high reliance on having human factors be 'Good' reinforces the result that these factors have a greater influence on effective wayfinding than environmental factors.

Table 3. The combination of probabilities of 'Human Factors' and 'Airport System' to achieve completely effective or ineffective wayfinding

Wayfinding	Human Factors	Environmental Factors
100% Effective	Good: 94.17% Bad: 5.29%	Good: 79.17% Bad: 20.83%
100% Ineffective	Good: 19.57% Bad: 80.43%	Good: 67.88% Bad: 32.12%

3.2. Influences on Human Factors

An investigation of which factors have the greatest influence on Human Factors and hence effective Wayfinding finds that Spatial Anxiety has the largest impact (12.59%) on Human Factors which results in a 9.34% change in the probability of effective wayfinding. This is followed by a person's Cognitive & Spatial Skills, which changes the probablity of 'Good' Human Factors by 7.96% and the probability of effective wayfinding by 5.85%. Interestingly the model shows that the purpose of the passenger's travel, whether it be business or personal, does not result in a change in Human Factors or the effectiveness of wayfinding in an airport.

3.3. Influences on Environmental Factors

There are only two nodes, Navigation Pathway and Terminal Design that directly influence Environmental Factors. Of these, the former causes a 16.90% change in 'Good' environmental factors compared to the latter which causes an 11.78% change. Despite these factors having a more than 5% impact on Environmental Factors, the resulting change in the probability of effective wayfinding is 1.72% and 1.19% by Navigation Pathway and Terminal Design respectively. If we compare the impact of these nodes with the nodes that influence Human Factors, and hence Wayfinding, it can be seen that the nodes associated with Human Factors have a greater influence on Wayfinding (with the exception of Travel Purpose) than those associated with Environmental Factors.

3.4. Influences on Communication

The model also allows for the investigation of a number of relationships. It shows which mode of communication (the Public Address System, Person to Person, Visual or the Web) has the greatest impact on effective Communication in an airport.

Public Address System causes the greatest change (30.77%) in the probability of effective communication followed by the Visual Elements of Communication (29.66%), the Website information of an airport (13.5%) and lastly by Person to Person communication (9.08%). Even though the impact of the Public Address System and the Visual Elements of Communication on the effectiveness of Communication is large, the overall impact on a change in the probability of the Effective Wayfinding is quite small, namely 1.49% and 1.45% respectively.

Of the three factors (Audibility, Clarity and Language) that influence the Public Address System, the suitability of the Language used had the greatest impact (40.04%) on whether the Public Address System was good. The audibility and clarity of the Public Address System only had an impact of 9.89% and 9.95% respectively.

The model found that the quality of the Signage in an airport has a greater impact on the effectiveness of the Visual Elements of Communication (18.58%) than other variables such as the quality of maps (11.26%), the frequency and location of the visual elements (16.19% and 13.66% respectively), and the level of visual pollution (2.14%).

3.5. Influences on Built Environment Elements

From the model, the Built Environment Elements have the greatest impact on the effectiveness of an airport's Terminal Design. The presence of Paths in an airport is the most important built environment element, with this node changing the effectiveness of a Terminal Design by 19.53%. The remaining elements of nodes, landmarks, districts and edges influence the effectiveness of the Terminal Design by 3.7%, 3.02%, 3.14% and 4.41% respectively.

3.6. Application to Brisbane International Airport

The Wayfinding Bayesian Network model can be used to analyse the current wayfinding effectiveness in an airport, how changes in the airport environment, and how changes in airport user factors can impact this effectiveness. In practice, analysing the environment and changing the states of the nodes to reflect the airport environment can find a measure of an airport's current wayfinding effectiveness. The nodes that would need to be investigated and states changed would be the green and blue nodes, and some of the purple nodes relating to communication. An analysis of the Brisbane International Airport Departure Area was undertaken and found that the wayfinding effectiveness of the area was 81.73%. This analysis required entering evidence into the model and changing the states of the following nodes: Clarity, Audibility, Public Address System, Web, Location, Frequency, Maps, Signage, Visual Pollution, Nomenclature, Light, Colour, Terminal Visual Elements, Distance to Travel, Transit or Transfer Required, Purpose, Between Activity Centres, Between Signs, Sightlines, Navigation Pathway, Terminal Change, Level Changes, Physical Changes, Nodes, Paths, Edges, Landmarks, and Districts. The result of the analysis shows that the wayfinding effectiveness in the Brisbane International Airport Departure area is slightly higher (81.73% compared to 80.18%) than the overall effectiveness experienced by travellers at other airports.

3.7. Scenario Testing

A series of what-if scenario results to reveal the influence of these scenarios on effective Wayfinding is shown in Fig. 2. These show that there is only a slight difference (4.29%) between effective Wayfinding between the males and females; a traveller's familiarity with an airport has negligible impact (0.29%) on effective wayfinding; if a traveller has good cognitive and spatial skills, their travel experience will increase effective wayfinding performance by around 5%.

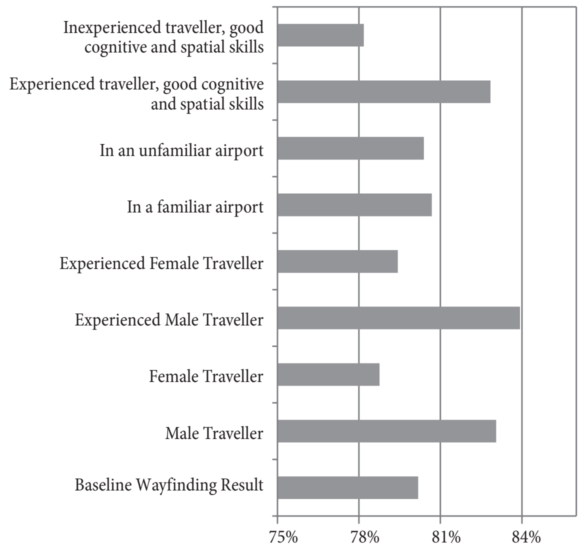

Fig. 2. The Wayfinding Bayesian Network model tested several scenarios and their impact on wayfinding effectiveness in airports (the baseline result of the model shows that the overall probability of effective wayfinding in an airport is 80.18%; the changes in this result can be seen in the graph above depending on the scenario being tested)

3.8. Sensitivity Analysis

The results of a sensitivity analysis of the model can be seen in Tables 4 and 5. This shows that Wayfinding is most sensitive to changes in Gender, Cognitive and Spatial Skills, Human and Environmental Factors and Spatial Anxiety.

Further sensitivity analyses were conducted and found that Human Factors was most sensitive to changes in Gender, Cognitive and Spatial Skills and Spatial Anxiety, and that Environmental Factors was most sensitive to changes in Terminal Design and Paths.

Table 4. Sensitivity analysis for the posterior network of the Wayfinding Bayesian Network (three analyses were performed: one for the output node, Wayfinding, and one each for the internal nodes, Human Factors and Environmental Factors; these nodes of interest were used as the reference point for the other nodes)

Wayfinding	*0.25*
Gender	0.04
Cognitive & Spatial Skills	0.03
Environmental Factors	0.03
Human Factors	0.02
Spatial Anxiety	0.02
Human Factors	*0.03*
Gender	0.06
Cognitive & Spatial Skills	0.04
Spatial Anxiety	0.03
Environmental Factors	*0.25*
Terminal Design	0.03
Paths	0.02
Sightlines	0.01
Between Signs	0.01
Between Activity Centres	0.01

Table 5. Sensitivity analysis of the posterior network of the Wayfinding Bayesian Network (the output node, Wayfinding, is used as the reference point for the other nodes)

Wayfinding	*0.25*
Air Travel Familiarity	0.38
Process Experience	0.25
Building Design	0.11
Environmental Factors	0.03
Language	0.03
Human Factors	0.02
Navigation Pathway	0.02
Visual Pollution	0.02

4. Discussion

Wayfinding is the interplay between human and environmental factors. This interplay to date has not been modelled fully. Our research has achieved this by using BNs to integrate the human and environmental factors that contribute to effective wayfinding.

Our model suggests that Human Factors have a larger impact on effective wayfinding in airports than Environmental Factors. This has particular relevance to transportation hubs, those airports where passengers already experience a certain level of stress associated with air travel, and consequently it is imperative that the environment is designed to allow human factors to be 'Good'. The greatest influences on human factors are found to be the spatial anxiety experienced by travellers and a traveller's cognitive and spatial skills. The implications of this is that while they cannot control a traveller's cognitive and spatial skills, the airport environment can be designed or adapted to lessen passenger anxiety. The model shows that the travel purpose has no impact on wayfinding effectiveness, and a traveller's familiarity with an airport has only a negligible impact.

The Wayfinding BN model also predicted that the Navigation Pathway has a larger impact on an airport's environmental factors than the Terminal Design. However, these nodes cause a negligible change in wayfinding effectiveness. The Paths in the Built Environment Elements heavily influence the Terminal Design of an airport.

Additionally, the model has shown that an airport's Public Address System and the Visual Elements of Communication present in the airport are the elements of Communication that are the most influential. Further investigation showed that the Language used, and Signage, were also important factors as they had the greatest impact on the Public Address System and the Visual Elements of Communication respectively.

Our study finds that gender differences do not have much of an impact on effective wayfinding. This contradicts the research undertaken in the cognitive fields, which show that gender does impact on wayfinding. However the difference in results may be due to the fact that the environment in an airport is a closed space and may mute the effect of gender. In contrast, the environment where cognitive studies are conducted are generally open spaces, such as towns and cities.

A sensitivity analysis of the model found that Wayfinding and Human Factors are sensitive to Gender and Cognitive and Spatial Skills; and Environmental Factors were sensitive to changes in Terminal Design and Paths.

Conclusion

The novel approach to effective wayfinding in airports presented here, integrates human and environmental factors involved in wayfinding and provides an insight into the important role that certain factors play in facilitating effective wayfinding in airports.

However, it is prudent to point out that this is based on the experiences of a focus group who have aggregated their travel experiences in airport terminals. Their interpretations and reflections of their experiences may represent a different 'generic' airport, which is modelled here.

A natural extension of this model would therefore be to analyse a specific airport, with data from that airport updating the nodes of the Wayfinding BN. This will allow for the comparison of Wayfinding effectiveness between airports.

Furthermore, the nature of BN modelling allows for the continual updating of the model to reflect the latest information and research on effective wayfinding in airports.

The model can 'learn' from new data and knowledge and so remain relevant and current.

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