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THESE

Présentée pour obtenir le grade de
DOCTORAT EN SCIENCE EN INFORMATIQUE

Par

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THEME

Modélisation des environnements virtuels urbains dédiés à la simulation du mouvement des piétons.

Modelling virtual urban environments dedicated to the simulation of pedestrian movement.

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Abstract

Although simulating pedestrian's movement in urban environment is a challenging task, it has attracted the interest of researchers of different fields. In the urban planning context, movement simulation is used in the optimization of city design for ease of wayfinding and prediction of movement patterns. In wireless communication domain, predicted mobility patterns became crucial in network management optimization, allocation of critical resources and development of assisted navigation technologies. However, a realistic simulation of pedestrian wayfinding behaviour requires not only a precise modelling of human decision making process regarding strategies and heuristics applied, but also an efficient description of the spatial environment.

We propose, in this thesis, a virtual urban environment model enriched by the information needed to produce realistic pedestrian movement simulation. This model describes the geometry, topology, and spatial configuration of the simulation environment. We also provide a path planning model that takes advantage of the enriched description of the environment to make virtual pedestrians show a certain behavioural realism, especially concerning their applied strategies and route choices, which are strongly affected by their familiarity with this environment. Therefore, we propose to endow each entity with a mental representation. However, our model allows creating and simultaneously managing many entities with low costs. All proposed models are inspired from spatial cognition and space syntax domains in order to achieve naturally pedestrian navigation.

Keywords: Wayfinding behaviour; mental map; modelling virtual environment; autonomous agents; space syntax; cognitive science; urban environment.

Résumé

Bien que la simulation du comportement de navigation des piétons en milieu urbain soit une tâche difficile, elle a suscité l'intérêt des chercheurs de différents domaines. Dans le contexte de l'urbanisme, la simulation du mouvement des piétons est utilisée dans l'optimisation de la conception des villes pour faciliter la recherche de chemin et la prédiction des mouvements. Dans le domaine de la communication sans fil, les modèles de mobilité prédits sont devenus cruciaux dans l'optimisation de la gestion du réseau, l'allocation des ressources critiques et le développement des technologies de navigation assistée. Cependant, une simulation réaliste du comportement de recherche de chemin des piétons nécessite non seulement une modélisation précise du processus décisionnel humain en ce qui concerne les stratégies et les heuristiques appliquées, mais également une description efficace de l'environnement.

Nous proposons, dans cette thèse, un modèle d'environnement virtuel urbain enrichi par les informations nécessaires pour produire une simulation réaliste des mouvements de piétons. Ce modèle décrit la géométrie, la topologie et la configuration spatiale de l'environnement de simulation. Nous proposons également un modèle de planification de chemin qui tire parti de la description enrichie de l'environnement, pour faire en sorte que les piétons virtuels manifestent un certain réalisme comportemental, notamment en ce qui concerne les stratégies de navigation appliquées et les choix d'itinéraire, fortement influencés par leur familiarité avec cet environnement. Nous proposons donc de doter chaque entité d'une représentation mentale. Cependant, notre modèle permet de créer et de gérer simultanément de nombreuses entités à faibles coûts. Tous les modèles proposés sont inspirés des domaines de la cognition spatiale et de la syntaxe spatiale afin de permettre une navigation naturelle des piétons.

Mots-clés: recherche de chemin; carte mentale; modélisation d'environnement virtuel; agent autonome ; syntaxe spatiale; sciences cognitives; environnement urbain.

ملخص

على الرغم من أن محاكاة حركة السير للمشاة في البيئة الحضرية يمثل مهمة صعبة ، إلا أنه قد اجتذب اهتمام الباحثين في مختلف المجالات. في سياق التخطيط الحضري ، يتم استخدام محاكاة حركة السير في تحسين تصميم المدينة وذلك لتسهيل عملية التحرك داخلها بالإضافة لتوقع أنماط الحركة. في مجال الاتصالات اللاسلكية ، أصبحت أنماط الحركة المتوقعة ضرورية في تحسين إدارة الشبكات وتخصيص الموارد الحيوية وتطوير تقنيات الملاحة المساعدة. ومع ذلك ، فإن المحاكاة الواقعية لسلوك تحديد مسارات المشاة لا تتطلب فقط النمذجة الدقيقة لعملية صنع القرار الإنساني فيما يتعلق بالاستراتيجيات والطرق المطبقة ، ولكن أيضًا وصفًا فعالًا للبيئة المكانية.

نقترح، في هذه الأطروحة، نموذج بيئة حضرية افتراضية غنية بالمعلومات اللازمة لإنتاج محاكاة واقعية لحركة المشاة. يصف هذا النموذج الهندسة ، الطوبولوجيا ، والتكوين المكاني لبيئة المحاكاة. بالإضافة إلى ذلك نقدم نموذجًا لتخطيط المسار يستفيد من الوصف الثري للبيئة، لجعل المشاة الافتراضيين يظهرون سلوك واقعي ، خاصة فيما يتعلق باستراتيجيات الملاحة المطبقة وخيارات المسار التي تتأثر بشدة بمعرفتهم بهذه البيئة. لذلك نقترح تزويد كل كيان بتمثيل ذهني. ومع ذلك، فإن نموذجنا يسمح بإنشاء وإدارة العديد من الكيانات في وقت واحد بتكلفة منخفضة. جميع النماذج المقترحة مستوحاة من مجالات الإدراك المكاني و البناء التركيبي للفضاء من أجل تحقيق الملاحة الطبيعية للمشاة.

كلمات البحث: البحث عن مسار ؛ الخريطة الذهنية؛ نمذجة بيئة افتراضية؛ وكيل ذو تحكم ذاتي ؛ بناء تركيبي للفضاء؛ العلوم المعرفية؛ البيئة الحضرية.

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General Introduction

The patterns of people’s movement in urban systems represent one of the most important areas of research within urban studies. Human movement has been of big concern to a range of disciplines such as traffic engineering, urban design and planning. Therefore, there is a considerable interest in applications of simulating pedestrian movement. Indeed, these applications represent a useful method to help designers to understand the relation between space and human behaviour.

Recently, pedestrian movement simulation has attracted also, the interest of researchers in wireless communication domain. Since wireless portable devices have become indispensable and inseparable objects to humans, they exhibit the same mobility behaviour of them. Consequently, understanding the human mobility has become crucial in network management optimization, allocation of critical resources and development of assisted navigation technologies.

Creating a virtual environment dedicated to simulate pedestrian movement is a challenging task which requires not only creating the virtual environment itself, but also creating the autonomous agents populating it, and modelling the interaction of agents with the virtual environment. At every one of these three tasks, so many challenges arise. Indeed, when creating an environment model we have to deal with several issues such as: how it is represented, how can this representation provide easy and fast accessibility to its data, etc.

When creating autonomous agents to simulate the behaviour of navigation we are confronted to a task which is just as difficult and complex. What makes the difficulty of this task is the fact that although navigation is one of the most basic behaviour in real life it is extremely complex and still not fully understood. Therefore in order to create the autonomous agents, we have to solve a set of problems: how to represent them, how to make them move, how to make them reason, plan, and act.

Other important problem as complex and essential as the creation of the environment and the agents themselves: how to make the agents interact with the virtual environment, perceive it, plan their actions according to the virtual environment's characteristics. Indeed, the agents immersed in the virtual environment should be able to perform all the tasks the real pedestrian can: perceive their surroundings, gather information and memorize it, detect and avoid obstacles as well as other agents as they move, and plan a path according to what they see and what they know.

Problem Statement

When simulating large groups of agents, it is not sufficient to only have realistic low level movement for the agents, it is also necessary to endow the agents with a high level behaviour that can closely simulate the decision making process of real people. Most of the work in crowd simulation either deals with simple environments, or assumes every agent has complete knowledge of the environment. Therefore, it is necessary to simulate autonomous agents that can plan a realistic path inside a more or less known environment. Agents should interact with the environment as real people do; therefore the environment model is a very important feature in crowd simulation.

Problems to be addressed in this thesis can be summarized in four points as follows:

1. **Creating an environment model that captures the fundamental properties relevant to the wayfinders.** From the ecological psychology point of view, the people's movement is considered to be a self-organised phenomena arising through the interaction between among people and their environment. Indeed, people when navigating, they are affected by not only the environment's geometric or topologic characteristics. Studies in psychology and urbanism have shown that visibility and spatial configuration are also important in the navigation task. Thus, building simulation frameworks using agents which can reason about space not only requires appropriate computation algorithms, but also an efficient description of the spatial environment. Such a description must represent besides the geometrical and topological information the visual and configurational features.
2. **Making use of this model in spatial reasoning algorithms in a realistic way to achieve some human like navigation behaviour**. This point is concerned with the way to access and exploit information, provided by the environment model, in a realistic manner. The first way that our autonomous agent can access information from the environment comes from his ability to perceive it, then to organize his memory and the information he stores there. As for the exploitation, simulations usually resort to path planning. A typical method for doing this planning is to use graph traversal algorithms. Different criteria can be evaluated for the cost of the existing algorithms. Nevertheless, few of these methods combine several criteria at once. Although it seems that the fusion of this information is necessary to get closer to a realistic procedure, since psychological studies have suggested that several of these parameters must be taken into consideration simultaneously. The mixture of criteria therefore seems essential for considering the application of path planning methods to the simulation of virtual humans.
3. **Development of a virtual human as realistic as possible**. It will therefore have a behavioural chain integrating the capacities that can influence its displacement, such as decision-making regarding navigation. Wayfinding further requires a decision which path (out of multiple options) to take and subsequent locomotion

toward the goal. Several path choice heuristics have been identified that people apply when planning a trip on a map or in a real environment. These movement decisions are influenced by a number of factors, including familiarity with the environment. However, people when they differ in their moving behaviour, this implies that the movement patterns formed by them are fundamentally different.

4. This point arises because of two **constraints imposed by the underlying purpose of this subject**, which is movement simulation in an outdoor environment. First, the proposed algorithms must be sufficiently powerful to simulate a large number of entities, in order to manage crowds of people microscopically. Second, these algorithms must be realistic enough to allow an evaluation and a validation by comparison with real situations, and to produce data which can be studied.

Some commercial software already exists to simulate and analyze crowd movement. Nevertheless, these applications do not completely answer our problem, especially concerning the first and the third points.

The Proposed Approach

In order to design a model of an urban environment, dedicated to simulating pedestrian pathfinding behaviour with a high level of realism, we started from the assumption that it would be interesting to implement theoretical views from two fields: spatial cognition and space syntax. Spatial cognition research is concerned with the acquisition, organization, utilization, and revision of knowledge about spatial environments. It is interested in both the representational format of spatial information as well as in the mental operations that translate such information into navigation behaviour. Space syntax is a term that is used to describe a family of theories and techniques concerning the relationship between space and society. Space syntax research has developed quantitative descriptors of the topological form of settings that are good predictors of where people will be found walking.

The proposed approach is inspired from these two domains, in order to achieve naturally crowd navigation. Thus, we propose a method and associated algorithms to generate virtual environment model populated with autonomous agents. For these agents to be realistic, they handle the necessary behavioural procedures to be able to move and so to plan a path. This model is based on an informed hierarchical abstract graph. This description is enriched with some pre-computations such as potential visual field characteristics, or densities of people, which can be used individually by simulated entities. Furthermore, the way to accesses and to use this informed graph to perform a realistic and efficient path planning, which takes care of individual knowledge of the environment as well as individual preferences. The environment description is also used to endow agents with mental maps which contain the regions supposed to be experienced by them without going through a learning phase. Moreover, the path planning method we propose is influenced by the familiarity of the entity with the environment, which allows the entity to adapt its pathfinding strategy in consequence.

Contributions

The first contribution of this thesis is the description of virtual environments in an automated way, and renders information concerning this environment judged to be relevant in wayfinding, available at low costs: spatial morphology, visual field, etc. The second contribution is a path planning method which is: realistic thanks to the type of managed criteria and the navigation process specific to the level of familiarity; individual to each entity thanks to the environment knowledge and the preference costs; and automatically adaptive thanks to the incremental navigation process; efficient in computation time thanks to the pre-calculations. The third contribution is a method to endow a great number of agents with a mental map. Although, this method doesn't require a learning time, in order to be efficient in computation time, it permits to simulate the content of the mental maps of real people.

Thesis structure

The thesis is composed of two parts: 1) the state of the art which provides a theoretical background to the thesis by reviewing the body of relevant literature across several fields and 2) the contributions which proceed with a full explanation of the virtual environment model that we propose, the means of its enhancement, and the way we leverage it for movement planning purposes, without forgetting path planning and mental map models.

The first part is itself composed of three chapters: *Human movement*, *Space syntax and wayfinding*, and *Modelling pedestrian movement*.

> **Chapter 1** provides an overview of relevant concepts and existing literature in the field of spatial cognition on mental maps and wayfinding.
>
> **Chapter 2** discusses space syntax topics related to the study of space representation and pathfinding.
>
> **Chapter 3** is the last chapter of this first part and it introduces the movement simulation research field. First, it provides an overview of the approaches used to model pedestrian movement. Then, it presents previous works on virtual environments representation as well as virtual humans cognitive maps. It also details existing path planning algorithms.

The contributions part of this thesis is composed of three chapters: *Virtual environment model and mental map model for pedestrian movement simulation*, *Simulation model of the pathfinding behaviour in familiar and unfamiliar environments*, and *Experiments and results*.

> **Chapter 4** this chapter is divided into two principal parts. The first part, presents our methodology for the generation of informed virtual environments. The second part, presents the structure of the mental map then it details the different steps which compose its creation process.

Chapter 5 presents our incremental path planning algorithm which leverages the hierarchical topologic graph resulting from the abstraction process. It details how we support spatial agents' navigation in informed virtual environments.

The model presented is then implemented and tested on a test dataset. The computational implementation and the results of the tests are discussed in **Chapter 6**.

Finally, conclusion and perspective section draws conclusions from our work, discusses the main contributions of the thesis, outlines its limits, and discusses avenues for future research and applications.

Part I State of the art

Chapter I Human movement

I.1 Introduction

The capacity of moving is, without doubt, one of the basic behaviours indispensible for a human being. People move within cities with different objectives, such as to do shopping, to socialize, to go to some particular place or only to wander. Everyone moves in his own way, with their unique mental and physics distinctive peculiarities and motivations. However, human behaviour is based on a number of shared decision-making parameters and spatial accessibility restrictions imposed by the environment where it occurs.

This chapter reviews previous work in the fields of spatial cognition, related to wayfinding, and the acquisition of spatial knowledge. Without trying to be exhaustive in this domain, we will synthesise a set of studies that have served – or can serve – to the elaboration of computer models. First, section I.2 discusses different definitions of the terms "human movement", "navigation" and "wayfinding". Then, section I.3 introduces theories dealing with the mental representation of space. While section I.3 presents theories attempting to explain pedestrian wayfinding behaviour and the cognitive and perceptive processes at work during individual spatial decision-making. Finally, Section I.5 concludes this chapter.

I.2 Human movement, navigation and wayfinding

I.2.1 Human movement

When searching the literature for the definition of the term human movement we found that the term is rarely defined. According to Skorupka this is may be caused by the fact that the term wayfinding is often used on movement (Skorupka 2010). Therefore, we need, from the beginning, to differentiate this term from the term wayfinding. In one of the few definitions, movement is considered as *any spatial displacement of the body or bodily part initiated by the person himself* [herself] (Buttimer & Seamon 2015). Skorupka (2010) defines human movement as *deliberately walking or making one's way through some space*. Therefore movement can include, among others, travel between known places, navigation to novel destinations, or exploration with no specific destination.

On the other hand, wayfinding is defined by Golledge (1999) as *finding* one's way from an origin to a destination. Allen (1999) further defines it as *purposeful movement to a specific destination that is distal* and, thus, cannot be perceived directly by the traveller. By comparing the two definitions, "*wayfinding*" is also making one's way, and it falls into the category of movement as an intentional act of making one's way through the space. However, Skorupka suggests that the term movement encompasses other types of making one's way through some space, such as exploration, or movement to known destinations. While Allen (1999) and Wiener, Büchner & Hölscher (2009) in there suggested taxonomies, consider exploration or moving to a familiar destination as wayfinding tasks.

As for human navigation, Montello (2005) describes this term as being a special type of movement of the entire body that is "coordinated and goal-directed". He advises that navigation is composed of two skills, wayfinding and locomotion. He describes wayfinding as a cognitive process enabling us to plan our movement toward the goal. Locomotion is the skill used to reach the goal by moving the body in a synchronised fashion through, around, over or under obstacles and features of the environment. Next section discusses different definitions of the term "wayfinding".

I.2.2 Wayfinding

A. Definitions of wayfinding

Emo mentioned in (Emo 2014a) that the word *wayfinding* owes its roots to the word pathfinder. He argued this connection by the fact that the German word ***"pfadfinder"*** closely relates to what we mean by the term wayfinding. This term was used for the first time by Lynch, in the late 70s, to replace the term *spatial orientation* (Hochmair 2002). Which refers to a person's ability to determine his or her location in a setting, thus, describes the static relationship of a person to his or her spatial setting. Because the *spatial orientation* concept cannot encompass the dynamic aspects of people's movements, the concept *wayfinding* filled this missing part. Therefore, wayfinding was used to account for people's movement in space and their sense of being orientated, it described the process of reaching a destination, whether in a familiar or an unfamiliar environment.

There are a number of alternative definitions of wayfinding. Lynch (1960) defines this term as based on: "a consistent use and organisation of definite sensory cues taken from the external environment". As described by Allen (1999) and Golledge (1999), wayfinding is a directed and motivated movement, with a starting and ending point, whereas such destination is not visible or tangible by the "navigator". Such behavior involves interactions between the navigator and the environment. Human wayfinding takes place in large-scale spaces (Downs & Stea 1977) (Kuipers 1978). Such spaces cannot be perceived from a single viewpoint therefore people have to navigate through large-scale spaces to experience them. Examples for large-scale spaces are landscapes, cities, and buildings.

Another way to understand "wayfinding" is described as being a series of direction choices, taking place at decision points within the urban grid (Klippel et al. 2004), or still as the ability of finding paths to a particular destination, in a convenient way and being able to recognize the destination once it is reached (Peponis, Zimring & Choi 1990). The definition used in this thesis, based on the (Montello 2001) definition, identifies wayfinding as the decision-making process of navigation; it refers therefore to individual spatial decision-making.

B. *Wayfinding elements*

Hochmair (2002) analyzed several wayfinding definitions and found some terms that seem to describe a kind of central meaning of wayfinding:

– **Decision points**

Decision points are those areas where a navigator has the opportunity to select among different paths. Raubal & Egenhofer (1998) distinguish between areas where the navigator has *one* obvious option to continue the wayfinding task (*enforced decision points*) and points where subjects have *more than one* choice to continue the wayfinding task (*decision points*).

– **The agent has a goal**

The goal is a desired position that the agent tries to reach. During the wayfinding process, goal and mental position have a different value. The goal is reached if these two components become equal.

– **Order of actions**

Actions in wayfinding are ordered. When executed in a sequence, the steps give a certain *path* of positions. In wayfinding, making a step needs *one specific* pre-condition (i.e., a specific position in the environment) in order to be performed. Thus, a permutation of a sequence of actions does not give a path (the unique precondition for some of the permutated actions is not given).

I.2.3 Taxonomy of wayfinding tasks

Allen (1999) suggested a taxonomy of wayfinding tasks based on functional goals. It consists of three categories:

1. ‘**commute**’: travel with the goal of reaching a familiar destination; involves following a familiar route from a known origin to known destination with low levels of uncertainty for the traveller.

2. ‘**explore**’: exploratory travel with the goal of returning to a familiar point of origin; This involves a familiar start and destination, often the same place, with the aim of finding new places and new paths between these new places and places already known to the traveller. Unlike commute wayfinding which generally uses automatic memory and low levels of effort, explore wayfinding involves conscious cognitive processing.

3. ‘**Quest**’: travel with the goal of reaching a novel destination. The traveller is proceeding to a specific destination which is unfamiliar to them and which they may not have previously visited. ‘Quest’ wayfinding requires high-level cognitive abilities, greater than those required for explore wayfinding.

Wiener, Büchner & Hölscher (2009) proposed an extended taxonomy of wayfinding that distinguishes tasks by external constraints as well as by the level of spatial knowledge that is available to the navigator. Their classification takes the navigator's knowledge, a key factor in wayfinding, into account (Figure I-1).

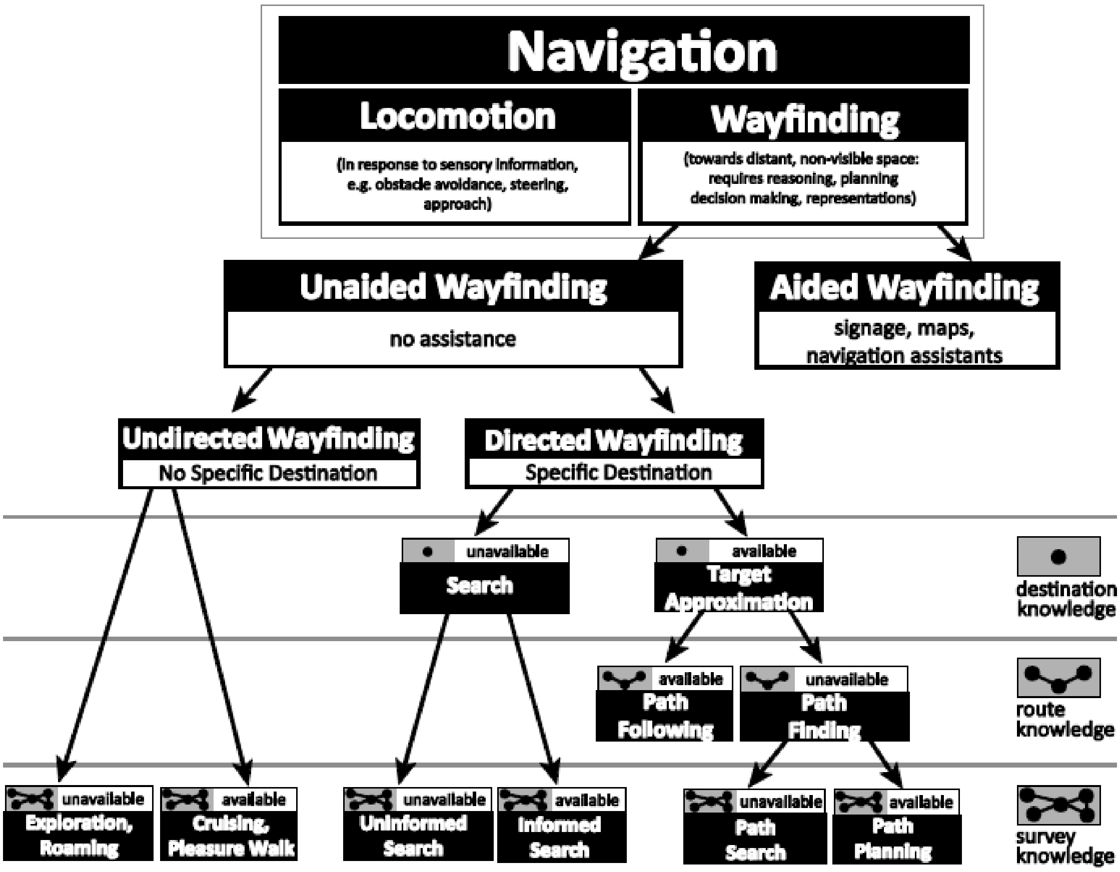


Figure I-1 : Proposed taxonomy of wayfinding tasks, classified by the existence of an external aid, a specific destination and the availability of different levels of knowledge (Wiener, Büchner & Hölscher 2009).

I.3 Mental representation of space

It is to the mental representation allowing the first type of reasoning –navigation that we will attach here. Human being needs to represent the environment even before being able to move in it. Indeed, this mental representation will serve him to reason about this environment, to evaluate a path to achieve a precise location or to organize the tasks he has to perform. People learn the layout of their environment through continuous interaction. They perceive the environment through senses, learn the layout of the environment and store the knowledge acquired in mental representations (Figure I-2).

Mental representation that corresponds to people's perceptions of the real world is called "cognitive map". This term appeared for the first time in a paper by Tolman (1948). Other terms, such as cognitive collage (Tversky 1993) or cognitive atlas (Hirtle 1998) have also been proposed.

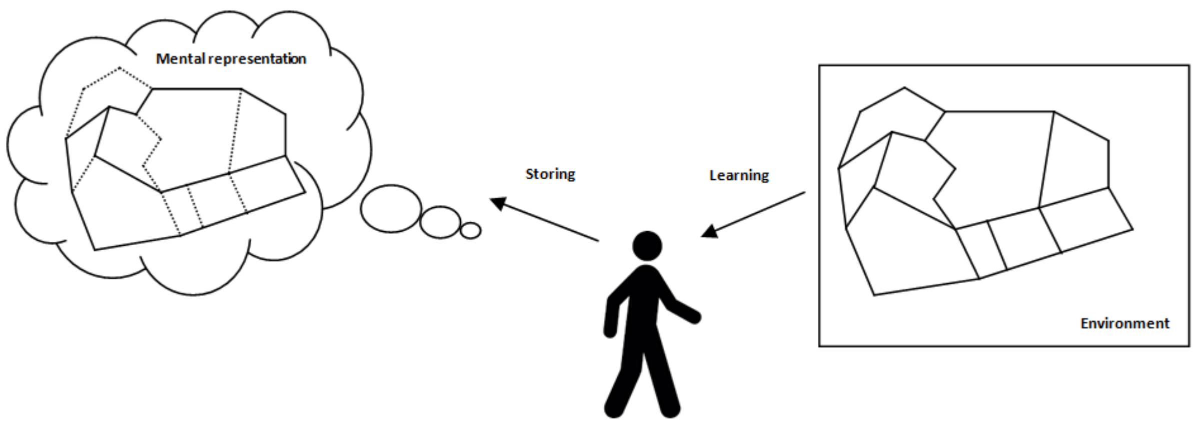


Figure I-2: **Acquisition of spatial knowledge. A person perceives the environment, learns its layout, and stores this knowledge in a mental representation.**

I.3.1 Conceptualisation of Space

A number of studies have examined the role of cognitive maps on wayfinding behaviour, notably on how information is ordered and depicted. In cognitive neuroscience, recent researches found that there are three types of cells representing different types of spaces: place cells describing where, head direction cells on the direction, and grid cells reflecting the distance (Dalton, Hoelscher & Spiers 2015). Although, following the representational theory of mind, the basic elements of mental representations are called concepts (Margolis & Laurence 2010). Concepts are the result of a cognitive process of categorization of the knowledge acquired while perceiving the world (Rosch 1978). The goal of the cognitive process is to create a simplified, abstract model of the knowledge acquired, in order to reduce its complexity and thus the mental effort required to store it. Furthermore, conceptualizations allow generalizations and abstract reasoning about the domain of knowledge processed.

An important contribution to the conceptualization of space is the work of the urbanist Kevin Lynch, studying the phenomenon of imageability of urban environments. Lynch (1960) interviewed residents of three cities and found out that people build their mental model of a city based on five spatial elements. These elements present the basic concepts in the static spatial mental representations, i.e. the image of the city people retain after experiencing it. Briefly, Lynch defines the elements of the city form as follows:

1. *Landmarks*, distinct points in a city that serve as reference to the user.
2. *Paths*, channels of movement.
3. *Nodes*, strategic spots in the city where the observer can enter.
4. *Edges* are linear but do not facilitate movement. They form physical barriers.
5. *Districts* are areas in a city that have some common characteristics such as a particular architectural style.

I.3.2 Scale of environment

Scale is an essential component in the process of navigation because different size spaces result in qualitatively distinct knowledge acquisition (Bell 2002). The widely accepted classification includes small-, medium-, and large-scale based on the absolute sizes of space. Gärling & Golledge (1989) suggested that small-scale space is comprehended from a single vantage point, from which the whole environment could be perceived. A single room or a small triangular route has served as an example of small scale space in empirical studies (Foo et al. 2005). Knowledge can be acquired directly in both small-scale and medium-scale space, though the latter is slightly larger than the former. For large-scale spaces such as a neighbourhoods, towns, or cities which are much more complex and of a larger size, spatial relationship cannot be perceived directly. In this space locomotion is required for a traveller to acquire and update information to make navigational plans (Garling, Book & Lindberg 1984).

Montello (1993) proposed another systematic classification based on the relative size of the space to the human body, which consists of *figural*, *vista*, *environmental*, and *geographical* space. The *figural* and *vista* spaces share similar characteristics with the previous small-scale space as they could be perceived from a single vantage point. In a *figural* space the human body is larger than the space in question. The *vista* space is relatively larger than the human body but still can be comprehended from a single point. In Montello's description, an *environmental* space is larger than the body and cannot be comprehended directly without locomotion. Finally, *geographical* space is much larger than human body and must be learned through symbolic representations like maps.

I.3.3 Development of cognitive maps

The development of cognitive maps is incremental, i.e. at the beginning, cognitive maps are fragmentary, and then, with further spatial experiences, they are completed and substantiated (Hochmair 2002). However, several authors (Siegel & White 1975; Thorndyke 1981) assume that spatial knowledge acquisition follows a main sequence of landmark, route and survey knowledge in ascending order.

1. *Landmark knowledge* comprises distinct, typically familiar points in the environment.
2. *Route knowledge* is characterized by the knowledge of paths between landmarks (topological information).
3. *Survey knowledge* allows people to locate landmarks and routes within a general frame of reference (i.e., incorporating metric measurements).

Landmarks are the first elements to be included into spatial representations. At that early stage, we speak of **landmark knowledge**. People can describe single features of the route, but most of them are not able to retrieve the route alone.

Further on, these points are connected by the most frequently travelled routes. Route knowledge consists of the familiar routes connecting junctions and/or landmarks. **Route knowledge** is acquired gradually and therefore features a sequential structure. The sequence of landmarks and turnings is used to proceed on the entire route. People are able to retrieve the route and the goal and possibly to go back and find the starting point.

At both levels, spatial knowledge is egocentric, i.e. depending on the actual position and viewing direction of the navigator, whereas at the third and last distinguished level, **survey knowledge**, spatial knowledge is allocentric, i.e. independent from the individual. In order to gain an overall picture, landmarks and several routes are integrated in a more and more complex network. Survey knowledge exists if shortcuts and bypassings are found, good direction estimations and beeline distance estimations are made, and if some variations in the specific routes do not prevent subjects from finding their way (Tolman 1948).

The speed with which people learn the environment and transit between these stages of spatial mental representations depends on each individual, and his spatial abilities (Allen 1999) and the frequency of interaction with the environment. Continuous interaction with the environment allows proceeding from landmark to route to survey knowledge. It has been recently hinted, however, that these types of knowledge may be acquired simultaneously (Ishikawa & Montello 2006), depending on the individual's spatial abilities. For instance, some individuals may acquire basic metric characteristics of space after relatively little interaction. Thus, continuing interactions allows the accuracy and completeness of the acquired spatial knowledge to improve, although individual differences in spatial abilities effectively impose a limit to such improvements. Thus, individuals with innate good spatial abilities or good spatial training (e.g. geographers (Golledge 1995), taxi drivers) may quickly form accurate and relatively complete spatial mental models of the environment. This progression happens, however, not in months or years as previously suggested, but within a few trips through the environment in question (Ishikawa & Montello 2006).

The mental representation acquired through direct experience of the environment is further supported by secondary, indirect spatial learning. Inhabitants of a city enhance their spatial knowledge from sources such as maps, news articles, advertisements and Web resources. These spatial narratives (Levine & Klin 2001) and geo-referenced descriptions (Winter & Tomko 2006) add to the spatial mental representations of people residing in a specific city during longer periods of time.

When orientating and navigating, people use their present spatial knowledge to develop an action plan. The navigation strategies are based on the spatial information available. Thus, a subject disposing of survey knowledge can choose from a larger number of strategies than a subject disposing only of landmark or route knowledge.

Although Golledge (1999) argues that cognitive maps are necessary for human navigation, people have the ability to find their ways in unfamiliar environments—such as a newly experienced airport or hospital—without referring to a previously acquired cognitive map. One could argue though that people build some sort of mental collage at each bifurcation, which is essentially an integration of different views at a decision point. Such representation helps them in making a decision of how to proceed further.

I.3.4 Graph-based models of space

In spatial cognition and artificial intelligence, graphs have been used for decades as model for mental representations of environments. For example, in 1979, Byrne suggested that the memory for urban environments is realized in a network of places. Ever since, a multitude of such graph-like models of spatial memory have been developed (Franz et al. 2005).

The particular appeal of graph structures as models for spatial memory arises from their superior flexibility as compared to map-like representations of space. For example, while basically being topological structures, by labelling or weighting single edges of graphs, distance and direction information can be included that allow for metric navigation abilities such as short-cutting behaviour (Hübner & Mallot 2002). Additionally, various non spatial information can be attached to the nodes, for example, places can be labelled with emotional or episodic information (Franz et al. 2005) . Also, graph structures permit the representation of inconsistencies and incomplete knowledge, factors that appear necessary to explain several empirical findings in human spatial cognition. Taken together, due to their minimalism and efficiency, graph-like mental representations of space are ecologically plausible, sufficient for the explanation of a wide range of behaviour, and, last but not least, they fit well to the neural structure of human brains (Franz et al. 2005).

I.3.5 Hierarchical Structure of Spatial Mental Representations

Human spatial memory has a certain property, namely its hierarchical organization that lately has been shown to influence route planning and navigation behaviour (Wiener & Mallot 2003). Hierarchical theories of spatial representations state that spatial memory contains nested levels of detail. Such a memory structure can be expressed in graph like representations of space in which locations are grouped together and form super ordinate nodes.

I.3.6 Experiential Hierarchies

Experiential hierarchies form in mental representations as a product of the interaction of wayfinders with the environment. The intensity of experience of a spatial feature is related to its functional, structural or semantic (individual) prominence in a specific environment. This experience of prominence establishes a partial order between the mental representations of the individual spatial features, and an experiential hierarchy emerges (Tomko, Winter & Claramunt 2008).

I.4 Spatial reasoning and decision making

Spatial reasoning involves a variety of decision-making methods and choice behavior. Decision theory covers a large range of models with different foci on describing how decisions could or should be made and on specifying decisions that are made (Golledge 1997). Mathematically, a decision rule is a function that assigns a value to each alternative, showing what will happen when a particular strategy is adopted. Decision-making criteria are a set of procedural rules that oversee the evaluation of the outcome when decision rules are applied to a task situation. A strategy contains decision rules that seek a result from all possible ways of making a relevant decision. Golledge (1997) argues that in many cases human decision-making is not strictly optimizing in an economical and mathematical sense and therefore emphasize behavioural decision theory.

I.4.1 Spatial cognition

The word spatial is defined as "*concerning or existing in space*" (*Oxford advanced learner's dictionary of current English* 1992) or "*relating to space*"(*Collins dictionary of the English language* 1986). Spatial cognition refers to both the perceptual and conceptual processes that are involved in understanding the physical environment. This theory proposes that the perceiver has certain cognitive structures called schemata that enable the perception and therefore pick-up of information from the environment.

Spatial abilities are cognitive functions that enable people to deal effectively with spatial relations, visual spatial tasks and orientation of objects in space. One aspect of these cognitive skills is spatial orientation, which is the ability to orient oneself in space relative to objects and events; and the awareness of self-location (Arthur & Reber 1985).

Human spatial cognition is a part of the interdisciplinary research area of cognitive science. Researchers from many academic disciplines, such as psychology, linguistics, and computer science investigate about the mind, reason, experience, and people's conceptualizations of the world in which they live. The discipline spans a vast number of topics, such as spatial perception, spatial memory, cognitive modelling, individual differences, neuroscience and navigation.

I.4.2 Individual differences in the human wayfinding decision making process

Individual differences are the ways in which people differ in their behaviour. Psychological research has shown that individual differences exist for spatial task performance.

- ***Decision style***

Each pedestrian makes decisions based on a decision style, which may be different for the various types of decisions (Bovy & Stern 1990). Decision styles are based on herding behaviour, utility maximisation, and habitual behaviour (Avineri & Prashker 2006).

- ***Age***

Previous research has shown that older adults do not perform as well as younger adults on a variety of spatial tasks, including those requiring information about specific environmental layout (Kirasic 2000) and forming cognitive maps or surrounding environment (Iaria et al. 2009).

- ***Gender***

According to Seneviratne & Morrall (1985) and (Verlander & Heydecker 1997) the choice of route appears to be not much different between the two sexes, while Chebat, Gélinas-Chebat & Therrien (2008) found that males are more efficient than females; for example, some researchers have found that men are more efficient at finding destinations(Malinowski & Gillespie 2001). Males have better knowledge of geographical maps and draw better maps (Harrell, Bowlby & Hall-Hoffarth 2000), which is usually attributed to the fact that men are more socialised with maps (Lawton & Kallai 2002).

Another implication of gender differences is that women and men may differ in strategies for finding a destination where females are more likely to adopt the egocentric strategy and the males are more likely to adopt the allocentric strategy (Chen, Chang & Chang 2009). Another possible implication of gender differences is that women and men may differ in the way they feel about performing tasks that appear to require a sense of direction. Women show a higher level of anxiety than men such as trying a new shortcut without the aid of a map or figuring out which way to turn when emerging from a parking garage (Lawton & Kallai 2002). Women show a higher level of anxiety than men such as trying a new shortcut without the aid of a map or figuring out which way to turn when emerging from a parking garage (Lawton 1994).

I.4.3 Mechanisms, strategies and heuristics of route planning

Golledge (1995), with a series of pilot experiments, has demonstrated that the path selection problem is the result of minimizing procedures such as selecting the shortest path, the quickest path or the least costly path. This statement has been assumed by researchers; indeed, when walking from a trip origin to a destination, a pedestrian typically tries to minimize a variety of costs, including distance, travel time, cognitive cost. However, the critical issue identified by these researchers is which mechanisms, strategies and heuristics are applied during route planning that allows deriving the shortest path, the quickest path or the least costly path?

There exists a large body of research that analyses the different criteria a pedestrian may consider when choosing a route from among a variety of path alternatives. This section discusses the cognitive and perceptive processes at work during individual spatial decision-making.

- ***Initial segment strategy***

The initial segment strategy (Neisser 1976) (Bailenson, Shum & Uttal 2000) suggest that people tend to focus disproportionately on the initial portions of the route and that they prefer routes with longer straight initial segments, regardless of what the later portions of the routes look like. This strategy is motivated by the idea that people, by turning as late as possible, try to minimize the cognitive effort required for navigation. They did not worry about when and where to turn until they had to turn.

Results of experiments conducted by researchers among them Dalton (2003) have revealed that subjects choose the straightest possible routes and defer turns in situations with several path choice options that were equal with respect to distance, time, and number of turns when crossing a street. These findings confirm the initial segment strategy. It also support a hypothesis by Hillier (1997) that people tend to follow the longest line of sight that approximates their heading. This strategy offers a possible explanation for the fact that people’s route choices are often asymmetric; i.e. people choose different routes from A to B than from B to A (Dalton 2003).

– ***Least-angle strategy***

With the least-angle strategy (LA) (Hochmair & Frank 2000); (Dalton 2003), the navigator aims at maintaining track of the target direction throughout the trip. This heuristic states that people choose the path that is closest (in terms of angularity) to a direct line between their current position and the goal.

– ***Least-decision-load-strategy***

The least-decision-load-strategy states that subjects, when having the choice between alternative paths, choose the path that minimizes the number of possible movement decisions (Wiener, Ehbauer & Mallot 2007). Such a strategy could be employed, because the risk of getting lost is smaller on less complex routes.

– ***Progressive planning based on landmarks***

Landmarks are often stored in memory and recalled later because of the dominance of their visible form, the peculiarity of their form or structure. A marker also helps insofar as it can indicate where the action or movement should change (the point where you have to turn, for example), the location near other landmarks, where the path that we have just taken is good (confirmation function by reference). It is absolutely essential to have a good knowledge of the geometry of the roads to be able to go from one landmark to another without difficulties. The frequency with which landmarks are mentioned as an aid to navigation gives rise to inter-individual differences. For example, it has been shown that women's strategies are largely based on visual cues and more often than men's (Tom & Denis 2003).

– ***Regionalized environments***

Stevens & Coupe (1978) demonstrated that people construe spatial representations that are geared to existing structures in the environment. Wiener, Schnee & Mallot (2004) conducted a study in a Virtual Reality (VR) setting in which they found that people performed better in a search task when target landmarks were grouped by colour than when they were not. This study indicate that people do mentally divide space into regions and that regionalized environments and respective representations can facilitate wayfinding, resulting in better performance. The regions are perceived and encoded in spatial memory very early during the process of learning an environment. During navigation such regional information could be used to overcome missing or imprecise spatial information on the detailed level.

– ***Fine-to-coarse***

A second line of research describes heuristics derived from hierarchical representations of space. Wiener & Mallot (2003) proposed the fine-to-coarse planning heuristic, a cognitive model that describes this simultaneous use of spatial information at different levels of detail during route planning (Figure I-3). The core of this fine-to-coarse heuristic is the ‘focal representation’ that is generated from the hierarchical reference memory of space by using fine space information (place-connectivity) exclusively for the current location and the close surrounding and coarse space information (regions-connectivity) exclusively for distant locations. In this focal representation, the shortest path to the next target (target-place or target-region) is planned. Planning a route in such a focal representation results in a detailed plan for the close surrounding allowing for immediate movement decisions, while only coarse spatial information is available for distant locations. The route plan therefore has to be refined during navigation.

– ***Cluster-strategy***

The cluster-strategy states that human route planning takes into account the distribution of target locations within an environment, resulting in a preference for paths that allow visiting as many target places as fast as possible (Gallistel & Cramer 1996).

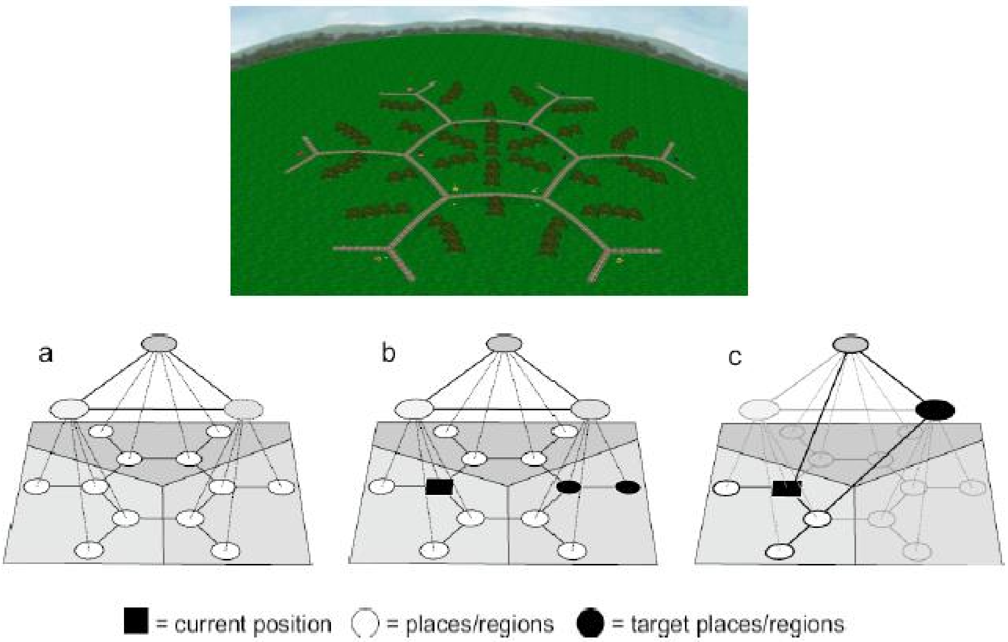


Figure I-3 : Hierarchical mental representation for path planning according to Wiener & Mallot (2003). At the top, the test environment, and its equivalent mental model. In b the starting conditions (position and destinations), and in c the hierarchical paths.

I.4.4 Decision levels

In the 80s, *wayfinding* was modelled as spatial problem solving (e.g. (Downs & Stea 1977)), which comprises four distinct stages. These are:

– spatial orientation which is the identification of the self location and target location within the environment;
– the selection of the initial route from the starting location to the target;
– continuous monitoring of the route taken, modified by estimates of self location and target location and reassessment or confirmation of route choice;
– and finally, the ability to recognise when the target has actually been reached.

(Arthur & Passini 1992) have an alternative view of wayfinding which comprises three specific but interrelated processes:

- Decision making and the development of a plan;
- Decision execution, which transforms the plan into appropriate behavior;
- Information processing, comprising environmental perception and cognition.

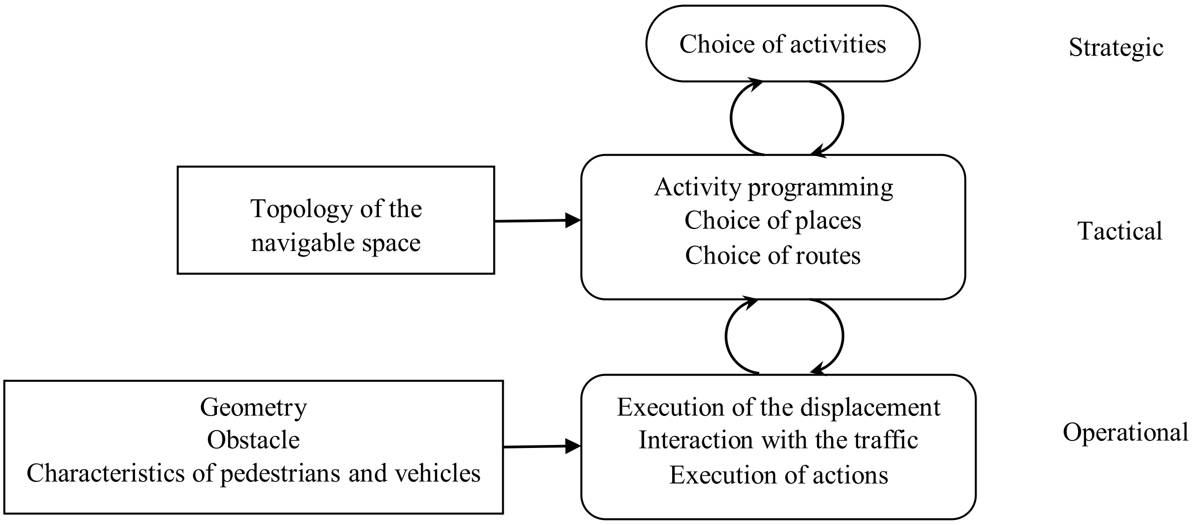


Figure I-4: Levels of decision (Daamen 2004).

In (Hoogendoorn, Daamen & Bovy 2003); (Hoogendoorn & Bovy 2004);(Daamen 2004). The authors distinguish three levels of decision making in a pedestrian's behavior: a strategic level, a tactical level and an operational level (Figure I-4):

1. At the ***strategic level***, the pedestrian decides on the activities he intends to carry out in his environment and, if necessary, the scheduling between these activities (example: read a newspaper, validate his ticket before entering the bus, and buy a sandwich). The choice of activities is related to the pedestrian's preferences and predispositions and the services available through the environmental infrastructures.
2. Activities identified at the strategic level can be carried out in different ways or in different places. The precise way to achieve them and the choice of routes to reach these places are considered to be at the ***tactical level***.
3. At the ***operational level***, pedestrians make decisions for every moment according to tactical choices. The choice of the trajectory, the speed of movement, the attitude, or any other action to be carried out immediately falls within this level (Daamen 2004).

There may be interactions between different levels of decision. In particular, the impossibility of carrying out an action may encourage the pedestrian to consider other alternatives for the activity in progress or to modify the scheduling between the various activities that he wishes to carry out.

I.4.5 Perception of distance

Distance is not only an important factor on which route choice is based, it also influences the way pedestrians choose their routes. In recent years, research results have accumulated in cognitive sciences which suggest that the metric distance assumption is unrealistic. People do not move through the environment using rulers or tape measures. When viewing a scene the result is a retinal image that is of quantitative nature, but people's knowledge about the scene is qualitative (Freksa 1991). By using abstract geometrical analysis, Piaget & Inhelder (1967) demonstrated that fundamental spatial concepts are topological, but not Euclidean at all.

Instead of doing exact calculations, people apply qualitative methods of spatial reasoning (Frank 1992); (Freksa 1991) that rely on magnitudes and relative, instead of absolute, values. As a consequence, our notions of distance are compromised by the visual, geometrical and topological properties of networks. For example, estimates of distance have been shown to be affected by the division of routes into discrete visual chunks (Kim & Penn 2004), by a tendency to correct bends to straight lines and turns to right angles (Allen 1981), and even by the direction in which the estimate is made (Golledge 1995). Magel & Sadalla (1980) asked people to estimate the length of different pedestrian journeys. They found that people found trips shorter if they had fewer turns, even if the physical distance covered was longer.

Different types of distance are therefore distinguished in literature. (Khisty 1999) and Montello (1991) distinguish between **'perceived' distance** and **'cognitive' distance**. Cognitive distance concerns people's beliefs about distance where the destination cannot be seen; perceptual distance concerns beliefs about directly observable destinations. Note that 'belief' is used in place of estimate, as 'estimate' involves the communication of the belief to the experimenter.

I.4.6 Factors influencing wayfinding

Several theories in the field of human spatial behaviours have been proposed in order to explain how people navigate in the physical world, what people need to find their ways, and how people's visual abilities influence their decisions. Several factors influence wayfinding behaviour. Some relate specifically to the individual, such as whether they are familiar with the environment, the type of spatial knowledge available to them, the nature of their destination and what their spatial abilities are. Other factors relate to the environment itself, such as spatial configuration. We found that the factors influencing the choice of routes may be categorized in two groups: environment characteristics and pedestrian characteristics.

A. Environment characteristics:

This group is itself composed of two subgroups:

Route characteristics:

- **Distance** (Seneviratne & Morrall 1985); (Verlander & Heydecker 1997). Pedestrians appear to frequently choose the shortest route, although they are seldom aware that they are minimising distance as a primary strategy in route choice.
- **Time** (Seneviratne & Morrall 1985). Since pedestrians choose the route with the shortest length, this route often takes the least walking time. Reason for this is that congestion only occurs at specific areas, such as transport stations. For longer routes, pedestrians are less apt to choose not the shortest route in distance, as they have to supply their own energy.
- **The initial street segment of the route**. Besides deviation angle Hochmair & Karlsson (2004) suggests that the following parameters (which can all be perceived at a decision point) may among others play a role in the navigator's choice between street alternatives: a) the length of the initial street segment, b) the number of streets intersecting with an initial street segment, c) and the hierarchy or width of the initial street segment.
- **Pleasantness or number of attractions along the route** (Bovy & Stern 1990), (Seneviratne & Morrall 1985). As routes become more attractive, walking time becomes a less important factor.
- **Directness** (Dalton 2003); (Helbing & Molnar 1997). Directness is defined in relation with visibility, that is pedestrians walk straight towards a visible destination, unless they are hindered by obstacles, other pedestrians, or diverted by other attractions. Hill (1982) uses another definition of directness, in which route length and route complexity are combined (Hill 1982). However, route length is already included in the characteristic ‘distance’ and is therefore omitted from the aspect ‘directness’.
- **Crowdedness** (Helbing & Molnar 1997); (Seneviratne & Morrall 1985). Even if the progress on a direct route is relatively slow (until approximately 3/4 of capacity flow is reached), still the choice for a longer route (in distance) is seldom made.
- **Safety** (Seneviratne & Morrall 1985). Safety may be influenced by a number of factors (such as number of street crossings, size and speed of car traffic flows along the sidewalk, but also whether pedestrian and cycle traffic is mixed).
- **Weather protection, noise, and air pollution** (Bovy & Stern 1990); (Seneviratne & Morrall 1985). These are all environmental influences of the chosen route, which are not evaluated as important factors influencing pedestrian route choice. Despite the availability of an elevated enclosed walkway system, hardly anybody chooses this route due to bad weather (Seneviratne & Morrall 1985).
- **Quality of the walking surface** (Bovy & Stern 1990); (Helbing & Molnar 1997). When a route is so unfavourable that large detours have to be made and the walking surface is of acceptable quality, pedestrians make their own paths, so-called ‘stamped paths’(Helbing & Molnar 1997).

Road network characteristics:

- **Network configuration** The role of spatial configuration on individual spatial decision- making is particularly interesting because it suggests that the layout of the environment itself affects the choices that individuals make. The term spatial configuration refers to the way every space in the built environment relates to every other. Several studies have identified this factor as a relevant one for wayfinding studies (Emo 2014b); (Haq & Zimring 2003). Road networks have an underlying structure. This structure is defined by the layout, arrangement and the connectivity of the individual network elements, the road segments and their intersections.
- **Number of routes available** (Seneviratne & Morrall 1985). One of the most important characteristics is overlap in routes.
- **Attractors' distribution** (Bovy & Stern 1990; Golledge 1995). The presence of attractors has a strong influence on wayfinding activity. Attractors are defined as those elements that skew wayfinding behaviour towards them; common examples are people, vehicles and also light (e.g. study of Antonakaki (2006) on the social dimension of the effect of light). Previous research has indicated the effect of some of these factors, notably the presence of people (Dalton et al. 2011).

B. Pedestrian characteristics:

- **Familiarity**. The amount of previous exposure to an environment is a critical factor affecting wayfinding. Indeed, wayfinding activity depends on what level of knowledge the subject holds about the destination location, how to get there, and the intervening locations. These three types of knowledge have been termed landmark, route and survey knowledge (Siegel & White 1975). People in an unfamiliar setting make choices based on information within the scene. The effect of previous experience on wayfinding performance was found to be critical in (Garling, Book & Lindberg 1984); (Hölscher, Brösamle & Vrachliotis 2012); (Hölscher et al. 2006); (Abdul Khanan & Xia 2010). Familiarity with the environment does influence strategy choice in directed wayfinding tasks (Hölscher et al. 2006). Abdul Khanan & Xia (2010) have found that the type of landmark used was related to the familiarity that tourists have with the site. Linear landmarks such as pathways were used more often by those tourists that are either totally familiar or have never visited the site (Xia, Packer & Dong 2009). In another research by Xia, Packer & Dong (2009), it has been discovered that the more tourists that are familiar with the environment, the less chance they use landmarks.
- ***Travel group.*** Individual differences between types of travel groups may be an important factor in wayfinding behaviours and strategies because of the various influences each member may have on decisions. The difference between various travel groups can be observed in the usage of landmarks. Individuals are less likely than other travel groups to navigate using signposts, while couples are more likely than other types of groups to do so (Xia, Packer & Dong 2009).
- **Age.** The proportion of persons selecting a route according to a given factor changes marginally between the distinguished age groups (Seneviratne & Morrall 1985).

- **Gender.** Gender differences can influence wayfinding performances if we admit findings of researchers which suggest that the choice of route is different between the two sexes.
- **Decision style.** As we have cited previously each person has a decision style, which may be different for the various types of decisions (Bovy & Stern 1990). Different decision styles imply different wayfinding behaviours.
- **Purpose.** (Bovy & Stern 1990); (Seneviratne & Morrall 1985); (Verlander & Heydecker 1997). The extent to which route attributes play a substantial role in route choice behaviour depends mainly on trip purpose (Bovy & Stern 1990), e.g. scenery is very important for recreational trips, but it plays no role for work-related walking trips. It follows that the same subject looking at the same scene in two instances, with a different purpose in mind in each case, might well reach a different conclusion as to which way to go. In contrary to these findings, Jiang & Jia (2011) relying on random and purposive moving agents, he simulated human movement in large street networks and he found that aggregate flow, assigned to individual streets, is mainly shaped by the underlying street structure, and that human moving behavior (either random or purposive) has little effect on the aggregate flow. This finding implies that given a street network, the movement patterns generated by purposive walkers (mostly human beings) and by random walkers are the same.

I.4.7 Synthesis

The focus of spatial cognition is the process in which people perceive, memorize, encode and use spatial information for locating themselves and travelling in space. Spatial cognition allows humans to define alternative routes when connecting a pair of origins and destinations. Several factors such as the number of intersections, angles of incidence or amount of information available during the trip have been found to be influencing in the perception of distance. Because of that, it has been argued, route selection is far from being defined solely by its metric implications. Indeed, besides the metric distance, topologic simplicity and angular deviation have been found to be playing a decisive role in selecting a path.

But this is not the most interesting findings. On the one hand, metric and topological distances interact with two implicit spatial principles: the desire to preserve linearity and the desire to not deviate from the destination. All these factors are in most cases assessed unconsciously at several locations along a journey, especially at certain decision points offered by the route, where individuals can continue or modify their trajectories. On the other hand, visual information on the spot seems to prevail over knowledge from previous experience. This means that individuals will minimize distance and deviation from their vantage point, which does not necessarily coincide with the minimum of the whole trip. Thus, the visual field offered at decision points has an important role to play in the route choice. However, the variable has a backlash effect: while in most contexts a visual field will tend to increase its attraction as it becomes longer and wider, when the vision offered has a negative connotation (i.e. dangerous, menacing) the opposite will occur, becoming a detractor.

I.5 Conclusion

The quick overview of the psychological studies in this chapter has allowed us to become familiar with the rules governing pedestrian behaviour. Thus, we were able to see at first that the mental representation of the environment of a human being is much more focused on topology than on the geography of places, with abstract and hierarchical classification processes.

Then the wayfinding process entails the planning and execution of a sequence of movement decisions. However, route planning like many other cognitive tasks, can be difficult and time consuming. Thus, people when choosing a path, apply different strategies and heuristics in order to make a quick and efficient decision. Heuristics give them a way to make reasonable guesses without expending the effort needed to find an optimal solution. The navigation strategies are based on the spatial information available. Thus, a subject familiar with the environment can choose from a larger number of strategies than a subject moving in an unfamiliar one.

Finally, the role of the geometric and configurational features of the environment on individual movement decision- making is particularly interesting because it suggests that the layout of the environment itself affects the choices that individuals make. The term spatial configuration refers to the way every space in the built environment relates to every other.

In conclusion, it seems obvious that the reproduction of the properties stated is a minimum condition of validity when developing a computer model. Nevertheless, the exact implementation of these processes seems difficult, especially for the scaling up of a crowd, because of the complexity of the necessary models and the number of factors that come into play.

Chapter II Spatial syntax and wayfinding

II.1 Introduction

As part of our work we have been brought to direct our attention to the different areas dealing with the analysis of space and more specifically of urban space. Indeed, as we mentioned in the introduction of this document, the purpose of our work has been to model an informed urban environment dedicated to the autonomous agent movement simulation. To do this, we needed to capture environmental determiners of individual human navigation decisions and to formally describe them in the environment model. This led us, to be interested to theories and techniques offered by Space syntax.

This chapter provides a theoretical background to the thesis by reviewing the body of relevant literature across the field of space syntax. The review is grouped into four sections: first, section II.2 introduces space syntax theory. Then, section II.3 presents environment and space representation in space syntax domain. Section II.4 summarizes methods and measures used to analyse the spatial configuration of the environment. Section II.5 highlights some researches in space syntax domain about wayfinding. Finally, we end this chapter with a conclusion in section II.6.

II.2 Space syntax theory

Space syntax, originated and developed in the 1970s at the Bartlett Unit for Architectural studies, University College, London, is a theories and techniques that can be used to describe and analyse patterns of architectural space both at the building and urban level. It grew out of a desire to understand the social logic of space (Hillier & Hanson 1984), that is, how the environment shapes us and in turn how society shapes the environment (Hillier & Leaman 1973). The book *The Social Logic of Space* was published in 1984. It deals with the theory of the impact of spatial configuration on the social life and vice versa (Hillier & Hanson 1984). Space syntax attempts to explain human behaviours and social activities from a spatial configuration point of view (Hillier 1997).

From its beginnings the method was used as a tool to help architects to simulate the likely effects of their social projects. Since then the methodology has been developed as a design method, which can determine the nature of space, help to understand how buildings, areas, and even entire cities operate. The most important factor in the SSA remains space configuration, and relations that occur in it. The theory proves that the way in which elements are brought together affects the behavior of its users (Hillier 1996). The theory is based on several principles described mathematically, which gives a possibility to generate graphs and numerical results, map and analyze linear space availability (*spacesyntax.com* 2019).

II.3 Space syntax environmental model

Space syntax provides a set of techniques for producing an abstract model of an urban environment (a building interior or a part of an urban area); space syntax is concerned with how the continuous system of space can be broken down into discrete spaces. In an urban setting, a component space is what we inhabit at home or at the office. The city is the sum of all component spaces and is continuous; we can move from location to location by passing through a number of spaces. Cities can also be defined as large collections of buildings held together by a network of space: the street network. The network is the largest thing in the city. It is what holds it all together. It has an architecture, which is certain geometry and a certain topology and a certain scaling (Hillier 2014)(Figure II-1). Space is the unit within which all human activities occur. It reflects the social and cultural aspects of the city, in spaces much human behaviour like eating, gathering, interacting and dwelling occur, having their spatial form.

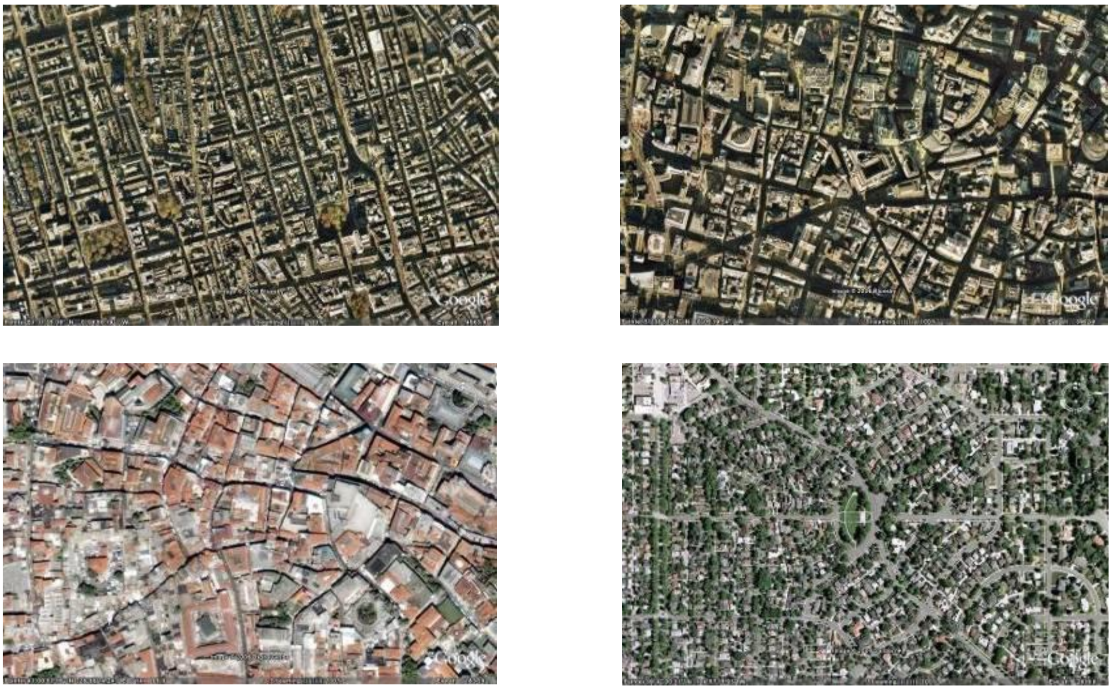


Figure II-1: Cities with different grid street plans (Hillier 2014).

The word syntax refers to the relationships between words in a sentence. It is the system by which we arrange words to create meaning. In the same way, space syntax is a method for describing and analyzing the relationships between spaces of urban areas and buildings. It deals with the question: how can be public and private spaces arranged so that they make sense to the people who use them?

II.3.1 Space representation

A space in the space syntax method is the basic building block of urban and building systems combined. There are a number of ways of describing space, which can be summarized in three geometric ideas: linearly when people move in it, convex space (in which every point can see each other) when they interact within it and finally isovist which from any point of space can be seen as a variably shaped, often spiky visual field (Benedikt 1979). Figure II-2 presented below is a simple representation of the three different ways how people perceive space.

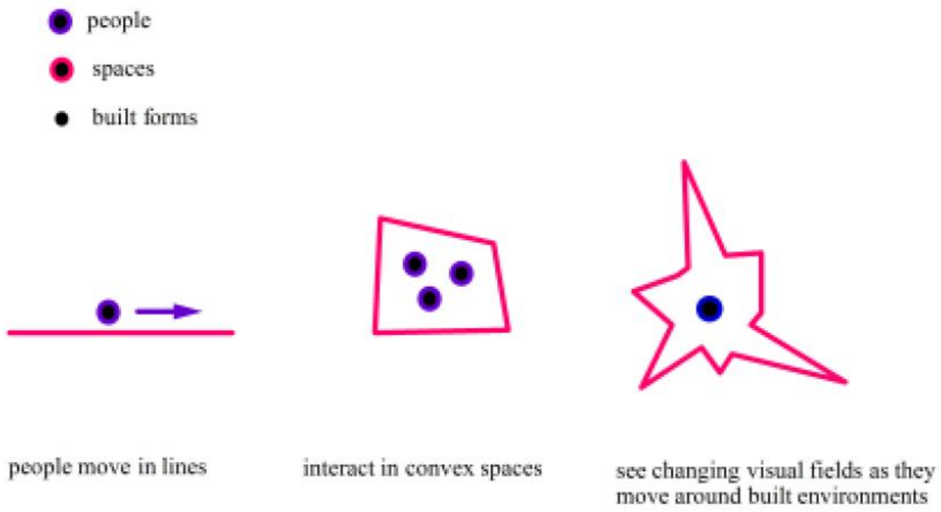


Figure II-2: (left) representation of the way people move, mostly along a line; (middle) convex space where users see each other and in which interactions take place; (right) the visibility filed (isovist), which has a different shape depending on where the observer is located (Hillier 2014).

These three ways of representing space show the same thing from different perspectives. The first representation is mostly used in axial maps to analyze urban systems. The second one is the best one to analyze rooms, and other closed structures. *Isovist* encompasses the area that can be seen or perceived by a particular user from a particular point in space. It is mostly used to show different perspectives in squares and open public spaces. The type of analysis depends on the selection of the space representation. It is possible to run an analysis of an axial map, a convex map, a convex space, or analyze changes of the isovist fields.

A. Axial map

The space syntax urban network transforms the street grid into a set of lines, known as axial lines. Axial lines are defined as the longest and fewest lines of sight with potential for movement completing the network (Figure II-3). The ensuing network can be analysed as a graph. Initial space syntax methods were based on axial lines. This led to graph measures constructed around the topological properties of the grid. Analyses of urban environments have mostly been focussed on the layout of the street grid (rather than on three-dimensional representations); in space syntax research the street grid is often represented as the longest and fewest set of lines completing the network. In simple terms, every straight road on a map of a city is translated into a single line, so that the resulting map is formed solely of a network of interconnecting lines.

B. Segment map

In more recent years syntactic analysis has been refined in several ways. One major path of refinement has been to break axial lines into shorter segments, usually equivalent to road segments spanning between successive street intersections (each segment begins and ends at an intersection with another line, see Figure II-4). The impetus for this change has been the desire to account for pronounced differences in pedestrian counts along different spots on the same axial line.

Figure II-3: Axial map (*otp.spacesyntax.net* 2019).

A refinement of the analysis allows the graph to be weighted according to angular displacement (Dalton 2001); (Turner & Dalton 2005); (Hillier & Iida 2005). The graph of the segment angular analysis has the segments as nodes and the intersections as the links connecting them.

Figure II-4: Segment map (*otp.spacesyntax.net* 2019).

The other major path of refinement has been the desire to the direct application of syntactic analysis to GIS-based street centre line maps, without constructing new representations such as the axial map. The analysis is based on standard segment- based representations of street networks according to street centre lines. The unit of analysis is the road segment. Road segments extend between choice nodes, or street intersections at which movement can proceed in two or more alternative directions. Road segments may contain one or more line segments. A line segment is the basic unit of the map drawn and is always defined as a single straight line. Thus, the analysis treats the unit of analysis (the road segment, for which the individual values are computed) and the unit of computation (the line segment which provides the base metric for values) as different entities. Figure II-5 illustrates the new unit of analysis by clarifying the difference between road segments and line segments.

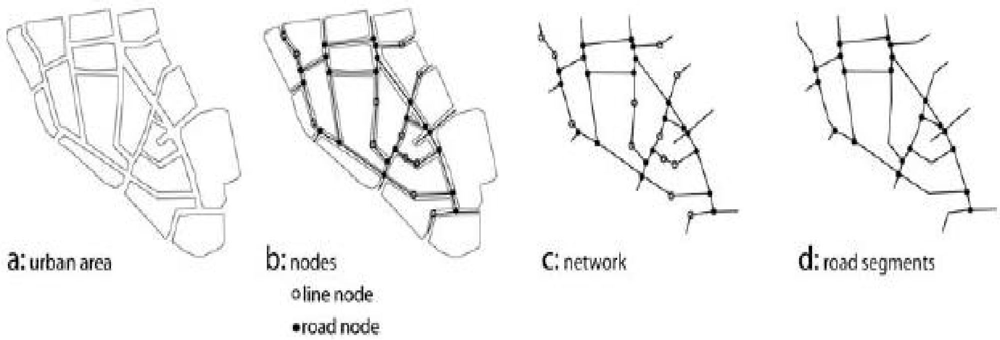


Figure II-5 : Difference between road segments and line segments (Peponis, Bafna & Zhang 2008).

C. Convex map

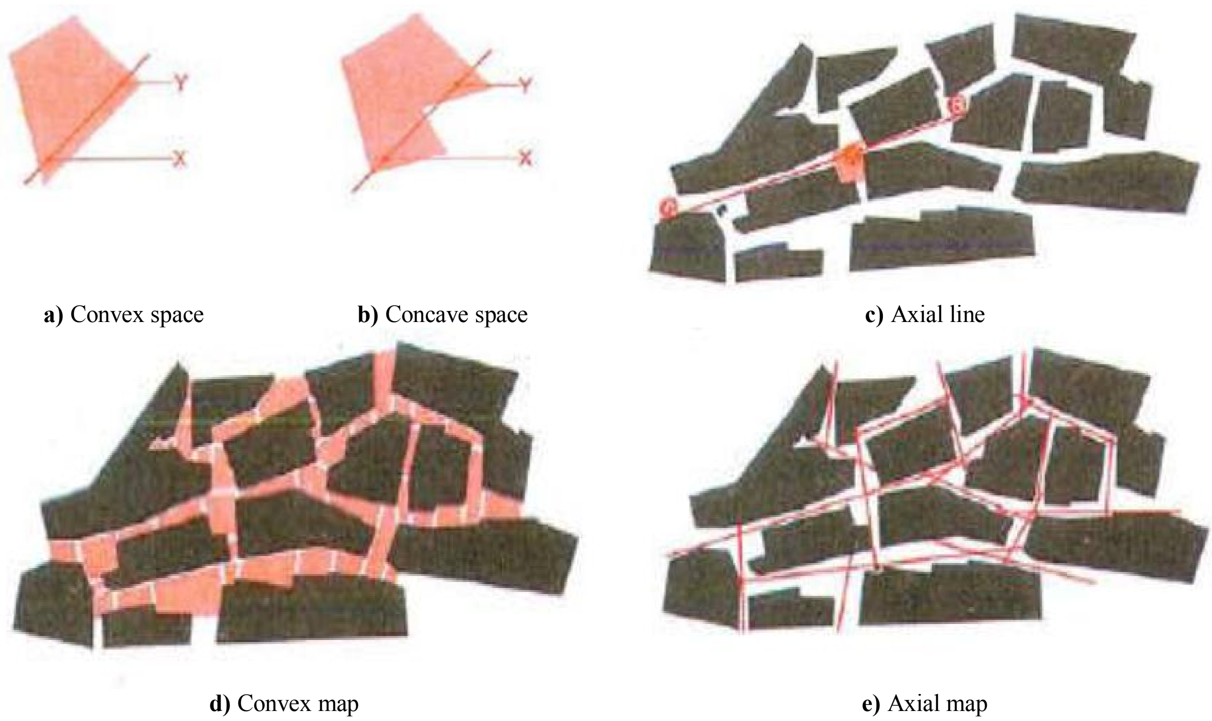


Figure II-6 : Space syntax tools (Hillier & Hanson 1984).

A convex space is defined as "a space that will not contain concave parts" (Hillier & Hanson 1984). It is an area outlined by a border of straight lines, any two points in this convex space can be joined by a straight line which doesn't go outside the space.

Convex map consists of the largest and fastest convex spaces that cover the area (Hillier & Hanson 1984). The convex space offers the most localized perspective because any selected point taken within it appearing visible and directly accessible to all other points within that same space (Hillier & Hanson 1984). Convex spaces are used when studying interaction.

D. Isovist

Benedikt (1979) adopted the term isovist from Tandy (Piaget & Inhelder 1967) who had used it to describe landscapes. Isovist is a relevant form of analysis which examines the viewshed from the current standpoint. An isovist is a 2D polygon, taken at a stated height (commonly either floor level or eye-height) that represents the visible area from a point (the generating location of the isovist). It is the field of view within which the entire space boundaries can be defined through the transportation of observer's eye around 360 without geometric obstacle (Figure II-7).

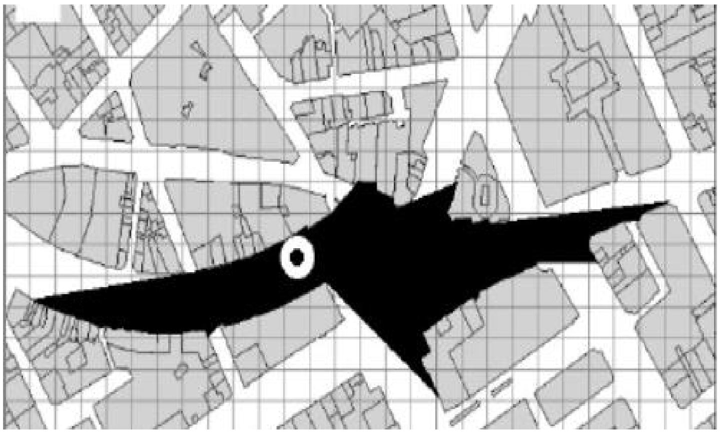


Figure II-7 : Isovist (Batty & Rana 2004).

Later improvement of isovists includes direction-specific isovists (Meilinger, Franz & Bülthoff 2012) which restrict the scope of visibility to only facing direction (see Figure II-8). The boundary-shape of an isovist is sensitive to location of point of seeing when the space is non convex, as there would be many isovists with different shapes. The key criterion in defining isovist is how far can one see or move from every point in the space.

In a mathematical sense to designate an isovist the term visibility polygon is used; a visibility polygon covers all points that can be linked to a given root-point by a visibility line that is not interrupted by any boundary. When isovists are drawn at eye level, they capture the objective properties of the visual field as structured by the affordances of environment (Gibson 2014). When they are drawn at floor level, they capture the objective properties of environment affecting movement.

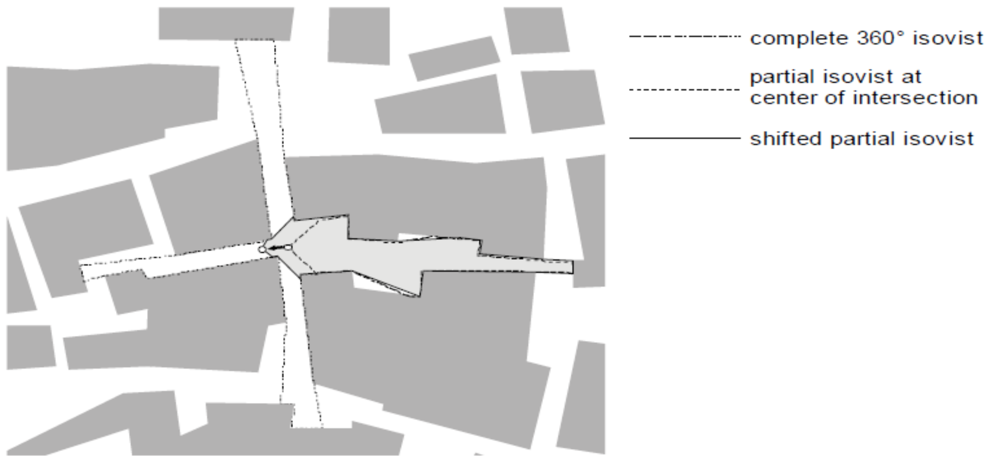


Figure II-8 : Exemplary illustration of the applied partial isovist (Meilinger, Franz & Bülthoff 2012).

II.3.2 Distance

In space syntax, distance always means topological distance and it is referred to it as 'depth'. Depth is measured in steps. The depth between two lines that intersect is 1. Later, segment analysis has been utilized by an increasingly number of researchers. The basic element in segment analysis is the street segment between intersections. Therefore, three definitions of the distance between each segment and each of its neighbours are allowed: *metric*, that is the distance in metres between the centre of a segment and the centre of a neighbouring segment; *topological*, assigning a value of 1 if there is a change of direction between a segment and a neighbouring segment, and 0 if not; and *geometric* - assigning the degree of the angular change of direction between a segment and a neighbour, so straight connected are 0-valued and a line is a sequence of 0-valued connections, so that the linear structure of cities is captured.

II.3.3 Notion of scale

Space syntax incorporates the notion of scale in its analysis. Cities have two predominant scales, a global and a local one that reflect different socio-spatial experiences. The global scale can be said to refer to the background network, which is characterised by proportionally fewer and longer streets that intersect each other at obtuse angles. This is in contrast to the local network which is embedded within the foreground, has a larger number of shorter streets that tend to intersect at near right angles (Hillier 2009).

II.4 Spatial configuration

Configuration as defined in Hillier's book *Space is the machine* is “a set of interdependent relations in which each is determined by its relation to all the others”. Spatial configuration is defined as the way the relationship between any two spaces is altered by their connection to a third space (Hillier 1996) (see Figure II-9). Consider a simple spatial layout where two spaces **a** and **b** (e.g. rooms) are connected to an outside space **c** (e.g. an entrance). In the first instance, we have spaces **a** and **b** connected directly to space **c**. In the second instance, the connection **b-c** is closed off, so that only space **a** connects directly to space **c**. It is clear that the relationship of space **c** to spaces **a** and **b** changes the relationship between the three spaces. We can say that the configuration of space has changed significantly from the left to the right hand image. This concept is easily grasped by comparing the graphs of the two instances, in which the spaces are depicted as nodes and the connections between the spaces as links.

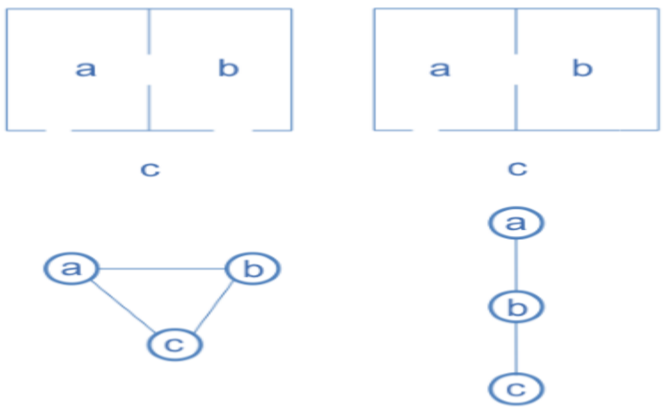


Figure II-9: Illustrating spatial configuration.

II.4.1 Space configuration analysis

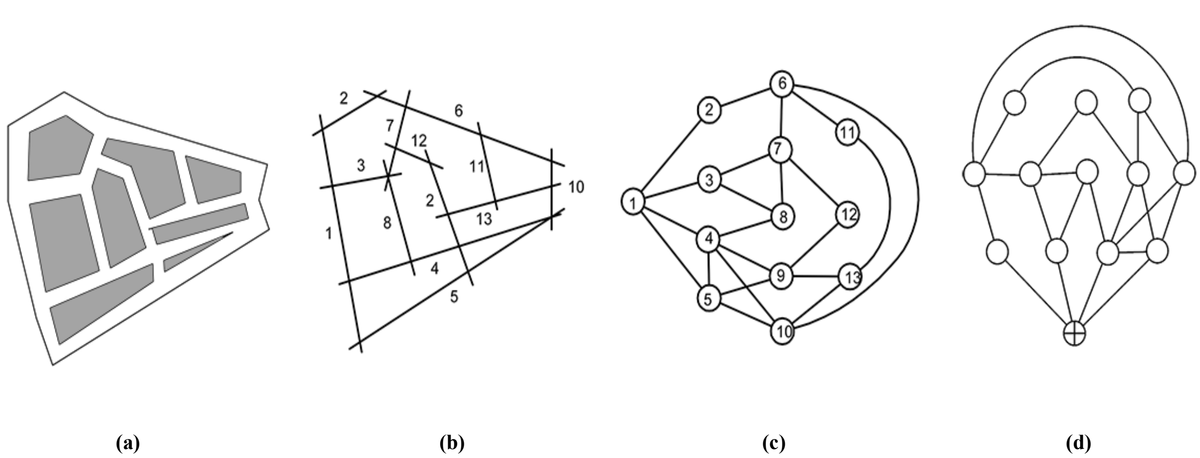


Figure II-10: (a) fictive urban system; (b) axial map; (c) connectivity graph; (d) justified graph (Jiang & Claramunt 2002).

Space syntax offers a way of measuring spatial configuration that has proved to be a useful tool for practitioners. A common space syntax method represents an environment (indoor or outdoor) as a network of nodes and interconnecting links, which can then be analysed as a graph.

The graph of availability (*connectivity graphs*) is obtained from an axial map (Figure II-10 (b)). It represents the relationships of accessibility between all axial spaces of a layout model. Axial lines which represent spaces are presented as circles (nodes) which are linked by lines showing intersections with subsequent axes. Nodes are numbered according to the numbers on the axes (Figure II-10 (c)).

A *justified graph* could be reconstructed afterwards so that a considered space is placed at its bottom (Figure II-10 (d)). Such a space is called *the root space*. At the first level above the root space all spaces one syntactic step away from it are placed, on the second level, all spaces two spaces away, etc. Justified graphs offer a visual picture of the overall depth of a layout model seen from one of its points.

II.4.2 Basic syntactic measures

The theory of space syntax offers four syntactical measures to perform space configuration analysis. Space syntax has adopted two of them from graph theory. This later proposes a number of ways of analysing any graph; the most relevant for the space syntax analysis of street connectivity are centrality-based measures.

A. Depth / degree of depth

It is defined as the smallest number of syntactic steps (in topological meaning) that are needed to reach one space from another (Figure II-11). Depth is counted in a graph and is determined by parameter *k*. Parameter *connectivity* considers immediate neighbours and depth considers the neighbours of the *k-th* degree.

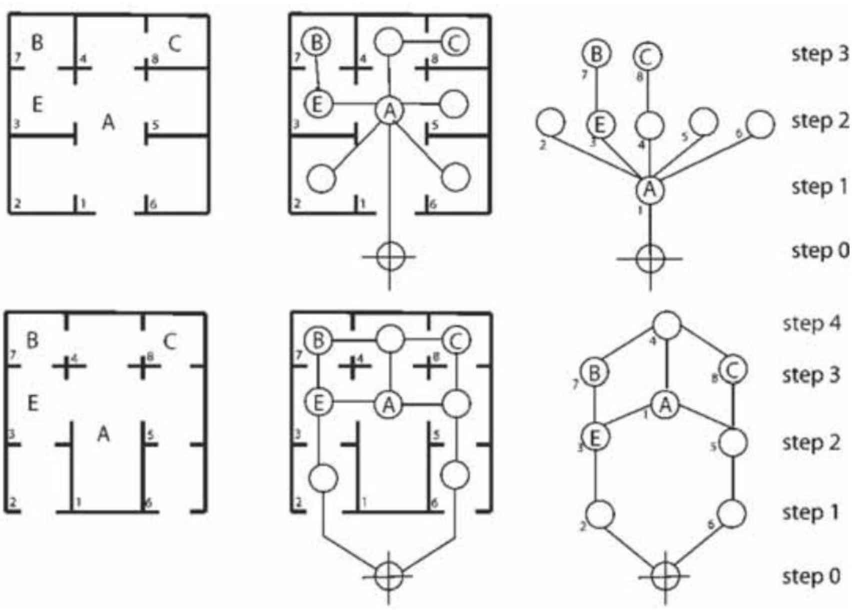


Figure II-11 : Connections in a building.

Connectivity and *depth* measures can be written as a sum:

$$\sum_{s=1}^{m} s \times Ns = \begin{cases} connectivity\ if\ m = 1 \\ local\ depth\ if\ m = k \quad 1 < k < l \quad (local\ depth\ (until\ k = 3)) \\ global\ depth\ if\ m = 1 \end{cases}$$

Where:

k – parameter,

s – operator (s is an integer),

l – the shortest distance,

Ns – the number of nodes with the shortest distance *s*.

Where 1 < *k* < *l*, usually three steps are adopted for the calculation of *local depth*, i.e. *k* is equal to 3 (this means that we consider lines within three steps from an axial line). We can also note that connectivity is equivalent to *local depth* if *k* = 1(Jiang & Claramunt 2002). *Local depth* in Figure II-10 for the root node (for m = 2) = 4 * 1+5 * 2 = 14, *Global depth* in Figure II-10 for the root node = 4 * 1+5 * 2+3 * 3 = 23, and in this case m = 3.

B. Connectivity (Degree centrality)

Measures the number of neighbour axes directly connected to a space. It specifies the number of immediate neighbours of an axis. It is a local measure (parameter *k* = 1). In Figure II-10, *Connectivity* for axis 1 = 4.

C. Integration (Closeness centrality)

Integration, is a measure reflecting the average length of the shortest paths from the axis a_i to all the other axes of the network. Axes with integration have low average length of the path to all other axes in the network. When applied to a given urban network, this measure reflects global properties of the structure of the city, revealing its core.

Integration is a variable that refers to how a space is connected with other spaces in its surroundings. In all studies conducted in different seasons and at different times of the day results confirm that there is a relationship between integration of the space and the presence of people in it. The most important observation is the fact that the axis system will lead users into the best integrated spaces in that system. The greater integration of the space, the more people will appear in it. For this reason, integration is sometimes called *accessibility* by space syntax analysis researchers (Dettlaff 2014).

– **Local integration**

A localized measure of integration, considering only the network within a radius of three steps, is frequently used to reveal the variation of integration across the network, and shows the scale of the pedestrian movement. This step-distance is based on empirical findings related to the average length of pedestrian walks. As research has shown, this varies in different cultures. In most European cities, the average topological depth has a value close to three. In most US cities it is two, while it is five in Arab cities (Van Nes & Yamu 2017).

– **Global integration**

It is a measure of integration, measured throughout the system. It takes into account the distance from the starting point to all points in the system (Hillier & Hanson 1984).

The relationship between the global availability of space (*global integration*), and the local availability of space (*local integration*) is the clarity and readability of the space (*intelligibility*). The better the correlation between these measures, the better user moving along a given axis is oriented in space and knows where they are in the context of the entire city (Dettlaff 2014).

D. Choice (Betweenness centrality)

Choice reflects the likelihood a graph node lies on a shortest path between two other nodes of the graph. Betweenness centrality C^B_i of the vertex N_i was defined by Freeman (1977) as follows:

$$C_i^B = \sum_{i \neq j \neq k} \frac{n_{jk}(i)}{n_{jk}}$$

Where $n_{jk}(i)$ is the number of paths between N_j and N_k leading through N_i. Betweenness centrality provides a global value of a network element and thus allows its structural characteristics to be compared with all other nodes in the graph.

II.4.3 Isovist analysis

Isovist analysis is a useful tool for understanding how individuals perceive and act in space. It is often used in space syntax research as part of a set of techniques that examine users' visibility of space. From the isovist polygons, several basic geometric descriptors can be derived such as area, perimeter length, number of vertices, and length of open or closed edges (see Figure II-12). These basic measures can be combined to generate further integrated values. For example, the quotient of area and squared perimeter can be conceived as the isovist polygon's roundness value.

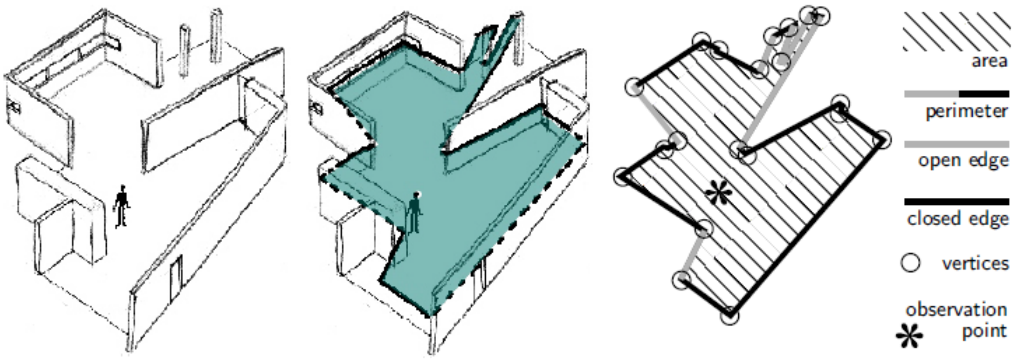


Figure II-12 : Generating isovist: (Left) a hypothetical indoor environment; (middle) the shaded area is visible from the person's observation point within the environment; (right) the resulting isovist and its basic measures (Wiener et al. 2007).

Isovists basically describe local physical properties of spaces with respect to individual observation points. The technique of visibility graph analysis (VGA) as developed by Turner et al. (2001) overcomes this limitation by encoding the intervisibility of multiple observation points distributed regularly over the whole environment. Typical visibility graph measures are, for instance, neighbourhood size (i.e. the number of directly connected graph vertices, corresponding to isovist area), clustering coefficient (i.e. the relative intervisibility within a neighbourhood), and similar to original space syntax, global topology-oriented characteristic values such as integration (e.g., mean shortest path length). Figure II-13 (a) shows the VGA mean depth calculated in the standard way for the Tate Gallery on Millbank.

II.4.4 Angular analysis

Angular analysis is essentially an extension of visibility graph analysis and axial analysis (Turner 2001). Angular analysis uses a *weighted* graph to calculate space syntactic metrics rather than the *non-weighted* standard measures. Figure II-13 (b) shows the angular VGA mean depth for the Tate Gallery on Millbank. In terms of an axial map, for example, when calculating the path length from *A* to *B*, as one would to calculate integration for example, rather than count the number of edges (that is, connections) between those locations calculates instead the weighted sum of the edges, where each edge is weighted by the angle of connection. An example of angular integration analysis is shown in Figure II-14.

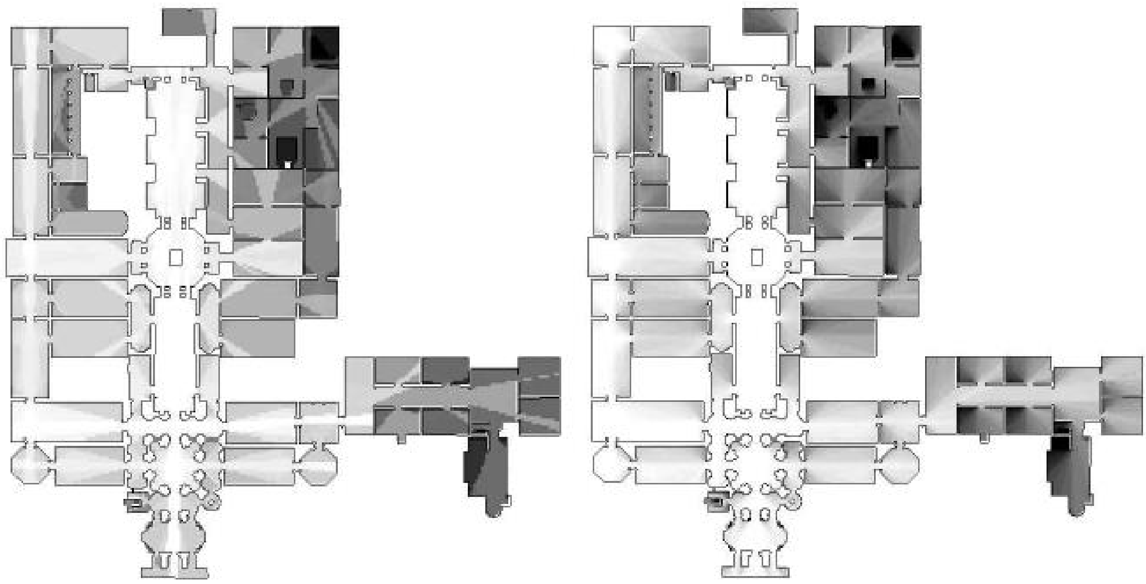


Figure II-13 : (Left) The Tate Gallery on Millbank analysed using VGA mean depth. Low values in white, high values in black. (Right) The gallery analysed using angular VGA mean depth (Turner 2001).

II.4.5 Main application and objectives of space syntax analysis

Initially, space syntax methods were developed in order to allow architectural space to be represented and its pattern properties quantified so that comparisons could be made between differently designed buildings or urban areas. The aim of the research was to develop an understanding of the way that spatial design and social function were related. It was soon found that a primary effect of spatial configuration on social function resulted from the way that space patterns determined pedestrian movement patterns and so co-presence between people in space

In its initial form, space syntax analysis focused mainly on patterns of pedestrian movement in cities. The basic aim has subsequently been extended to a number of other aspects, such as modelling urban traffic, predicting air pollution levels, assessing the occurrence of burglaries in different neighbourhoods and estimating the potential for retail development in the streets (Ratti 2004). Although primarily space syntax analysis was used only for urban spaces, now it is possible to use it also at a micro level (for rooms or buildings). It is used in most cases to study pedestrian movement.

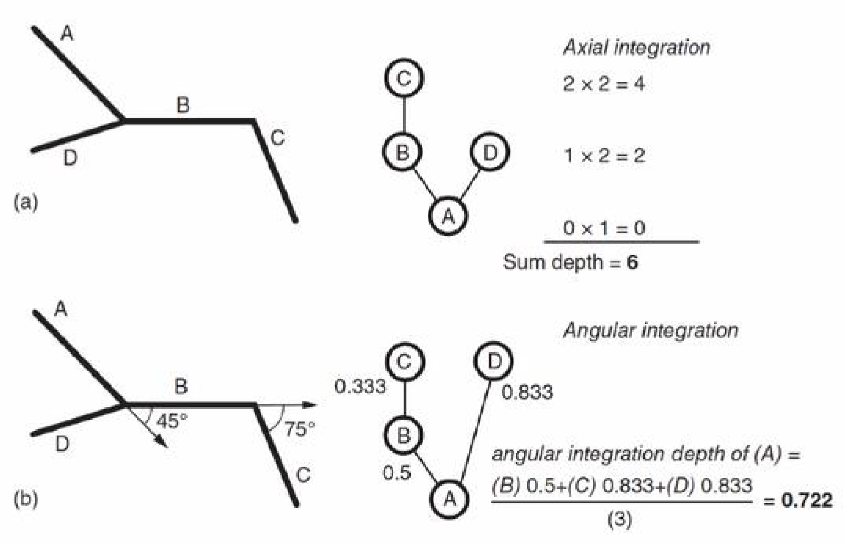


Figure II-14 : Axial and angular relationship of four street segments (Van Nes & Yamu 2017).

Syntactic measures and numerical results give a chance to draw conclusions about how the space functions. Each measure will identify structure in the network which can be made intuitively clear by using colours to represent mathematical values, as usual from red for high through to blue for low (Figure II-15). For example, a very isolated space characterized by a measure of *integration* is susceptible to increased risk of crime. Through such observation, it is possible to diagnose how to improve the quality of such space. Remodelling of the system, such as a change of connections in the space, generates opportunity to tackle the problem and predict how the newly designed space will function.

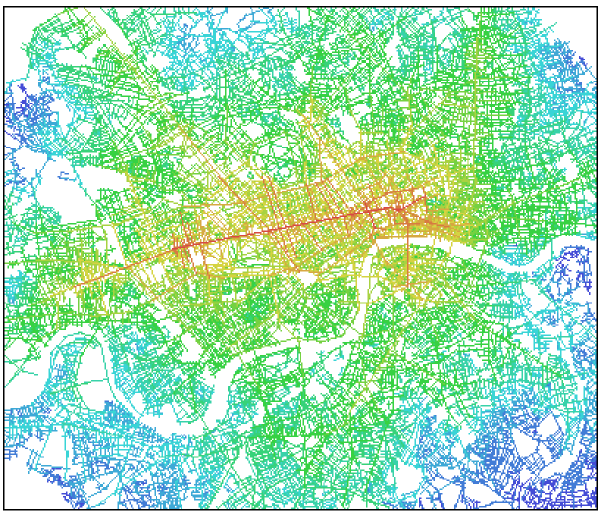


Figure II-15 : Global Integration of Central London.

II.5 Space syntax and wayfinding

Space syntax method is like grammar used to arrange spatial elements and analyze them. The first objective of the analysis is to understand the users. Through observation of where and how people move in the existing spaces, it can be predicted where to locate its specific functions. The value of understanding the relationship between the users and the space lies in predict how spatial configuration will shape user experience.

Much of our behaviour and attitudes towards built environments is influenced by the physical properties of these built-environments which have been shown to influence behaviour in the form of navigation and path selection (Hillier & Hanson 1984). Architects and design professionals understand that the design decisions they make will have a profound impact on how an individual will experience and feel within the space.

A rigorous attempt to examine the relationship between objective measures of the components of physical environment as determined by Syntax analysis and observational measures of wayfinding performance was undertaken by Peponis, Zimring & Choi (1990). This study concluded that some users were “biased towards some spaces more than towards others, in proportion to their degree of integration” and “when in doubt, go to an integrated space” (Peponis, Zimring & Choi 1990), pp. 570 & 573).

II.5.1 Space of navigation

An urban environment consists of two parts: spatial obstacles such as buildings, and free space within which human beings are able to move from place to place. Space syntax focuses on free space and decomposes an entire area of free space into small pieces of space. As seen previously, several space syntax representations can be applied, depending on the degree of linearity of the free space. This linear property represents the fact that the built environment is relatively dense, so that the free space is stretched in one orientation at most points. Common examples of this type of urban environment are a city, a town, a village or a neighbourhood. When humans are walking in this type of free space, at most points (if not all) such a free space is perceived as a ‘vista’ that can be approximately represented as an axial line (Jiang & Liu 2010).

When we are moving along a linear corridor space most opportunities are likely to lie ahead, however when we reach a junction the opportunities are defined by the morphology of the local visual field. Conroy (2001) found that it was exactly at these junction locations that people paused and looked around before moving on, suggesting that it was at these locations that the cognitive load of decision making required a slower pace of movement and gathering of additional information. In those places the isovists tend to be larger and often spread in different directions, permitting the observer to evaluate the information and to take spatial decisions based on it.

II.5.2 Movement patterns prediction

The patterns of people’s movement in urban systems represent one of the most important areas of research within space syntax studies. A fundamental proposition in space syntax is that any set of spaces, of sufficient complexity to be described as a configuration, forms a spatial hierarchy in which some spaces become more strategic and others less so. These strategic or, on average, more accessible spaces will tend to attract a higher rate of pedestrian movement than other, more segregated, spaces. Thus, attract retail and other land uses that rely on the volume of pedestrian traffic, and consequently the volumes of both pedestrian and uses are multiplied, as the allocated functions then increase the importance of the location itself and attract other functions, this phenomena is what Hillier has called *Multiplier effect* (Hillier 1996).

One of the key methods of analysis used in space syntax research is a graph-based technique that is able to identify and represent this varying pattern of more-to-less strategic spaces. Although such techniques were not originally developed as tools for predicting pedestrian movement, it has been found that there does exist a powerful relationship between movement and spatial structure and so this graph-based analysis may be used to predict relative rates of pedestrian flow. It is this predictive ability of space syntax analyses that has caused it to be adopted as a design tool by many architects and urban planners.

For example, in Figure II-16 right is a *visual integration* analysis – meaning using visual isovists as the basis for integration calculation– of the Tate Britain Gallery. On the left are traces of 100 visitors entering the gallery and moving for ten minutes. Although each individual takes a different route, the two patterns are remarkably similar, and in fact statistical analysis shows a 70% correlation between the two patterns.

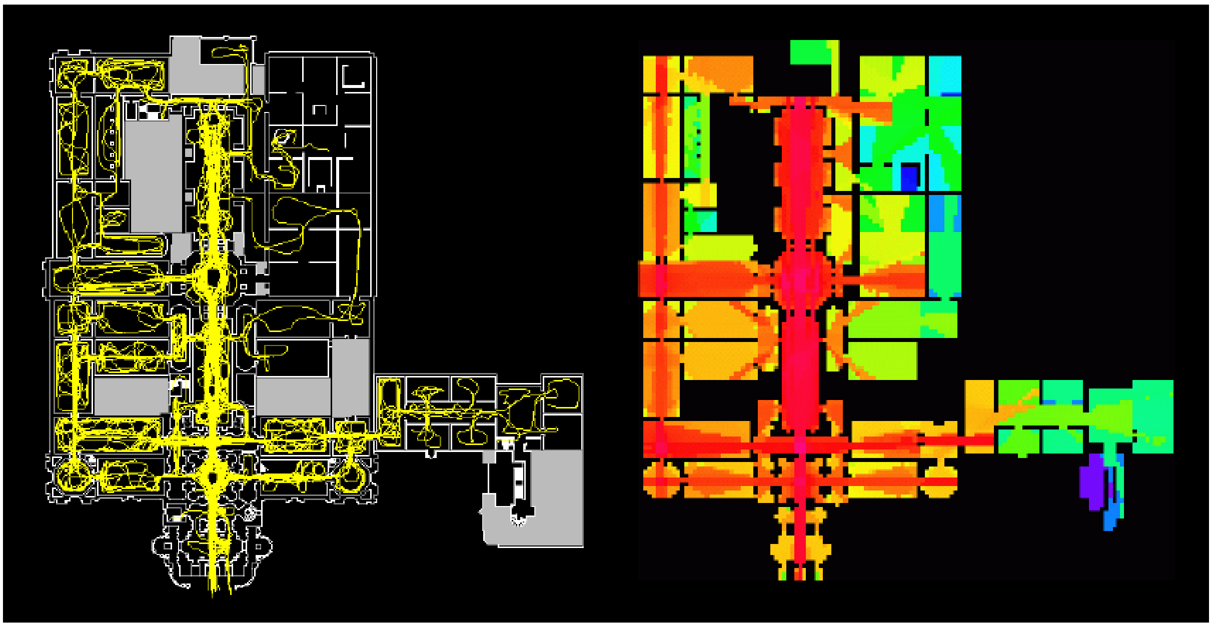


Figure II-16 : Tate Britain Gallery: traces of visitors (left), visual integration analysis (right) (Hillier 2014).

II.5.3 Models of motion flow prediction

According to Hillier et al. (1993), two models have been developed to predict the flow of pedestrian movements (Figure II-17) in cities:

A. Attraction models:

Attraction models predict the pedestrian movement, taking into account the different points of departure and arrival that are built forms or urban spaces. These receive different degrees of attractions according to their importance. These models predict the frequencies of traffic and especially congestion places. They propose alternatives to pedestrian circulation spaces at the local level. These models do not seem to give much importance to the spatial structure of cities, especially the nature of urban grids. They do not seem to take into account some pedestrian choices in real life situations within urban grids. Situations such as the choice of the most accessible, the most frequented or the shortest path, are common in reality, whereas they are not considered in these models.

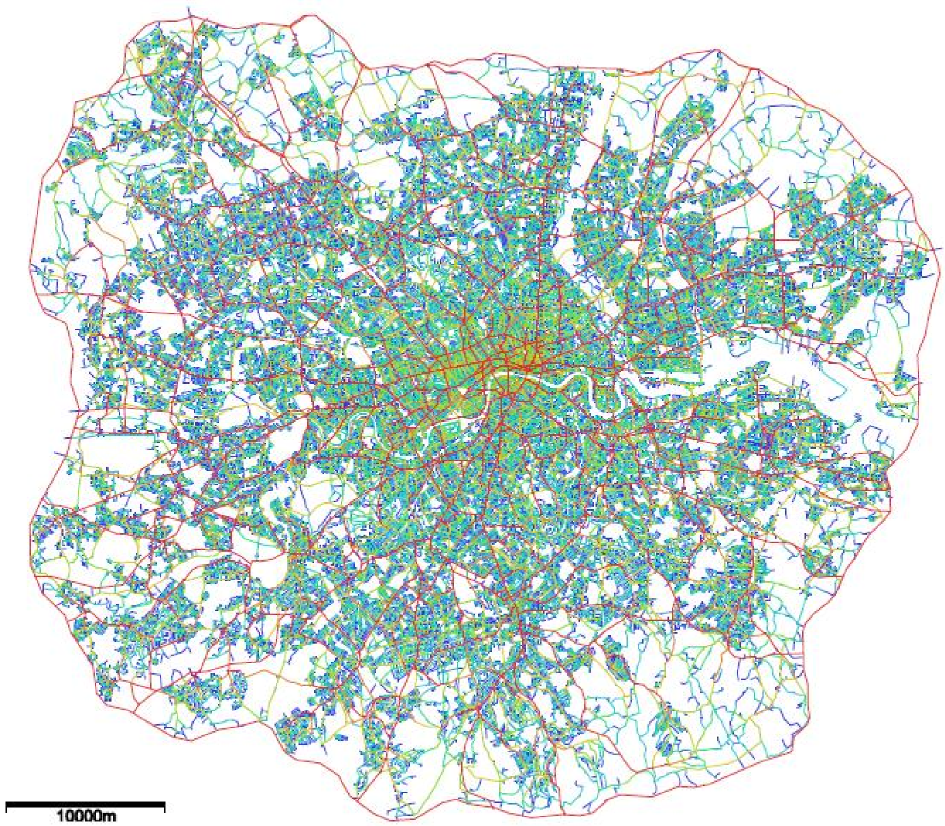


Figure II-17 : The movement potentials of each of the 285000 segments of London (Hillier 2014).

B. Configuration models:

This model is based essentially on the configuration of the urban grid more than on the effect of the attractors. It was developed by (Hillier et al. 1993) and is called the "***natural movement"*** model. It is essentially based on the spatial configuration of urban grids. Movement flows depend on the spatial configuration of cities rather than the attraction of different local points. It is formulated through the theory of spatial syntax. According to this model, the spatial configuration of urban systems is the first pedestrian movement generator in urban space (Hillier et al. 1993). Other local attractors in cities equalize or amplify the motion frequencies that are generated primarily by the spatial pattern of urban grids. Hillier defines natural movement as the proportion of urban pedestrian movement determined by the spatial pattern itself.

According to (Hillier 2006), human movement in an urban spatial configuration corresponds to two components:

- **To-movement.** This is the movement that is established in urban spaces that directly overlook the destinations of moving subjects.
- **Through-movement**. This is the movement in spaces that serve as passage for other destinations.

The model was discovered during space syntax research. His proposals were experimentally verified early, but critics of this model insist that it does not take into account factors that appear to be generators of movements in the city, such as densities, land use, urban activities, or in relation to the individual scale, such as individual motivation or goal-directed behaviours (Turner & Penn 2002). More recent research such as (Turner & Penn 2002) (Turner 2007b) allowed a correspondence between the spatial configuration of the urban grid and spatial cognition at the individual level. Hillier mentions the need to combine this model with other models based on attraction.

II.5.4 Movement pattern characteristics

Spatially speaking, every human trip is made up of two elements:

- an origin-destination pair—every trip is from an origin space to a destination space—we can call this the destination choice component. Called, as previously cited, by Hillier "*to-movement*" ;
- The spaces passed through on the way from origin to destination—we can call this the route choice component. Called by Hillier "*through-movement*".

In fact, both of these potentials can be measured:

- to-movement is about the closeness or accessibility of spaces from all others; which is our measure of integration: how close is a space to all other spaces;
- through-movement is about the propensity of spaces to be passed through on the way from all origins to all destination — we call measure of choice for a space: how likely is a space to be chosen as part of a route between spaces.

If across cases there are consistently better correlations with one or other weighting, then the only logical explanation would be that this weighting reflects better how people are biasing spatial movement choices, since everything else about the system is identical. In fact, across four separate studies in areas of central London, we consistently found that geometric, or least angle weightings yields the strongest movement prediction, with an average of around 0.7 for vehicular movement and 0.6 for pedestrian, closely followed by the topological or fewest turns weighting.

II.5.5 Movement simulation architectures based on space syntax

Within the field of space syntax simulation architectures have been employed to provide a tool to study how human movement can be predicted, and to act as an alternative evaluation tool to observations for understanding the relationship of movement to the various parameters that describe space.

From space syntax point of view, there are two main approaches that have been developed to address the issue of pedestrian movement analysis, modelling and simulation. The first approach defined as ‘configurational analysis’ – to cover methods based on representing and quantifying aspects of the spatial configuration or morphology of the environment within which movement takes place, and the second ‘pedestrian simulation’ – to cover methods that seek to represent the individual pedestrian or the pedestrian population, where the aim is frequently to populate environments with realistic individual virtual humans, and crowds.

Supporting the first approach Turner & Penn (2002) have developed an agent simulation architecture based on the visibility graph analysis, in which agents have access to pre-computed information about what is visible from any given location in the map. In addition information can be attached to the nodes of the graph describing attributes of the visible nodes. Amongst these attributes are space syntax measures of the configuration properties of the graph at each node, but they can also attribute information regarding goods on display or other static aspects of the environment. They call this architecture an ‘exosomatic visual architecture’ since it in effect provides agents with a form of exosomatic (outside the body) memory common to all agents in an environment.

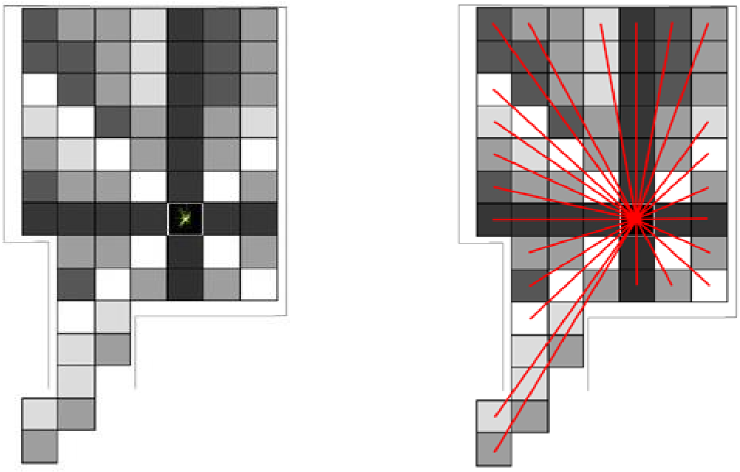


Figure II-18 : Visualisation of bins for a specific point (left) and visualisation of bins and distances from a specific point (right) (Turner 2007b)

However, the application of this architecture to larger scale spaces has proved less successful. Turner (2007b) suggested that extra features, relying on an axial map, are necessary to drive the agents in open areas, and that can be lodged in the environment as an exosomatic axial map (Figure II-18). In a later study (Turner 2007c), this suggestion has been realized through the concept of “through vision”, which is the summation of all visibility lines for each location on a visibility graph grid.

Ferguson, Fridrisch & Karimi (2012) suggested to complement the EVA model with a second lookup table of origins and destinations that reflect each activities at those locations. An agent can then use this information to choose a direction based on how closer it takes him or her to the assigned destination, making this destination a form of attractor.

On the other hand, Jiang & Jia (2011) examined the movement patterns formed by two kinds of agents (purposive agents) and random agents. They implemented these two kinds of moving agents to simulate movement in street networks, which move randomly from junction to junction or follow shortest path routes. The first is random agents that can hop arbitrarily from one street to another. The second is purposive agents that randomly decide their goals and then target them purposively. However, they found that the movement patterns formed by the different agents remain similar, which demonstrates that higher cognitive abilities are not required in the formation of movement patterns at a collective level.

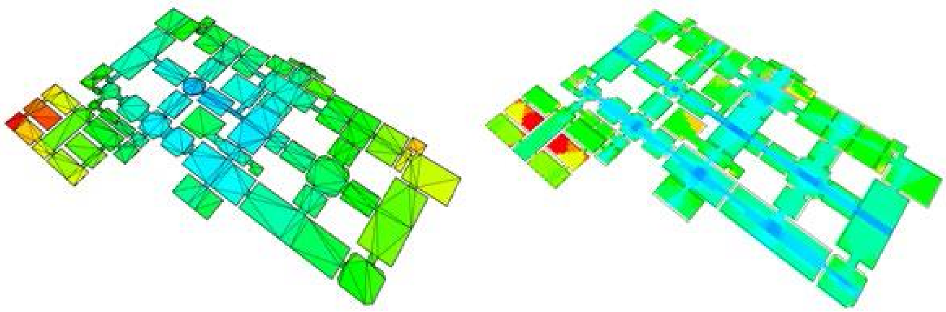


Figure II-19 : Depth on a navigation mesh (left) and Visual Mean Depth on a grid (right). From deeper (segregated) areas shown in red, to shallower (integrated) shown in blue (Koutsolampros & Varoudis 2017).

Recently, a hybrid model have been developed which represent a first attempt to introduce novel methods from video game research to the classic space syntax agent simulation by using a different type of underlying representation of space, known as a navigation mesh. This mesh of polygons can also be thought of as a graph. Each polygon is a node and if two are adjacent, they are connected through an edge. This allows for creation of metrics similar to VGA, such as the mean depth from any polygon to all others, which can be seen in Figure II-19 (left) in comparison to the VGA Visual mean depth (right) (Koutsolampros & Varoudis 2017).

II.6 Conclusion

We presented in this chapter the theory of space syntax and addressed the issue of human navigation and wayfinding through the lenses of this discipline. The methodology of space syntax consists of a structural analysis of space, quantifying it in terms of visual accessibility and the connectivity of its parts. This analysis has been linked to path choices and prediction of people movement patterns.

Although, the lens that space syntax provides is in fact not a “traditional” spatial cognition perspective; while space syntax study how space appears and is experienced by humans spatial cognition aims to understand how space is perceived or cognitively represented. The two disciplines complementary. The whole theory of space syntax is based on the rejection of the metric properties of space. Instead, spatial configuration is represented by topological data. Intrinsic properties are shown on topological graphs.

To conclude, we made the choice of presenting in this chapter the theory of space syntax. This choice is motivated by the fact that first, space syntax provides us with a set of techniques for producing an abstract model of the configuration of a building interior or a part of an urban area. These models can represent and allow for analysis of salient social and cognitive aspects of building interiors and urban areas. Second, is in agreement with research in cognitive science

Chapter III Modelling pedestrian movement

III.1 Introduction

Pedestrian flow is inherently complex, more than vehicular flow, and development of models of pedestrian flow has been a daunting task for researchers. This chapter presents a critical study of the models used to simulate pedestrian movement and to represent virtual environments. The first objective of this study is to identify the advantages and the limits of these models with respect to the issue discussed in the introduction of this thesis. The second objective of this chapter is to identify modelling elements that promote more complete solutions.

This chapter is organized as follows. Section III.2 starts by presenting a short survey on the different approaches used in pedestrian movement simulation. Next, section III.3 reviews approaches and techniques of modelling virtual environments and highlights the riches of the informed environments. Section III.4 introduces cognitive map models to address knowledge representation of the simulated entities in virtual urban environments. Finally, section III.5 proposes a synthesis on path planning and spatial behaviours models in virtual environments while section III.6 concludes this chapter.

III.2 Approaches used to model pedestrian movements

A large number of models for pedestrian simulation have been developed over the years in both research and commercial applications and in a variety of disciplines including computer graphics, robotics, and evacuation dynamics. These can be grouped into three main approaches: macroscopic, and microscopic. Macroscopic models focus on the system as a whole, while microscopic models study the behavior and decisions of individual pedestrians and their interaction with the environment and the other pedestrians in the crowd.

III.2.1 Macroscopic models

Macroscopic simulation models are historically the first computer models that have enabled crowd simulations. In fact, they simulate the totality of individuals by a combination of mathematical functions, requiring only a relatively low computing power. Thus, these models abandon any evolved individual behavior, in favour of a very fast simulation of a large number of entities.

A. Hydrodynamic models

Hydraulic models have been proposed to simulate crowds of high density. In these models, the movement of people through corridors, stairs, and doors, is assimilated to that of water through pipes, valves, or others.

Although these models have found many applications (in the context of evacuation simulations for example), particularly because of their ease of implementation, it suffer from the simplicity of the assumptions on which they are based. Fluid analogies also contradict with some observed crowd behaviours, such as herding behaviour, multi-directional flow, and uneven crowd density distribution. For example, herding behaviour is often observed during the evacuation of a crowd in a room with two exits — one exit is clogged while the other is not fully utilized (Low 2000). However, a fluid analogy would likely predict that both exits were being used efficiently. Furthermore, it is difficult for fluid system to properly model bi-directional flows (with people moving in opposite directions) in a very crowded environment (Still 2000).

B. The gas model

Henderson (1971) proposes in 1971 to assimilate the movements of people in low density conditions to those of gas molecules. Based on Maxwell Boltzmann's kinetic theory of gases, Henderson draws a parallel between the density of pedestrians and that of the particles of a gas, by assimilating their difference of states (stopping, walking, running) with the differences of energy of the gases.

III.2.2 Microscopic Models

Unlike macroscopic models, the microscopic approach allows simulations in which each entity is managed individually. An individual will therefore have its own functioning; which takes into account his environment including the entities (agents or objects) around him as well as any information on the current situation. The internal capabilities available to individuals can vary in complexity from the simplest, fully reactive (simple avoidance of collisions) to highly sophisticated behaviours.

A. Physics based models

Physics based methods use laws of physics to model movements of pedestrians. Attraction and repulsion forces are used in Teknomo's forces model (Teknomo, Takeyama & Inamura 2001), Helbing's social forces (Helbing & Molnar 1995) and Okazaki's magnetic forces method (Okazaki & Matsushita 1993). However, each of the three models uses different physical concepts and rules to model interactions of pedestrians.

B. Rule based models

Rule based model uses behavioural rules to simulate crowd of simple creatures like flocks of birds, group of fishes and herds of animals (Reynolds 1987). The model has also been used to simulate movements of groups of pedestrians. Actors in the model behave based on their perception of the other group members and the surrounding environment. Three behavioural rules are used in the model. Creatures in the flock try to avoid collision with the others (collision avoidance), try to follow and match their speed with the group (velocity matching) and finally try to stay near other members of the group (flock centring).

C. Cognitive models

Cognitive models focus on the representation of an agent's knowledge (beliefs, intentions). Intentions allow an agent to reason about his internal state and that of others. Cognitive models do not depend only on stimuli from the environment, but also on a common goal pursued by each agent. The latter is endowed with learning ability, which allows virtual agents to make decisions based on their experiences by creating, for example, a mental map of the environment (Thomas & Donikian 2003). Decision-making requires reasoning or planning to accomplish long-term tasks in order to achieve full agent autonomy (Paris, Donikian & Bonvalet 2006).

Cognitive models have been used in combination with rule-based models to achieve more realistic behaviours for pedestrian simulation (Shao & Terzopoulos 2005a). Different behavioural rules can be applied to the crowd, group or individuals to achieve more believable overall crowd behavior (O'Sullivan et al. 2002).

Pelechano et al. have incorporated psychological models into crowd simulation (Pelechano Gómez et al. 2005). They proposed an orientation process based on social forces that allow individuals to explore and learn the internal structure of a building. Thus, agents can generate a mental map for navigation and find their way in an environment they do not know beforehand. Communication and roles are added to achieve individualistic behaviours and transmit information about the environment.

D. Cellular Automata models

A cellular automaton consists of a regular uniform lattice (2D array) with a discrete variable at each site (cells) (Dijkstra, Timmermans & Jessurun 2001) (Figure III-1). Walls and other fixed obstacles are black, while the white cells are areas that can be occupied by pedestrians. These models use simple and flexible transition rules to identify the cell to which a pedestrian will move in the next step. Each cell accommodates a pedestrian. At each simulation time step, pedestrians move into one of the neighbouring cells or stay where they are.

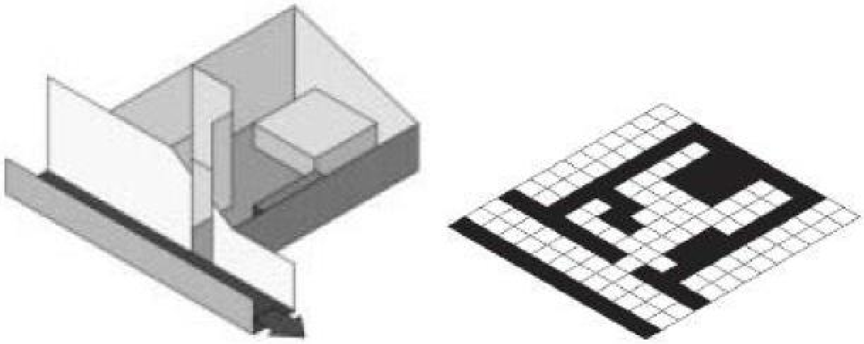


Figure III-1: 3D environment and its corresponding grid of cells.

Pedestrian transition to neighbouring cells is based on simple rules. Cellular automata transition rule could be simple mathematical equations which determine the next transition cell for each pedestrian. Since the rules are simple and flexible, and the calculations are performed for individual pedestrians almost independently from others (i.e. except checking the occupancy of grid cells by others), it is easy to integrate higher level behavioural models (e.g. way-finding, decisions and actions) and the simulations are fast.

Among the researchers who have used cellular automata for the simulation of pedestrian movements Dijkstra, Timmermans & Jessurun (2001), and (Sarmady, Haron & Talib 2014) can be mentioned.

III.3 Environmental Modelling

A virtual environment is a computer generated scene, composed of objects, in which an autonomous agent operates (Badawi 2006). The geometric data, which makes up the virtual environment, may be provided by Computer Aided Geometric Design (CAGD) tools in order to design curves and figures in two-dimensional (2D) space, or surfaces and solids in three-dimensional (3D) space for computer animations purposes (Farin, Hoschek & Kim 2002). Geometric data may also be provided by Geographic Information Systems (GIS).

To enable virtual characters to interact with their virtual environment, made up of a great number of polygons, a suitable representation of the environment is indispensable in supporting efficient sensing, navigation, or path planning. While the first available environmental modelling techniques were developed in the robotics community for robot navigation, novel environmental models have then appeared in the field of computer animation with the growth in interest in autonomous agents and behavioural animation and microscopic approach. We briefly survey the different techniques in the remainder of this section.

III.3.1 Spatial decomposition

The space decomposition techniques consist to build a subdivision of space in which free and occupied regions denote navigable and impassable areas of the environment. Based on free and occupied regions, it is possible to support the agents' navigation and path planning capabilities. The aim of these techniques is to represent the environment free space. The first approaches come from the field of robotics (Latombe 2012) with three general approaches, differing in their representation of free space: roadmaps, cell decomposition and potential fields. Then, behavioural animation has shown an interest in this subject, by adapting and improving these theories.

A. Roadmaps

The roadmap approach consists in computing a network of standardized paths (lines, curves) passing through free space. Once the roadmap has been constructed, a path can be calculated by connecting the initial and final positions in the network and finding a path in the roadmap (Figure III-2). Several methods exist to create path maps: Probabilistic Roadmaps, Visibility Graphs and Generalized Voronoi Diagarams are examples of these methods.

Roadmaps present the advantage of providing a highly condensed description of the environment and produces visually plausible animations. However, its working is too far distant from human behavior to be exploited in realistic simulations.

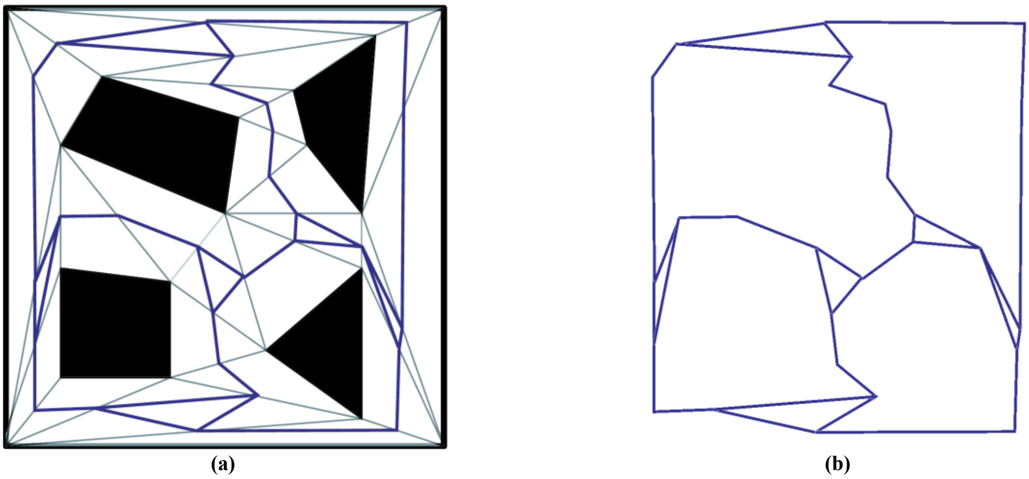
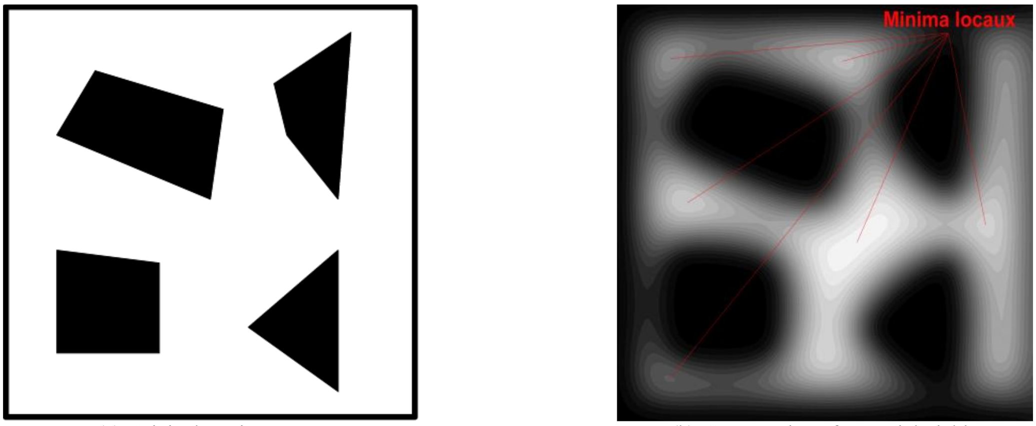


Figure III-2 : An example of Road Map generation using a Delaunay Triangulation.

B. Potential fields

Potential field method consists in computing an artificial potential function in order to guide the entity to its goal by using gradient methods. It associates repulsive powers with the environment obstacles, and an attractive one with the agent destination. The potential fields approach easily lends itself to extensions. For example, since potential fields are additive, adding a new obstacle is easy because the field for that obstacle can be simply added to the old one. However, potential fields have some limits, especially their computational complexity. Moreover, the method's major drawback is the existence of local minima. Because the potential field approach is a local rather than a global method (it only considers the immediate best course of action), the moving entity can get stuck in a local minimum of the potential field function rather than heading towards the global minimum, which is the target destination. This is frequently resolved by coupling the method with techniques to escape local minima, or by constructing potential field functions that contain no local minima (Figure III-3).



(a) Original Environment. (b) Computation of Potential Fields

Figure III-3: An example of Potential Fields corresponding to the original environment: clear (grey) areas correspond to attractive regions (minima) and dark (black) areas correspond to reject (repulsive) regions.

C. Cell decomposition

The cell decomposition method consists in decomposing free spaces into cells. Cell decomposition can be carried out in different ways. An approximate decomposition which covers a subspace included in the environment's free space. An exact decomposition, generally by convex cells, covers exactly the whole of the environment's free space. In both cases, a graph is obtained whose nodes represent cells, and arcs describe connectivity relations.

– *Approximate cell decomposition*

The approximate cell decomposition consists in using predefined cell shapes (uniform grids, quadtrees, circles), whose union is strictly included in the free space. The first approximate representation model uses regular grids formed of square cells in two dimensions (Figure III-4 (a)) and cubes in three dimensions. The environment is completely covered by these cells, which can have three states: free, partially obstructed, and totally obstructed or obstacle.

The accuracy of the obtained representation basically depends on the cell size: the larger cells are, the less precise is the representation. Of course, increased precision leads to an increase in memory use. The memory footprint of this method is thus its first weak point. It directly affects the complexity of path search in the environment. In order to reduce this problem, an extension of this model has been proposed in the form of hierarchical grids (Shao & Terzopoulos 2005b). This method describes the space by a set of overlay grids which are increasingly accurate, organized as a tree (Figure III-4 (b)). This method is advantageous when the environment contains a limited number of obstacles.

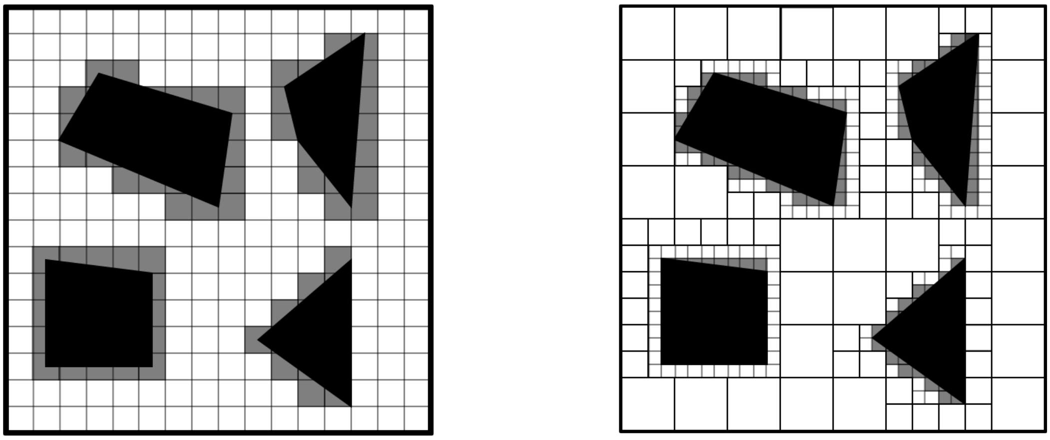


Figure III-4 : (a) Approximate decomposition by grids (b) Grid abstraction using a three levels quadtree. White boxes are free, grey are obstacles.

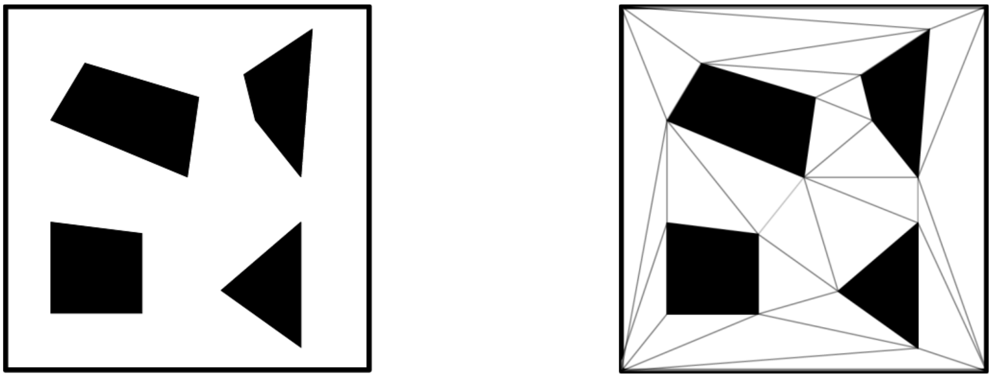
The grid based model has been widely used in behavioural animation because of its simple yet rich representation, but it has two main drawbacks: 1) the grid cannot capture the topological relationships between regions; 2) it usually suffers from high cost in both time and memory use when fine grids are used. Moreover, this model is also difficult to generalize to any kind of environment, particularly if they involve obstacles not aligned with the axes. Finally, it should be noted that the discretization level of the grid introduces an implicit limit to population densities that can be simulated (Andersen, Berrou & Gerodimos 2005).

– ***Exact Space Decomposition***

The exact space decomposition aims to organize spatial data in order to accurately represent the environment while preserving its geometric and topologic characteristics. The exact cell decomposition techniques decompose an environment into a collection of non-overlapping cells so that the union of all the cells exactly equals the environment. The geometry of cells may be triangles or convex polygons. Much work has been done on decomposition methods which can be placed into one of two categories: 2D space decomposition and 3D space decomposition.

- ***2D Space Decomposition:***

2D space decomposition algorithms provide space decomposition from a plane (2D environment). The most used decomposition techniques Delaunay triangulation, as well as its evolutions. The Delaunay triangulation (Boissonnat & Yvinec 1998) creates a set of triangles by bringing together points provided as input. The unification algorithm is constrained by the fact that the circle circumscribes a triangle contains no point other than the three vertices that compose it. Thus, this triangulation can be used to represent the navigable space, the entry points being derived from the obstacles (Figure III-5).



(a) Original environment (b) Constrained Delaunay Triangulation

Figure III-5: Example of constrained Delaunay triangulation.

- *3D Space Decomposition:*

In games and behavioural simulation fields there has been an increasing interest in automatically computing space decomposition from complex 3D environment. Indeed, many games and simulations feature characters navigating complex 3D environments, such as environments with stairs, beams or pillars. In order to generate plausible animations, determining navigable zones of the environment, with respect to humanoid characteristics, became a challenging problem in its own right. Thus, several methods have been proposed and two general approaches, differing in their algorithm of walkable surface's extraction can be distinguished. First voxel-based algorithms that approximate the walkable surfaces from raw 3D geometry, and second exact algorithms that require pre-processed input (e.g. a set of 2D layers) to compute a space decomposition.

Voxel-based methods (Mononen 2009);(Oliva & Pelechano 2013);(Pettre, Laumond & Thalmann 2005) usually take an unprocessed 3D environment as their input. We mean by a 3D environment a raw collection of polygons which may include floors, ceilings, walls, or any other type of geometry (Figure III-6 (a)).

To construct space decomposition, these methods discretize the environment into a 3D grid of voxels, extract the voxels that correspond to walkable regions, and summarize this information in a set of convex polygons that approximates the geometry of the space subdivision. This reconstruction is based on the assumption that the environment has a single direction of gravity, and that characters are cylinders with a fixed height and (sometimes) a fixed radius. It needs also to specify various parameters that describe on which surfaces a character may walk. Examples of such parameters are the maximum slope with respect to the direction of gravity, the maximum height difference between nearby polygons (e.g. the maximum step height of a staircase), and the required vertical distance between a floor and a ceiling.

Voxel-based methods can handle arbitrary 3D geometry. However, the precision and efficiency of these methods depends to a certain degree on the grid resolution.

The quality of the navigation mesh depends on how well the free space is extracted from the 3D geometry (Van Toll et al. 2016).

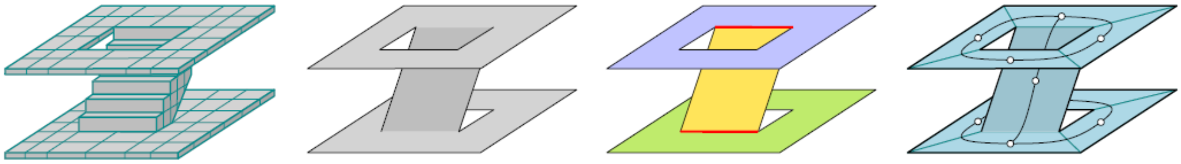


Figure III-6 : Different representations of an environment, and an example of its navigation mesh: (a) A 3D environment; (b) A walkable environment; (c) A multi-layered environment and (d) A navigation mesh (Oliva & Pelechano 2013)).

Many Voxel-based methods and tools have been proposed for a 3D space subdivision, among which:

NEOGEN structure provides a near optimal 3D spatial subdivision from a 3D environment (Oliva & Pelechano 2013). This approach computes a GPU voxelization of the geometry in order to obtain a first approximation of the walkable area. Then, the potentially walkable area is subdivided into layers, using an ordered flooding where each layer is refined by using the fragment shader at higher resolution and the space decomposition is computed using the ANavMG generator (Automatic Navigation Mesh Generator) (Oliva & Pelechano 2011). Finally, all those individual decompositions are merged into a single one, which represents the walkable space of the entire scene (Figure III-7).

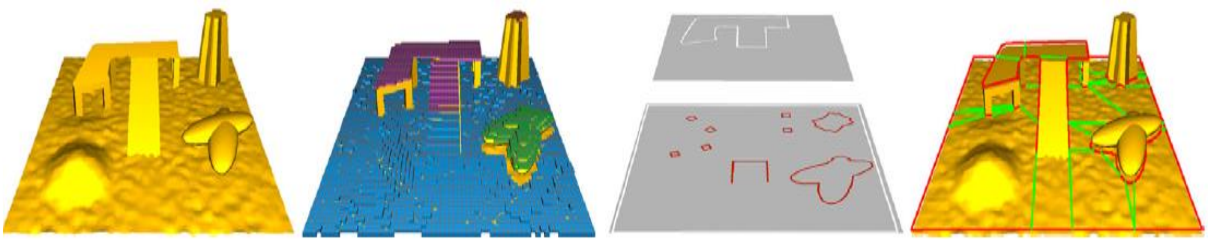


Figure III-7 : NEOGEN subdivision. From left to right we can see the original scene, the result of the layer extraction step after the coarse voxelization, the 2D floor plan of each layer, and finally the near optimal navigation mesh (Oliva & Pelechano 2013).

Exact methods (Jorgensen & Lamarche 2011);(Van Toll, Cook & Geraerts 2011) require that the exact geometry of the space subdivision is already known, and that this free space has been pre-processed into one or more planar layers. In exchange, they represent their input precisely, and they often have provable worst-case construction times and storage sizes, which implies better scalability to large environments.

TopoPlan takes a triangle mesh as input (Lamarche 2009). The algorithm first obtains a prismatic spatial subdivision, which maps every point on the ground plane to every triangle above it. It then uses this subdivision to quickly determine which triangles are walkable given a set of characteristics related to the agent capabilities, like the minimum required floor-ceiling distance and the maximal navigable slope (Figure III-8).

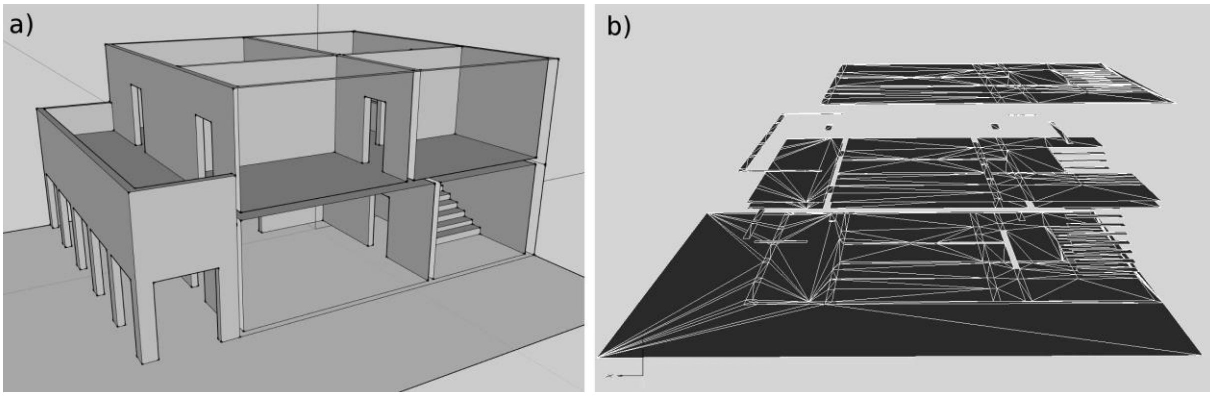


Figure III-8 : (a) A simple example environment (wall and ceiling masked for more visibility); (b) Its prismatic decomposition as generated by TopoPlan (Jorgensen & Lamarche 2014).

III.3.2 Topological and semantic abstraction

The environment abstraction is an additional process used to better organise the information obtained at the time of spatial subdivision. This topic is often approached jointly with spatial subdivision since it is a complementary process. The aims of this process are: 1) reduction of the number of elements necessary in the environment description and; 2) proposition of a more conceptual and intuitive representation of the walkable surfaces.

The abstraction algorithm aims to generate an abstraction tree by merging interconnected cells while trying to preserve topological properties. When merging several cells into a single one the composition of cells is stored in a graph structure, in order to generate the abstraction tree (Figure III-9). The unification heuristic is principally approached in two ways. The first way unifies basic subdivision cells in a mathematical way (Lamarche & Donikian 2004); it's a pure topological unification. The second way unifies cells in a more conceptual way, to introduce a semantical definition of the environment.

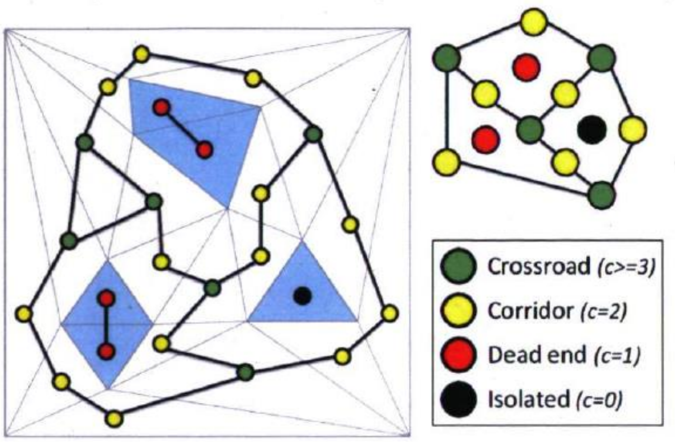
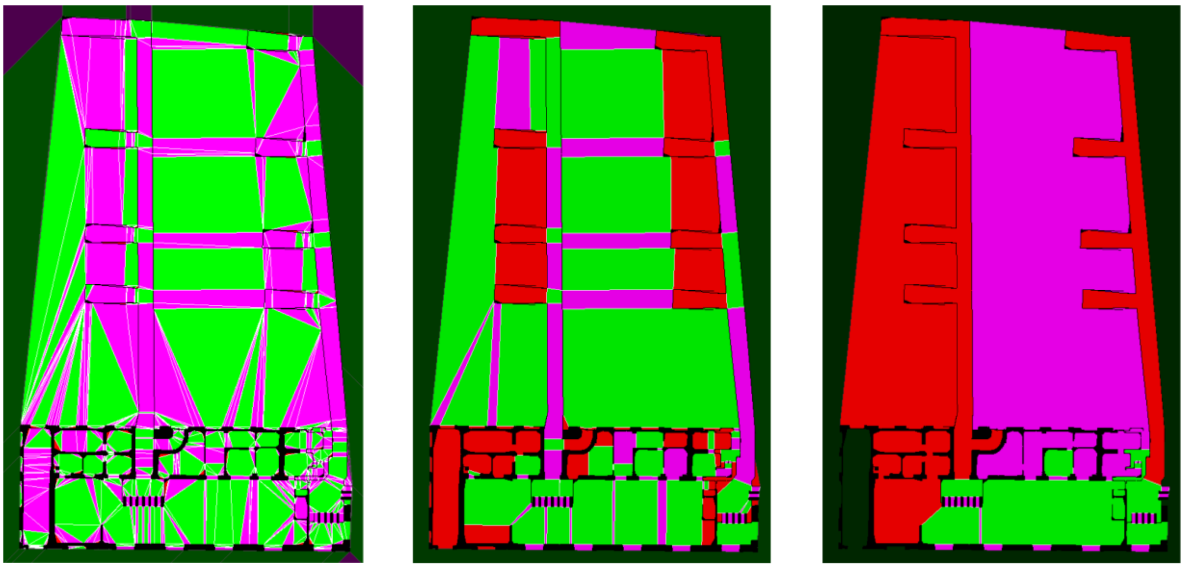


Figure III-9: An Example of a topological abstraction.

The topologic abstraction approach proposed by Lamarche & Donikian (2004) assigns to each node of the graph resulting from the space decomposition a topological qualification according to the number of connected edges given by its arity (Lamarche & Donikian 2004). This qualification enables the topological abstraction of the environment. For example, a sequence of corridor cells can be interpreted at a certain level of abstraction as a unique corridor.

The primary advantage of the topological abstraction is that spatial analysis can be done without using coordinate data, because spatial relationships (operations such as contiguity and connectivity analyses) are easily derived from the graph structure. Topological approaches provide more compact representations than those generated by space decomposition techniques, which facilitates certain tasks, such as path planning, since this representation allows exploitation of efficient algorithms provided by graph theory. But on the other hand, it does not support detailed navigation due to its lack of metric information, such as absolute position. Topologic approaches combined with exact space decomposition techniques provide an accurate and compact representation of the virtual environment (Figure III-10). The resulting graph contains fewer nodes and preserves the topologic and geometric characteristics of the virtual environment. However, the topological characteristics are not sufficient to abstract a virtual environment when dealing with a complex environment involving areas with various qualifications (buildings, roads, parks, sidewalks, etc.).



(a) Spatiale subdivision. (b) First abstraction. (c) Second abstraction.

Figure III-10 : Topological abstraction of a virtual environment (a) Corresponds to the original model, (b) and (c) first and second level of abstraction respectively source (Paris, Donikian & Bonvalet 2006).

III.3.3 Informed Environment

To enable autonomous agents to interact with their environment and increase the realism of simulations, the notion of informed environment has been introduced. The idea is to associate a data structure with regions of the environment. This data structure stores information dedicated to the behaviour. Indeed, agents not only need the geometric and topologic data which describe the environment but also semantic information that qualifies regions of the environment. Such a semantic information enables agents' spatial reasoning and enriches the description of the virtual environment and objects located in it. This approach has been used to model populated cities and to propose semantic abstractions of a city structure.

Farenc has first used the notion of Informed Environments (Farenc 2001). She defined informed environments as a database which represents urban environments with semantic information representing urban knowledge (Farenc, Boulic & Thalmann 1999). An urban scene is decomposed into a hierarchy of *Environment Entities* that provide not only geometrical information but semantic notions as well, allowing a more realistic simulation of character behavior (Farenc, Boulic & Thalmann 1999). One main aspect of informed environments is the fact that they need to be modeled with specific tools or manually informed on the basis of the original geometry.

Sung, Gleicher & Chenney (2004) proposed a more "meaningful" environment model, which embeds composable character behaviours in the regions where they are relevant. These behaviours can be added into characters' behaviour repertoire when they enter the associated regions. While this model is unnatural, it provides an interesting solution to the problem of interpreting and interacting with the environment after it is perceived.

Paris, Donikian & Bonvalet (2007) proposed an informed environment model aiming to improve the behavioural possibilities of the simulated humanoids. They used an automated process only based on a graphical definition of the virtual environment. A three level hierarchical graph is built from the environment subdivision into convex cells. Then, this graph is informed with some pre-calculated data, like densities of populations, flows of people, the potential visibility sets and individual knowledge. These data can be used by agents to quantify the traversal cost of a graph node. According to Paris et al. since simulated agents can get any information at the time it is needed, this would lead to the simulation of non omniscient beings besides optimising the simulation computation costs. Their environment model offers also an interaction description engine, BIIO (Paris, Donikian & Bonvalet 2007). The latter allows a hierarchical modelling of the interactions, and also to make the link between the topological representation and the behavioural procedures of the humanoid. This last aspect could then be used to perform a rational planning since the planning algorithm can find a path to an object, or choose an object between many.

III.3.4 Virtual geographic environment

Data used to build virtual environments in the computer and behavioural animation research fields are mostly provided by Computer Aided Design and Graphics (CADG) systems. In contrast to GIS data, CADG data are used to create precision drawings or technical illustrations for animation and visualization purposes without taking into account the geo-referencing of spatial data; that is, explicit mapping of a data point to its geographic location on the surface of the earth. The CADG data model lacks the definition of spatial relationships between features that is defined by GIS data models both in raster and vector formats. In addition, interactions between agents and the environment are most of the time very simple, permitting the agents only to perceive and avoid obstacles in 2D or 3D virtual scenes. Therefore, designers of multi-agent simulation models have shown an increasing interest in linking agents to real locations and geographic data by coupling these models to geographic information systems (GIS).The Multi-Agent Geo-Simulation (MAGS) approach allows the simulation of pedestrian's interaction with these environments (Mekni 2013), and the spatial simulation involving an urban virtual geographic environment (VGE) became a growing field of research (Mekni 2017). Examples of recent applications include pedestrian dynamics, urban growth models and land use models.

(a) Triangulated elevation map (2:5D). (b) Merged semantics map (2D). (c) Unified map (2:5D).

Figure III-11 : The two processed maps (a, b) and the unified map (c) (Mekni & Moulin 2011).

Mekni & Moulin (2011) proposed an automated approach to compute the Informed Virtual Geographic Environment (IVGE) data using vector GIS data. This approach is based on four stages: input data selection, spatial decomposition, maps unification, and finally the generation of the informed topologic graph.

***GIS Input Data Selection**:* The first step consists in selecting the different vector data sets which will be used to build the IVGE. The input data can be organized into two categories. First, elevation layers contain geographical marks indicating absolute terrain elevations. Second, semantic layers are used to qualify various types of data in space.

***Spatial Decomposition**:* The second step consists of obtaining an exact spatial decomposition of the input data into cells. First, an elevation map is computed using the Constrained Delaunay Triangulation (CDT) technique. All the elevation points of the layers are injected into a 2D triangulation, the elevation being considered as an attribute of each node. Second, a merged semantics map is computed, corresponding to a constrained triangulation of the semantic layers. Indeed, each segment of a semantic layer is injected as a constraint which keeps track of the original semantic data by using an additional attribute for each semantic layer.

***Map Unification**:* The third step to obtain the IVGE consists of unifying the two maps previously obtained (Figure III-11).

***Informed Topologic Graph**:* The resulting unified map now contains all the semantic information of the input layers, along with the elevation information. This map can be used as an Informed Topologic Graph (ITG), where each node corresponds to the map's triangles, and each arc corresponds to the adjacency relations between these triangles.

III.4 Cognitive maps

We will present in this section three sets of works on cognitive maps. The first presents a multi-hierarchical map for mobile robots which includes spatial and semantic information. The second and third presents a cognitive map model coupled to a spatial memory model.

III.4.1 Multi-Hierarchical Semantic Maps

A. Data structures

One of the application domains of spatial cognitive maps is robotic navigation. In the approach proposed by Galindo et al. (2005), a mobile robot is endowed with an internal representation of its environment from two different perspectives: 1) a spatial perspective, that enables it to reliably plan and execute its tasks (e.g. navigation); and 2) a semantic perspective, that provides it with a human-like interface and inference capabilities on symbolic data (e.g., a bedroom is a room that contains a bed). These two sources of knowledge, spatial and semantic, are interrelated through the concept of anchoring, which connects internal symbols (e.g. bed) to sensor data that refers to the same physical entities in the environment (e.g. an image of a bed).

Figure III-12 depicts this approach. It includes two hierarchical structures, the spatial and the conceptual hierarchies. The Spatial Hierarchy arranges its information in different levels of detail: 1) simple sensorial data like camera images or local grid maps, 2) the topology of the robot environment, and 3) the whole environment represented by an abstract node. Additional intermediate levels could also be included. The Conceptual Hierarchy represents concepts (categories and instances) and their relations, modelling the knowledge about the robot environment. This permits the robot to do inferences about symbols that is instances of given categories.

B. Navigation

This approach allows users to give symbolic instructions to the robot. For example, a user can ask the robot to solve the task *go to the bedroom*. To do so, the inference system needs to find an instance of the general category bathroom to be used as the destination for the robot, i.e., room-C. This symbolic information, however, cannot be directly handled by the navigation system, which requires instead the spatial information related to the destination. Such spatial information is retrieved by following the anchoring link that connects the desired destination to the topological element in the Spatial Hierarchy. In this way, the initial symbolic task is translated to the executable task *go to D*. This task is then performed using the topological and metric information for navigation stored in the Spatial Hierarchy.

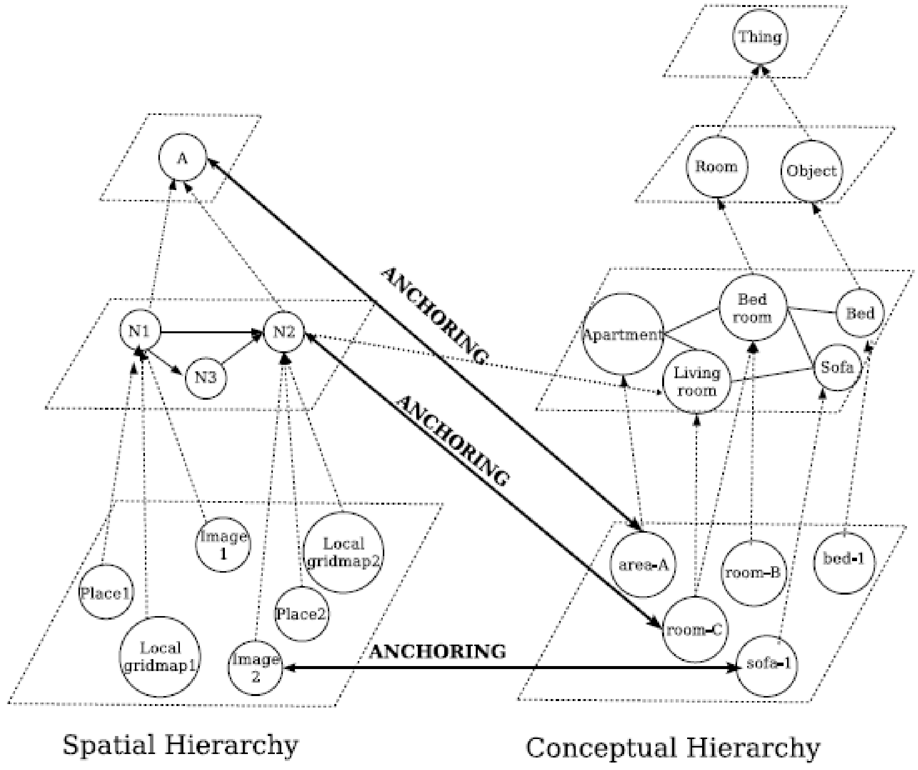


Figure III-12 : The spatial and semantic information hierarchies. (Left) Spatial information gathered by the robot sensors. (Right) Semantic information that models concepts in the domain and relations between them. Anchoring is used to establish the basic links between the two hierarchies (solid lines). Additional links can then be inferred by symbolic reasoning (dotted line), (Galindo et al. 2005).

III.4.2 Absolute Space Representation and Memory for Immediate Surrounding

Jefferies and Yeap have developed a cognitive map system (Yeap 1988; Yeap & Jefferies 1999), coupled with a human memory system (Jefferies & Yeap 1998). To develop their system they start from theoretical consideration on the structure of a spatial cognitive map. Jefferies and Yeap have therefore created a data structure called ASR for Absolute Space Representation to represent the space immediately surrounding the individual. An ASR is a surface representation of an environment portion determined by the scope and occlusions of the visual field of the navigating entity, having boundaries and entry and exit points. For the global data structure they represent a set of ASR as a topological graph as shown in Figure III-13.

However, one of the major problems is related to the problem of identifying ASRs. Indeed, as shown in Figure III-14 (b), it is difficult to determine when one enters a new space if this space has been visited before. To overcome this problem, they create the MFIS (for Memory For Immediate Surrounding). An MFIS is a limited-capacity memory structure for storing ASRs recently visited by the agent in its immediate vicinity (as shown in Figure III-14 (c)). Each new ASR created the MFIS system determines if this ASR is part of a pre-existing ASR. The navigation system generally consists of moving between the different ASRs from points of entry to exit points.

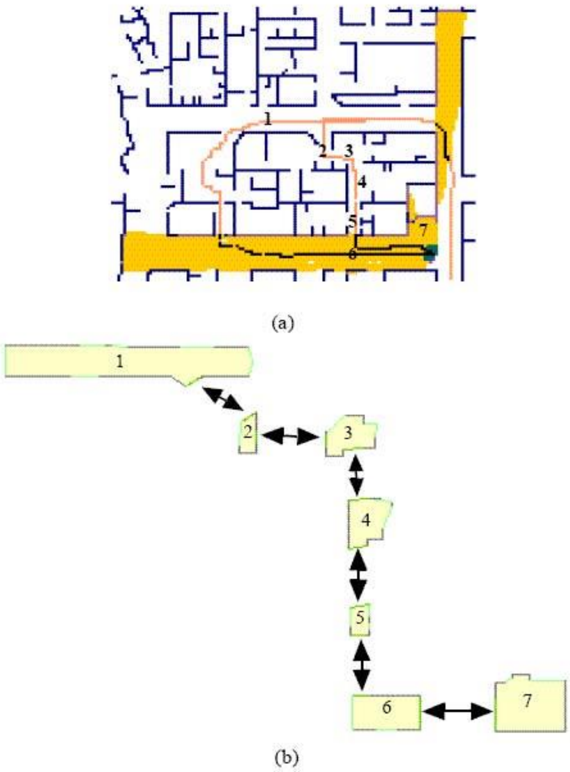


Figure III-13 : (a) The environment (b) The topological graph ASR (connections are based on the agent's navigation experience), (Jefferies & Yeap 1998).

Details on the navigation system are not given; it generally consists in walking between the different ASRs, from point of entry to point of exit.

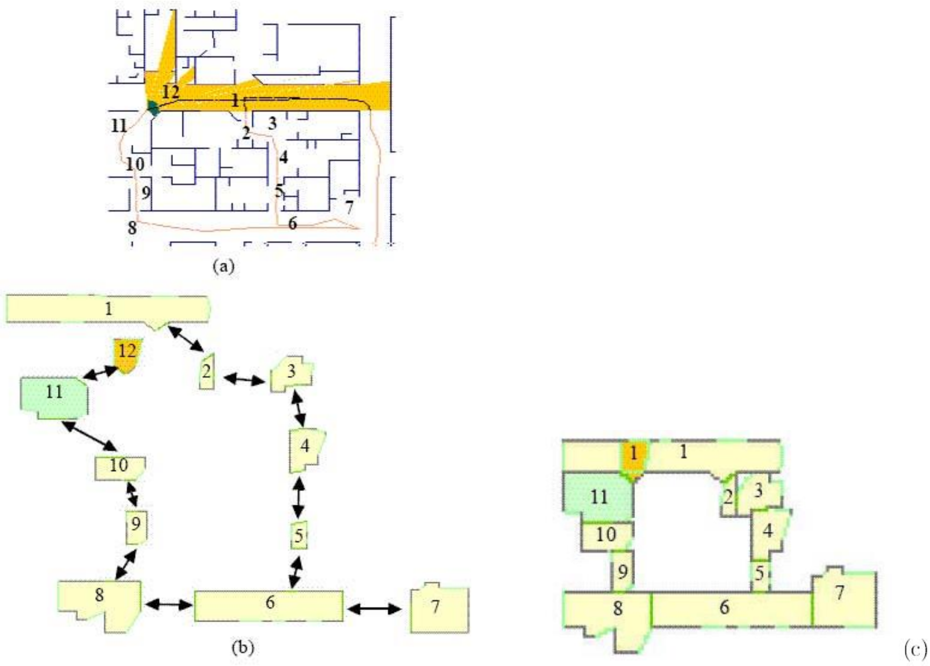


Figure III-14 : Problem of identification of the ASR;(b) it is difficult to detect that the ASR-12 and the ASR-1 account for the same space (c) ASRs-12 and 1 should logically be grouped together (Jefferies & Yeap 1998).

III.4.3 Hierarchical cognitive map and human memory

A. Data structures

Thomas & Donikian (2003) proposed to merge a spatial cognitive map model with a model of human memory. They used a semantically and geometrically informed hierarchical topological graph as a representation of a large environment to be navigated in (Figure III-15). Their model of cognitive map has a topological and hierarchical graph structure which partially maps the regions of the environment the agent has explored during the simulation (Figure III-16). It does not contain geometrical nor semantic information about the urban objects encountered, but only controls the partial access to the database while the agent recalls or perceives the urban objects (Figure III-17). As a simplified model of human memory, they use the recall and recognition attributes, and their respective thresholds of activation to parameterize in two different ways the cognitive map.

B. Navigation

Their algorithm is designed around two main steps:

- **The planning**. The agent is given a starting point and a destination, then it plans its route between this two points computing the plan with elements taken from the Filter IHT-graph (high-level planning) and the graph of landmarks (low-level planning).
- **The reactive navigation**. In case the agent is really lost, i.e. walks in a zone where nothing triggers recognition or recall in its cognitive map, it follows the same direction, preferably along bigger axis or road section until it likely meets a known landmark. Then it re-computes a new path.

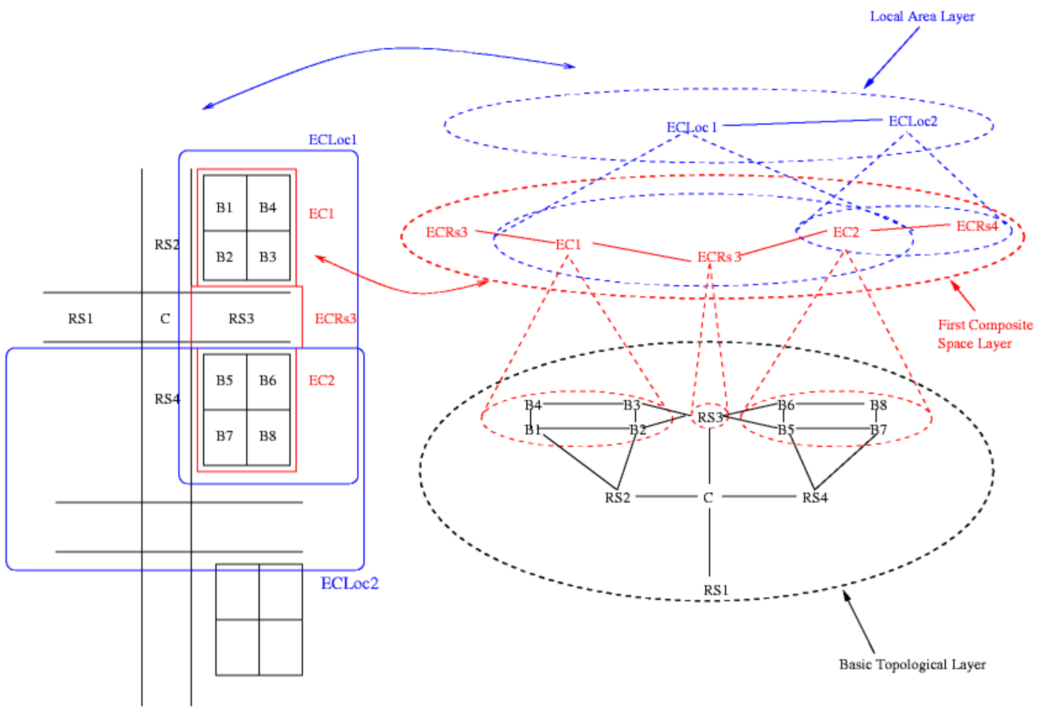


Figure III-15 : An example of an IHT-graph (Thomas & Donikian 2003).

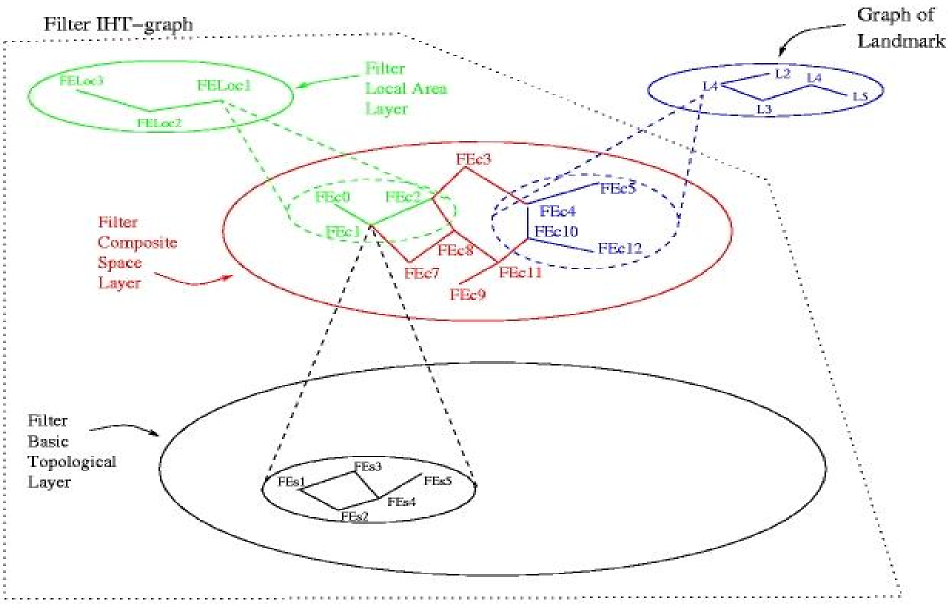


Figure III-16 : A simple cognitive map structure (Thomas & Donikian 2003).

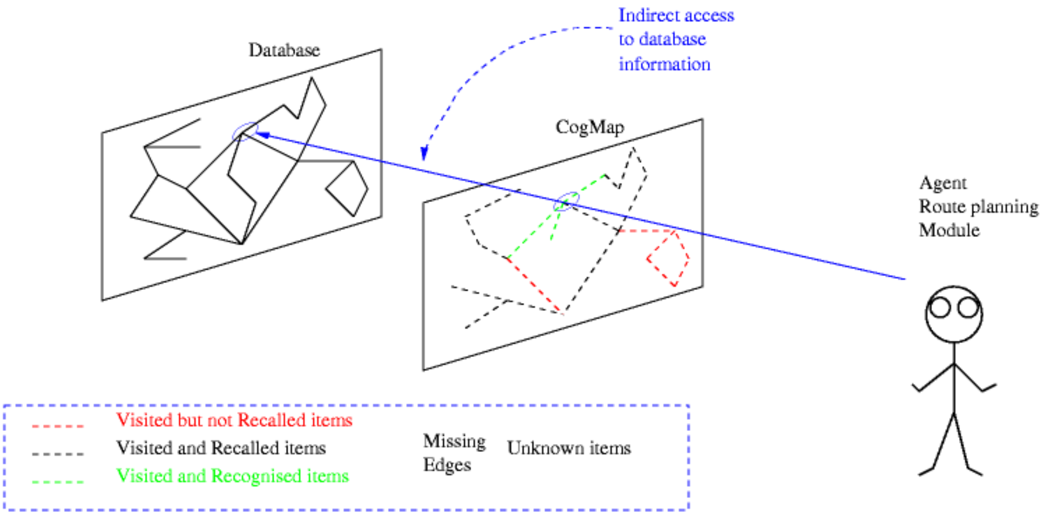


Figure III-17 : Database/CognitiveMap relation (Thomas & Donikian 2003).

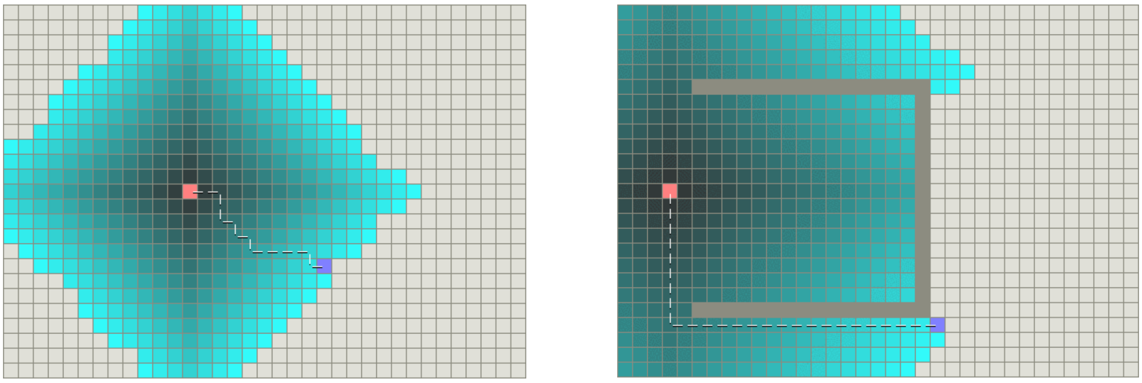
III.5 Path planning and spatial behaviour

The path planning issue, which consists in finding an obstacle-free path between two distinct positions located in a virtual environment, has been extensively studied. A short survey of this topic is presented in this section.

III.5.1 Path planning algorithms

A classic method for doing this planning is to use graph traversal algorithms, although certain methods use other techniques (such as gradient descent for fields of potential). Different algorithms can be used in this context. The ones we describe here are based on a criterion of cost minimization to extract the shortest path. This cost often represents a notion of spatial distance, but we will see in section III.5.3 that more complex heuristics can be used.

A. Dijkstra Algorithm:



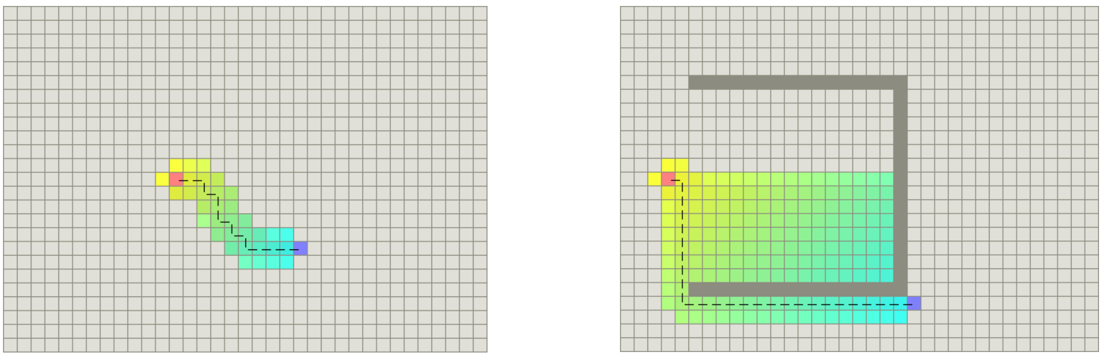
(a) Dijkstra Algorithm exploring cells to find a path in an obstacle-free environment.

(b) Dijkstra Algorithm explores more cells to find a path in a virtual environment with obstacles.

Figure III-18 : Cells explored by the Dijkstra Algorithm to find a path to the destination node. The pink cell represents the source node; the dark blue cell represents the destination node. The gradient of blue corresponds to the increase of distance, the lightest being the farthest.

Dijkstra's algorithm was conceived by Dutch computer scientist Edsger Dijkstra in 1959 (Dijkstra 1959). This algorithm works by visiting vertices in the graph starting with the object's starting point. It then repeatedly examines the closest not-yet-examined vertex, adding its vertices to the set of vertices to be examined. It expands outwards from the starting point until it reaches the goal (Figure III-18). Dijkstra's algorithm is guaranteed to find a shortest path from the starting point to the goal, as long as none of the edges have a negative cost. The major interests of this algorithm are its robustness (if a path exists it will be necessarily found). Its weak point is its computational complexity, being of the order of O (A + N. logN) where A is the number of arcs of the graph, and N is the number of nodes.

B. A* Algorithm:



(a) A* Algorithm exploring cells to find a path in an obstacle-free environment.

(b) Dijkstra Algorithm explores more cells to find a path in a virtual environment with obstacles.

Figure III-19 : The A*'s algorithm search for the shortest path. The pink cell represents the source node; the dark blue cell represents the destination node. The gradient of yellow to blue corresponds to the total cost of path distances (sum of the actual and predicted lengths).

A* was developed in 1968 (Nilsson 2014). This algorithm works in a similar way to the Dijkstra algorithm, but adding a predictive cost to the nodes corresponding to the rest of the path to go. The total cost is the actual length of the path to the node, incremented by a predicted value for the path to the goal, calculated by a heuristic. The algorithm will thus browse the nodes in ascending order of their associated costs (Figure III-19). The speed of convergence of this algorithm is directly dependent on the quality of the heuristic used. In the case of shorter search path, the heuristic employed is a distance estimates, usually the norm geometric separating the current node from the goal.

The advantage of this algorithm lies in its computational speed. Its major disadvantage lies in the use of a heuristic. Indeed, the longer the evaluation of the length path will be complex, possibly involving other parameters than distance (e.g. a cost associated with semantics), and the more this heuristic will be difficult to explain. Thus, it is difficult to use this algorithm for path planning whose purpose is not clearly identified in the topological graph.

III.5.2 Hierarchical Path Planning

The computational time required to find a path, using a search algorithm such as A* or Dijkstra, increases with the size of the search space, consequently path planning on large-scale environments can result in serious performance bottlenecks. Therefore, hierarchical path finding has been studied; it allows computing the shortest and optimal route between two locations in large terrains based on a hierarchical graph. Indeed, representing the virtual environment using the hierarchical approach allows a reduction in the size of the search space as well as the problem complexity in path planning.

Recently, there has been some research focused on hierarchical path finding techniques using the A* algorithm. Although A* generates optimal paths, it is computationally expensive, especially for large state spaces. One way to speed up pathfinding is to construct spatial abstractions which retain the topological structure of planar map graphs but contain fewer nodes.

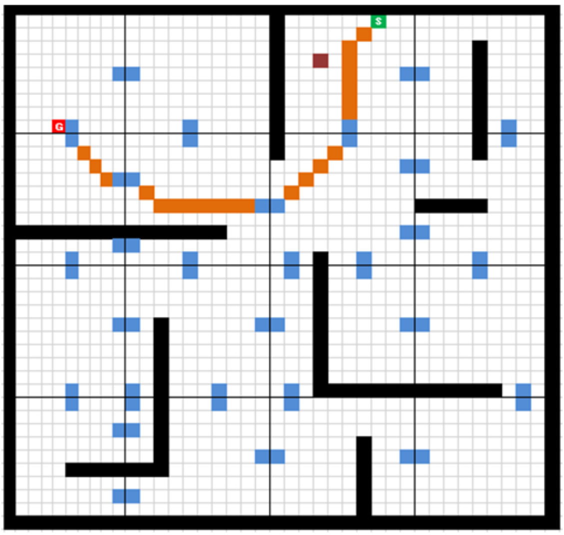


Figure III-20 : Abstract Graph: Black cells represent obstacles and walls. Entrances are blue cells. Green cell is the start and the red one is the goal. Path between them is with orange colour.

– **HPA*.** An earlier hierarchical pathfinding algorithm is HPA* (Botea, Müller & Schaeffer 2004). This method builds abstractions of the search space by segmenting the map into clusters. It assigns entrances along the borders between the clusters, which become nodes in the abstract graph. The example in Figure III-20 shows a small map. Edges are added between corresponding entrance nodes in adjacent clusters as well as between entrance nodes within the same cluster if there is a path between them which lies entirely within the cluster. The weight for an edge is set to be the cost of the shortest path in a lower level of the abstraction. The path corresponding to the edge weight can either be cached or recomputed when it is needed.

- **Triangulation A* and Triangulation Reduction A*.** Two hierarchical triangulation-based path planning approaches proposed by Demyen & Buro (2006). TA* makes use of the Delaunay Triangulation (DT) technique to build a polygonal representation of the environment. This results in an undirected graph connected by constrained and unconstrained edges, the former being traversable and the latter not. TRA* is an extension of TA* and abstracts the triangle mesh into a structure resembling a roadmap in order to maximise triangle size.
- **Hierarchical NavMesh Path-finding algorithm (HNA*).** Pelechano & Fuentes (2016) extend the benefits of the HPA* method to polygonal navigation meshes (Figure III-21). As opposed to regular grids, navigation meshes over representations with higher accuracy regarding the underlying geometry, while containing a smaller number of cells. Therefore, they presented a bottom-up method to create a hierarchical representation based on a multilevel k-way partitioning algorithm. Using this partitioning algorithm, they create a hierarchy of several levels of complexity with a decreasing number of nodes per level based on a user input variable that determines the approximate number of nodes to collapse between consecutive levels of the hierarchy.

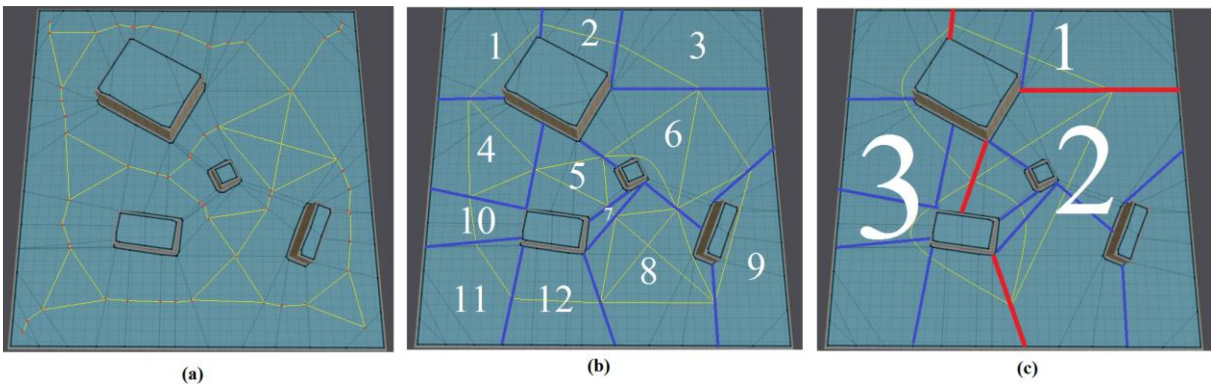


Figure III-21 : Hierarchical subdivision of a simple map. Red lines in (c) represent inter-edges and yellow lines in (b) and (c) represent intra-edges. Partitions are shown with black (a), blue (b) and red (c) separation lines respectively (Pelechano & Fuentes 2016).

III.5.3 Multiple criteria path planning

Different criteria can be evaluated for the cost of the pathfinding algorithms. The older methods, as well as most of those used in animation, are based only on the distance between the nodes. But, as the studies showed in psychology presented at the first chapter, this distance information is necessary, but certainly not sufficient to account for the complexity of the human reasoning. Thus, in simulations intended to be more realistic, other evaluation criteria are proposed.

When reviewing the literature we found that many methods are proposed in order to quantify and qualify a path in the environment. Nevertheless, few of these methods combine several criteria at once. Although it seems that the fusion of this information is necessary to get closer to a realistic simulation, the problem of finding a basis of comparison between data of different nature is the reason of this lack. The mixture of criteria therefore seems essential for considering the application of path planning methods to the simulation of virtual humans. This prompted researchers to propose solutions among which we can mention:

Paris, Donikian & Bonvalet (2006) proposed an evaluation of the path by a comparison of the travel time felt (expected) by the entity. Thus, every criterion is converted into an evaluation quantitative temporality (criteria of distance, density population) or qualitative (change of direction criteria, path width, direction of population flows, or discovery potential). This temporal evaluation is a succession of filters:

$$Cost = \sum_{i=1}^{n} Pi \times Vi$$

With Pi the degree of preference of the filter, and Vi the value of the filter ($V_i \in \{[0; 1],$ *infinite*$\}$). The value of the filter V_i is here obtained by a global calculation (i.e. independent of the entity) carried out on the environment. The degree of preference is specific to each entity, and can be positive (the criterion is unfavourable), negative (the criterion is favourable), or null (the criterion is ignored).

Jorgensen & Lamarche (2011) proposed a multi-criteria path planning algorithm that makes intensive use of their environment representation. The aim of the path planning process is to find a path going through zones that tend to match a multi-criteria request. This algorithm uses a zone matching function that evaluates the adequacy of a zone given a multi-criteria request. In their system, a request is a conjunction of criteria, which could be criteria relating to zones' nature (covered, does not belongs to a building) or its geometric properties. Therefore, in the function evaluating the cost of a path, paths traversing zones that match the request are encouraged; on the other hand the path length criterion is given importance.

In Figure III-22, an example was used to test the algorithm in the rainy day example. The planning request was set up by giving a constraint on navigating in covered zones (to avoid the rain) and changing weights associated to the covered and path length criteria. Computed paths are presented in Figure III-22 (Right). Path 1 has been generated by giving a weight of 1 to the covered criterion and a weight of 2 to the path length. Consequently, the shortest path was used. Path 2 has been generated by giving a weight of 2 to the covered criterion and 1 to the distance. In such a case, the character used the longest path but this path minimizes the exposition to rain. Finally, path 3 has been generated by giving an equal value of 1 to the covered criterion and the path length. The character navigated mostly in covered zones and was also exposed to rain.

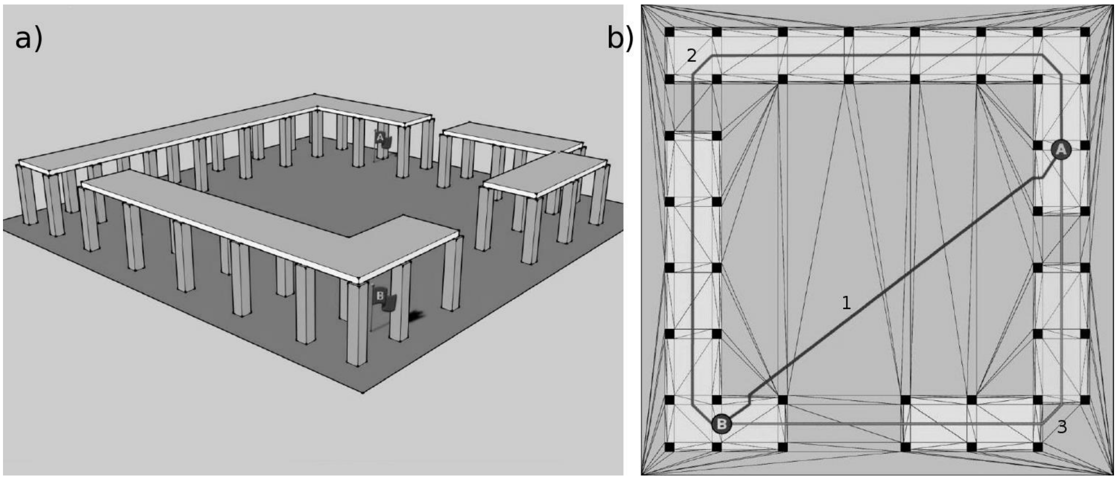


Figure III-22 : Environment used for spatial reasoning test and path calculated in it out of three different requests (Jorgensen & Lamarche 2011).

III.6 Conclusion

Throughout this chapter, we have focused on the reproduction of human pedestrian movement. We have thus treated approaches used to model pedestrian movement, and the representation of the environment as well as its use to generate mental maps and exploitation during the path planning process.

We started by introducing computer models that simulate crowds of pedestrians. The first models are all characterized by a total abstraction of the individual behavior, to concentrate on a quantitative macroscopic approach of the crowd. This is why these models have been used extensively in evacuation simulations, where the individual behavior can be almost ignored, being reduced to its simplest expression: to move to the nearest exit. This is why we can think that these models would be very difficult to exploit in more varied situations, where the impact of individual decisions would no longer be negligible. It would be interesting then to move towards a model allowing a fine control as with the microscopic models.

Recent microscopic models are generally organized in the form of two steps to reproduce the phenomenon of pedestrian movement. First, represent the environment by some form of abstraction to facilitate its exploitation. Indeed, in the context of modelling autonomous characters, an environment model must go well beyond a representation that facilitates all perceptual processes, interpretation, and interaction. Second, analyze the environmental data that are available: the entity will evaluate its way through the planning process.

Concerning the parameters to be taken into account when evaluating a path, some of these parameters are highlighted by different studies, but no comparison of their relative importance is available. It can nevertheless be deduced from psychological studies that many of these parameters must be taken into consideration simultaneously.

We can say that many computer models of mental representations of the environment exist, the majority of which were derived from experiments with human subjects. Some models are only formalizing a feature of the mental representation of the human environment. However, others propose a unified operational model of mental representation trying to include the maximum of notions and concepts from cognition. Nevertheless, because of their computational complexity, these models are generally only used for the simulation of a very limited number of humans, well below the size needed for a crowd.

Discussion

The objective of our study is the simulation of pedestrian movement in urban environments. Therefore, in the first part of this state of the art, we have considered the primary objective of our subject, human pedestrian movement. We have thus addressed this problem, first by the fields of spatial cognition and spatial syntax then by computer simulation, in order to specify the requirements for a realistic simulation of agents' wayfinding behaviour in virtual environments. We have also reviewed several approaches used to build virtual environments, to model situated agents, and to support path planning of agents within these environments. In this section, we will summarize and discuss this literature review, in order to outline the requirements of the architecture that responds to our objectives.

Spatial cognition and spatial syntax

To begin with, we have reviewed some psychological bases defining the outlines of the human navigation behaviour by the cognitive sciences. We retained from this review several points as important as each other, for our study framework. The first one is that people do not behave the same way when walking in a familiar area, or when visiting a region for the first time. These findings have been raised by researchers in spatial cognition domain when analysing linguistic data, and confirmed by researchers in the space syntax community, through enormous empirical studies. They have examined the characteristics of paths frequented by humans in an urban environment, and one of their findings has been the difference in movement patterns created by the accumulated trips of wayfinders, when they are familiar or not with the environment.

The second one is that people familiar with the environment when communicating spatial knowledge in route directions, rely primarily on certain elements, which is considered as reflecting cognitive prominence and memory content acquired by experiencing the environment. Indeed, these representations are hierarchically organized in individual hierarchies. Moreover, people familiar with an environment share common spatial knowledge due to similar experience of their environment.

The third one and it is one of the most provocative findings in cognitive psychology, it also concerns pedestrians familiar with their environment. According to researchers, they don't require planning the complete path in advance. Since finding a path needs an effort for accessing information from memory, the wayfinder leaves the route choice decisions to be made at each street junction.

Final point in the field of space syntax, simulating pedestrian movement is considered as one of the core tools of spatial analysis utilised to provide an understanding of space, such as what happens when the space configuration changes and how human movement can be approximated at this fact. They created agents that have a basic driver: the visual field. Therefore, an agent will move towards further available space as determined by his current visual field. Through a small set of simple rules to follow and the interactions between the agents a pattern of movement emerges. The resulting paths taken were compared to spatial analyses of the environment and observed movement in the corresponding real environment. On another hand, comparisons of this type have confirmed the impact of the environments' spatial configuration and the visual field characteristics on human route choices.

Computer simulation

Concerning the virtual environment models, first models have mainly focused on how to represent information. Two approaches were possible: a more performance-oriented, with the approximate representations such as grids, and the other on the preservation of information, with exact representations as the Delaunay triangulation. Then, as researches in spatial cognition showed that people tend to hierarchically organise their mental representation of the environment, informed representation based on different levels of abstraction was proposed. The abstraction can be topological or semantic. The first abstraction is mathematical, to obtain bigger structures. The second abstraction is more conceptual, to introduce a semantical definition of the environment. Later, designers of multi-agent simulation models have shown an increasing interest in linking agents to real locations and geographic data by coupling these models to geographic information systems. Thus, the Multi-Agent Geo-Simulation approach allows the simulation of pedestrian's interaction with these environments, and the spatial simulation involving an urban virtual geographic environment became a growing field of research.

The following point that we retain, in computer models, concerns the cognitive map models. The developers of virtual environment models have found that information used to navigate is identical for all autonomous characters and that is relevant to endow each agent with a cognitive map structure which should hold a personal view of the agent along with the simulation. Thus, many computer models of cognitive maps have been proposed. Some of them only focus on formalizing a characteristic of the phenomenon of mental representation of the environment in humans. Others propose a unified operational model. Some related to the robotic navigation and some merging cognitive maps and human-like memory models for navigation simulation in an environment. But the first point that has not been sufficiently addressed by these models concerns creating mental maps for an important number of agents. The second is the generation of the cognitive map without passing by a learning phase.

The last point to take into account, in computer models, is the path planning and navigation algorithms. The issue in the first proposed models was how to improve the performance of the algorithm. We can mention for example A* algorithm, then its improvement HPA* for Hierarchical Path-finding A*, and HNA* for Hierarchical Navigation Mesh Path-finding, which propose to plan a path based on a hierarchical description of the environment. After that, many studies have shown that even travelled distance impacts path planning; a certain number of other factors must be taken into account. Subsequently, multiple criteria path planning has been used in many crowd simulation systems. We therefore have a decision-making process based both on distance and on other criteria such as semantic information or on more individual parameters like knowledge or preferences.

We can conclude that the envisaged subject brings together a very large number of issues. All of these have already been discussed in computer science, but relatively rarely in our study framework. In addition, few unifying models exist, and those proposed do not cover our entire subject.

Requirements for the simulation of pedestrian movement

Creating a virtual environment dedicated to pedestrian movement simulation is indeed a complex task. Many aspects and factors have to be taken into account, at several different levels.

First, since we are interested in simulating pedestrian wayfinding in urban environments which can be used to predict movement patterns of real locations, we need a description of the environment that should be built by using data from Geographic Information Systems (GIS). However GIS provide standard geographic data representing the environment, thus a topological and semantic abstraction process should be used in order to optimize and to provide a meaningful description of the environment.

Second, the description of the virtual environment should include quantitative data to capture both the geometric and the topologic characteristics of the environment. It should also include qualitative information which consists of associating semantic information with certain elements of the city structure, in order to enable agents' spatial reasoning.

Third, according to our literature review provided in chapter 1 and chapter 2, the spatial configuration of the environment has a relevant role on individual spatial decision- making and it is particularly interesting because it suggests that the layout of the environment itself affects the choices that individuals make. Therefore, the description of the environment should capture the configurational characteristics of it.

Moreover, agents should be able to take advantage of such an informed description of the environment to support their spatial behaviours. Agents should be able to perceive their environment. In addition, they should be able to react to that perception, to extract the information (geometric, topologic, semantic, configurational) in order to reason about, to make a decision, and finally to act on the environment. They should be able to plan paths which take into account their individual knowledge as well as the virtual environment's characteristics. However, the framework application is not encouraging to move towards cognitive map mechanisms, which must be individual, which is not feasible if we consider a very large number of autonomous agents. Besides, time of simulation is too short to realize the learning phase. Instead, we need a mechanism which will mimic the role of cognitive map without implementing all of its mechanisms.

The last aspect that needs to be addressed is how to evaluate a path within the environment. This path planning can be achieved by graph traversal algorithms, now well known. However, what will really matter is the decision process and the influencing parameters considered. Agents should be able to perceive their environment; extract the visual, configurational characteristics of it, to support their spatial behaviours. In addition, they should be able to react to that perception, to make a decision according to individual knowledge, and finally to act on the environment.

Part II Contributions

Introduction

Path planning task through an environment constitute an important activity in our daily lives. A large body of research analysed this behaviour with the aim of understanding strategies and heuristics that are applied during route planning, and finding the different criteria a pedestrian may consider when choosing a route from among a variety of path alternatives. In the first part of this thesis, we presented a literature review in order to identify the issues that must be addressed in order to arrive at a model that allows realistic simulations. The second part of this thesis details our contributions and the way to address the above mentioned issues. Our contributions start with our proposed model of virtual environments, dedicated to support spatial reasoning algorithms such as agents' path planning and navigation. Then, we present our approach in generating agents' cognitive map, which allows movement simulation in familiar environments. Finally, we conclude by describing our model of virtual human and its behavioural mechanisms of pathfinding.

Chapter IV Virtual environment model and mental map model for pedestrian movement simulation

IV.1 Introduction

Simulation of pedestrian movement is a wide and complex topic, requiring the description of all possible actions for each individual. One of the principal capacities, necessary to the navigation of the simulated entity, is unquestionably the perception of its environment. To achieve this goal, a virtual environment description must be provided. It will integrate all the information necessary for the decision making of our entities, whether it is the geometry and the topology of the places, or even the spatial configuration of the environment. The second way that our entity accesses environment information comes from its individual knowledge base. We will thus present, in this chapter, the two sources of information: the virtual environment model and the mental representation model.

The rest of this chapter is organized as follows: we start in section IV.2 by presenting our proposed pedestrian movement simulation system, as we will aboard, in this chapter, two of the necessary models for such architecture. In section IV.3 we start with the first model; we will detail our methodology for creating the virtual environment model. We continue, in section IV.4, with the second model; we will present our approach to generate the virtual pedestrians' mental representation of the environment. Finally, section IV.5 concludes this chapter.

IV.2 Proposed approach

In order to arrive at a model that allows realistic simulations, we have identified several issues that need to be addressed. In this section we will present our approach to solve these issues and respond to the requirements dictated by a pedestrian movement simulation. We aim, in this section, to provide an overview of the nature of the proposed approach and contributions.

Our first contribution concerns the representation of the environment. The proposed environment model is close to reality as possible, and allows a quick extraction of information necessary to the route choices of the autonomous entities. Among this information we can consider all the geometric and topological characteristics of the environment, but also the location and characteristics of the zones of decision making, to enable the implementation of the situated aspects of the behaviour.

The second contribution concerns the actors of the simulation. People do not behave the same way when walking in a familiar area, or when visiting a region for the first time. Therefore, we believe that in order to generate credible pedestrian navigation behaviour in virtual cities we have to take into account familiarity factor. In a city, people are not all visitors; there are also pedestrians with a more or less complete knowledge of their environment. Our model must be able to show a certain behavioural realism, especially concerning the pedestrians route choices which are strongly affected by their familiarity with the environment.

The third contribution concerns the creation of the simulated entities mental representation of the environment. The proposed path planning process is based on an individual knowledge base about the environment. Thus we have to endow each entity with a mental representation. However, our model must be able to create and simultaneously manage many entities with low costs.

The three contributions compose our proposed pedestrian movement simulation system. Thus, as shown in Figure IV-1, this system comprises three different modules:

– *The informed virtual environment graph*: represents the environment and stores all the pre-calculated data.

– *The mental map*: represents agent's knowledge about the environment.

– *The path planning module*: implements the navigation algorithm.

This simplified vision only gives the overall architecture of our system that we will expand over this chapter and the next one.

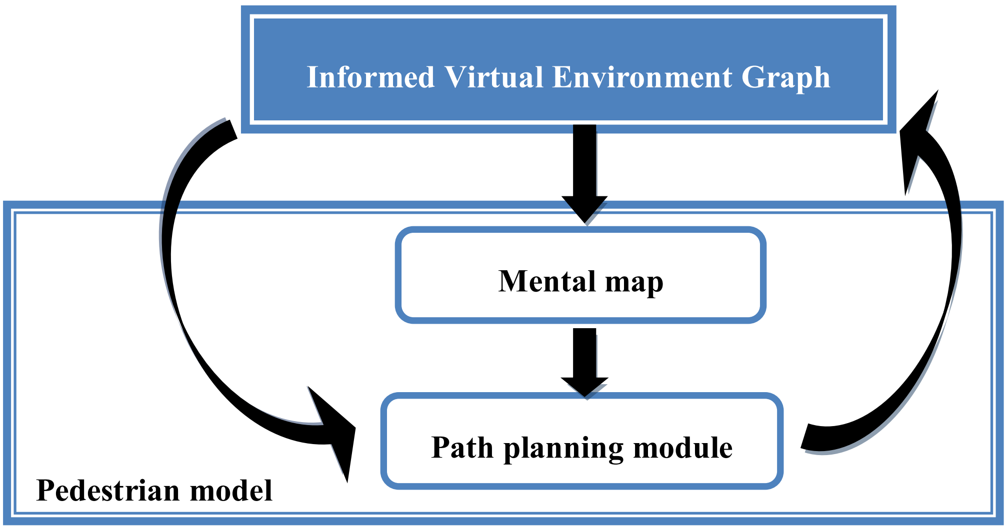


Figure IV-1 : Architecture of the proposed system.

IV.3 Informed virtual environment graph

An urban environment consists of two parts: physical obstacles such as buildings, and the space between the buildings on which people can freely move around. Although, the notion of navigable space is defined as the parts of an urban space available for movement of people, we consider that human movement at the city level is constrained by street networks rather than the free space between buildings; people can travel from anywhere to anywhere else in a city through streets. Moreover, the configuration of the urban street network is in itself a major determinant of movement flows (Dalton 2006). Thus, for the purpose of modelling human movement, we will consider the street network of a city as the environment of our simulated entities and we will present, in this section, our methodology for creating informed virtual environments dedicated to pedestrian movement simulation.

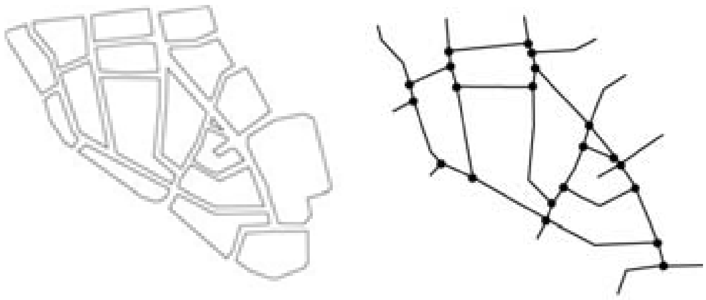


Figure IV-2: Urban area (Left) Road segments (Right) (Peponis, Bafna & Zhang 2008).

Pedestrians that we aim to simulate, when they are moving along a road their most opportunities are likely to lie ahead, however when they reach a road junction the opportunities are defined by the morphology of the local visual field. It is at these junction locations that people pause and look around before moving on; their decision making require gathering of additional information. Therefore, our proposed approach consists in representing the street system as a network of the streets that cover the system, translating the network into a graph in which intersections are nodes and streets are arcs. Thus, the unit is the street segment. As shown in Figure IV-2, street segments extend between street intersections or choice nodes at which movement can proceed in two or more alternative directions. The graph will integrate all the information necessary for the decision-making of our autonomous agents, such as the geometry and the topology of the places, and also the characterization of the visible spaces.

To compute the environment graph, we propose an approach based on four stages: input data selection, spatial subdivision, topological abstraction, and finally the generation of the informed graph (Figure IV-3). The work described here have been published in (Bouguetitiche, Cherif & Lamarche 2019).

IV.3.1 Input Data Selection

The first step consists in selecting the data sets which are used to build the informed graph from Geographic Information System (GIS) data. This step is the only one requiring human intervention. Since we decided to limit our study to outdoor urban areas, particularly the street network, we have to eliminate data about environment features such as buildings, green spaces … and keep only data on road networks.

The integration of GIS data to our model provides the ability to manipulate agents that are related to actual geographic locations. Besides, the increasing availability of volunteered geographic information contributed by individuals, which allows anyone to use the data freely.

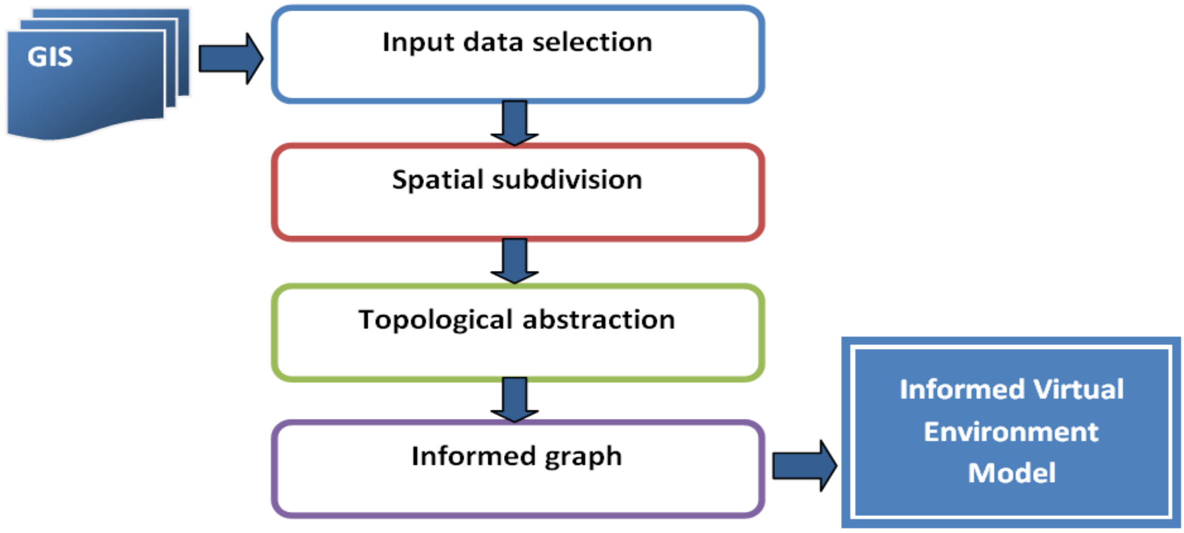


Figure IV-3 : The informed graph generation.

Several different levels of integration of agent-based models and GIS are possible. Gimblett (2002) has identified three approaches to integrated models which implement both agent-based models and GIS functionality:

1. models that use separate GIS and agent-based programs/libraries and communicate via files written to disk;

2. models that use separate programs but communicate via a shared database or virtual memory;

3. and standalone models that implement GIS functionalities within the agent-based model. In this category agents evolve and interact with an explicit representation of the virtual environment built using GIS data. The model that we propose falls in this category.

IV.3.2 Spatial decomposition

The first step in describing an environment is how to represent and organize its navigable space. We want to be able to characterize the navigable areas and to associate a first semantic with this areas by informing it with the typology of the zones extracted. Therefore, this step consists in converting the geometric data obtained from the previous step into a set of convex cells, which will cover the whole of the environment's navigable space (Figure IV-4). As we have noticed in the state of the art such a representation reproduces exactly the environment, and many tools and algorithms have been proposed for this method.

We rely for the spatial decomposition of the environment geometry on the Voxelization Watershed Partitioning algorithm (Mononen 2009). This algorithm used by Recast Tool, which is an automatic open-source navigation mesh generator toolset for games (Mononen). The Recast tool has seen widespread use in both games themselves, and games engines. There has also been significant interest from researchers in academia (Pelechano & Fuentes 2016) (Van Toll et al. 2016). The navigation meshes generated by this tool are generally simple (Van Toll et al. 2016), which make it useful for our model which requires fast path planning and don't need perfect coverage.

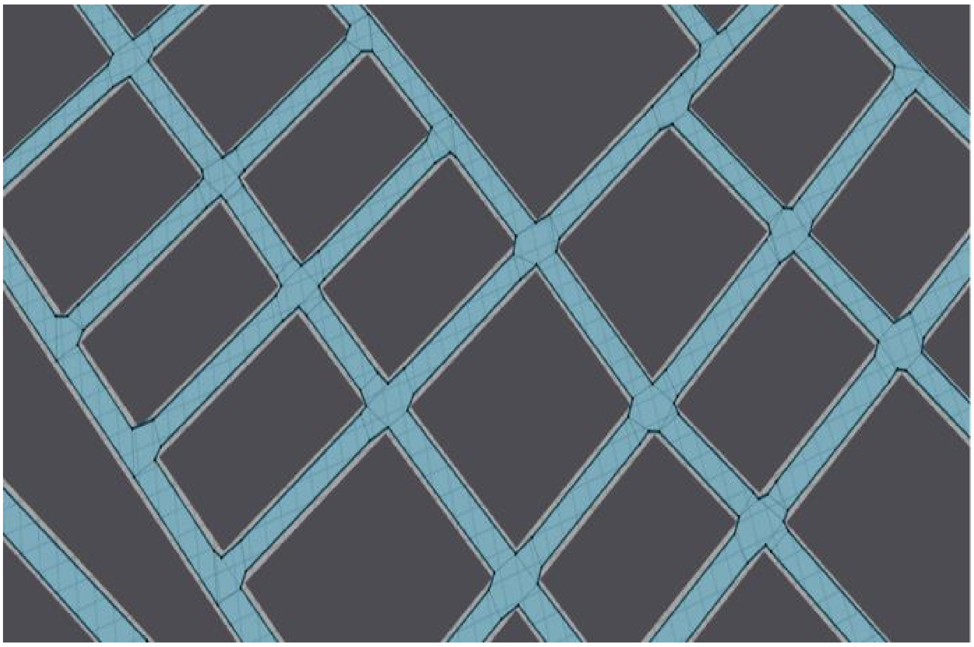
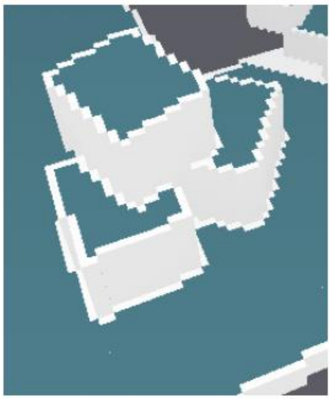


Figure IV-4 : Street network subdivided into polygons.

The Voxelization Watershed Partitioning algorithm when applied to a 3D graphical representation of the environment, converts the walkable voxels to non overlapping convex polygonal regions. To summarize how this algorithm works, the voxel mold is built from the input triangle mesh (environment geometry) by rasterizing the triangles into a multilayer heightfield (Figure IV-5 (a)). Some simple filters are applied to the voxel mold to prune out locations where the character would not be able to move, for instance: too steep slopes, too low places, etc. The Watershed Transform (Roerdink & Meijster 2000) (Figure IV-5 (b)) is applied to have as result a set of non overlapping simple regions (Figure IV-5 (c)) that can be used as input to triangulation step (Figure IV-5 (d)). The final step is to combine the triangles and find edge connectivity. The resulting polygons are finally converted to convex polygons.

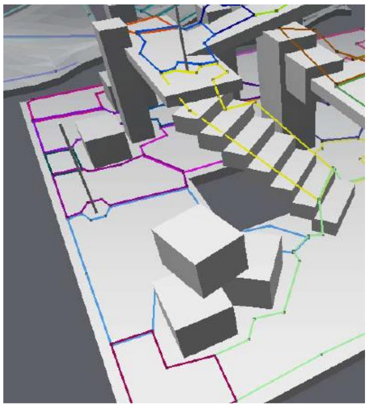
The resulting subdivision is a set of interior-disjoint polygons on which characters can stand and walk. Thus, this subdivision is based on the filtering parameters and character properties defined by the user. Any two polygons are directly connected if and only if characters can walk directly between them. All polygons in the walkable environment have a slope of 0 degree with respect to the ground plane. Figure IV-4 shows an example. It should be noted that only the navigable polygons are extracted from the subdivision, the obstacles being eliminated during the process of data selection.

A graph is extracted from this subdivision, whose nodes represent the polygons obtained and whose arcs represent their neighbourhood relations. Each node of the graph is typed according to its degree of connectivity ***c***, with the following denomination: dead-end (***c***=1), corridor (***c*** = 2) and crossroad (***c***>=3). This first subdivision produces an enormous number of cells. Mainly for reasons of speed of calculation, but also for a question of ease of exploitation, it is not possible to directly exploit this graph. Therefore, we must propose a complementary process (the topological abstraction) allowing a simplification of the manipulated data.

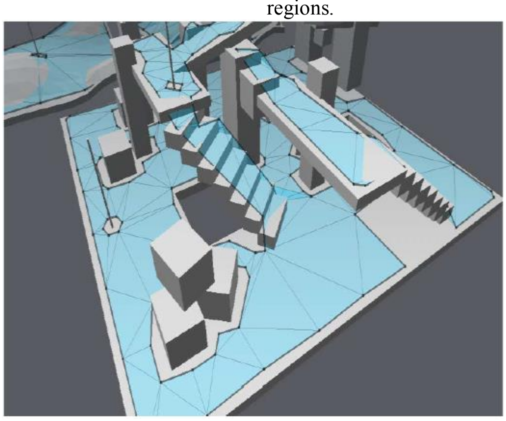


(a) Voxelization with walkable cells marked

(b) Build watershed partitioning and filter out unwanted regions.



(c) Regions traced contours



(d) Triangulation.

Figure IV-5 : Recast steps (from left to right) (Mononen 2009).

IV.3.3 Topological abstraction

This step, inspired by the work of Paris, Donikian & Bonvalet (2006), consists in regrouping polygons generated from the previous step according to their type. The topological abstraction will condense information about the navigable areas of the environment. Its goal is twofold: to reduce the number of elements necessary to describe the environment and to propose a more conceptual and intuitive definition of the navigable zones. The desired effect is to move away from the geometric definition provided at the base, to move closer to a more procedural definition, while seeking to retain essential information.

The proposed abstraction is based on a mechanism of grouping. A new graph is constructed whose nodes will correspond to a subset of the source graph, thus producing a more abstract hierarchical graph. In order to allow the exploitation of this hierarchical graph, its transversal path is allowed: each basic element knows its abstract equivalent, and vice versa.

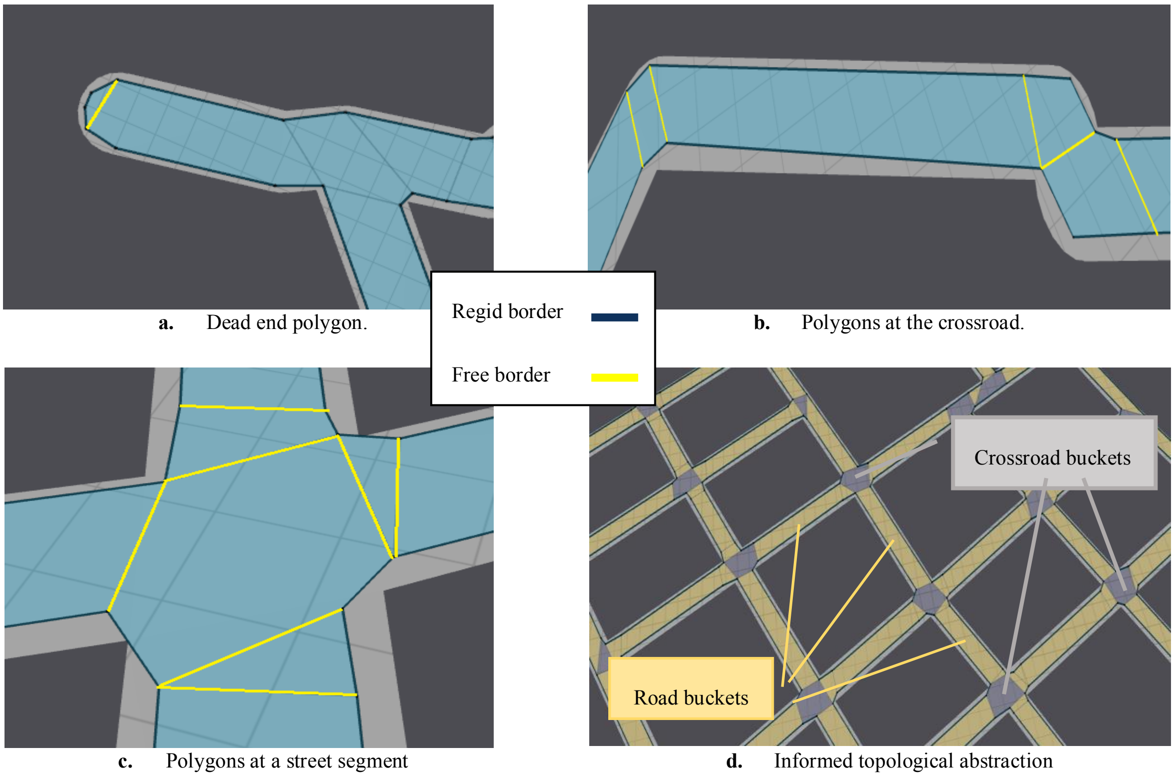


Figure IV-6 : Example of the topological abstraction.

We have chosen to propose only one level of abstraction from the subdivision graph, producing a two-layer hierarchical graph. We motivate this choice by the desire to produce more global zones, quickly characterizing the typology of the spaces, thus allowing an effective discrimination during the exploitation of the graph. Therefore, we propose to proceed as follows:

1. Set to every polygon its type which depends to its number of connection ***c***: dead end (***c***=1) (Figure IV-6 (a)), corridor (***c*** = 2) (Figure IV-6 (b)), and intersection (***c***>=3) (Figure IV-6 (c)).

2. Every intersection or dead end polygon represents a ***Crossroad bucket*** (Figure IV-6(d)).

3. All connex corridor polygons are grouped into a ***Road bucket*** (Figure IV-6(d)). Thus, a connectivity graph is built, whose edges represent road buckets, and nodes represent crossroad buckets. We will call this graph: ***Bucket Graph***.

The main purpose of this method is to organize the topology as well as possible in order to be able to extract information from it, in particular the pre-calculations which will be stored in the graph. But also it improves performance when operating this environment, especially during path planning.

IV.3.4 Informed graph

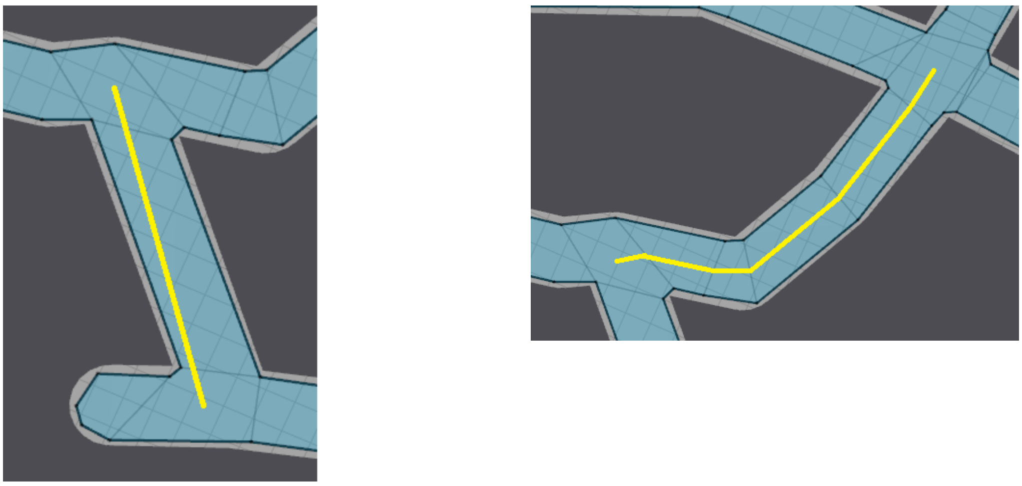
The preservation of information is essential to allow the exploitation of an environment model in a simulation framework. Moreover, the model must, not only, be able to restore the information from the original graphic definition, but also to best organize them to allow their efficient and rapid use. That's why we propose to inform our ***Bucket Graph*** with various data relating to the movement of people. We have synthesized in this information the various factors that can influence pedestrian decision making.

A. Static information:

The first type of information we associate with our ***Bucket Graph*** is based on static data from the environment. Thus, we propose to pre-calculate this data and to store it directly in the graph nodes and edges, in order to accelerate their access during the simulation. Note that this information is stored in the first level of the Bucket Graph hierarchy, and its pre-calculation is based on information from the spatial subdivision. Static data can be divided into three groups: Bucket characteristics, viewshed characteristics and Environment spatial configuration.

– **Buckets characteristics**

The intrinsic characteristics of the buckets are undoubtedly the information that will be used by the most mechanisms of the simulation. These characteristics synthesize the geometry of the buckets according to different points of view. Thus, we start to propose these characteristics as follows:



a. The distance is calculated from the centre of one crossroad bucket to the centre of the other one.

b. The distance is obtained by summering the distance between the midpoints of every polygon portal edge belonging to the road bucket

Figure IV-7 : Calculating road bucket length.

- **Road bucket length.** This property will be used to calculate the street length. It is measured from the centre of the current crossroad bucket to the centre of the furthest connecting crossroad bucket, in the case where the two corresponding buckets centres are mutually visible (Figure IV-7 (a)). Otherwise, the length is obtained by summering the distance between the midpoints of every polygon portal edge belonging to the road bucket (Figure IV-7 (b)).
- **Road bucket area.** The surface area of each road bucket is calculated and stored, enabling to compute the road density. It will be used to evaluate the presence of people criterion.

– **Viewshed characteristics**

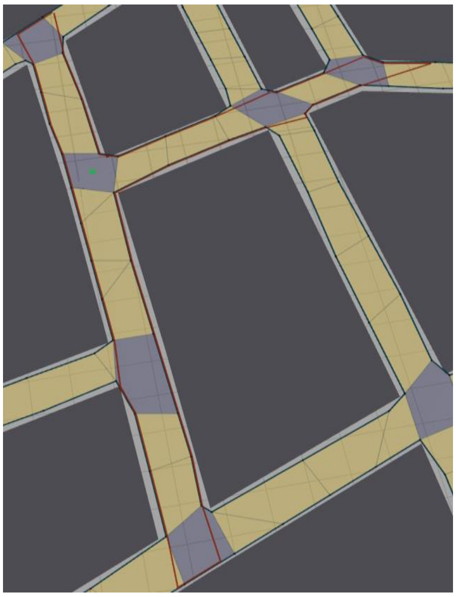
We have identified, in the state of the art, that the geometric properties of the visual field are preponderant in the navigation process. We therefore propose pre-calculations describing attributes of the viewshed. To do so, we make use of the notion of isovist and some of its corresponding measures. We remind that an isovist is defined as the polygon of visibility from a given viewpoint. Figure IV-8 (a) shows the visibility polygon from the centre of a crossroad bucket.

Because isovists, as originally conceived by Benedikt (1979), equally describe all possible view directions from a given single observation point while observers experience the environment mainly from a directed inside perspective along their main line of travel, we suggest to make use of the concept of directed partial isovists proposed by (Meilinger, Franz & Bülthoff 2012), to calculate the geometric characteristics of the viewshed. This type of isovist spans a horizontal angle of 90°, instead of ordinary 360° isovists. Thus, in order to estimate the partial isovist of the viewshed in the direction of each of the outgoing street segments at a street junction, we take the part of the viewshed that lies within the view-frustum when looking towards the direction of the specific street segment as shown in Figure IV-8 (b). Then, we attach to every node of the bucket graph the following pre-calculated partial isovist attributes:

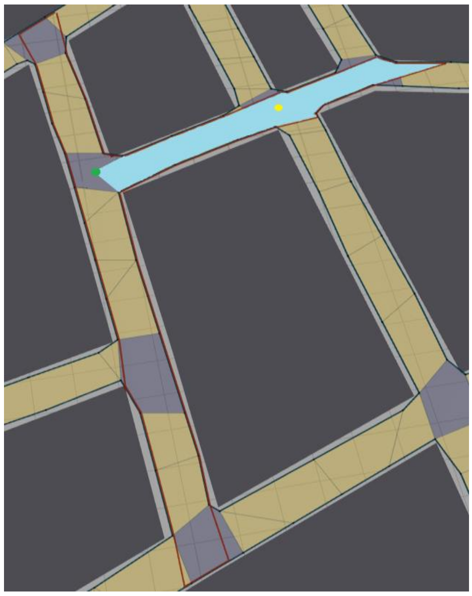
- **Partial isovist area.** For each crossroad bucket we compute the surface area of the partial isovist in each direction from the center of the crossroad bucket as the observation point of the isovist.
- **The partial isovist longest ray.** This is the greatest possible distance of a partial isovist from the observation point (Figure IV-8 (c)).

– **Environment spatial configuration**

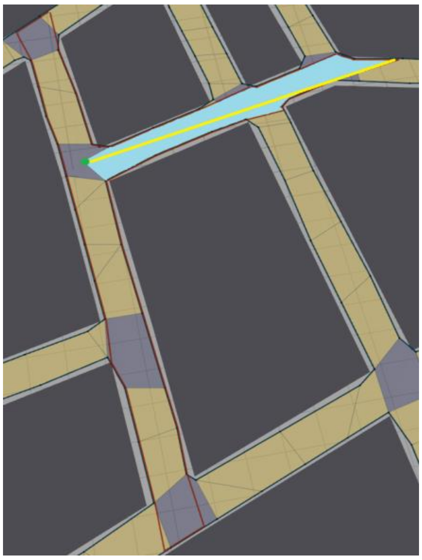
Due to the important role played by the spatial configuration of the environment in route choice decisions, we propose to add to the ***Bucket Graph*** nodes and edges data related to the configurational characteristics of the environment. The theory of space syntax offers several measures to perform space configuration analysis. Among these measures we have adopted two of them as they are the most relevant for human wayfinding behaviour:



(a) The isovist (red line) from the crossroad bucket centre (green point).



(b) Blue area defines the partial isovist from the green point towards the yellow point.



(c) The partial isovist longest ray (yellow line)

Figure IV-8 : (a) isovist, (b) the partial isovist, and (c) The partial isovist longest ray.

- **Betweenness centrality.** One of the centrality indexes provided by the network analysis domain. It is known as *'***Choice***'* in space syntax as this measure if calculated for an element of a street network will reflect the probability of being chosen by a frequent wayfinder. This measure will be used to build the mental representation of our agents. More details will be given in the next section (Mental map model).
- **Connectivity.** This refers to the number of other road segments that are directly connected to any intersection.

B. Dynamic information:

The second category of information that we want to manage concerns the dynamic data of the environment. In fact we are not going to make pre-calculations, but proposing functionalities allowing the fast recovery of this information. Information involved in these processes is:

- **Partial isovist density.** The calculation of density based on the entire area of a bucket does not take into account the perception of our autonomous entities. This problem is important because the density of people will be a factor in the path choice decision making of these autonomous entities. So we propose a solution to this problem by calculating partial isovist densities, associated with each partial isovist. Its calculation is based on the pre-calculated area of the partial isovist, as well as on a dynamic partial isovist population size.
- **Population size.** This dynamic value is updated automatically by entities moving in the environment. Thus, we associate a counter with each partial isovist that will be incremented automatically by an entity entering it, and decremented when an entity leaves. This counter therefore gives the total population size of the partial isovist.

Now that we have defined the model of the virtual environment and related information, let us focus on how the simulated agent will represent this environment mentally. To do so, we will describe in the next section the mental map model.

IV.4 Mental map model

We will finish this chapter dedicated to describing the simulation environment with the way we generate a mental representation of this environment for every autonomous agent. Indeed, we need to endow the agent with a mental map to allow it to exhibit navigation behaviours which are not standardized, due to the fact that each agent of the simulation plans its route using its individual knowledge taken from its mental map. An agent with a weak knowledge of the environment will still be able to compute a path in a different way than an agent endowed with a better knowledge of the environment.

We do not use the term cognitive map here for two reasons: the first one is that the mental representation which we propose is not created through perception nor updated during the simulation. The second, the model of the mental representation is based on the informed graph structure, and acts as a filter on it, in order to minimize calculation and memory costs. Thus, this filter allows access to the parts of the environment that the agent is supposed having experienced before the simulation and denied the others. Figure IV-9 presents a very simple example of the functioning of the mental representation as a filter. In the rectangle the database contains all the information present in the world of simulation. In the bubble info the mental map presents two types of spaces:

- **Known spaces** (bold lines): are spaces that can be activated because they are already known by the agent in the sense that they are supposed to be visited before the simulation and thus they appear into the mental map which has been generated to the agent at the beginning of the simulation. Therefore, the agent can have access to the information specific to these spaces in the environment graph.

- **Unknown spaces** (dashed lines) are spaces that are supposed to never been seen or visited by the agent. It is therefore impossible to obtain information about them.

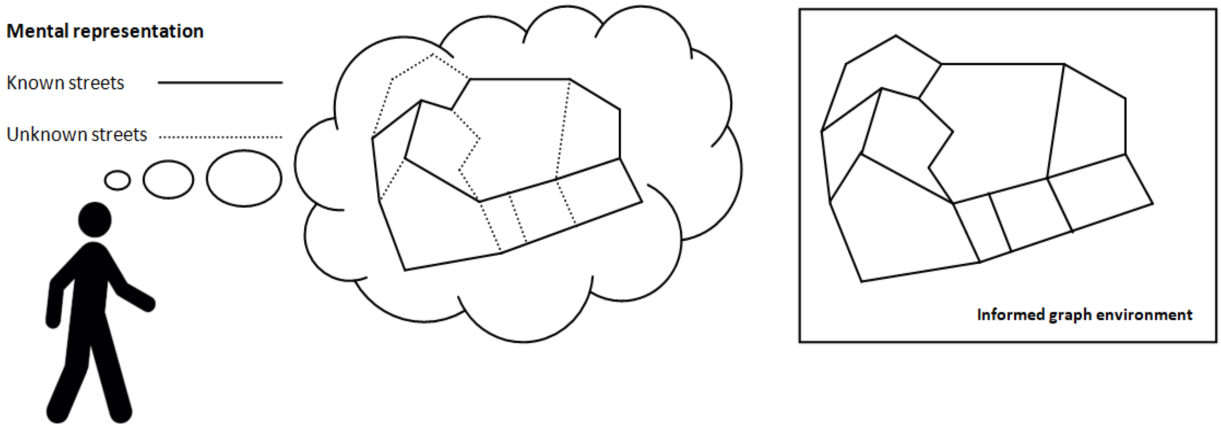


Figure IV-9 : Mental representation of the environment (Dashed lines represent unknown streets for the agent and bold lines represent known streets)

Note that the perception of the agent is always simulated by an interrogation of the database representing the simulation environment. However, our model uses an undirected interrogation where the decision-making module is not directly related to the database, we submit access to the information contained in the environment graph through a control mechanism (see next chapter for more details).

IV.4.1 Mental map structure

In this section, we present the structure of an agent's environment mental representation. The mental map will have almost the same structure like the environment, given that it will model the knowledge on the environment the agent has already acquired before the simulation. We will call ***Filter Informed Bucket Graph*** the hierarchical graph representing the mental map. It contains:

- **The filter buckets layer.** This layer is a topological graph containing all the filter bucket spaces corresponding to the bucket spaces already known by the agent.
- **The local space layer.** This layer does not have any corresponding one in the ***Informed Bucket Graph***. We added this layer to our architecture to model the local vision of the space surrounding the agent. A local space is a set of partial isovists that represents the agent visual field. As it will be in the next chapter, local spaces are employed to determine the visual field characteristics which take part in the planning and navigation process of the agent.

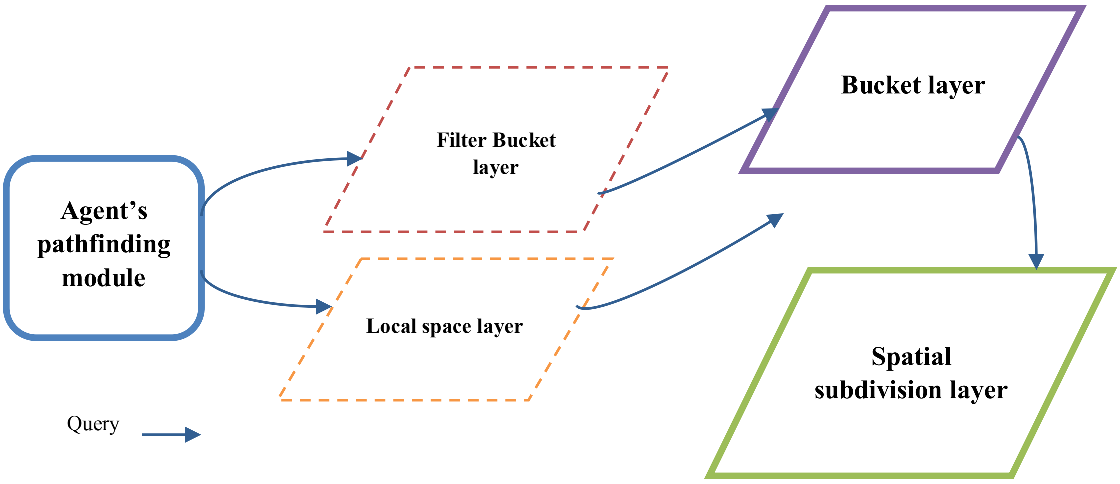


Figure IV-10 : Querying the environment graph through the mental map.

The ***Filter Informed Bucket Graph*** does not contain the geometrical, topological nor semantic information stored in the ***Informed Bucket Graph***, but only a reference to its corresponding spaces in the environment. Once the agent is created and his profile is defined, the spaces corresponding to its mental map are activated in the filter bucket layer. However, spaces of the local space layer are activated once the agent has visited the corresponding crossroad bucket. The activation of a space implies that the agent's decisional module can obtain all information from the corresponding space in the ***Informed Bucket Graph***.

IV.4.2 The mental map construction approach

We have presented in the first chapter a brief state of the art of the work done on human navigation in cognitive science. When developing our work we wondered about the best way to model a human cognitive map taking into account existing work in spatial cognition while keeping in mind that we had to apply it to a computer system. We aim to design a system based on solid theoretical foundations in order to achieve a realistic simulation, without being too complex because with our model we aim to conduct simulations with a large number of agents.

In fact, urban navigation is a vast cognitive field that uses cognitive mechanisms as varied as complex (orientation, perception, cognitive map, and so on…). Our choices were first guided by the restrictions imposed by computer simulation. In particular, our choices have been made for performance reasons, and are justified by the framework of use of this model: the simulated situations take place over a period of time that is too short for some mechanisms to be necessary.

Therefore, as we have declared earlier, the mental map that we propose is not created through perception nor updated during the simulation. In order to achieve this goal, we are facing a challenge: creating a mental map for an agent who is supposed to have experienced a given environment, without going through the learning phase. This may be possible if we manage to predict the content of the agent's mental map which should be close to the mental map that a human can have after experiencing this environment.

Predicting the content of a cognitive map consists in finding which elements are probably stored in the mental map of a pedestrian familiar with his environment. We mentioned previously, that our mental map model can be seen as a "filter" on the accesses the agent can have to the database, in the sense that it partially maps the structure of the database and gives access to the elements of the environment graph which have already been visited, and "hides" the others. Thus, it keeps the notion of space abstraction into crossroad and road buckets which constitutes the first two elements of the mental map. In addition to these two elements there is the graph of local spaces which constitutes the third element in the mental map. Because this third element represents the agent's visual field when navigating in the simulation environment, the construction by prediction of the mental map will concern only the bucket spaces: crossroads and roads.

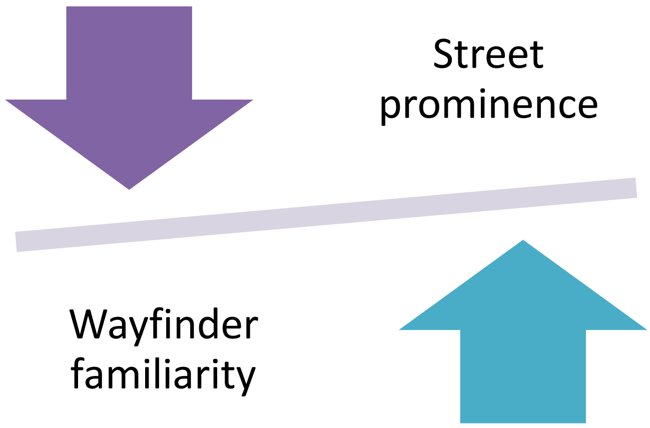


Figure IV-11 : As long as the prominence of the streets known by the wayfinder decreases his familiarity increases.

The spatial knowledge stored in a mental representation form an experiential hierarchy. Tversky (1993) found that streets which are stored in the mental representation are the frequently visited, and by the other side (Tomko, Winter & Claramunt 2008) state that the intensity of experience of a spatial feature like a street is related to its prominence in a specific environment. This experience of prominence establishes a partial order between the mental representations of the individual spatial features, and an experiential hierarchy emerges. Indeed, a street which is the more prominent in an urban structure has a high probability to be known by the wayfinder. Moreover, wayfinders interacting repetitively with streets in the city get a mental representation of the urban network structured hierarchically (Tomko, Winter & Claramunt 2008). In the different trips they perform, there are parts which are more experienced than others in the network. The more also they are experienced with higher frequency, thus they are better known. Consequently, the streets are ranked from high to low prominence in the mental representation of wayfinders reflecting wayfinder experience (Figure IV-11).

Which is remarkable in individual experiential hierarchies among people familiar with an urban environment is a common property: the overlaps in the content and the hierarchical organization of common spatial knowledge. Indeed, among these people, despite individual differences in mental representations, common spatial knowledge from these individual representations exists. The more prominent a street is, the more likely it is to be known by all familiar wayfinders. Some of them with continuing interaction, the completeness of their spatial knowledge and familiarity increases; streets which are less prominent will be discovered and known. People's common experiential hierarchies represent a fundamental structure on which we based our assumptions about the mental map construction approach.

Our hypothesis is that we can construct the shared part of the wayfinders' mental maps that will reflect in part the experience of space of each wayfinder. Indeed, the overlap in the mental representations of the familiar wayfinders, as well as in their hierarchical structures enables to predict the shared part in their mental representations. We assume that the emergence of the shared experience of the street network influences the pattern of urban movement flows.

The common knowledge of a spatial feature is due to its structural and functional prominence. Thus, the construction of hierarchical datasets following cognitively motivated principles such as experience prominence will provide means to draw estimates of the shared content of mental maps for agents in a given environment. Indeed, streets, which rank high in experiential hierarchy, are well known by all agents and shared in their mental maps. However, streets, low ranked, are known only by agents who have high familiarity with the urban structure (Figure IV-11). Thus, different levels of the experiential hierarchy can be used to define different levels of familiarity in agent's population.

Now, our goal is to quantify the streets' prominence and hierarchically rank them, reflecting the likelihood of the shared experience. Thus, the next step is the identification of the measure that will provide a plausible quantification of network elements' prominence.

IV.4.3 Quantifying street prominence

Experiential hierarchies of elements of street networks cannot be created without the ability to characterize the prominent parts of the street network by quantifiable properties. The experiential formation of hierarchies in mental representations is largely influenced by the structural properties of the urban network. Non-structural factors also contribute to the perception of prominence of streets; semantic and visual characteristics of elements of the city, such as landmarks, influence our experience of the street network. Although, the visual characteristics of certain elements in the city can be highly salient and the effect of semantic salience is certainly present as well, however, it is difficult to quantify these properties. The effect of semantic salience is harder to judge and it is unclear how these characteristics mix together to contribute to the overall prominence of a specific street. Thus, our effort is focused on the identification of a measure to quantify the structural properties of the street network. In fact, structural properties of the street network elements are distinct, as they condition the visual or semantic experience. A street not visited will not be visually nor semantically prominent to a wayfinder.

Among the most important structural properties of network elements are their centrality characteristics. We selected two basic centrality measures that allow the structural significance of a network element to be characterized. Our selection is motivated by its relation to the wayfinding behaviour. We explore these measures and derive the appropriate measure for the quantification of the importance of the streets, and the hierarchically ranking of them in a manner that is cognitively plausible. Table IV-1 summarizes the two measures presented and analyzed below (more details in section II.4.2):

- **Closeness centrality** is a measure reflecting the average length of the shortest paths to all other nodes of a graph. Nodes or segments with high closeness centrality have low average length of the path to all other nodes in the graph. In space syntax this measure is known as global integration. It represents the potential of a space for ***to-movement*** or how easy a space is to navigate **to** from all other spaces.
- **Betweenness centrality** provides the means to quantify the likelihood a graph node will lie on a shortest path between two other nodes of the graph. Betweenness centrality is expected to reflect the probability of being selected by a frequent wayfinder. Hence the frequent use of the term choice. This measure represents the potential of a space for ***through-movement*** or how likely a space is to be visited on trips **through** the network.

Network centrality measure	Betweenness centrality	Closeness centrality
Space syntax name	Choice	Global integration
Mathematical definition	The number of shortest paths between all elements that pass through a specific one.	The inverse of the mean shortest distances from a specific element to all other elements.
Interpretation	The degree to which each element lies on paths *between* elements	*Closeness* of each element to all others
Potential for	Through movement	To movement

Table IV-1 : The two main network centrality measures used for correlating with pedestrian movement (Frith 2017); (Hillier & Iida 2005).

As these two measures are based on the calculation of shortest routes they demonstrated their ability to correlate with pedestrian movement flows. Consequently, they are used to suggest the potential amounts of movement in each space of a network. However, we argue for applying betweenness centrality to quantify the importance of each street in the network for four reasons:

- The hierarchy created by experience needs to take into account the likelihood of the usage of a specific street and betweenness centrality is expected to reflect the probability of being selected by a frequent wayfinder. With the increasing number of trips performed by a wayfinder in a city, the likelihood that betweenness approximates the agent's experience of the urban environment increases. Tomko, Winter & Claramunt (2008) have proved that betweenness centrality and its derivatives can be used as plausible measures for explaining the experiential hierarchy of urban networks.
- The importance of streets measured with closeness centrality is influenced by distortions due to the boundary effects (Tomko, Winter & Claramunt 2008).
- The measures' potential for through movement, since we attempt to measure the importance of a street to be selected in a path, as opposed to closeness centrality which represents the accessibility of a space as it represents the potential for to-movement. Indeed, through-movement is used as people walks along thoroughfares to get to distant locations. However, to-movement—that is locations are more likely to be destinations for people.
- In comparison, when correlating with pedestrian movement, betweenness centrality correlates best (Frith 2017). Initially, researchers, in the space syntax community, found that human movement correlates with integration (Hillier et al. 1993), then Turner (2007a) has proved that betweenness centrality is a better metric for predicting human movement.

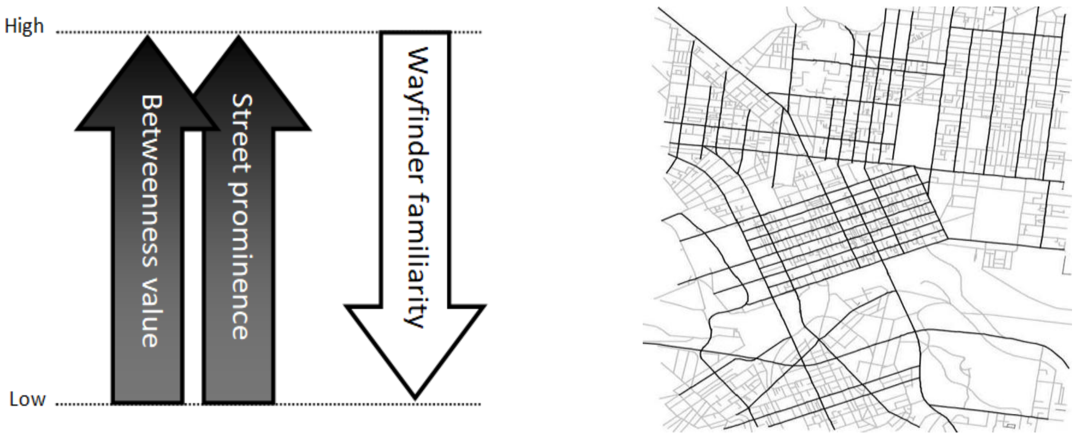
IV.4.4 The process of construction of the mental map

As we have mentioned previously, the shared experiential hierarchy represents the fundamental structure on which we based our assumptions about the mental representation model of our simulated entities and its construction approach. Thus, the mental map construction process that we propose counts three steps, and starts with the reconstruction of the experiential hierarchies.

A. Reconstruction of the experiential hierarchies

In this section, we propose a method to reconstruct experiential hierarchies of streets in urban networks. In the previous section we proposed to quantify the structural prominence of streets using betweenness centrality measure. Ranking streets based on this quantification allows reconstructing the experiential hierarchies. Thus, we start this step by performing an analysis of the urban pattern of the city, in order to calculate betweenness centrality distribution in the street network. Then, results of this analysis will serve as input for the reconstruction of an experiential hierarchy of the street network by a classification of streets into levels, as an example we can see in Figure IV-12 two levels of betweenness hierarchy of Melbourne

(Australia). Tomko et al. (Tomko, Winter & Claramunt) has demonstrated that the most prominent streets correspond to the streets with high betweenness centrality values.



(a) (b)

Figure IV-12 : a. Street experiential hierarchy and agent experience. b. Tow levels of betweenness hierarchy: grey line lower level, black line higher level (Tomko, Winter & Claramunt 2008)

B. *Definition of agent's familiarity levels*

In the first step, the objective was to rank streets in a hierarchy. Such ranking of streets allows the abstraction of the urban network at different granularities. The coarse structure of the city consists of streets known by the majority of locals. Indeed, as the structural position of a street affects its use in the street network, the parts of the network with high prominence attract more traffic flow and business. Consequently, this coarse structure fills the top levels in the hierarchical mental representations of the majority of locals. Because the locals' hierarchies are created through similar processes, and thus have similar structure, it seems that a part of the environmental knowledge is shared, at least at coarser levels of granularity. In our model, wayfinders which share a spatial knowledge limited to the most prominent streets belong to the low level of familiarity.

Regarding the other levels of familiarity such as medium or high, they correspond to the wayfinders knowing streets less and less prominent. Indeed, the intensity of use leads to overloading of the prominent parts of the network. When the overcrowding exceeds some acceptable threshold, wayfinders optimize their trips and seek shortcuts. The network properties of the alternative streets found have relatively less values of betweenness. Figure IV-13(Left) illustrates the principle behind the hierarchy of familiarity levels; the more prominent a street is, the more likely it is to be known by the majority of wayfinders. On the other hand, the less prominent streets are probably known by the wayfinders the more familiar.

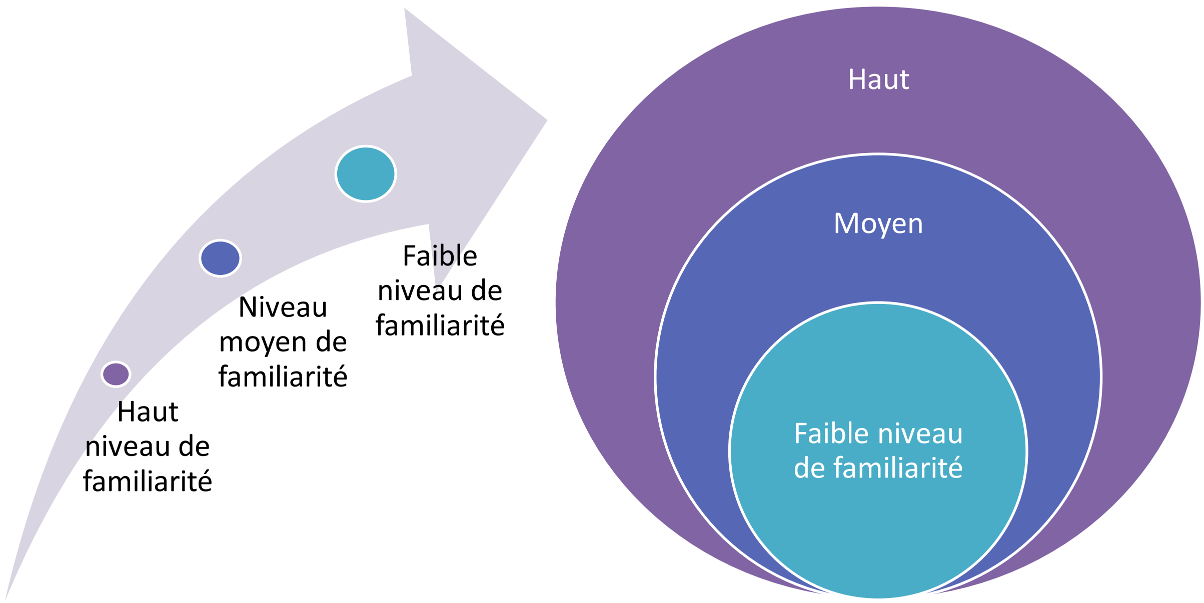


Figure IV-13 : Familiarity levels and street prominence.

Figure IV-13 (Right) represents the content of the mental maps of the different levels of familiarity in terms of streets and their corresponding level of prominence. The mental maps of wayfinders, which belong to the category of low level of familiarity, contain the most prominent streets. In addition to the set of streets of the low level of familiarity category, the mental maps of wayfinders of the second category of medium level of familiarity contain streets with less prominence. Wayfinders of the third category have in their mental maps streets from most prominence to less and less prominence.

C. *Initialization of the mental map*

At this stage, after the classification of the streets in a hierarchy and the definition of the different levels of familiarity we have to initialize the mental maps of the agents. We remind that the mental map is composed of two layers: the filter bucket layer and the local spaces layer. The layer concerned with the initialization is the first one, as the local spaces layer defines the visual field characteristics which take part in the planning and navigation process of the agent.

In fact the initialization of spaces of the filter bucket layer consists in activating them. The initialization of knowledge can be done in many ways, depending on the level of familiarity that we want to assign to the agent. First, the base is fully formatted with one of two values:

- **Never:** for an agent not familiar with the streets;
- **Known**: if it is a familiar agent (he knows the environment with a specific level of familiarity. Streets that do not belong to the experiential hierarchy level which corresponds to the familiarity level of the agent are formatted with **Never**).

Note that such initializations are done a priori, in order to create typologies of knowledge of spaces, which can then be directly assigned to autonomous agents. For example, in an urban area, we can create a local typology (high familiarity level) that has a thorough knowledge of his environment, and a passing category (low familiarity level) that only knows the streets where there are shops.

IV.5 Conclusion

In this chapter, we have presented our topological representation of the environment and related information. We thus proposed an exact spatial subdivision of the free space of navigation in an urban environment: the street network. We performed a topological abstraction of this representation, producing a hierarchical graph, in order to improve its performances and to synthesize its expressivity. The major interest of this type of representation comes from the information that can be associated with it. Thus, we have integrated all the information necessary for the decision of our autonomous agents as the geometry and the topology of the places, in addition to the spatial configuration of the environment. The environment description also provides easy and fast access to a set of data, such as density of people or the characterization of visible spaces.

In a second part, we have presented a model of mental map. The model is designed as a filter on the environment. It does not contain geometrical or semantic information about the urban objects encountered, but only controls the partial access to the environment database. This model remains simple to allow the generation of the mental maps for an important number of agents and without passing by the learning phase. That's why the central idea of this model was the prediction of the content of the agent mental map, in order to be efficient in computation time.

To conclude, we strongly focused our environment representation and mental map model on behavioural realism, trying to build our models using theoretical results from the cognitive science field dedicated to human navigation, so most of our assumptions are cognitively justified.

Chapter V Simulation model of the pathfinding behaviour in familiar and unfamiliar environments

V.1 Introduction

The virtual pedestrian is the exclusive actor of our simulations. Our goal is to propose a movement simulation model that is as realistic as possible from a behavioural point of view. Thus, the virtual pedestrian must be endowed with certain abilities of a real pedestrian, such as understanding his environment and making decisions to plan a path. As we have presented in the previous chapter, the first necessity of a navigation system, the environment model and the virtual pedestrian mental representation of this environment, we will continue, in this chapter, to present two mechanisms which are as fundamental as the environment description and the mental map, in our movement simulation system, since they form the core of the pathfinding behaviour. These two mechanisms are accessing to environment information and pathfinding strategies and heuristics.

Thus, we will describe in this chapter our virtual pedestrian pathfinding model. We will begin, in section V.2.by presenting the pathfinding module and its role in the movement simulation system. Then in sectionV.3, we introduce the different modes to access environment information. In section V.4, we detail the proposed pathfinding algorithms and heuristics. Finally, we conclude by discussing the model described in this chapter.

V.2 The pathfinding module

The pathfinding module is one of the three modules that belong to our movement simulation system. Let us first introduce the overall architecture of our movement simulation system (Figure V-1) then we will present the pathfinding module. The environment is modelled by an Informed Bucket Graph, containing two layers: the Bucket Layer and the Spatial Subdivision Layer. The mental map contains information the agent has acquired on its environment. It is composed of a Filter Bucket Layer and a Local Space Layer.

The pathfinding module, manages the navigation algorithms, uses the data collected from the environment and the mental map to elaborate a navigation plan. These algorithms are designed around two main agents' categories:

– Agents in unfamiliar environment; the agent lacks spatial knowledge relevant for making wayfinding decisions so, a pathfinding algorithm is applied using data collected from the environment.

– Agents having some knowledge about the environment also apply pathfinding algorithms but different than those used in an unfamiliar environment. Agents of this category use the two sources of data, the environment and the mental map, to choose a route.

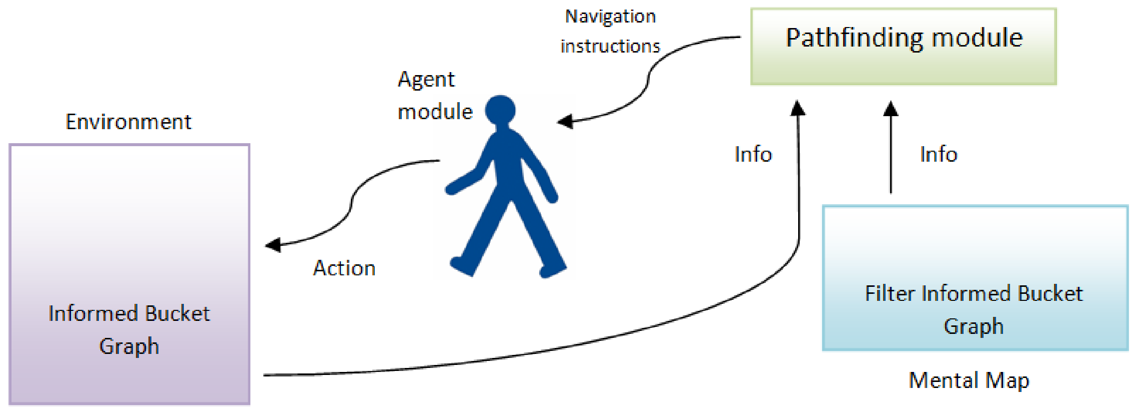


Figure V-1 : The movement simulation system architecture.

Consequently, we define the notion of profile as the grouping of all agent-specific information that it will be endowed with at the start of the simulation. This ensures the independent personalization of decision models in that we customize the elements on which the pathfinding model will act. The main component of this profile is the spatial mental map of the agent itself. Each agent of the simulation is provided with a map, supposed to be resulting from its experience of the environment before the simulation. The profile of an agent is determined at the beginning of the simulation. After the generation of the environment model, the agents can be parameterized. Thus, before the start of the simulation the agents are created in memory with their own characteristics.

V.3 Access to environnemental information

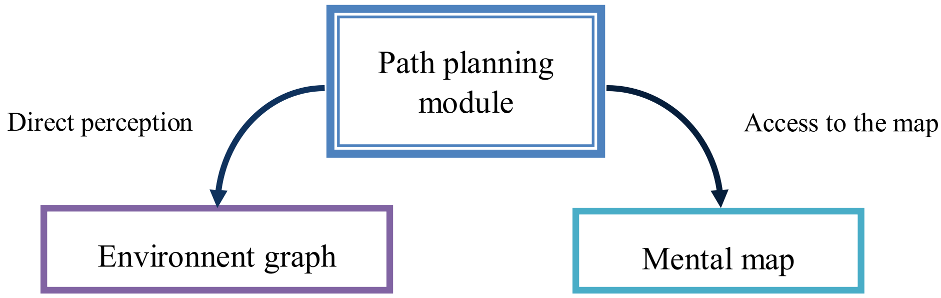


Figure V-2 : Modes of access to information.

The first necessity of a human being, in order to interact with his environment, is to perceive it. Therefore, the path planning module of the agent is supplied with information in two different ways (Figure V-2): either by interrogation of the mental map, to work on information corresponding to zones in which the agent is not at the moment of the interrogation, or by the direct perception, which consists of the direct interrogation by the agent of the database without filter.

V.3.1 Direct perception

We mean by direct perception the simulation of the visual perception of the agent in the simulation environment. This environment as we saw in the previous chapter is an informed graph. Information relating to the spaces of the environment is therefore completely contained in the graph which is the internal representation of the simulation environment. Thus the perception is simulated by a query of the simulation environment database by the pathfinding module of the agent. The internal representation of the direct perception is thus an interrogation of the decision-making module towards the ***Informed Bucket Graph***.

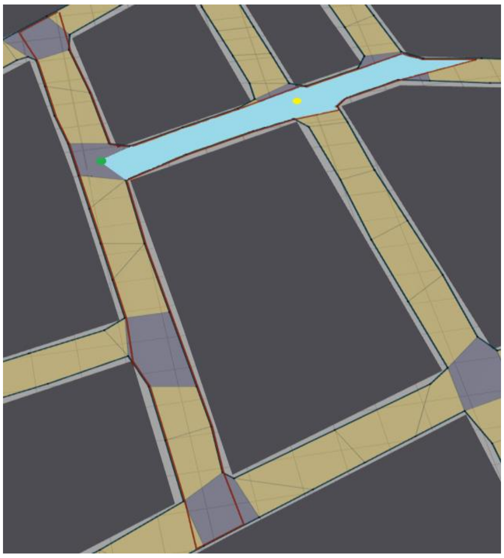


Figure V-3: Blue area defines the partial isovist of the green junction towards yellow junction.

By the visual perception our autonomous agent aims at extracting information when moving. The perception mechanism is based on the partial isovist. Then it consists in accessing this structure and retrieving the necessary information. Let us remember that the partial isovist is the visible area in the direction of an outgoing street segment as shown in Figure V-3.

The first type of information retrieved is directly related to the topology. So, each visible partial isovist is retained by the autonomous agent. This information is stored in a sorted list, and will be used to build a topological memory. This knowledge corresponds to a small subset of information; it is limited to 7 elements when the agent is visiting different crossroad buckets. We made this choice especially for memory occupancy issues, the humanoids to be simulated by thousands with limited storage capacity. Nevertheless, the agent needs this information to perform his task of optimising his path (see section Analysis and optimization of the evaluated path).

The second type of information retrieved concerns the geometric characteristics of the visual field at the decision zone. As we indicated previously, pre-calculations are included in our description of the environment such as the partial isovist area and longest ray. This information describes the geometric characteristics of the visual field and is needed by the agent to choose his path.

The direct perception algorithm is applied at each arrival of the agent in a crossroad bucket. Indeed, the agent does not use the direct perception to navigate within the space of a bucket. Direct perception has a role of researching information on the structure of the surrounding space, and not a help for guidance within a bucket space.

V.3.2 Access to the mental map

In the previous chapter we described the model of environment where the simulation takes place. The mental map has almost the same structure like the environment, given that it models the knowledge on the environment the agent has acquired before the simulation. The main idea is that the mental map acts as a filter between the environment and the agent's pathfinding module.

In our approach, the perception is simulated by a query to the database representing the environment: if the agent wants to obtain information on a space, the pathfinding module will query the ***Informed Bucket Graph*** for this information. The major limitation of this type of model is that it gives the agent omniscience which impairs the realism of the simulation. Limiting this omniscience to the set of spaces the agents previously experienced, allows them to exhibit navigation behaviours similar to the ones human beings can show: the agent navigating from an origin point to a destination one, will be able to build its route applying a certain type of strategies according to its individual knowledge about the environment. More details on the pathfinding process will be given in section V.4.

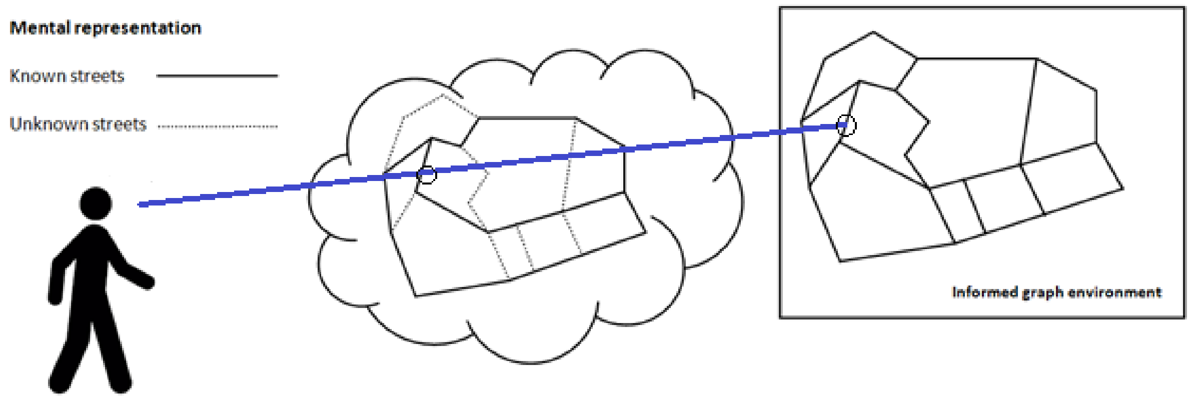


Figure V-4 : Querying the environment through the mental map.

Figure V-4 illustrates the query process through the mental map. When the agent wants to access information about an area it has to query the mental map first. If the filter object is activated in the mental map, access to the ***Informed Bucket Graph*** is allowed and the information is transferred to the agent's decisional module. We note that access to crossroad bucket related data is authorized if the agent is present in this space or if the filter object is activated in the local space layer of the mental map.

V.4 Path planning algorithms

Now that our virtual human is able to understand his environment, we will see its decision-making mechanism to plan a path. We will start with defining the general process of the planning path module then we will see two path planning modes.

V.4.1 Incremental path planning

As we have discovered in the state of the art, pathfinding is described as being a series of direction choices, taking place at decision points within the urban grid (Figure V-5). This definition let us understand that route planning constitutes an incremental process and that routes are not planned entirely in advance; which was indicated in wayfinding literature (Golledge 1999);(Spiers & Maguire 2008), and confirmed by experiments (Hölscher, Tenbrink & Wiener 2011).

Figure V-5: Route choice at each intersection.

Because, in our simulation model, we need autonomous agents which are able to plan paths close to reality, we propose a path planning algorithm that does not compute the complete path in advance. Individual navigation decisions are calculated at each decision point based on a local comparison of the benefit cost of each route choice. By benefit cost we mean optimisation of the evaluation criteria, not just the distance, on which we will come back later.

The proposed path planning algorithm is also hierarchical. Indeed, it evaluates a route choice in a global way, at the bucket level, but it refreshes this path only locally to focus on immediate interactions. Thus, this algorithm will alternately treat the two layers of the environment graph, starting with the most abstract (Figure V-6). The steps of the algorithm are therefore:

– **Plan globally at the bucket level.** This step is the one that actually makes the path decision. The produced path is a succession of buckets to cross, starting with the current bucket of the virtual human.

– **Refine the path obtained in the form of buckets by planning at the level of the spatial subdivision.** This final step produces a path composed of a succession of polygons of the spatial subdivision, starting with the current polygon of the entity. This step uses A* algorithm.

Compared to a total evaluation of the path in advance and directly in the lowest layer, the major interest of this approach comes from the division of the problem into sub-problems of much smaller dimension. First, the bucket graph has dimensions much smaller than the graph of the subdivision and few choices should be made in very limited research areas, making the graph exploration extremely fast. Second, it makes possible to distribute the computations over time, the evaluation and the refinement of the path taking place only as and when the entity moves and perceives new decision points. Which allows increasing the performances of our algorithm, this one needing to carry out analyzes only in parts.

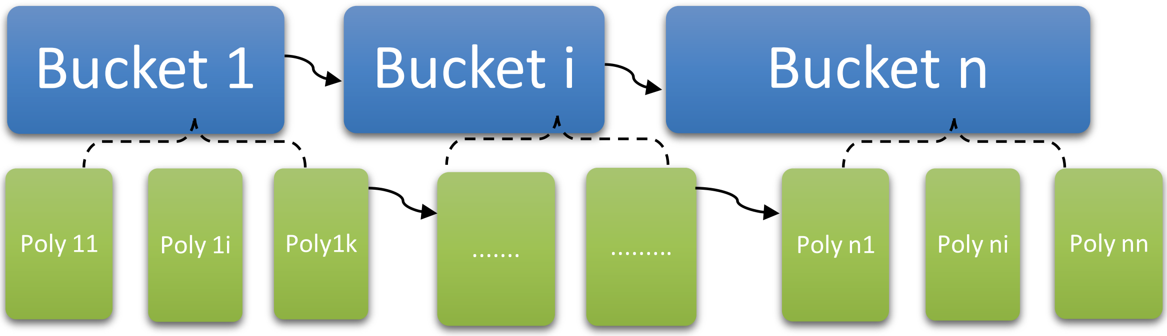


Figure V-6 : Two-level hierarchical path planning.

Two other interests result from incremental planning. First, the algorithm does not require heuristic estimating the cost to the goal. As we see it subsequently, it would be extremely difficult to evaluate, given the number of criteria that come into play, or even impossible in cases where the destination is not known a priori. Second, among the factors that may enter into the evaluation of paths there are those which are variable with time. An incremental planning thus, makes it possible to include those factors in the process of displacement, and thus reinforces the non-omniscient aspect of the virtual human.

Let us now detail how the proposed algorithm works. In fact, our algorithm works by parts. It focuses first on the choice of the initial segment of the route (Algorithm 1). Then, it calculates the rest of the path to the destination (Algorithm 2). Indeed, the first step in calculating a path is the Initial segment selection (Algorithm 1). It consists in selecting the initial segment of the route. There are two cases: the first case when the origin of the trip is situated on a street junction, and the second when the origin is on a street segment.

Algorithm 1: Initial segment selection

Input: start position, end position
Output: interm_bucket

```
If start_bucket_type = crossroad
        interm _bucket = choose_segment (start_bucket, end_pos);
Else
        next_bucket = choose_direction (start_pos,end_pos);
        interm _bucket = choose_segment (next_bucket, end_pos);
```

This algorithm uses the following denomination:

- **start_position**: the origin of the trip in geometric coordinates.
- **end_position**: the end of the trip in geometric coordinates.
- **start_bucket**: the bucket in which is located the start position.
- **start_position_type**: the origin may be located in a bucket of type street junction (crossroad bucket) or street segment (road bucket).
- **choose_segment (current_bucket, end_pos)**: selects a street segment between the outgoing segments of the current street junction.
- **choose_direction (start_pos, end_pos)**: selects a street junction (crossroad bucket) between the two ones situated at the extremity of the current street segment.

The second step is the intermediate path selection (Algorithm 2). This algorithm produces an intermediate path between the current bucket and the destination. It works in parts by focusing on a couple of segment streets at a time. Some of the functions used in this algorithm will be explained with details later as they depend on the pathfinding mode:

- **current_bucket**: the current intermediate bucket which represents the point of decision.
- **parent_bucket**: previous bucket in the intermediate path.
- **outer_edge (current_bucket)**: extracts the outgoing street segments of the current crossroad bucket.
- **extract_parameters (edge, param)**: retrieves the different characteristics of a street segment such as area, length ….etc.
- **benefit_cost (param)**: calculates the benefit of choosing a segment according to its parameters.
- **Min_cost ()**: returns the bucket that optimizes the cost.

Algorithm 2 : Intermediate path selection (choose_route)

Input: current_bucket, parent_segment, end_position
Output: interm_bucket

```
1: choices = select_alternatives (current_bucket, parent_segment);
2: For each segment ∈ choices do
3:     extract_parameters (segment, param);
4:     benefit_cost (param, end_position, cost_list);
5: end
6: interm_bucket = min_cost (cost_list);
```

Regarding details on how this algorithm works. As the intermediate path is initialized with the crossroad bucket calculated in the previous step. This algorithm allows calculating the following intermediate crossroad buckets that will constitute the path that leads to the destination. The first step in this algorithm is to retrieve the route selection alternatives among the different segment choices available from the current crossroad bucket (decision point) (line 1). The parent segment as some other segments should be expected from this list for reasons that will be explained later. Once the list of choices is determined we have to extract the characteristics of each segment (line 3) in order to calculate the cost of passing through this segment (line 4). We will come back later in the next section on the evaluation of the benefit cost. Line 6 permits to know the optimal solution. This algorithm is repeated until the destination is reached.

V.4.2 Multiple criteria route choice heuristic

Although the proposed path planning is incremental, it also needs a cost function as the classical algorithms of pathfinding. The different stages of the incremental path planning are also based on graph traversal and it requires the cost function to quantify the crossing of each node, so that the quality of a path can be judged. The best path will be the one that, on reaching the destination, minimizes the quantifications of the nodes to be crossed.

Indeed, the process of optimisation in classical algorithms is performed with the cost function. This function assigns each edge a numeric value indicating the cost or weight associated with the respective edge. In the simplest case, this measure of cost is usually the geometric distance covered. However as mentioned previously, some experimental research has shown that even if travelled distance impacts path planning, a certain number of other factors must be taken into account. Thus realistic pathfinding models often require more than a simple cost function, they need to consider a couple of different criteria simultaneously. Therefore, our proposed route choice cost function is multi-criteria; it takes into consideration various criteria conditioning the cost of travel.

The considered criteria are those we assume are the most critical in the decision process. In our selection of these criteria, we have taken inspiration from researches investigating the spatial cognitive properties of the navigation decision making. We remind that wayfinding behaviour is influenced by a number of factors which are heterogeneous and of various importance. They can be divided into two classes: physical environmental elements and human subjective elements. The physical environmental elements relate to the environment itself, such as spatial configuration and route characteristics. The human subjective elements relate specifically to the individual, such as whether he is familiar with the environment and trip purposes.

In order to evaluate the cost of the different available choices, we will consider criteria from the two classes; which were chosen according to a number of reasons:

1. To keep in line with the results from researches about factors influencing the route choices.
2. To make the decision process as realistic as possible, reactive to the environment and more specific to each simulated entity.
3. To have variables that might be critical in the pathfinding process and lead to credible results.

Each of the chosen criteria is described in detail below. However, the method to take into account these factors simultaneously in the cost evaluation will be presented later. Thus, the considered criteria are:

Familiarity:

This criterion reflects the entity experience of the street network. We assume that pedestrians have a tendency to choose streets which they know and have experienced before. The lack of information may push them to take less risky routes and avoid time consuming detours, thus they prefer known streets as opposed to unknown ones.

Destination direction:

This criterion reflects the aim of the entity to find the route approximately in the direction of its destination. This criterion is related to the *least-angle strategy* (LA), with witch the navigator aims at maintaining track of the target direction throughout the trip (Hochmair & Karlsson 2004).

Street length:

This criterion reflects the aim of the entity to minimise its direction changes through the path by choosing the longest street. People prefer turning as late as possible in order to minimize the cognitive effort required for pathfinding. Additionally, in spatial cognition domain, it was argued that straight lines may be perceived as shorter than curved lines (Thorndyke 1981).

The street length criterion is related to the *initial segment strategy* (Bailenson, Shum & Uttal), with witch people tend to focus disproportionately on the initial portions of the route and that they prefer routes with longer straight initial segments, regardless of what the later portions of the routes look like.

Linearity:

This criterion reflects the aim of the entity to follow route as straight as possible by minimizing the angular deviation from a straight line on condition that this choice always approximates the direction of its final destination. Indeed, Dalton (2003) has found that the most frequented routes are more linear.

Density:

This criterion reflects the fact that the entity is influenced by the presence of other entities. This factor may be considered as an attractor as well as a detractor; the presence of people in a road may attract some pedestrians as its congestion may be also repulsive and push others to choose other alternatives (Dalton et al. 2011). In order to compute density the *floor area* of each road is precomputed and stored in the Informed Bucket Graph.

Floor area:

This criterion reflects "how much" an entity "can see"; measured by the partial isovist area. This variable was incorporated in the proposed model because:

– the floor area is important during navigation because it is what pedestrians use physically when they navigate;
– the connection between floor area and navigation has been made in studies using isovist analysis that have correlated behavioural responses with isovist area (e.g.(Wiener et al. 2007));
– and it is sensitive to road width.

Visual length:

This criterion reflects "how far" an entity "can see"; measured by the longest ray of the partial isovist. This criterion was chosen because:

– this criterion supports a hypothesis by Hillier (1997) that people tend to follow the longest line of sight that approximates their heading.
– it represents a property of accessibility, important for an environmental model;
– it has been suggested that depth of view is a principal component of wayfinding behaviour, with the related wayfinding strategy of following a linear route wherever possible, gaining increasing weight in the literature; depth of view represents the 2D geometry of the environment and is thus connected with measures that can be derived from isovists (Emo 2009).

A limitation of the above two variables is that they are heavily dependent on the precise location of the point of view, with only slight variations in the location affecting the measure. It was felt however that the method of pre-measuring those variables to the centre of the crossroad bucket despite the position of the entity.

Number of streets intersecting with a street segment:

It is a useful variable because it draws on connectivity; which is a crucial measure in the space syntax environmental model. This criterion was included in the proposed model because it is related to the notion of "promise of more information" that Kaplan describes by the term Mystery (Kaplan 1979). The existence of an intermediate location from which all of the following streets are visible attracts pedestrians.

Discovering potential:

This criterion reflects the aim for the entity to discover novel shortcuts not familiar. People sometimes seek to improve their individual topological knowledge.

V.4.3 Path planning modes

We have highlighted that the real choice of the path, to reach a destination, is made by an incremental adjustment at the bucket level. Two specializations of this planning are proposed, making it possible to have two categories of pathfinding strategies. Each of these specializations is mainly differentiated by the evaluation of the benefit cost. We remind that we have found in the literature that one of the criteria that controls the choice of a certain strategy is the type and amount of information that is actually accessible to wayfinders. Therefore we propose two modes of planning a path:

- **Path planning in a familiar environment.** This first mode corresponds to a classic path planning, aiming to reach a place identified in a more or less familiar environment.
- **Path planning in an unfamiliar environment.** This second mode of path planning is applied when aiming to reach areas in an environment unknown by the entity. Two types of this path planning mode can be considered: directed and undirected.

We will thus present the two modes of pathfinding and we will detail for each of these modes the proposed approach to evaluate the benefit cost of route choices.

V.4.4 Path planning in familiar environment

Before presenting this pathfinding mode, let us start by summarizing the path finding process in a familiar environment according to cognitive sciences domain as well as the scientific context behind this behaviour, which we were able to discover in the state of the art.

A. Principle

According to theories addressing general features of human rationality and cognitive heuristics, humans confronted with complex problems adopt principles of cognitive economy. This leads to the choice of a simplification strategy or heuristics that involves optimally low cognitive costs. In the current pathfinding mode concerning wayfinders with good knowledge of the environment, the choice of wayfinding strategy may represent a trade-off between the effort of accessing information from memory, and the risk of setting out on a suboptimal path. Indeed, planning an optimal (e.g., the shortest) route through the environment requires detailed information, while a sub-optimal route may be identified based on more superficial topological information.

Because retrieving metric directional information for each route choice at intersections from memory involves a high amount of cognitive effort as well as potential systematic errors and biases. The wayfinder don't plan the complete path in advance; individual navigation decisions at each intersection can then be computed based on a local comparison of the bearing of each outgoing street segment (or its projection towards the next intersection) with the direction of the known goal location. He uses local metric information to inform the next step including information about the length of the directly visible street segments and their curvature. Moreover, the visual information can serve as a recall cue for information about subsequent street segments and their metric properties. This cue may remind the wayfinder of small streets – potential shortcuts – that are not yet visible.

As we aim to reproduce these mechanisms in order to achieve a realistic simulation of navigation behaviour, we built our model on the key results presented above. Indeed, our algorithm does not compute the complete path in advance, as described earlier. Individual navigation decisions are calculated at each intersection based on a local comparison of the benefit cost of each outgoing street segment with the direction of the goal location. To take care of the factors influencing the route choice decisions, we use a multi-criteria heuristic in the benefit cost analysis.

B. Route Selection alternatives

As we have seen in the incremental path planning section, the first operation in algorithm 2 consists in defining the list of the route selection alternatives. Indeed, the agent at each intersection has to select from a small number of route alternatives. Thus, the agent is not allowed to return to the previous crossroad bucket in its subsequent step (dead ends are an exception). This restriction prevents oscillation back and forth along the same segment street, which would otherwise occur within the street networks. Such oscillation would yield simulated navigation behaviour very different to human route-choice behaviour.

In addition to the previous street segment which has to be eliminated from the list of available route choices, other street segments can be excluded from this list. The inclusion or exclusion is determined by the benefit cost analysis. We aim by filtering the choices list to reduce the number of alternatives, and consequently reduce the computational cost.

C. Benefit cost analysis

The benefit cost we evaluate is divided into two parts. First, the **environment configuration cost** represents the characteristics and configuration of the street network. Second, a **preference cost** includes or excludes a segment street by filtering it using individual affinities.

The **preference cost** is the first to be evaluated, in order to eliminate the corresponding street to be compared with the other alternatives. Therefore, this part is computed as:

P(s, e) = F and E and D

Where:

- ***F*** is the familiarity; it takes the value true if the segment ***s*** exists in the mental map of the entity ***e*** and false in the other case.

- ***E*** is the potential of exploration; entities with a low level of familiarity may have the potential to explore novel streets and to discover novel shortcuts (***E*** takes the value true) as may not (***E*** takes the value false).

- ***D*** is a parameter that reflects the desire or not of the entity to avoid overcrowded or unused streets. ***D*** of the segment street ***s*** is computed as:

$$D(s) = \begin{cases} true & if\ 0.3 < density < 3 \\ false & \text{otherwise} \end{cases}$$

The density is compared to 0.3 and 3 values following the work of Paris, Donikian & Bonvalet (2006).

We notice that if a false value is produced by the **preference cost**, then the corresponding segment street is considered as ignored by the entity.

The second part to be evaluated is the **environment configuration cost**. The following three geometric parameters interfere in the entity's preference behaviour between several street segments: destination direction, linearity and street length. The strategy applied by our agents consists in following a route as straight as possible on condition that this choice always approximates the direction of their final destination. Therefore, we propose to evaluate the environment configuration cost of a street ***s*** and a destination ***D*** as:

EC(s, D) = D*p+Le*p'+L*p''

Where:

- ***D*** represents the destination direction factor;

– ***Le*** represents the street length factor;
– ***L*** represents the linearity factor;
– ***p, p', p''*** *values to express* priority between the different factors.

We remark that the destination factor ***D*** is related to the deviation angle strategy (LA) and the street length factor ***Le*** can be related to the initial street segment strategy (ISS). Hochmair & Karlsson (2004) analyzed the observed preference behaviour with respect to these two strategies and suggested an underlying mechanism (minimum triangle path) that explains in which situation either of the two strategies or both are applied.

Indeed, Hochmair & Karlsson (2004) compared the two strategies in a Virtual Reality setting by systematically varying length and angle of the initial path segment. In order to clarify the analysis of the route selection behaviour, they subdivided the street-leg combinations into four classes. The first class (Figure V-7(a)) is the group of leg pairs, where the deviation angles for each of the two compared legs are equal, whereas the length of one leg is different from the other ($\alpha_l = \alpha_r$ and $l_l \neq l_r$). The second class is the group of leg-pairs (Figure V-7(b)) of equal length but different deviation angles ($\alpha_l \neq \alpha_r$ and $l_l = l_r$). The third class (Figure V-7(c)) includes leg pairs where one of the two compared legs has a larger deviation angle and a smaller initial length. The fourth class (Figure V-7(d)) includes (expected) conflicting situations where one of the two compared legs has a larger deviation angle (i.e. should be rejected according to LA), but has a longer initial length (i.e. should be preferred according to ISS).

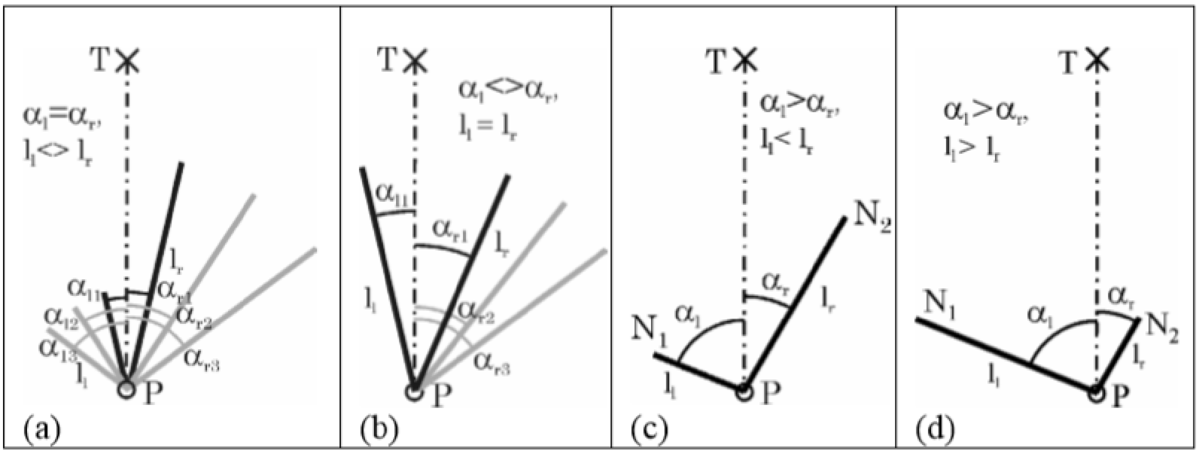


Figure V-7 : Four classes of leg combinations (Hochmair & Karlsson 2004).

The observed data revealed that the average participant preferred the initially shorter segment, if this segment deviates equally or less from the target direction compared to the alternative (cases a and d in Figure V-7). Further, between equally long initial segments, the less deviating segment is preferred (case b). Regarding the preference behaviour related to Figure V-7(c), the navigator makes the mental trade-off between a shorter leg and a smaller deviation angle for each situation individually.

From the results obtained they suggested a mechanism in route choice where the decision maker tries to minimize the estimate length of the total route that would have resulted if the route had continued straight towards the goal after the initial segment (triangle path length). They found that the minimum triangle path strategy is appropriate to explain the decision behaviour for all four classes of decision situations.

Therefore, we propose to replace the environment configuration cost function proposed previously by this function:

EC(s, D) = T+L*p

Where:

- ***T*** is the triangle path length. As shown on Figure V-8, ***T*** is calculated as the sum of the length of the line segment AB (AC) and the length of the line segment BD (CD) (alternative 1: ***T*** = *AB* + *BD*, alternative 2: ***T*** = *AC* + *CD*).

- ***L*** represents the linearity factor; it is evaluated as the angle between the current and previous directions as vectors, which are obtained as shown in Figure V-9.

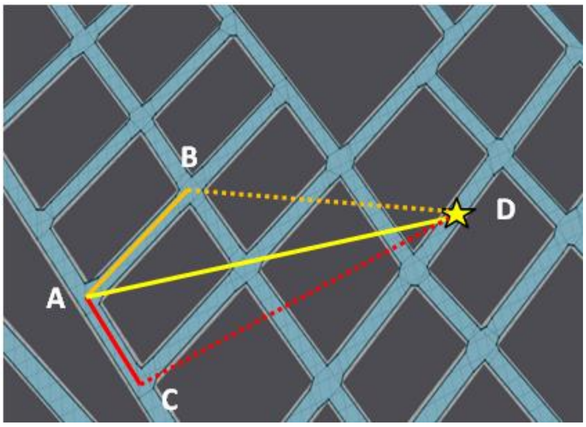


Figure V-8 : Triangle path length.

We notice that the values ***T*** and ***L*** are normalized in order to make the two parameter values comparable between each other. ***L*** is multiplied by a value ***p*** (***p***<1) to give the criterion triangle path length ***T*** greater priority than linearity.

We affected priorities to the benefit cost function parameters for the following reason. The benefit cost function that we propose allows us to assign costs for traversing a node; a street intersection. This function is context-sensitive because, depending on the choice of an incoming and outgoing edge, the costs can vary. The context encoded in the cost function can be represented as objectives of the short path problem. A cost function can evaluate these objectives and map them to a numeric value. The goal in the cost function is to find an optimal solution that simultaneously optimizes all objectives. However, two or more objectives may be in conflict. For example, in the proposed benefit cost evaluation function minimizing linearity parameter can load to maximizing triangle distance parameter and vice versa. In order to improve our algorithm, we chose the method of aggregating the different objectives using weights; affecting the weights so as to favour one or another objective permits to balance conflicting objectives.

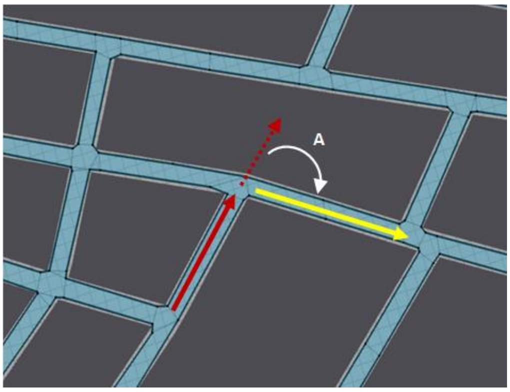


Figure V-9 : Linearity factor evaluated as the angle between previous direction (red) and current direction (yellow).

V.4.5 Path planning in unfamiliar environment

This second path planning mode answers the problem of finding a way in an unfamiliar environment. Finding ones way in unknown or not very familiar environments is a frequent task that people experience in their daily lives. The wayfinder lacks the relevant knowledge required to select the optimal route, and must therefore rely on wayfinding heuristics.

The targeted wayfinding behaviour in this mode of pathfinding may occur in a situation in which the navigator:

– lacks structural information regarding the environment (such as the position of landmarks, street names and the street hierarchy),
– cannot match information perceived from traffic signs with his or her destination (that is, the destination is not explicitly indicated on traffic signs and cannot be derived from perceived information),
– cannot ask other passersby, and
– has no external information sources such as maps or mobile navigation systems at hand.

Two specializations of this pathfinding mode are proposed: ***directed*** and ***undirected***. Each of the specializations is differentiated by the familiarity with destination (Figure V-10). The first one involves a familiar start and a familiar destination (can be the same place) with the aim of finding new places and new paths between these new places and places already known to the wayfinder. In the second specialization, the wayfinder is proceeding to a specific destination which is unfamiliar to him and which he may not has previously visited.

Figure V-10 : Directed (Left) and undirected (Right) pathfinding modes in unfamiliar environments.

Therefore, we propose a path planning algorithm that implements two wayfinding strategies which will be applied for the modes described below. In each mode and on the basis of the available information, the simulated entity selects a route among the available options by applying the correspondent strategy.

A. Directed pathfinding

In the directed pathfinding mode, the information which the navigator possesses is the target vector (the direction of the destination and its position). A human navigator, when travelling through a street network, has several ways to derive the destination position. The destination may either be directly observed, or the navigator can use knowledge about his or her current position to maintain a sense of what the target vector is. The following examples represent some real-world situations which correspond to the directed pathfinding mode:

- A target description from a passing pedestrian may consist of a point in the direction and rough distance information if a detailed route description is too complex for the navigator to comprehend or the time is too short for a detailed route description.
- A visitor without a map may try to navigate to a distal landmark he or she perceives.
- A visitor may try to find a shortcut through an unknown district without navigation aids.
- A visitor may get lost but maintain a sense of direction and consequently try to find his or her way back to a known location.

Principle

In cases in which the navigator wishes to find the shortest path but lacks structural knowledge about the environment one strategy is to proceed to the direction of the destination. Least-angle (LA) is a wayfinding heuristic that can be applied. Even an incorrectly perceived direction will make a navigator eliminate turns that appear to direct him away from the approximate target direction. If the deviation angles for each of the segment alternatives are equal there is a preference for the shortest leg more or less, as shorter initial legs would provide them with the opportunity to explore further choice options quickly at the next intersection, which in turn reduces the cost of potentially required backtracking when compared to long segments.

Besides deviation angle and initial leg length among others the following three geometric parameters affect preference behaviour between several street segments: The number of intersections that are visible along the street segment, the visible area of the street, and the density of the street segment.

B. Undirected pathfinding

In the undirected pathfinding mode, the wayfinder doesn't possess information on the direction of the destination or its position, but has the capacity to identify the destination once arrived at it. Although this type of wayfinding is a process not utilized as much today due to the increase in advanced navigational technology, it is still a needed process for when that technology fails. The following examples represent some real-world situations which correspond to the undirected pathfinding mode:

- A visitor without a map may try to navigate to a distal landmark he or she cannot perceive but has previously seen its picture.
- A visitor may get lost and consequently try to find his or her way back to a known location.

Principle

In an unfamiliar setting, pedestrians usually make route choices at key decision points which are the street junctions in the environment. Different types of information are useful, such as visual, linguistic and structural information. Non-familiar people have to ‘‘read’’ the environment based on immediate affordances. Among the affordances there is the spatial geometry of the visual field offered at decision points which has an important role to play in the route choice. There is also the presence of people in the environment which may be suggestive of the popularity of that place and affect exploratory type behaviours such as exploring a new city, or even generate a sense of security.

C. Benefit cost

In the two proposed strategies, ***directed*** and ***undirected***, the wayfinding process is incremental; individual navigation decisions are made at each intersection where the decision is based on a local comparison between the benefit costs values assigned to each of the included choice alternatives. However, the benefit cost is evaluated differently in the two strategies. The directed search is characterized by the fact that it is affected mainly by the destination direction while in the undirected search it is the visual field which plays a principal role in the decision making process.

Therefore, the benefit cost evaluation function is composed of two parts. The first one is specific to the corresponding strategy and the second part is common between the two strategies. The benefit cost in the ***directed mode*** (BCD) and ***undirected mode*** (BCU), of a street ***s*** and a destination ***D*** are evaluated as follows:

BCD(s, Dest) = T*p+D*p'+A*p'' +N*p'''

BCU(s) = VL*p+D*p'+A*p'' +N*p'''

Where:

– ***T*** is the triangle path length.

– ***VL*** is a parameter that represents the longest line of sight factor.

– ***D*** represents the density factor. The density *D* of the segment street ***s*** is computed as:

D(s) = 1 if 0.3 < density < 3

or 0 otherwise

The density is compared to 0.3 and 3 values following the work of Paris, Donikian & Bonvalet (2006).

– ***A*** is a parameter that reflects the amount of floor space directly visible from each intersection in the direction of the street segment ***s***.

– ***N*** represents the number of streets intersecting with the street segment factor**.** It is evaluated by the connectivity of the crossroad node. The value null of this parameter means that the intersection is not visible.

We notice that all the values are normalized in order to make different parameters values comparable between each other. The parameters also are multiplied by weights **(*p, p', p", p''')*** to give to each criterion a priority. Affecting weights so as to favour one or another parameter permits to balance conflicting parameters.

V.4.6 Analysis and optimization of the evaluated path

Now that we have defined how to evaluate a path in the environment, let us see how to analyze and optimise the produced paths. This phase aims to improve the quality of the computed path, for two reasons:

– The result of the planning has an abstract component, indicating globally the path in the form of a segment to cross, and a fine geometric component, indicating locally the succession of polygons to cross.

– The urban street network is abstracted as a graph. That is, the entity may get caught in a circuit or cycle and may therefore never reach its destination. To be caught in a circuit, the entity must enter any road bucket at least twice from the same previous crossroad bucket; the only parameter which affects the decision outcome at a revisited road bucket is the previous crossroad bucket. All other parameters, namely the target vector between the crossroad bucket and the destination, and the streets configuration, stay constant between recurrent visits. This means that an edge may be visited several times (from different directions) within a circuit.

A proposed solution that is possibly a closer approximation to human route choice as concerns the repeated traverse of edges is the ***memorized random choice*** algorithm (Lovas 1998). This algorithm remembers which of the edges the navigator has traversed before, and selects the edge among the set of alternatives that has been previously traversed least often. We have integrated this heuristic into our algorithm to overcome the problem of becoming caught in a cycle or circuit. Indeed,

V.5 Conclusion and discussion

We have presented in this chapter the pathfinding model as well as all the mechanisms involved in this behaviour. The architecture proposed is strongly focused on the principles evoked by cognitive psychology. Thus, our entity is subdivided into independent functioning behavioural modules, communicating with each other through synthetic information. These modules are then integrated into a global process, governing the triggering of actions of the humanoid over time.

The first proposed module is the visual perception. This allows the entity to analyze its environment as and when it moves, in order to make virtual humans non-omniscient. The principles of individual abstraction of information, as well as reinforcement and recovery in memory are voluntarily neglected in the proposed model. We justify this choice by the targeted field of application, with the simulation of short-term situations, which is small enough not to require these mechanisms.

The second proposed reactive behaviour is path planning. This one allows three categories of planning, responding to different issues. This behavioural module can also be driven by higher level processes, simply by performing queries on one of the three path search specializations. The approach presented in this module has three major advantages: efficient in computation time thanks to the incremental aspect; realistic thanks to the type of managed criteria; individual to each entity thanks to the preference costs and the individual knowledge about the environment.

We can conclude that the proposed models are far from representing the complexity of human reasoning, but still form realistic virtual human wayfinding behaviour that meets the realism requirements of our study framework. This model allows the simulation of non-omniscient virtual humans, with a great deal of realism in decision-making. It remains very open, proposing a defined general mechanism supporting the extension of some of its constituents, such as cognitive tasks and affordances.

Chapter VI Experiments and results

VI.1 Introduction

The primary objective of this work is the study of pedestrian's movement by simulations. To do so, we have proposed in the previous two chapters a set of models that can achieve a certain level of complexity of human behaviour. Indeed, these models cannot be used without being unified in an application. Therefore, we will propose in this chapter a complete architecture, which will meet the objective of the work. Moreover, another aspect will be addressed which concerns the validation of the results obtained.

We will present in this last chapter the proposed application, the experiments conducted and the results obtained during this thesis. We will begin, in section VI.2, by describing the software that integrates the proposed models and to explain the simulation chain in section VI.3. This application materializes the models presented and demonstrates their feasibility. Then, in section VI.4, we will address the validation of the models by their comparison with observations and findings available in the literature and discuss the results and performances of the various modules that compose the proposed application. We will conclude in section VI.5.

VI.2 The software architecture

In this section, we will describe the software architecture dedicated to perform the simulations. In order to develop this architecture we adopted a modular development approach that allows us to carefully implement and integrate the different models required by the project. Moreover, this modularity allows the reuse of the output products of each step. Thus, the ***Informed Bucket Graph*** created for a simulation can be directly provided for other modules of the same category.

The proposed software architecture is organized in the form of three integrated modules within the same application (Figure VI-1): IBG Builder, Crowd simulator and Pathfinding Tester. These modules includes, of course, all the models proposed in the contributions. Let us now introduce these modules.

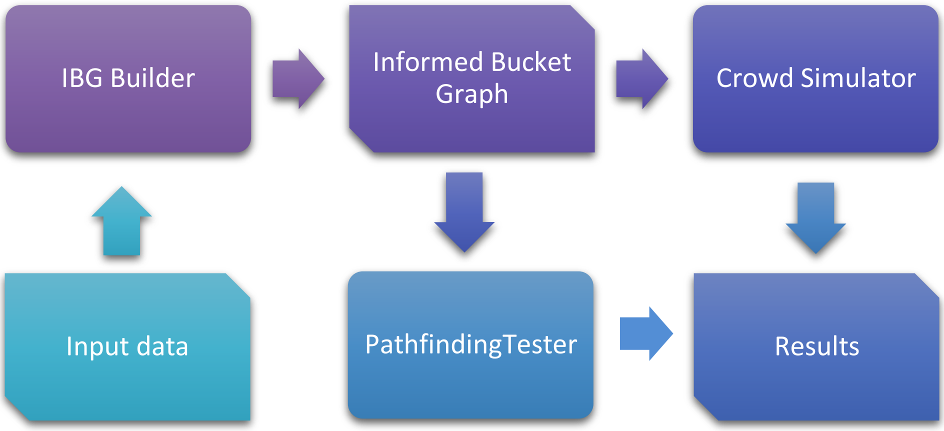


Figure VI-1 : Software architecture.

VI.2.1 The Informed Bucket Graph builder (IBG Builder)

The representation of the environment in the form of an informed graph is the main module of the software. Hence, we needed a module to create the environment description. We developed this software module that we called IBG-Builder which allows us to create the Informed Bucket Graph (Figure VI-2). Indeed, IBG-Builder defines the graph-based description of the virtual environment, and allows us to enrich the bucket graph with pre-calculated data, leading to the creation of the Informed Bucket Graph.

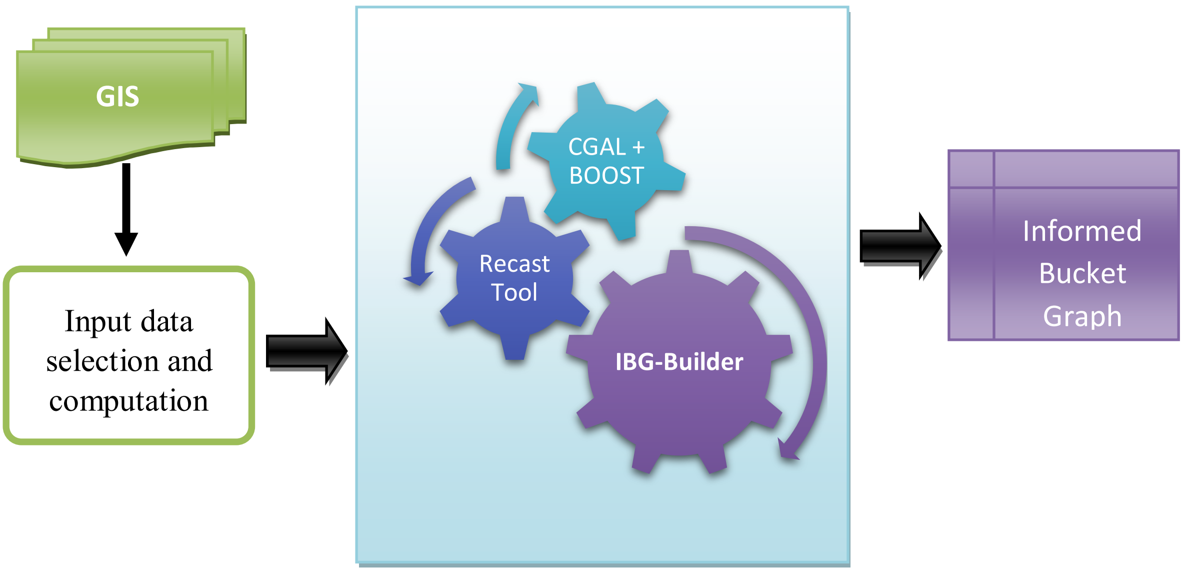


Figure VI-2 : Creation of the Informed Bucket Graph.

As illustrated in Figure VI-3, this module is based on two software packages: Data calculator and Topologic Environment. It also uses three software packages: External libraries (CGAL and BOOST); and Recast Tool.

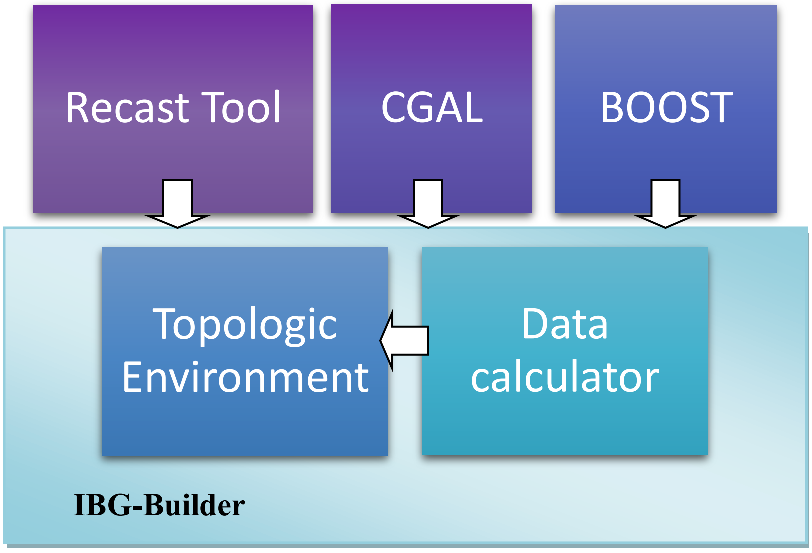


Figure VI-3 : Software Architecture of IBG-Builder.

- **Topologic Environment.** This package allows us to store and manipulate geometric, topologic and semantic information representing the simulation environment. It provides the object-oriented data structure which defines the graph-based description of the virtual environment as well as the pre-calculated data associated with its features.
- **Data calculator**. This package makes the calculation of data that will be attached to the abstracted graph created by the Topologic Environment package.
- **CGAL**. Standing for Computational Geometry Algorithms Library (*Computational geometry algorithms library (CGAL)* 2019), is an open-source library providing geometrical algorithms such as Delaunay triangulation.
- **Boost**. Boost provides free peer-reviewed portable C++ source libraries; among them we use the Boost Graph Library which provides high-quality implementations of graph data structures and algorithms (*Boost C++ Libraries* 2019).
- **Recast Tool**. Is an automatic open-source navigation mesh generator toolset for games (Mononen 2018).

VI.2.2 Crowd Simulator and Pathfinding Tester

The **Crowd Simulator** module runs a simulation and extracts information needed to characterize the results. As illustrated in Figure VI-4, this module is based on three software modules:

- **Crowd Manager.** This module is used to create crowds and manage them.
- **Crowd Agent.** This module is the implementation of the pedestrian model of the proposed system (see section IV.2). It allows creating an agent (profile and mental map) as well as calculating its paths.
- **Simulation Tool.** This module permits to configure the simulation, whether it is choice of the population, definition of agents' targets, or presentation of results. In addition to the configuration this module starts the execution of the simulation.

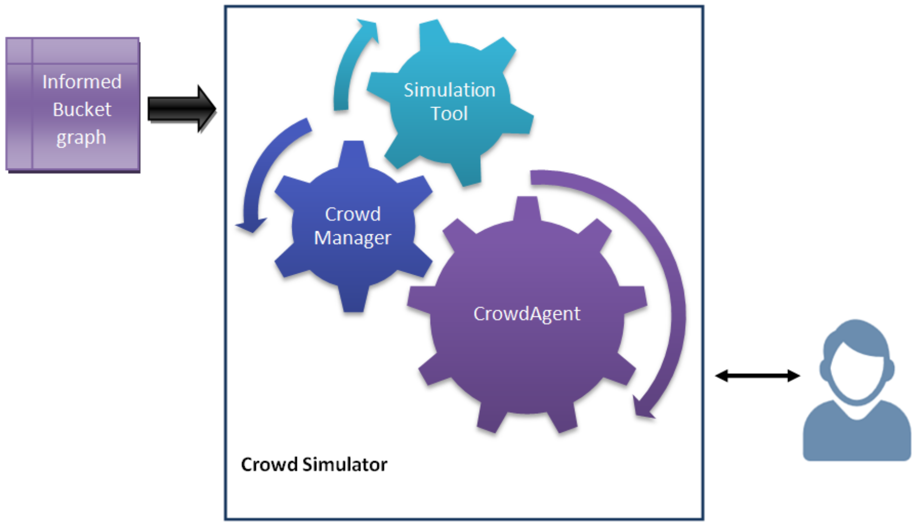


Figure VI-4: Running a simulation with Crowd Simulator.

As regards the **Pathfinding Tester** module is has been implemented to test the performance of the proposed pathfinding algorithms and examine the characteristics of the calculated paths. Thus in addition to the proposed pathfinding algorithms a simple A* path planning algorithm has been implemented.

VI.3 Running a simulation

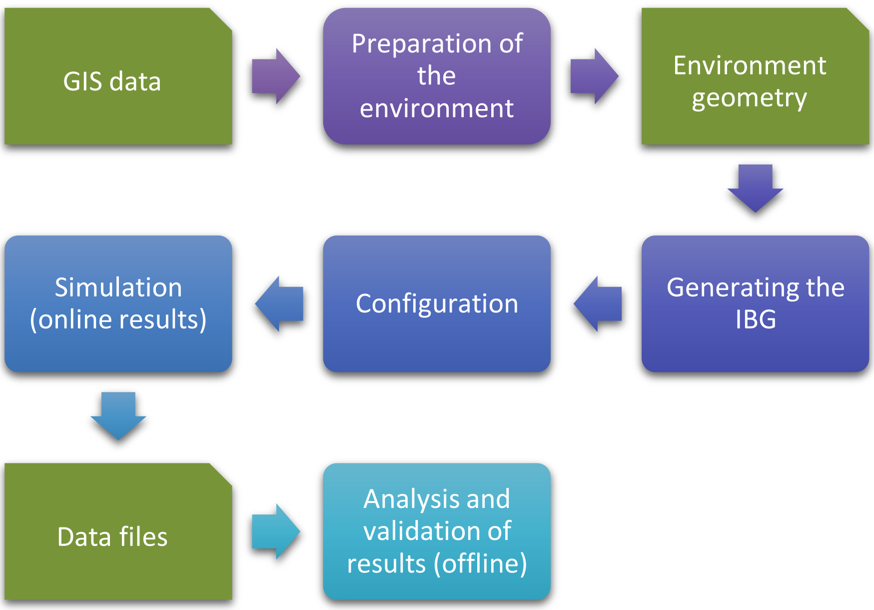


Figure VI-5 : Simulation stages.

A simulation is organized in the form of four stages (Figure VI-5):

– **Preparation of the environment**. This first stage permits to prepare the necessary environment for the desired simulation.

– **Configuration**. This second stage consists to configure the simulation parameters.
– **Simulation**. This third stage consists to run a simulation and extract the results.
– **Analysis and validation of results**. This last stage allows an in-depth analysis of the data extracted from a simulation.

VI.3.1 The simulation environnement preparation

The first step to run a simulation consists in selecting the data sets which are used to build the informed bucket graph from Geographic Information System (GIS) data. This step is the only one requiring human intervention. The preparation of the simulation environment is divided into three successive steps (Figure VI-6).

Figure VI-6: Stages to configure the simulation environment.

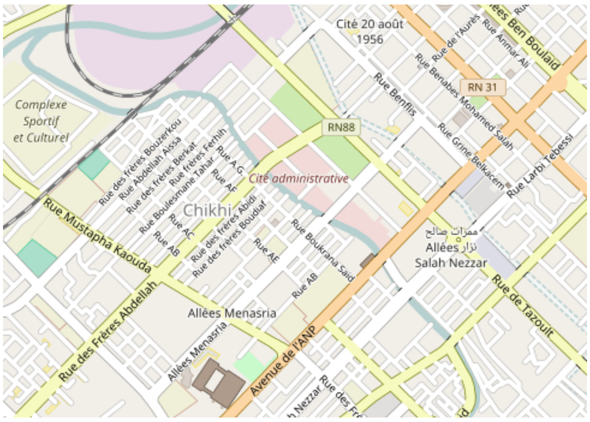
Input data selection. A wide variety of freely available geographic information exists. Among them, we chose Open Street Map (OSM) (*OpenStreetMap* 2018). Open Street Map is a well-known collaborative mapping project that involves volunteers from all over the world in the creation of a free, global geospatial database. Figure VI-7 (a) shows an example of the map of an urban environment retrieved from Open Street Map (*OpenStreetMap* 2018).

The choice of Open Street Map has been motivated by certain number of reasons:

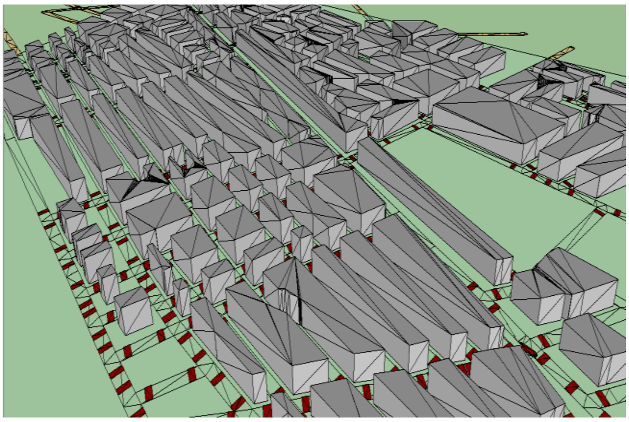
– The availability of the OSM database under a fully open license, which has attracted the interest of a multitude of end users such as industry, professionals, governments and the academic community. OSM is now considered to be a research topic on its own.
– The OSM database is also extremely rich, as it includes a variety of thematic layers. The OpenStreetMap community has collected and contributed over 1049 gigabytes of street network data for the entire world (*wiki.openstreetmap.org* 2019).
– The OSM database is constantly updated and enriched by contributors, and each new version is immediately available for use.
– According to many studies the quality and quantity of the OSM data can be compared to that of the authoritative datasets (Fonte et al. 2019) (Liu & Jiang 2012). The large number of contributors over time, more than 5 M registered contributors in April 2019 (*wiki.openstreetmap.org* 2019), has ensured that OSM data have reached a high degree of quality.

Conversion to 3D data. Once the urban area chosen, it is converted to a 3D graphical format (Figure VI-7 (b));

Street network selection. Only data on street network is kept; other data is eliminated. This data is then saved in the .obj format in order to be used by the proposed software (Figure VI-7 (c)).



a. Example of the map of an urban environment from Open Street Map



b. 3D graphical format of the chosen area.

c. The street network used as input to the Informed Bucket Graph generation.

Figure VI-7 : GIS input data selection.

VI.3.2 Configuration of the simulation data

The simulation data represent all the information needed to run a simulation. In order to meet the specific needs of a pedestrian movement simulation, we have developed specific input interfaces that include the generic interfaces provided for Recast Tool. Let's detail the possibilities offered for this configuration step:

General configuration

The general configuration of a simulation makes possible the specification of the environment modelling parameters. We can find among the different possible choices:

- The environment's file: corresponds to the input geometry seen above.
- Parameters controlling the spatial decomposition of the environment.
- Different options controlling the type of the graphic representation to be used for the environment model viewing.

Population configuration

The population configuration makes possible to assign general parameters to the entities created during the simulation. Two levels of configuration are available:

Population. A population is a distribution of archetypes defining in which proportions they compose it.

Archetype. An archetype allows configuring the internal parameters (profile) of the generated humanoids, such as:

- Level of familiarity: high, medium and low.
- Factors influencing navigation such as: discovering potential, presence of other entities.

Destinations. The configuration of destinations covers only their number.

VI.3.3 Analysis and validation of results

This last stage allows the synthesis of the results produced by the simulation, and thus their validation. First, we will start by introducing the proposed representations of the simulation results. Then, we will discuss our approach to analyze and validate them.

Regarding the simulation results we propose three representations: 3D animation, coloured map and text file. The 3D animation allows to see the results online during the course of the simulation (Figure VI-8). Pedestrians are represented by cylinders, since the point we have focused on, in this study, is the way an agent can plan a realistic path, not his appearance. The coloured maps represent emergent patterns of movement densities through colours from red for high values of density to blue for low values (Figure VI-9). It helps to highlight streets of high traffic visually. Finally, in order to permit the calculation of correlation between flows of the virtual pedestrians and space syntax measures such as integration and betweenness centrality, we will use text files that save the results.

Once the results collected comes the validation step. This later present an essential problem for a model intended to reproduce real situations. In spatial cognition domain, theories about human wayfinding and navigation strategies would most effectively be tested in “real world” situations and in physical environments. Thus ideally, to verify the validity of the proposed model an evaluation should be carried out in a real urban environment, in which the routes chosen by the pedestrians would be recorded to be compared with those computed by the software.

Comparisons between simulation results with empirical data should occur in high-level global features such as movement patterns and low-level data such as individual trajectories. The high-level comparison would focus on the movement density of pedestrians in each street. Pedestrians go under their own volition from everywhere to everywhere else, some spaces get more used than others, creating a movement pattern which will be compared to the simulated one. In the low-level comparison, the pathfinding behaviour of real pedestrians is captured by tracking the complete set of routes chosen by them from a given starting point to a given destination. Then, the spatial-cognitive aspects of the model are validated by comparing the real routes to the simulated predictions in terms of route characteristics like complexity and efficiency.

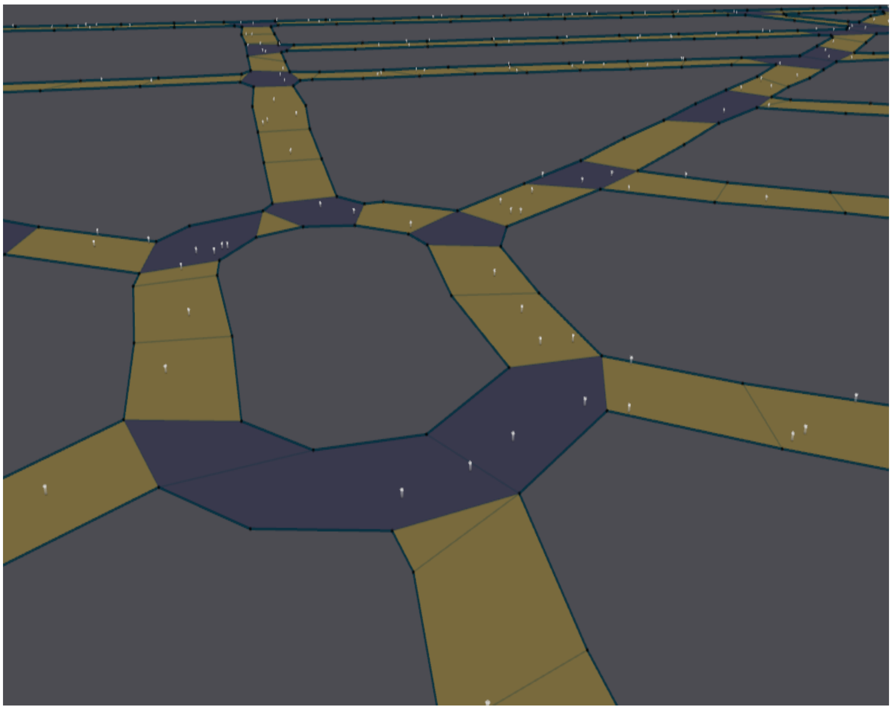


Figure VI-8 : A view in the 3D rendering of the simulation.

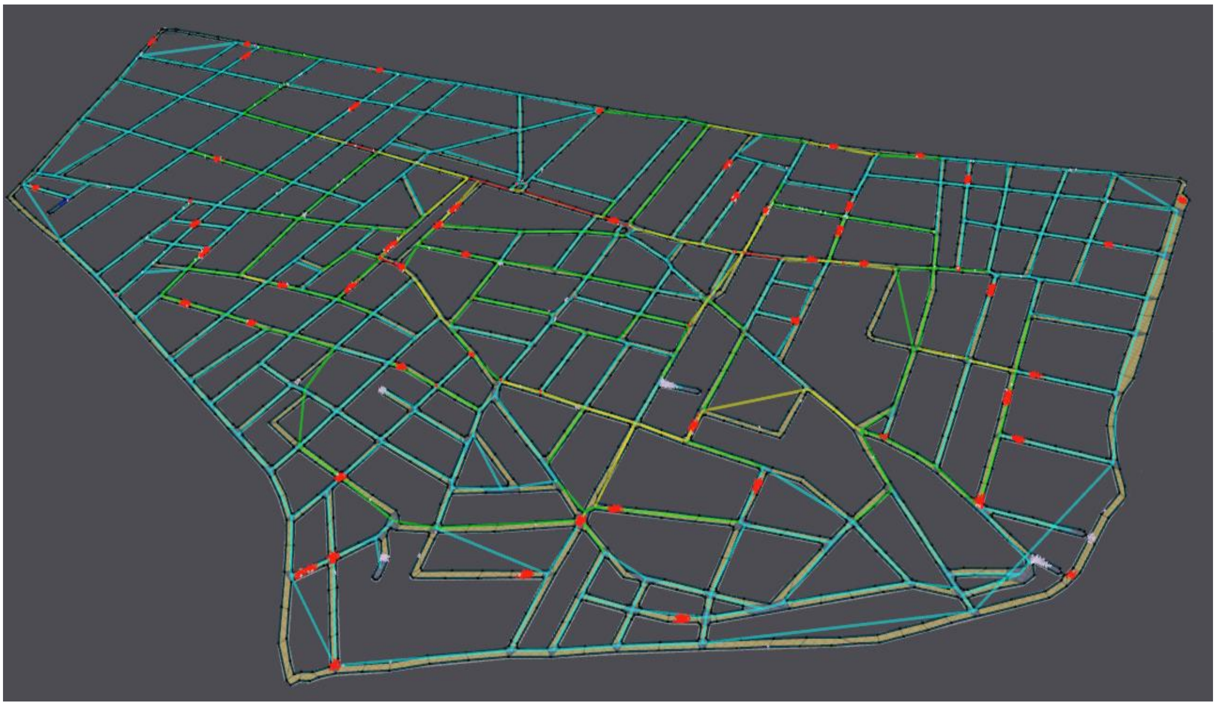


Figure VI-9 : Simulation results in the form of a coloured map using a colour scheme that ranges from the most frequented streets (red) to least frequented (Blue & Adler).

However, this being unfeasible due to obvious practical reasons and due to resource constraints it was decided to envisage the validation with reality in the future. Nevertheless, we propose to perform the validation as described below:

Validation of the logics of displacement

The first point to evaluate is the wayfinding strategies proposed in our model, and the validity of the calculated paths. Therefore, this step aims to characterize paths calculated by the software. Several researchers have examined the characteristics of paths frequented by humans in an urban environment. Among these researches we found some route characteristics that can be used to reveal systematic differences in route choice behaviour between different strategies. Thus, we will characterize the chosen routes according to their asymmetry, efficiency and complexity:

– **Asymmetry**. One of the findings in cognitive psychology regarding wayfinding is the selection and planning of asymmetric routes. Different route is chosen when travelling between two locations depending on which point is the origin and which is the destination.
– **Route efficiency.** The most efficient route is considered, by Hölscher, Tenbrink & Wiener (2011), as the shortest possible path between two locations. They propose to measure route efficiency by comparing the length of the chosen route (*dwalked*) to the length of the shortest possible path (*dshortest*). This measure is described in (Hölscher, Tenbrink & Wiener 2011; Wiener, Ehbauer & Mallot 2009) by the Percent Above Optimal and it is calculated as follows:

  $$PAO = ((dwalked - dshortest) / dshortest)*100$$

  We notice that the most efficient routes have lower *PAO* values.

– **Route complexity.** The complexity of a route is expressed by the number of turns, where the turn is defined by the decision to deviate from the straight ahead by more than 45°, at intersections where street alternatives are available (Hölscher, Tenbrink & Wiener 2011).

Macroscopic study of emerging phenomena

The second type of validation, still investigating the pathfinding strategies, this time involves a larger number of entities. The goal here is to study the emerging movement patterns captured in familiar and unfamiliar environments.

Researchers in the space syntax community, through enormous empirical studies, have examined the characteristics of paths frequented by humans in an urban environment and their major finding has been the strong correlation of human movement with some space syntax measures. The correlation analysis with these measures has been used to show the influence of the environment spatial configuration on the movements of people. Therefore, in this validation we will adopt the correlation analysis with space syntax measures to demonstrate the validity of the simulation results. We will see if our virtual pedestrians will show navigation behaviour similar to that of real pedestrians; are they going to be influenced by the spatial configuration of the environment.

VI.4 Tests and Results

In this section, we present the results obtained with our environment model and our incremental path planning algorithm. We propose to evaluate the performance of our model and validate its results by conducting some experiments. Our interest here is not the controversial discussion of factors influencing pedestrian's movement but confirmation of how well the model simulates pedestrian wayfinding behaviour. We investigate to fine tune our model's parameters such as the benefit cost function.

All of the experiments were performed on a PC with a 4.20 GHz Intel Core i7-7700K processor, an NVIDIA GeForce GTX 1070 Graphics card, and 32 GB of RAM. The machine uses Windows 10 (64-bits).

VI.4.1 Test environments

In order to test the proposed models, we have chosen six different urban patterns (Figure VI-10). The chosen test environments are part of several cities in Algeria and Tunisia. Two of them with an almost orthogonal grid-like city plan. In this type of city plan, streets run at right angles to each other. We have also considered two irregular grid plans. A pattern is irregular when it lacks geometric properties such as repetition, symmetry, parallel elements, and alignment and so on. To supplement the study of labyrinthine networks, we have investigated these ones in Arab cities like Ksar Ghardaia in Algeria and La Medina in Tunisia. This type of irregular grid is known to be topologically deep (More details can be found in Table VI-1). The major criterion in choosing these examples is that the test environments should be of different grid plans and contain as large a variety of junction types as possible for two reasons. First, we aim to test our approach in generating the environment description and how well it detects decision areas. Second, we want to make entities to be presented with a range of alternative choice decisions at every junction.

Environment	Width (Km)	Grid map	Number of road buckets	Number of crossroad buckets	Abstraction memory size (KByte)	Build time (s)
Oran 1, Algeria	1.36	Irregular	506	312	59	1125
Oran 2, Algeria	2.19	Orthogonal	499	292	57	1944.9
Medina, Tunisia	1.93	Labyrinthine	789	577	99	1156
Oran 3, Algeria	1.90	Irregular	434	271	51	403.9
Algiers, Algeria	1.99	Orthogonal	635	434	77	1096
Ksar Ghardaia, Algeria	1.16	Labyrinthine	286	193	35	135.4

Table VI-1: Details of the chosen test environments.

Table VI-1 recapitulates for each environment: the obtained number of road and crossroad buckets in the spatial subdivision, size of the memory space necessary for the topological and informed abstraction, and the build time. We note that build time comprises the whole generation process, including all pre-calculations like bucket area, betweenness centrality and global integration, except the spatial subdivision step as it is performed by Recast tool. In Figure VI-11, we can see a close-up on some regions of the spatial subdivision extracted from each chosen test environment. Figure VI-12 shows the connectivity graph coloured according to the betweenness centrality value of each edge (road bucket). An agent's memory cost independently of the environment, including its mental map, is 280 Bytes.

VI.4.2 Scenarios of the different tests

A. First test

The first test we carried out concerns familiar pedestrian route choices in different situations. Hölscher, Tenbrink & Wiener (2011) found that familiar navigators choose smaller, less frequented streets and include many turns in the chosen paths, which would be also asymmetric; since the direction of navigation is adjusted locally, as it was found by (Golledge 1999). Thus, in this test we will investigate the efficiency, complexity and asymmetry in the paths calculated by our simulated entities familiar with their environment.

To do so, we will first start by affecting to agents different tasks of pathfinding, where the start and destination locations are reversed. We will repeat the same test but with agents applying the shorter path strategy, in order to compare the calculated paths between the two strategies. Then, we will affect to agents, with different levels of familiarity, tasks of pathfinding while measuring the efficiency and complexity of the computed paths for each level of familiarity, in order to compare between them. In this test also we will repeat the same tasks with agents applying the shortest path strategy in order to calculate efficiency measure.

A. Second test

In the second test we investigate the most frequented route pattern and if it correlates with space syntax measures. Several researchers have examined the characteristics of paths frequented by humans in a familiar environment. They found that movement patterns correlate with betweenness centrality. Therefore, in this test agents are distributed randomly in the streets of the whole environment; the destination location may be any point in the environment. We let the simulation run over a certain number of frames while counting how many pedestrians go through each segment street. We repeat this test several times, every time with a different population. Table VI-2 lists the agent population assumptions regarding the level of familiarity.

Figure VI-10 : The chosen test environments maps from Open Street Map (a) Oran1 (b) Oran3 (c) Oran2 (d) Bordj El Bahri (e) Ksar Ghardaia (f) La Medina, Tunisia.

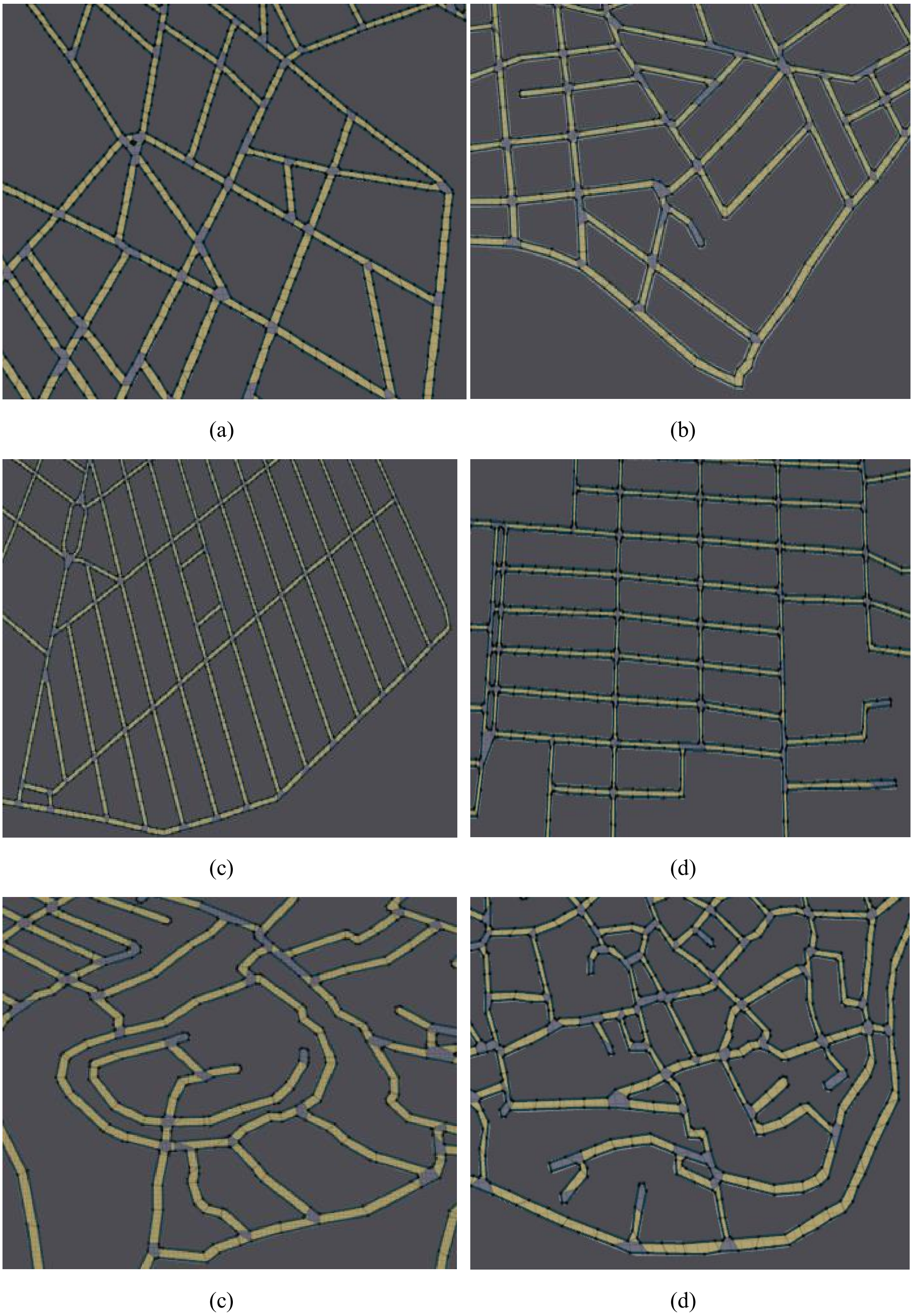


Figure VI-11: Close-up on the generated environment spatial subdivision (a) Oran1 (b) Oran3 (c) Oran2 (d) Bordj El Bahri (e) Ksar Ghardaia (f) La Medina, Tunisia.

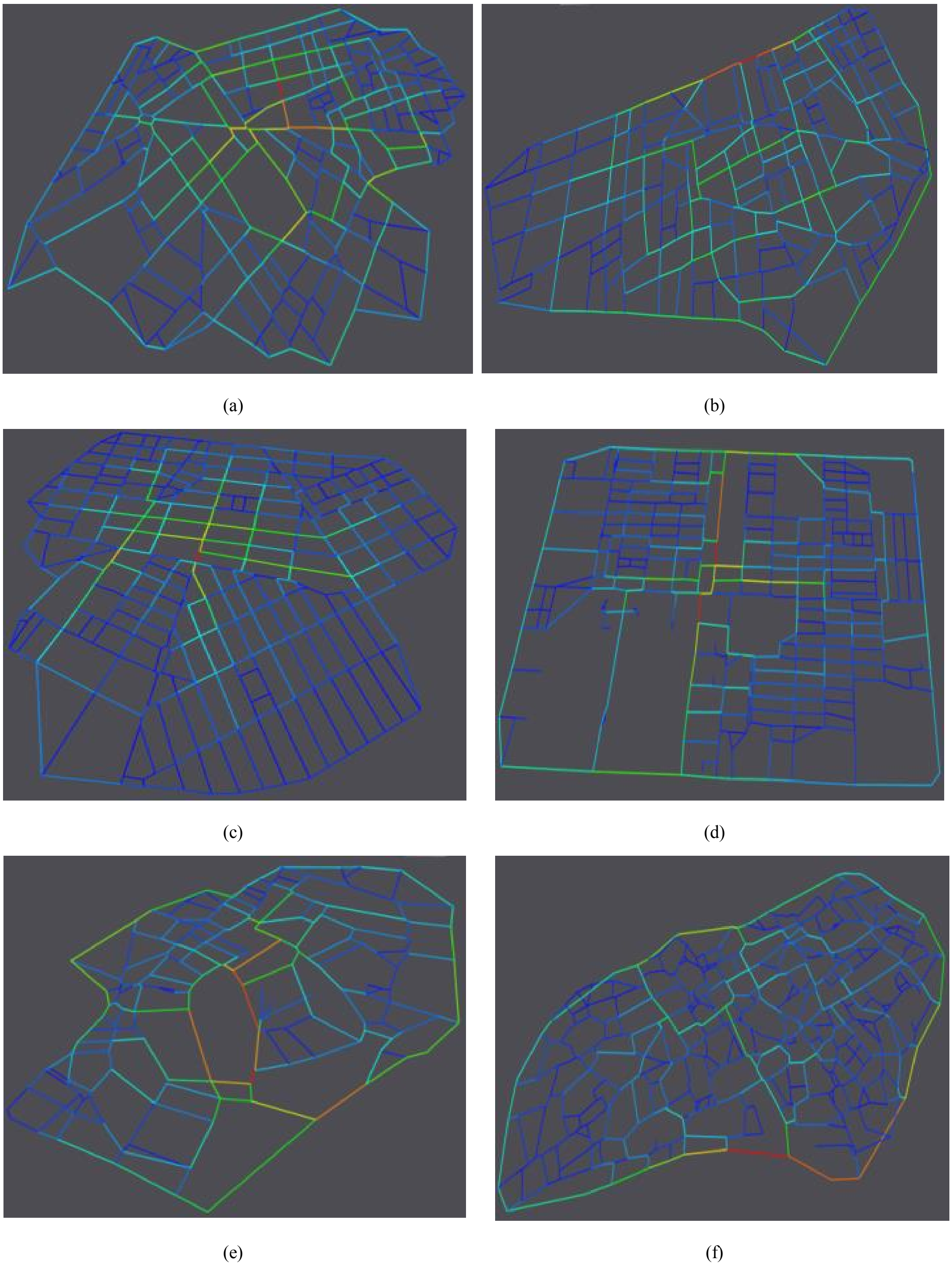


Figure VI-12: Connectivity graph coloured with betweenness centrality using a colour scheme that ranges from the most prominent (dark red) to least prominent (dark blue) (a) Oran1 (b) Oran3 (c) Oran2 (d) Bordj El Bahri (e) Ksar Ghardaia (f) La Medina, Tunisia.

	Level of familiarity with the environment		
Test 2	**High**	**Medium**	**Low**
A	10%	30%	60%
B	50%	30%	20%
C	60%	30%	10%
D	25%	50%	25%

Table VI-2 : Agent population assumptions of the second test.

B. Third test

In the second test we examined the pathfinding behaviour model in a familiar environment. In this test we will discuss the characteristics of paths frequented by humans in an unfamiliar environment. According to space syntax researches pedestrians unfamiliar with their environment increase on primary routes which make their movement pattern correlates with the global integration measure, due to the more global role of these routes in the city's movement structure. Thus, through this test, we investigate the most frequented route pattern and if it correlates with global integration.

Therefore, agents are distributed randomly in the streets of the whole environment; the destination location may be any point in the environment. We let the simulation run over a certain number of frames while counting how many pedestrians go through each segment. We repeat this test several times, every time with a different population; in test A agents are devised randomly between those which use directed and undirected strategy to choose their paths, in test B all agents use directed strategy whereas all agents in test C use undirected strategy (see Table VI-3).

Third test	Strategy
Test A	**Directed / Undirected**
Test B	**Directed**
Test C	**Undirected**

Table VI-3: Used strategies in the third test.

VI.4.3 Results

A. First test

Asymmetry. Screenshots of this test are demonstrated in Figure VI-13. We can see that the paths calculated when applying the proposed strategy are different if we reverse the start and destination locations as shown in (Figure VI-13.a vs. Figure VI-13.b) and (Figure VI-13.e vs. Figure VI-13.f). However, when applying the shortest path strategy, in the two cases we have the same path; (Figure VI-13.c vs. Figure VI-13.d) and (Figure VI-13.g vs. Figure VI-13.h).

Route efficiency and complexity. Table VI-4 recapitulates the results of this test. We remark that agents with a high level of familiarity chose the most efficient routes (2.54% PAO vs. 8.68% PAO with a medium level of familiarity, and 9.30% PAO with a low level). We remark also that the number of turns along the chosen routes differed between levels, and that agents with a high level of familiarity chose the most complicated routes. Indeed, these agents used an average of 5.5 turns, while in the medium level case; chosen routes contained 3.5 turns on average and 3.5 turns in the low level case. Figure VI-14 shows some examples of paths, computed with the proposed pathfinding algorithm, compared to shorter paths strategy.

Level of familiarity	Route efficiency (PAO)	Number of turns
High	2.54	5.5
Medium	8.68	3.5
Low	9.30	3.5

Table VI-4: Results of the first test.

B. Second test

In this test the simulator was able to support 3000 pedestrians, navigating in each of the different test environments, running at 30 frames per seconds in real-time. Screenshots of this test are demonstrated in Figure VI-15. The spawning of pedestrians through random locations and having them walk to other random locations, worked well. In the four situations (Test.2 A, B, C and D) navigation behaviour appears “natural”; we have seen that certain streets have a lot more density than others (Figure VI-15.b and Figure VI-15.c) and this seems to match quite closely the salient streets of the network, which is confirmed by the test of correlation.

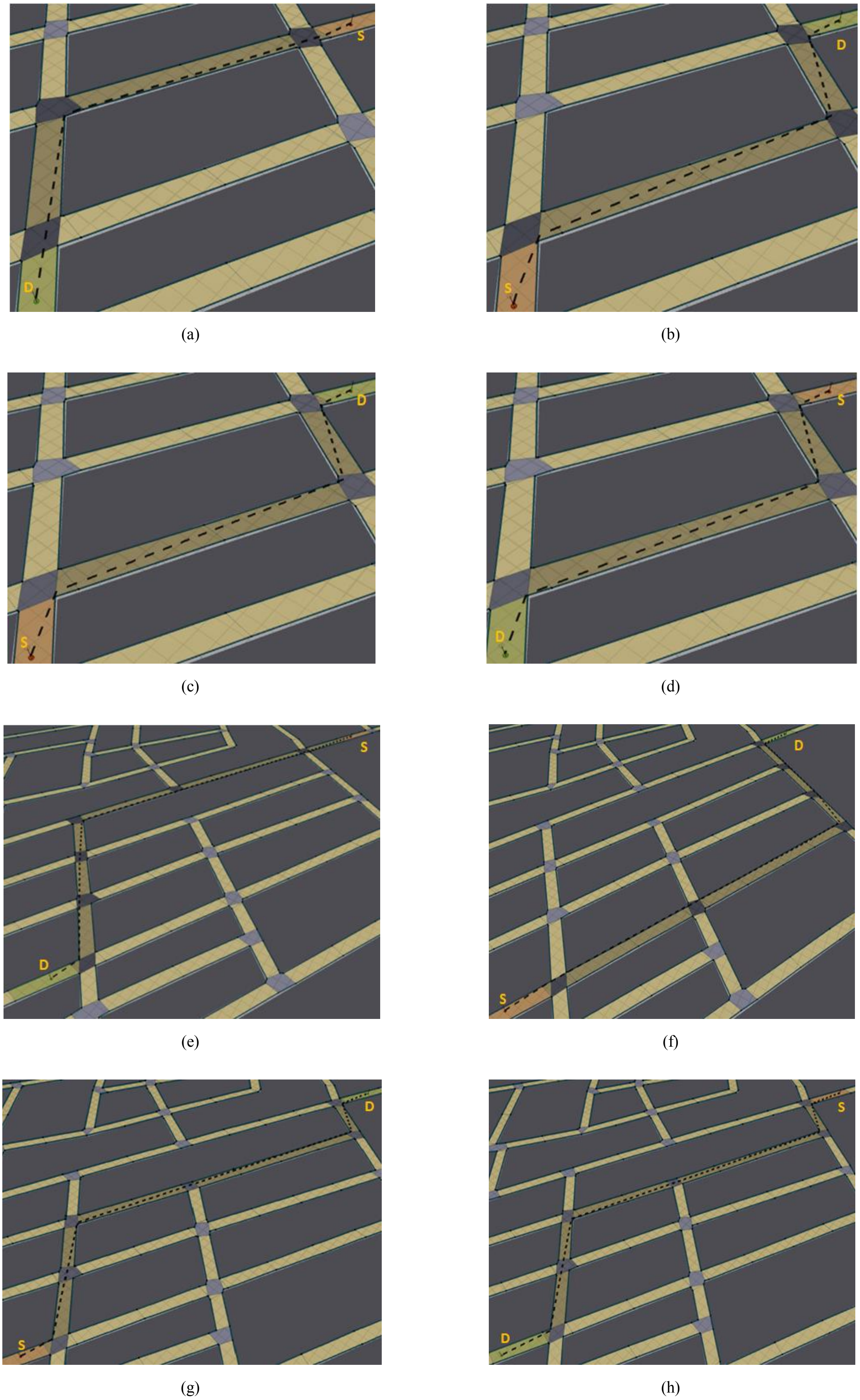
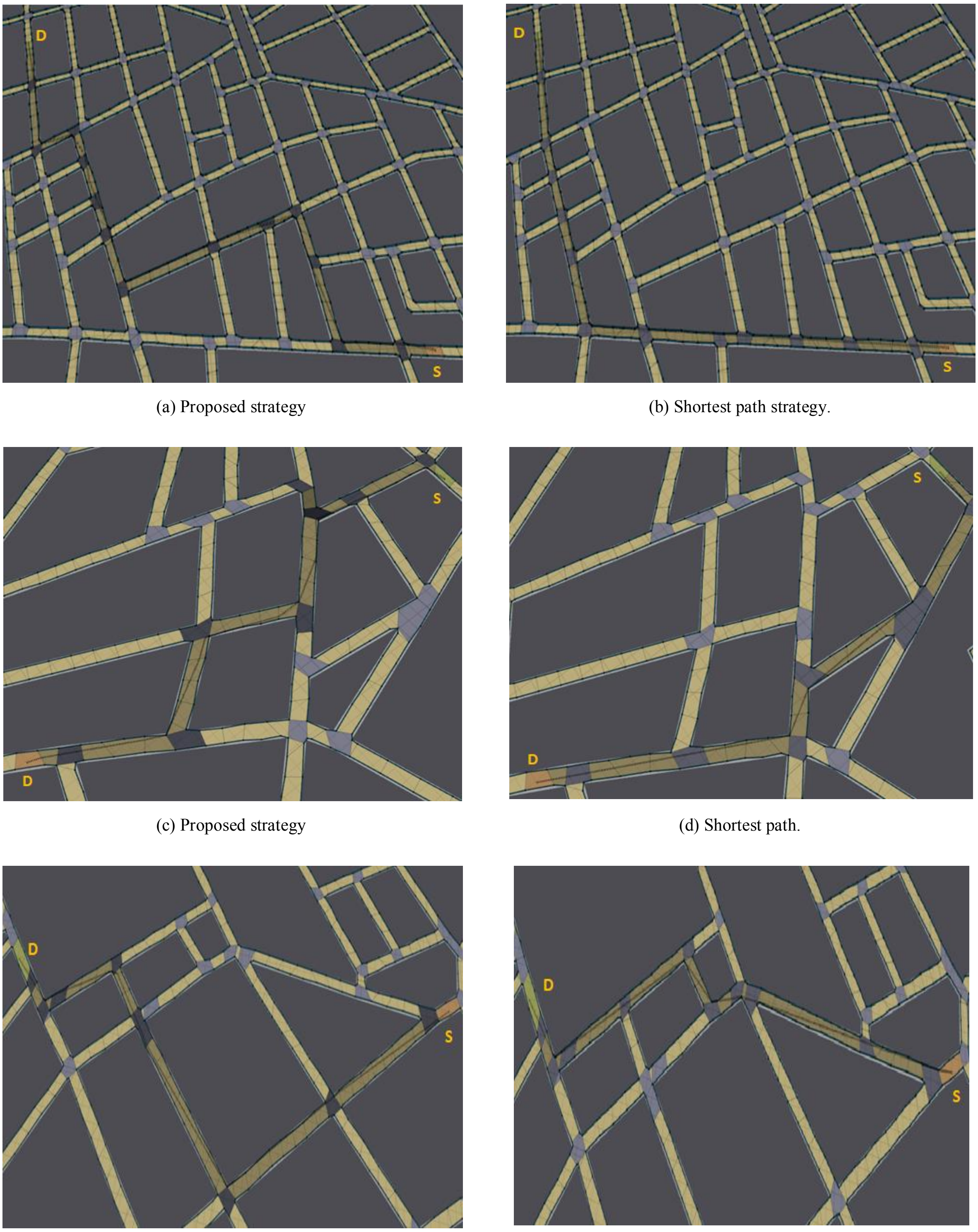


Figure VI-13 : Test of asymetry (S : start location, D: destination location).



(a) Proposed strategy (b) Shortest path strategy.

(c) Proposed strategy (d) Shortest path.

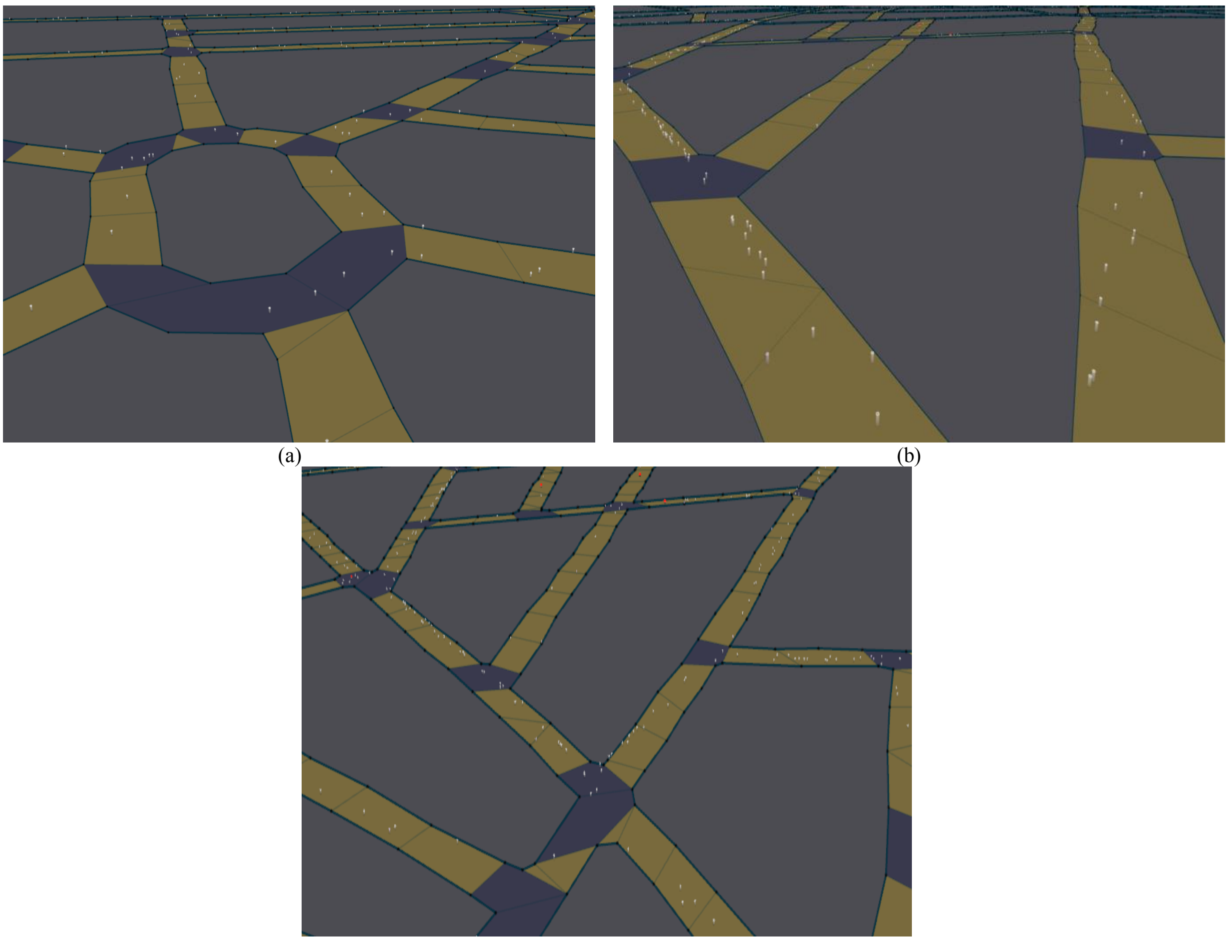
(e) Proposed strategy (f) Shortest path.

Figure VI-14 : Screenshots of the first test (a) and (b) Case of high familiarity; (c) and (d) case of medium familiarity; (e) and (f) case of low familiarity.

In Table VI-5, we can notice that the frequency with which each street segment was chosen is significantly correlated to betweenness centrality; the highest correlation value obtained is 0.80 whereas the lowest one is 0.42. However, the correlation in test C is lower as compared to the others, in all the environments except one, where it was lower only to the correlation of test A. It can therefore be argued that the routes chosen in test C were more efficient and complex because the majority of agents (60% agents with high level of familiarity, see Table VI-2) have an excellent knowledge of the environment, thus they chose small streets (potential shortcuts) which have lower values of betweenness centrality.

Betweenness centrality						
Second test	**Oran1**	**Oran2**	**La Medina**	**Oran3**	**Bordj El Bahri**	**Ksar Ghardaia**
Test A	0.70	0.80	0.70	0.50	0.61	0.61
Test B	0.69	0.77	0.69	0.49	0.42	0.64
Test C	0.66	0.73	0.66	0.44	0.47	0.57
Test D	0.69	0.70	0.50	0.48	0.57	0.61

Table VI-5: Correlation between pedestrian movement simulation and betweenness centrality.



(a) (b) (c)

Figure VI-15 : Screenshots of the second test (a) A close up of the scene showing agents spawned at random locations (b) Certain streets are more frequented than others (c) Red dots represent agent destinations.

C. Third test

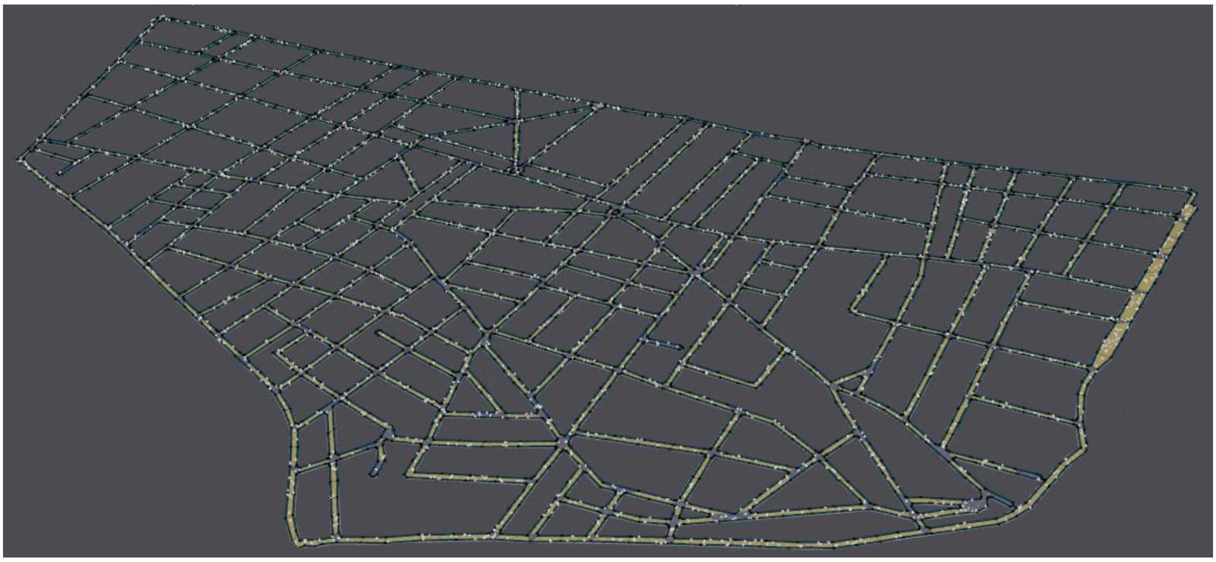
In this test the simulator was also able to support 3000 pedestrians, navigating in each of the different test environments, running at 30 frames per seconds in real-time. The spawning of pedestrians through random locations and having them walk to other random locations, worked well. In the three situations (Test.3 A, B and C) navigation behaviour appears “natural”; we have seen that certain streets have a lot more density than others and this seems to match quite closely the most integrated streets of the network, which is confirmed by the test of correlation (Figure VI-16). In Table VI-6, we can notice that the frequency with which each street segment was chosen is correlated to global integration, which is consistent with findings in space syntax researches.

Global integration						
Third test	**Oran1**	**Oran2**	**La Medina**	**Oran3**	**Bordj El Bahri**	**Ksar Ghardaia**
Test A	0.66	0.66	0.45	0.48	0.56	0.58
Test B	0.68	0.62	0.49	0.40	0.57	0.47
Test C	0.68	0.61	0.48	0.44	0.62	0.60

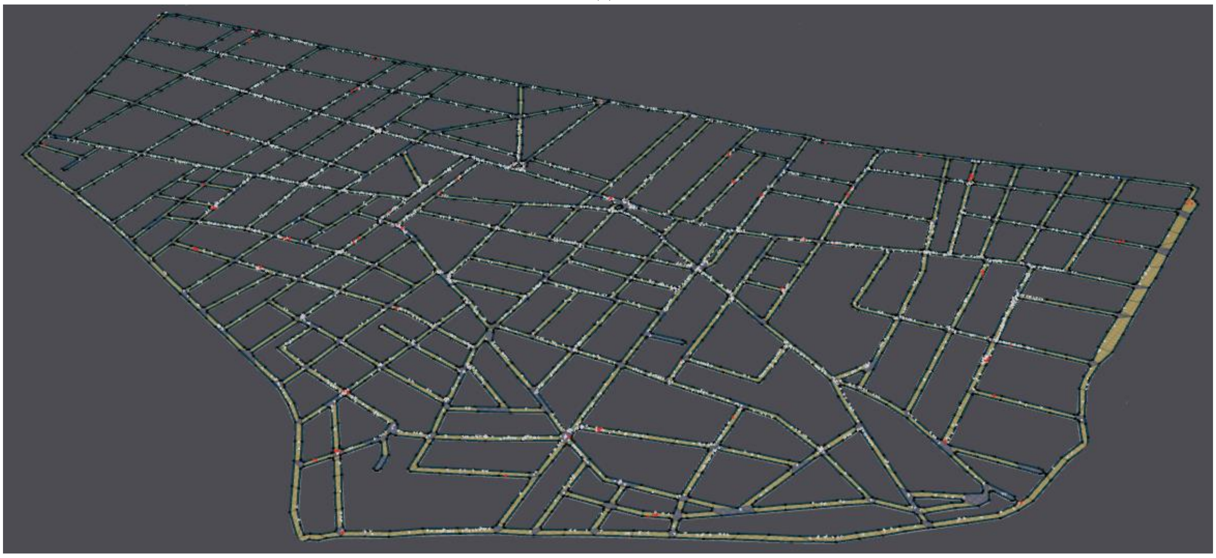
Table VI-6: Correlation between pedestrian movement simulation and global integration.

VI.4.4 Discussion

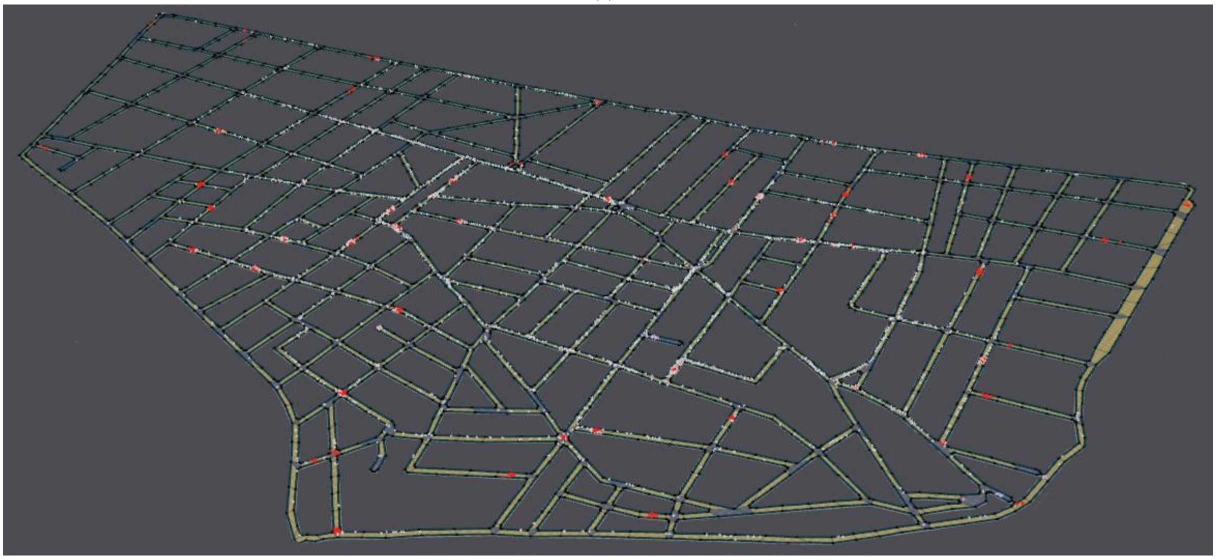
We tested the system thoroughly to make sure that our assumptions lead to realistic results. One of the issues we wanted to test is the environment description. Thus, we had chosen test environments covering large areas (width varying from 1 to 2 Km). Although the chosen environments were of different type of grid plans, the corresponding models were successfully created; the navigable surfaces are subdivided into two types of areas: road and crossroad buckets. Even though it is not an accurate subdivision the result is satisfactory. The informed abstraction process is time consuming due to some pre-calculations such as betweenness centrality and integration. However the discriminating value for performances concerns memory costs rather than computation time. Indeed, this topic is a part of the simulation initialisation process, as it can be pre-calculated. The abstraction memory is low cost as it is the agent’s mental representation. For this later, memory cost is also the determining value, since we need to simultaneously manage a great number of entities.



(a)



(b)



(c)

Figure VI-16: Screenshots of the third test (a) A close up of the scene showing agents spawned at random locations (b) Certain streets are more frequented than others (c) Red dots represent agent destinations.

As regards the pathfinding behaviour, in attempt to validate the proposed model we analysed the paths computed by our algorithms at two levels; microscopic (logics of displacement) and macroscopic (emerging movement patterns). The validation is based on some key results in space syntax and spatial cognition. The first validation we carried out concerns chosen paths characteristics; asymmetry, efficiency and complexity. According to spatial cognition researches, familiar navigators choose efficient, complex and asymmetric paths. If we return to the obtained results, we note that efficiency and complexity increase when the simulated entities are more familiar with the environment, and that computed paths by the proposed model are effectively asymmetric.

The second validation uses measures of space syntax to discuss the validity of the obtained movement patterns. As mentioned previously, in space syntax, it was found that movement patterns correlate global integration in the case of unfamiliar environment, and with betweenness centrality in the case of familiar environment. The obtained results show similarities with these findings. This means that the proposed pathfinding model produces movement patterns similar to real patterns and that simulated entities prioritize certain paths with characteristics similar to those chosen by real people. Our model has succeeded to simulate the pathfinding behaviour including the application of the appropriate strategy and showing the influence of the environment spatial configuration.

The analysis presented above demonstrates both the potential and the limitations of our model. Our software does an excellent job of predicting how pedestrian traffic will flow on a given map. However, we suggest that, with additional experiments (comparing with real cases), a better validation of the model could be achieved. As such, we suggest our approach provides a useful starting point for further study. In our opinion, there are one main issue that require additional attention. To better simulate pedestrian movement, it may be necessary to consider additional aspects, such as destination selection. Indeed, locations that have higher integration see more pedestrian traffic than the other locations. Some of this effect comes from through-movement— as people walk long thorough fares to get to distant locations. However, this effect is also fuelled by to-movement—that is, well-integrated locations are more likely to be destinations for people than poorly integrated ones. Thus, destination selection could affect the emergent movement pattern and that additional work is needed to establish its relative importance in different contexts.

As discussed in the Introduction, an understanding of pedestrian route choice has many practical applications. From this perspective, we suggest that, despite the complexity of pedestrian route choice behaviour and the limitations of our model, it is encouraging to see the extent to which our simple pathfinding model reproduces the research findings.

VI.5 Conclusion

We have presented in this chapter the proposed software architecture integrating all the models presented in this thesis. The entire simulation chain has been explained, from its lowest level specification, with the preparation of the simulation environment, to final evaluation and validation of results. The modular aspect of the software has allowed a progressive evolution of this architecture, and still allows the enrichment of its constituents.

In this chapter, we have also presented the stages of validation during this thesis. The proposed approach of validation focused on the pathfinding model, which is one of the most important compared to the objective of this work. As we pointed out before, few tests have been conducted. We have nevertheless proposed another validation concerning the path finding model. We thus compared the results obtained with the observations and analyzes proposed in the literature, whether in the field of spatial cognition or the domain of spatial syntax. It is therefore envisaged to continue this validation by simulation of a real case, and its comparison with real data.

The prospects for evolution in the application mainly concern the elaboration of a complete method for the automated generation of the environment model based on data provided by Geographic Information Systems (GIS).

Conclusion and Perspective

In this thesis, we have dealt with the problem of modelling virtual environments dedicated to pedestrian movement simulations. This problem is reinforced in our application framework by the need to model the wayfinding behaviour including the decision making process and the virtual human mental map. We can generally conclude that the contributions presented in this document answer the problematic. In addition, the implementation of the models has been carried out, proving their feasibility. Finally, the proposed works are forward-looking, allowing many changes.

In this section, we present the conclusion and the future perspectives of our work on modelling urban virtual environments. First, we provide a synthesis of the models and approaches that we presented throughout this thesis. Next, we highlight the contributions of our work. Then, we discuss and outline the limits and shortcomings of this thesis and present some future works.

Synthesis

Throughout this thesis we proposed models to simulate the movement of pedestrians. These models focus on three issues: representation of the environment, pedestrian's mental map and the wayfinding behaviour.

The first proposed model concerns the informed description of the environment. We have based this model on an exact type representation, ensuring the conservation of the geometric information. This representation is then abstracted, in order to move away from a geometric definition to the benefit of a more conceptual description, which allows characterizing the global areas of circulation. This abstraction is then informed thanks to numerous data relevant to the wayfinding behaviour, in order to provide effectively the information that will be needed by the simulated entities.

Second, we proposed an approach to manage knowledge about the environment in order to support the agents' mental maps. Our approach uses the enriched description of the environment and creates the agents' mental map. The mental map allows agents to not be omniscient and thus provides agents with the capability to plan paths and to choose routes according to their familiarity with the environment.

Third, we proposed a path planning model which uses the enriched and hierarchical topologic graph-based description of the environment and allows to efficiently supporting path planning and navigation of the simulated entities. The proposed pathfinding algorithms allow agents to plan paths with respect to their familiarity, while taking into account both the environment's and the agents' characteristics.

Contributions

The first contribution of this thesis is the description of virtual urban environments, which renders information concerning this environment judged to be relevant in wayfinding, available at low costs: spatial configuration, visual field characteristics, etc.

The second contribution is a path planning method which is: realistic thanks to the type of managed criteria and the navigation process specific to the level of familiarity; individual to each entity thanks to the environment knowledge and the preference costs; and automatically adaptive thanks to the incremental navigation process; efficient in computation time thanks to the pre-calculations.

The third contribution is a method to endow a great number of agents with a mental map. Although, this method doesn't require a learning time, in order to be efficient in computation time, it permits to simulate the content of real people mental maps.

Limits and Shortcomings

The first main shortcoming of our approach concerns the GIS data selection. The data used to build the virtual environment can be provided by Geographic Information Systems. However, we have to select the street network data manually to be used to build the virtual environment model, which is time- and effort-consuming. Therefore, this process should be automated as much as possible.

Our model has been tested with different kinds of environments but always as a part of a city. However, when dealing with large-scale urban environments, the pathfinding process may suffer from realism. Indeed, at the city level for example, a real human evaluates his way globally, but only refines this path locally to focus on immediate interactions. Thus, we might consider some improvements in the environment description model and the pathfinding process.

Future Work

We already mentioned several improvements that can be explored in future works. The first interesting improvement concern the elaboration of a module that imports GIS data, extracts data on street network and converts them to a graphic format automatically.

The second improvement is the hierarchical graph environment which should have more hierarchical layers. It is therefore conceivable to express with this model several interconnected environments. It would then be possible to simulate different environmental scales based on a single representation.

Regarding our incremental path planning algorithm, we take advantage of the hierarchical definition of the environment, proposing a hierarchical path planning. When an agent has exhausted all the targets in a particular region, planned incrementally, and is at the last target for that region, it will plan ahead for the next target, it will start the process all over again, with the present location as the starting point and the remaining target points as the set of destinations.

A perspective on validation concerns the path planning model. Indeed, this one is for the moment configured with arbitrary degrees of preference for all the individual factors (preference for a strategy …). It seems essential to conduct a series of real experiments to characterize their relative importance, the ultimate goal being to propose standard configurations representing different categories of populations.

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