Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 25 (2017) 551–567

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2016 Shanghai. 10-15 July 2016

Survey of detection techniques, mathematical models and simulation software in pedestrian dynamics

C. Caramuta, G. Collodel, C. Giacomini*, C. Gruden, G. Longo, P. Piccolotto

Dipartimento di Ingegneria ed Architettura, Sezione di Strade, Trasporti e Topografia, Università degli Studi di Trieste, via A. Valerio 6/2, 34127 Trieste, Italy

Abstract

The study of pedestrian dynamics has become in the latest years an increasing field of research. A relevant number of technicians have been looking for improving technologies able to detect walking people in various conditions. Several researchers have dedicated their works to model walking dynamics and general laws. Many studiers have developed interesting software to simulate pedestrian behavior in all sorts of situations and environments. Nevertheless, till nowadays, no research has been carried out to analyze all the three over-mentioned aspects. The remarked lack in literature of a complete research, pointing out the fundamental features of pedestrian detection techniques, pedestrian modelling and simulation and their tight relationships, motivates the draft of this paper.

Aim of the paper is, first, to provide a schematic summary of each topic. Secondly, a more detailed description of the subjects is displayed, pointing out the advantages and disadvantages of each detection technology, the working logic of each model, outlining the inputs and the provided outputs, and the main features of the simulation software. Finally, the obtained results are summarized and discussed, in order to outline the correlation among the three explained themes.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: Pedestrian Behavior, Detection Techniques, Simulation Software, Mathematical Models

* Corresponding author. Tel.: +39-040-558-3582; fax: +39-040-558-3580.
E-mail address: cristian.giacomini@dia.units.it

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.
10.1016/j.trpro.2017.05.438

1. Introduction

The increase of global population and the resulting widespread urbanization have often involved the expansion of congested areas and the possible uprising of transport problems: the need of making mobility more eco-friendly, urban design more suitable for walking people, as well as the management of crowded areas, the design and integration of transport terminals within the urban context, safety and security of people.

The need of facing these problems and, at the same time, the development of a society which is more careful towards environmental safeguard, inhabitant health, easier accessibility and, in general, towards a better living quality, have brought to an inversion of tendency in urban design. In fact, from now on, technicians have focused their attention on the pedestrian point of view, managing to highlight the difficulties and necessities of walking people. Consequently, various adaptations of infrastructures have been defined, which facilitate pedestrian mobility, with the aim of satisfying transfer demand.

In order to achieve all those goals, in the latest decades, detection and tracking technologies have been improved, walking dynamics have been analytically modelled and simulation software have been developed.

In Section 1 the three topics are briefly described; in Section 2 the pedestrian detection and tracking techniques are deeply analyzed, focusing on their way of operation. In particular, the provided outputs are explained through some real applications. In Section 3 the main mathematical models of pedestrian dynamics are illustrated, stressing the required inputs in order to describe those phenomena. Section 4 deals with the most referenced pedestrian simulation software, evaluating the needed inputs and the given outputs. Finally, the conclusions highlight the relationship among the three themes.

2. Focus on the issues

The need of analyzing pedestrian mobility requires a deep knowledge of several aspects of the modelling process, as data acquisition, model definition and software simulation.

The lack of data about walker behavior is one of the greatest problems that researchers have to face. It is known that detecting and tracking human beings is very difficult: as a matter of fact, while walking, pedestrians keep on changing their shape; moreover, people have several peculiar features and they often move in crowded places. These complexities have brought to the development of many detection and tracking technologies, providing more precise and autonomous methods. The main used detection techniques are video and RGB+D cameras, GPS devices, laser scanners, pressure sensors and localization sensors. These technologies have been analyzed in order to highlight their pros and cons and the outputs they provide, referring to different application fields.

The main reference studies about detection technologies are the following: in [1] detection methods have been evaluated with the aim of providing a classification based on established criteria.

The authors of [2] have analyzed pedestrian passive detection technologies used at unsignalized intersections.

[3] introduces some methods for pedestrian detection, in order to simplify the choice of the best technique for planning.

The aim of representing pedestrian behavior has led studiers to develop various models, that can be classified into two categories: the macroscopic and the microscopic ones. As already confirmed by previous works, the firsts define pedestrians in an aggregated way, so that the smallest representable entity is the flow. The latters consider each pedestrian individually, as an agent interacting with other moving subjects and the environment.

In the macroscopic field the two main models are the continuum and the fluid-dynamic ones.

From the microscopic point of view, many models have been carried out, like the social force model, the utility maximization one, the magnetic force one, the cellular-automata one, benefit- cost one, the queue one, discrete-choice one and agent-based one.

In the modelling field, Teknomo et al. have focused their attention on the state-of-art about microscopic models in various papers [4,5,6].

Also Shiwakoti et al. have dealt with both microscopic and macroscopic pedestrian modeling, in order to present an overview of the main models useful under emergency conditions [7].

Duives, Daamen et al. have proposed a recent state–of–art in pedestrian modeling.[33]

In their work, Abdelghany et al., presenting a new microsimulation assignment model, focus on existing pedestrian models, with the aim of outlining differences and similarities of their studies.

Thanks to the advancement of information technology, several simulation software have been developed. In this way, the simulation of pedestrian behavior in various contexts has been possible. Among the available products provided by the different software houses, some of the most referenced software have been selected and their main features have been deeply analyzed.

Software have been distinguished according to the implemented model, evaluating the required inputs and the provided outputs, in relation to the application fields.

Regarding this issue, a lack of states-of-art has been noticed: as a matter of fact, papers proposed in literature are related to their application at real cases or to comparisons between two software.

In [8] some software have been selected, with the purpose of recognizing the most suitable ones to describe the multiple aspects influencing urban design.

[9] compares two simulation software: Viswalk and Legion for Aimsum.

The authors of [10] introduce features and potentialities of the software Legion.

This paper wants to differ from the over mentioned ones, because it deeply describes all the three issues, presenting for each theme a state–of–art composed both by traditional and innovative approaches.

Moreover, an aim of this work is to highlight also the strict connection between pedestrian detection techniques and the field of mathematical models and computer programs, because it is not as ordinary as the relationship between these two last issues.

Another goal of the paper is to link the themes, in order to provide a useful tool both for researchers and technicians.

3. Detection technologies

Several detection techniques have been developed during the years. Classical techniques have been appeared restrictive for the detection costs, long time length and the small quantity of acquired information, considering the large amount of data required by current studies.

In order to fill in these gaps, new techniques have been carried out: innovative technologies have allowed to make data collection and analysis more and more automatic, assuring shorter time length and a larger amount of acquired information. Nevertheless, it is important to keep attention on the biases produced by the specific technology. This is one of the reasons why last developments in detection techniques prefer to improve data acquisition through the combined use of more technologies.

In the following, manual counting, video, RGB or HSI cameras, infrared, laser, GPS, piezoelectric sensors, ultrasonic and radar techniques are described, with the aim of giving an overview of the existing technologies for pedestrian detection.

3.1. Manual counting

Manual counting is the simplest counting method. It just needs staff provided by the required material to perform a systemized counting. In particular, it may include pens and pencils, time watches, instruction forms, count forms, location maps and clipboards, hand-counters, board-counters and tally sheets. [11]

Generally, manual counts are performed as following: the counting person stands on a side of the location and, imagining or signing a line on the pavement, it counts people passing over the line in each direction. Usually, the information collected with this method are the direction of pedestrians, the approximate age and gender. [11]

It is possible to distinguish between a mechanical and an electronic counter: using the latter, an operator can record from 2000 to 4000 pedestrian passages per hour. Moreover, multiple counters are able to diversify the counting.

Other manual methods are questionnaire surveys, which gather information about route choices, trip purpose and individual habits. Also stalking has been used as manual method [12]: specifically, this way of gathering information consists in supervising each person in its trip. [12]

Advantages of this technique are the quickly set up and perform, the low costs and the fact that the operator can detect further information during the counting. Anyway, it is very important to plan a precise data-gathering campaign; in fact, few parameters have to be set: the duration of the operation, the position of operators and the data to collect. This phase of work is influenced by weather conditions, that can be troublesome for operators.

3.2. Video

Video Image Processing has attracted researchers because of the opportunity of detecting multiple lanes and zones and obtaining a large amount of information. However, data cannot be directly used, but they have to be elaborated and interpreted by a qualified operator or through a specific software. A Video Image Processing is typically made of one or more video cameras, a microprocessor – based equipment for processing the imagery and a software to elaborate data and outputting information.

Advantages of this technology are the wide spread, the easy installation and control. Moreover, using a camera network it is possible to cover large areas. The obtained images represent exactly reality, so even crowded situations can be deeply analyzed; finally, they can be registered and filed.

Disadvantages of this technique are the lacking data collection in case of automatic analysis, the difficulty of pedestrian detection and tracking in crowded situations and the suffering from environmental changes, such as light variation, shadows and snow.

Here follow examples of the use of cameras in pedestrian study.

In [13] a single overhead camera allows to determine the position and the trajectory of pedestrians inside buildings; in [14] the same results are provided by a method based on an integrated system of cameras, with the restriction to industrial buildings.

In [15] and in [16] video technologies are used to detect and track pedestrians, vehicles and animals: the first one operates in crowded situations and even in low resolution conditions, the second one can run a facial recognition and it can classify captured faces according to their quality.

The use of cameras to track pedestrian trajectories is explained in [17] and in [18],but in the latter this operation can be run also in occlusion conditions, in case of speed changes and in crowded places.

[19] describes the use of cameras to count pedestrians, track their trajectories, recording speed and acceleration, and distinguish different human types (adults or children).

In [20], besides counting pedestrians and determining their position, cameras are able to provide pedestrian sizes and they can work efficiently at entrances and exits of buildings.

3.3. RGB or HSI cameras

In the field of image elaboration, the RGB space is used to acquire and elaborate images. The most advanced color cameras have three independent sensors, and each of them is able to detect the three color components.

A color image in a standard format (JPG, BMP, TIF, etc...) can be easily imported in Matlab, so that a matrix is created: the components of this matrix correspond to the components of red, green and blue (which means to a RGB space).[21,22]

The RGB space is not the only way to represent colors: in fact, another one is, for example, the HSI (Hue, Saturation, Intensity) space providing a color representation which is closer to the human color perception.[21,22]

H (Hue) represents the dominant color perceived by the observing person and it is related to the wavelength of the light received by the camera. S (Saturation) represents the clearness of the color and the lower it is, the more the color is diluted by the white component. I (Intensity) represents the quantity of received light.[21,22]

The HSI space and its several variations can be obtained from the values of the three RGB prime colors through some formulas. [21,22]

In [23] the use of RGB or HSI cameras allows to obtain information about the number of pedestrians and their trajectory. Moreover, it permits to create a database containing the travel time and the tracking of pedestrians, even outside the monitoring area.

In [24], the camera is integrated with a RGB+D system in order to determine both macroscopic (flow) and microscopic (single pedestrian) trajectories. It is possible to recognize moving objects and their sizes, to count people according to human types (adults or children) and vehicles according to vehicular types. Moreover, it recognizes different body features and actions of pedestrians (e.g. fall) . Finally, this device allows to determine vehicular speed and parking capacity. Thus, it can be used in several conditions: public contests, terminals, for safety and security in crowded and/or emergency situations.

3.4. Infrared

Two kinds of infrared devices exist: passive infrared systems and the active ones.

A passive infrared system is able to measure the energy emitted by the bodies in the field of view. When an object enters the field of view, the difference in emitted energy is used by the detector element to detect the object. Passive infrared systems can detect volume, presence, occupancy, direction of movement and speed within multiple detection zones [25].

Active infrared systems are made of three components: a transmitter, a receiving sensor and a data collection unit. The transmitter emits invisible infrared low-energy by light – emitting diodes or high – energy by laser diodes to the detection zone and it measures the time in which reflected energy returns to the detector. The presence of a moving object is denoted by a lower return time. The speed of objects is measured by sending two or more beams and recording the time (s) at which the object enters in the detection area of each beam. The typical radius of these devices is of 30 m.

Pros of these techniques are the low costs and electric energy consumption, the easy installation and transfer and the independency from weather conditions; the disadvantages are linked to the fact that it can just count the number of passages, without distinguishing single pedestrians from groups. The detection area is limited and its use is strictly dependent on weather conditions.

In [25], the combined use of a sensor and an emitter of radiations in the infrared, ultraviolet and visible spectrum provides 2D – information about the study area plan and 3D - information about detected pedestrians. Thanks to these technological devices it is possible to distinguish humans from all other objects and beings, to identify different pedestrian classes and to define the people's orientation.

3.5. Laser

Recently, laser techniques, also known by the names of LIDAR (Light Detection And Ranging) or LADAR (Laser Detection And Ranging) have been developed. These techniques use laser beams to determine the distance of the objects: the detector sends a laser impulse towards the detection area, which is reflected by the objects. The distance is determined by measuring the time gap between sending and receiving the laser impulse. [26]

The device can scan the environment up to 360 degrees: it allows not only to detect and count pedestrians and vehicles, but also to measure their sizes and speed and to track their trajectory. According to their layout, two kinds of laser scanners exist: horizontal - scan sensors and vertical – scan ones. The possibility of obtaining a large amount of data in short time, of evaluating the interactions among the detected subjects, of creating a net of collaborating sensors and of working in any weather conditions are surely advantages of this technique. Moreover, data can be elaborate in real – time, or they can be collected for future utilization. [26]

Disadvantages of this technique are that it cannot recognize different pedestrian types, it needs a high energy amount and its detection radius is quite short. Besides, these devices are expensive and they have to be carefully installed; because of the recent finding of this technology, there are just few operative experiences. [26]

As explained in [27] and in [28], laser scanners allow to obtain many data. In particular, [27] permits to detect people and to determine their position and height on crosswalks; in [28] this technology is used to estimate pedestrian traffic and to determine the direction of moving subjects at entrances and exits.

3.6. GPS

GPS sensors are used to measure speed, stride frequency, stride length and adaptation of the gait to the slope.

Many kinds of integration systems have been proposed: the most common GPS integrated system is constituted by GPS and accelerometers, but several studies propose also other implementations.

In [29] an integrated system of cameras, WI-FI - connected GPS devices and pseudolites, provides pedestrian trajectories and the count of pedestrian flow, determining direction, flow, delay, preferred time, alternate time to travel, alternate route selection, speed and acceleration. The application field of this method is restricted to buildings and places where an electronic device to track pedestrians is available.

3.7. Piezoelectric sensors

Piezoelectric sensors are made of piezoelectric materials and they are usually embodied in the floor of pedestrian infrastructures. Each time a person walks on the piezoelectric board, an electric impulse is generated and the passage is recorded.

The main advantages are the low maintenance costs, the low energy consumption, the possibility of covering a wide study area through several devices.

Disadvantages are the expensive installation of the sensors, the restricted study area covered by a single board, the need of ensuring the effective passage of people on the board. Moreover, some devices are not able to distinguish single pedestrians from groups.

In [30] a technological device composed by a reference location sensor and a inertial sensor permits to track people, mobile devices, vehicles and robots.

In [31] pressure sensors are used to detect pedestrians and to track their trajectories inside buildings. This method provides a density value for a predetermined flow; the sensors are embodied in the floor and they can track several possible routes, according to the pressure applied by the subjects themselves.

3.8. Ultrasonic

Ultrasonic detectors can be both active and passive. Active ultrasonic detectors transmit sound waves towards the detection zone; the objects passing in the zone reflect the sound waves, which are sensed by the detectors. [1,32]

Passive acoustic detectors measure the audible sounds or the acoustic energy produced by passing objects. Sound energy increases when an object enters the detection zone and decreases when it goes out. [1,32]

Using many sensors, a large study area can be covered.

Some disadvantages of these sensors are that they are influenced by weather conditions and they can be subjected to vandalism. Moreover, the sensors have to be kept tidy, in order to do not disturb the sonic waves emission. [1,32]

3.9. Radar

Radar technologies were already used during World War II. They transmit electromagnetic radiation towards the interested area from an antenna, which is put overhead or on a side and illuminates arriving objects. When an object passes the beam, a part of the radiation is reflected back to the antenna [1,32]. Two types of radar detectors exist: one transmitting continuous wave of constant frequency and the second transmitting a saw-tooth waveform [1,32]. The first ones use frequency changes to determine the speed of the objects on the basis of the Doppler principle; this kind of radars cannot find motionless objects. The second ones, also known as FCWM(Frequency Modulated Continuous Wave), use continuously changing frequency. They can individuate both the presence and the passage of objects.

The overview of pedestrian detection methods let notice that video, RGB, infrared and laser techniques provide the largest amount of data, which are useful to obtain a precise description of walking agents.

4. Models

Pedestrian modeling has always been a central theme in the study of pedestrian dynamics.

A lot of already established models have been developed and many adaptations of them are rising in recent years.

Several authors have tried to give an overview of existing pedestrian modeling approaches [4,5,33], and the increasing interest in this issue let appreciate an up-to-date state of the art.

This chapter is going to describe both classical and innovative approaches, in order to give a useful overview of the broad choice available within pedestrian modeling.

In the following Section, microscopic and macroscopic models are reviewed.

About the microscopic field, the physical force based models are discussed, in particular the social force model, the utility maximization model and the magnetic force model; the Cellular Automata based models [CA] are reviewed, as cellular automata model and benefit – cost model; finally, queuing models are described.

Belonging to the microscopic approach, Helbing's fluid dynamic model and Hughes' continuum model are discussed, as well as Henderson's molecular model is introduced.

A short overview about velocity based models and hybrid models is carried out.

For each kind of model the main features and the working way are highlighted and the newest adaptations of the models are pointed out.

Social force model is a microscopic approach, where individuals are led with attractive and repulsive forces. A similar idea is used in the utility maximization model. The magnetic force model represents pedestrians and objects as magnetic poles, which attract or repulse each other.

Cellular Automata models use a discrete space representation through a grid, in which walkers move following a rule set. Benefit – cost models let pedestrians move on the basis of a gain score, assigned to each cell.

Queuing models are mainly used for evacuation simulation and they describe facilities as a network of arches and nodes.

Among microscopic approaches, the most used and adapted are the Cellular Automata – and social force models.

In the continuum model the crowd is treated as a continuum "thinking fluid", characterized by well-defined hypotheses.

Henderson's approach follows the analogy between pedestrian crowds and molecular fluids.

Among macroscopic models the continuum one is the most analyzed and changed.

Finally, two kinds of models, that are not often discussed, are introduced: velocity based models and hybrid models. While previous approaches have been already mentioned in various works [4,5,6,7], these two models have been considered just in few papers, in specific in [33].

In the former, pedestrians try to move following the most direct path to their goal, while the latter tries to combine the pros and cons of both microscopic and macroscopic models.

4.1. Microscopic models

This Section is going to deal with existing microscopic pedestrian models. Up to now, several models have been developed, but they differ in their assumptions and capabilities [34]. Microscopic models describe pedestrian movement starting from the smallest representable entity, the single pedestrian in a crowd, and treating it as an individual agent occupying a certain space at an instant in time [7].

Three main groups of microscopic models can be recognized: physical force based models, cellular based models, and queuing network models.

Among the physical forces based models, three kinds stand out: the magnetic force[5,6,35], the utility maximization [36,37] and the social force models [36,37]. The first one has been carried out by Okazaki, the second and the third one have been developed by Helbing [4].

Among the cellular based models Gipps and Marksjo' s benefit – cost model [5,6] and Blue and Adler's cellular automata model [38,39] can be recognized [4, 40].

Finally, queuing network models have been developed and used particularly for evacuation studies [4].

The over – mentioned approaches represent the basis of microscopic pedestrian modeling and, as it is asserted in [4], differences and similarities, as well as pros and cons, among them can be stated. First of all, it has to be noticed that each model cannot relate to each other and data useful for a model cannot be interchangeable with another kind of approach [4]. Moreover, to guarantee the suitability of microscopic model to every general case it has to be run a statistical calibration, that means it is necessary to measure individual movement data [4]. This fact let notice the strict relationship between pedestrian detection and modeling.

Nevertheless, all the models follow a common structure, represented by two terms: a first term, that leads pedestrians toward their goal and a second term, that represents the repulsive effects among pedestrians and between pedestrians and obstacles.

The first term is represented by the gain score in the benefit – cost model [4,5,6], by attractive forces in magnetic force model [4, 35], and by the intended velocity in the social force one [4,36].

The second term is performed by the cost score in the benefit – cost model [4,5,6], by the repulsive forces in the magnetic approach [4,35], and by the interaction forces in the social force one[4,36].

Two kinds of model do not explicitly follow the previous structure: cellular automata and queuing network models. The firsts are governed by a set of updating rules, from which can be derived the two terms; the seconds use a weighted random choice to allow the movement of pedestrians toward their goal and priority rules to govern pedestrian interactions [4].

In the following, two aspects of microscopic models will be analyzed: firstly, the basis – models of pedestrian dynamics, secondly, the innovations and observations made on them.

4.2. Physical force models

The physical based models recognize that the crowd is made up of individuals who react to events around them [7].

Social force model has been developed by Helbing and consists in the fact that each person is characterized by its desired velocity and its target time and it moves towards a certain destination driven by the so-called social forces [36,41]. These forces represent the effects that determine the motion of the pedestrian and they are mainly three: the will of reaching its destination without detours, the interaction with other pedestrians and effect of the environment [4,5,6, 36, 41] . The inputs required by the model are the destination of each agent, the real speed and the desired velocity.

An adaptation of the Social Force model has been carried out by Teknomo et al. [6]. The difference with the social force model stands in the attractive and repulsive forces. In their model, the authors consider two repulsive forces: the former comes into play if there is at least one pedestrian in front of the considered walker, the latter exists only if the radius of two or more pedestrians overlap one another. Moreover, this model does not need a target time as inputs, and it rather gives the dissipation time as output.

In [42] the authors modify Helbing's model to make it suitable both for normal and panic situations.

In normal situations the authors consider an additional term describing the joining behavior of groups that have been accidentally separated.

In panic situations, some new physical interaction forces are added to represent the behavior of pedestrians getting more and more close to one another.

As [37] let notice, also other adaptations have been proposed: XI et al. implemented a vision field, collision offset/bias and group formation.

Helbing's model of utility maximization is based on the hypothesis that pedestrian behavior is determined by rules linked to utility maximization [43]. The author has recognized that pedestrians are inclined to move with an intended speed and they approach or avoid particular objects or persons.

The magnetic force model, theorized by Okazaki and Matsushita, describes pedestrian movements with the equation of motion in the magnetic field [5,6,41]. Pedestrians are positive poles, while their destination is a negative pole. Pedestrians move towards their goal, attracted by it, avoiding obstacles. Two forces work on each pedestrian: the Coulomb's one, depending on the intensity of the magnetic load of each person and the distance between people, and a law that makes people avoid collisions with obstacles. [35,41] This model requires as input data about both the area and pedestrians. In specific, it needs inputs about the geometry of the area, such as the sizes and position of walls, openings and corners, and others about the single pedestrian, like its initial position, its destination and orientation, its maximum speed, the time it starts to walk, and its walking behavior (the indicated route, the shortest one or the way finding).

4.3. Cellular based models

The Cellular Automata model is a discrete, time based simulation approach, based on a regular cell grid, that describes the walk of a single pedestrian according to rules for the cell occupancy [38, 44].Each cell can be in one of a few states, typically two, 0 or 1 [44], and its state is updated at each time step, on the basis of its previous state and the previous state of its neighbors [44]. The main rule is that a pedestrian can occupy a cell only if it is free [6,38,40,41,44,45]. The motion of the agent is governed by probability, and the three main possible movements are: a lateral movement, a frontal one and a mitigation of the conflicts. [38] The needed inputs are origin and destination of each person, the maximum speed and pedestrian density, given as grade of grid occupancy.

CA models have been the most adapted approaches. The authors themselves have sometime changed their original model, to make it more general, adapting it to various conditions.[38,39] Beginning from the unidirectional model, passing through the bidirectional one, they arrived to the four directional Cellular Automata model. The model is constituted by an extended rule set and considers three kinds of motion: pedestrian following behavior, head – on conflicts and cross – directional conflicts.[39]

Dijkstra et al. in [46] adapt the CA approach to simulate pedestrian behavior in public places.

The innovation introduced in [46] is that the authors consider many kinds of agents: user agents, subject agents and actor agents.

Also [47] uses a multi agent based model, to simulate pedestrian evacuation in public spaces. The studiers focus on both congestion and panic phenomena, dividing walkers in four classes, different for age and sex, and recognizing three statuses: normal, overtaken or casual.

Another adaptation of CA model is proposed in [48]. This approach classifies pedestrians into three groups, in order to reproduce the behaviors induced by attracting incidents. Pedestrians may be unaffected, if they are not interested in the incident and they follow their normal dynamics, stopped, if they are attracted but unwilling to move close to the event, on-looking, if they demonstrate strong interest.

Various studiers have modified the CA model with the so-called floor field.

In [45] the floor field is used to govern long range interactions among pedestrians, in order to predict pedestrian collective phenomena.

In [49] the environment is made up of a set of grids, each one containing a floor field that can influence pedestrian behavior. Three floor fields are recognizable: a path static field, an obstacle static field and a density dynamic field.

Schadschneider [33] used a combination of two floor fields to represent dynamic effects induced by the motion of other pedestrians; Chraibi et al. [33] implemented a floor field to model the repulsive forces introduced by obstacles and other walkers.

Another model change is the calculation of pedestrian speed: Sarmady [33] proposed to adapt velocity, extending the stepping possibilities during each iteration; Song et al. adapted stepping probability to adapt speed, if other pedestrians are in the nearby [33].

Other authors have preferred changing grid features, as the number of stepping directions, size and location of the cells. [33] let notice the particular adaptation carried out by Alghady et al., who allowed more pedestrians to be in the same cell.

Benefit – cost model has been developed by Gipps and Marksjo [4,5,6,34,40]. It is a discrete and deterministic model, that describes the space through a grid of cells, and it simulates the agent as a particle in a cell [5,6,34]. A benefit value is assigned to each cell. It is calculated as the difference between the utility of a pedestrian to reach its goal and the cost due to the interactions with other pedestrians: these values are chosen arbitrarily. Each person selects the cell with the highest benefit value, and each cell can be occupied at most by one pedestrian. [4,40].

The origin and destination of each agent are the inputs required by the model.

4.4. Queuing models

The queuing model uses a Monte Carlo simulation based on discrete events [4,50]. Each pedestrian is modeled as a single flow object interacting with other objects, while facilities are represented as a network of arches and nodes: each room is represented by a node and openings are described through arches. In each node the route and the evacuation time are recorded, beside that, in the initial node a certain time to react is given to the pedestrian before it moves [51]. The arch choice is weighted and its weight is based on the population attending in the room. [4]

This kind of model has been developed to study evacuation dynamics. Sometimes pedestrian behavior is not well defined and the priority laws can be unrealistic [4].

In [52] an agent - based model is introduced. The authors model the environment like a network of zones linked by arches with features of the routes, while they describe walkers with two kinds of agents, normal and susceptible ones, with the aim of representing the behavior of pedestrians if there is an attractor.

A change in the structure of queuing models has been done by Daamen et al. [33], who reverse the use of arches and nodes: links represent parts of the facility, while nodes are the connections between the zones.

Borgers and Timmermans [33] proposed a network model, in which nodes represent city – center entry points (and they also correspond to street intersections) and links are shopping streets.

Chalmet et al. [33] use queuing approach to model evacuation from a building. This model represent portions of building through nodes and building exits as destinations.

4.5. Macroscopic models

Differently from microscopic models, macroscopic approaches deal with pedestrian dynamics assuming the crowd as the smallest representable entity: as a matter of fact, they use the aggregate representation of the crowd through flow, density and speed relationships, to describe pedestrian movement [7]. This kind of modeling depicts pedestrian behavior as a continuous fluid characterized by average quantities, like flow, average speed and area module, without considering the behavior of the individuals [4,7].

Unlike microscopic approaches, macroscopic ones do not consider interactions among pedestrians to predict pedestrian flow performance, they rather focus their attention on walker space allocation in pedestrian facilities [4].

As many authors let notice, the first macroscopic modeling attempts are due to Hughes and Henderson [7,40,53,54]. The former related a theory where pedestrian flow is modeled as a continuum "thinking fluid", characterized by well –defined hypothesis [7,54]. The latter explained pedestrian behavior through an analogy with molecular fluid [53]: starting from measurements in various low density situations, Henderson found a good agreement of velocity distribution function with Maxwell – Boltzmann distribution [40].

Surely, a benefit of macroscopic modeling is the suitability to very high-density situations, where an appropriate behavior of the groups is recognizable [7]. As [55] let notice, macroscopic models allow the possibility of studying phenomena of intermittent flows. Nevertheless, without considering the behavior of the single components of the crowd, these models can show significant problems in approaching to emergency situations, in which the behavior of the individual influences more and more the aggregate system [7].

The fluid dynamic model classifies pedestrians into groups on the basis of their direction of motion and of magnitude which is strictly connected to their intended velocity [56]. These groups are characterized by average features, such as their place, their speed and, certainly, their intended velocity [56]. The model uses relations among densities and the above mentioned mean values to describe the movement of each pedestrian group. [56]

The density variation is related to four aspects: the tendency of pedestrian to reach their intended speed with a relaxation time, the interactions with other pedestrians, the change of motion - for example changing the direction of movement, and the increase or decrease of density linked to the entrance or exit of some pedestrians in/from the groups, [56]. The inputs needed by the model are the number of groups, their direction of motion and the intended velocity.

The Continuum model describes pedestrians as a flow characterized by two mean qualities: density and speed [53]. The behavior of the crowd is modelled making three hypotheses on the nature of pedestrian motion: firstly, the speed is determined by the flow density and by the behavioral features of the pedestrians; secondly, the model attributes to walking people a sense of task, called potential, that drives them to their common goal; finally, pedestrians try to minimize their travel time, paying attention to avoid high densities. [53] The required input is the density.

An adaptation of the continuum model is proposed by [57]. The studiers change the original approach in a multi – class continuum model: both global and local route choices are considered, in order to describe strategic and tactical level decisions, and various pedestrian classes are introduced, each one related to the same goal.

In [58] a model considering a time varying demand, a cost function and that let density, flow and walking speed be governed by the conservation equation is introduced. The author noticed this formulation makes pedestrians choose the path which minimizes their instantaneous travel cost to their goal. This allows the use of the approach to model walkers who have to make sudden route choice decisions.

An innovative macroscopic approach is proposed by [59] The paper introduces a macroscopic, dynamic, bi-dimensional and continuous model, which assumes pedestrians move on the path minimizing their travel cost, on the basis of the environment, goal and traffic conditions. The travel cost decreases with the distance from the goal and it is estimated within a macroscopic modeling framework.

5. Pedestrian simulation software

Due to the lack of state-of-art articles concerning pedestrian simulation software, for this survey a detailed research of these computer programs has been developed.

As reported in [60], which refers to [61], the process to identify the most appropriate software packages consists in a few steps: after having established some initial criteria, the choice of adequate devices is made through a filtering operation. The first phase of the systematic method adopted by Horne deals with the definition of the requirements, which means the characteristics that a software must offer in order to be taken in account in the survey. The second phase represents the actual research of software and, consequently, the determination of their features and potentialities. Then, in the third phase, it is possible to make a comparison between the initial attributes and the software capabilities. Finally, the result obtained from the evaluation is a few selected computer programs, which perfectly suit the desired benchmarks.

Here follow the established requirements for pedestrian simulation software in this survey:

- The microscopic approach of the mathematical models implemented in the programs;
- Specific libraries for pedestrians allowing users to define physical and behavioral features of entities, activities and routes.

The following pedestrian simulation software are ordered according to the mathematical model they are implemented by and to the release year. The only exception concerns the software called Mass Motion, which is the first to be described since it is implemented by both the social forces and the least-effort model.

5.1. Mass Motion

Mass Motion is a pedestrian simulation software developed by Oasys Limited in 1976 and it is implemented by two different mathematical microscopic models: the social forces and the least-effort ones [62].

In order to obtain a more realistic pedestrian simulation, it is possible to change the default values of inputs.

The agent radius can vary between 0.15 and 0.4 meters, but it is recommended to take 0,25 meters because it is the value through which simulations have been optimized.

The desire speed is fixed at the beginning of the simulation and depends on the chosen distribution (constant, uniform, normal, triangular, log normal or exponential) and on the density. In fact, the desire speed is inversely proportional to the density; the relationship between these two parameters has been optimized according to the research of John J. Fruin, as reported in [63].

Another feature influencing the agent desire speed is represented by the obstacles on the route, such as elevators, ramps or stairs, queues, etc...

As Mass Motion is based on the least-effort model, it is possible to define the cost of some routes or actions (horizontal or vertical walking direction, waiting in line or passing through doors, etcetera...) and it will affect the agent choices. Moreover, this software permits to impose a trajectory on pedestrians, for example they are forced to walk on the right or left side or along the central way [62].

Since Mass Motion is implemented also by the social force model, the agent is influenced by the position, the speed and the size of other agents.

This software provides some output data like the number of frames, the identification of each agent and the XYZ components of its position. It is possible to obtain further optional information about modeled walking people, such as the clock time, the speed, the heading and the move state.

Mass Motion can be used in different planning fields: airport and railway terminals, urban spaces, health buildings, stadium, arenas and evacuation plans.

Some cases of study are the Transbay terminal in San Francisco, the Union Station in Toronto and the T5 Gate of the JFK Airport in New York [62].

5.2. Pedestrian Dynamics

Pedestrian Dynamics is a pedestrian simulation software developed by the company Incontrol Simulation Solution, in collaboration with the University of Utrecht, in 1990. It is possible to run both mesoscopic and microscopic simulations; in particular, the latters are based on the least-effort mathematical model [64].

In order to obtain a more realistic pedestrian simulation, it is possible to change the default values of inputs.

Initially, a MEC network is automatically created along the routes of the study area to achieve the aim of providing an optimal trajectory for pedestrians.

This software permits to name different types of agents, so that it is easier to recognize them. The agent radius is constant and is equal to 0,239 meters, which is a typical value for a common pedestrian.

It is also possible to define the maximum and minimum speed and a multiplicative coefficient influencing the agent speed when it lies on a surface characterized by its own speed, such as elevators.

As a default option, the agent is inclined to follow a route contained in the MEC network but, using the density algorithm for the direction, the agent can avoid crowded places [64].

Pedestrian Dynamics provides result data for both the 2D and 3D model. It is possible to obtain a report, including tables, charts and screenshots, containing the following output elements: flow counter, density area, output layer, activity route, density map, frequency map and travel time map.

Pedestrian Dynamics can be useful to run pedestrian simulations in different application fields: industry and logistic, public transport terminals (rail stations), crowd management (in airports, urban and commercial areas, events, stadiums and arenas), emergency situations and large vessels.

It has been used for various case studies: crowd simulation and infrastructures in Brisbane Airport (Australia), in the soccer stadium of PSV Eindhoven (the Netherlands), in Dutch pavilion "Happy Street" (China), in World Expo Shanghai 2010 (China), during the abdication of the queen (the Netherlands), in the Station Island (the Netherlands) and crowd simulation in Arena Porto Alegrense (Brazil) [64].

5.3. Legion

Legion is a simulation software developed by the software house Legion International Limited in 1997 and it is implemented by the benefit – cost model. It is possible to run microscopic simulations, as the calibration operation of the mathematical model has been made gathering data through pedestrian detections in 14 cities, over three continents, in 40 different contexts. According to the results of these detections, during simulations each agent's speed is 0,6 sec/step.

Following the principles of the benefit-cost model, each entity is inclined to reach its destination trying to minimize a route cost function, which is a weighted sum of three items: inconvenience, frustration and discomfort. The first one represents the additional physical effort to reach its destination in comparison to not crowded situations, the second one is the cost function rate related to the preferred speed decrease due to congestion and the third one consists in the perception of insufficient personal space [65].

This perceived cost can vary along the route towards the target because pedestrians have to adapt their walking behavior in relation to environmental circumstances and the presence and direction of other agents [66].

As far as the inputs are concerned, it is possible to define different entity profiles containing social, physical and behavioral characteristics. In fact, some social properties such as gender, age, culture and pedestrian type can be set as well as the physical aspect, like the body size, in particular the physical radius. Moreover, pedestrian behavior is influenced by a few features such as memory, willingness to adapt, preferences for unimpeded walking speed, personal space and acceleration. It also depends on what kind of facility the agents walk through, for example stairs or escalators [10].

These population profiles can change according to the types of pedestrian (for example commuters, sport spectators or tourists), to the origin region (Continental Europe, UK, USA or Far East) and to the context (indoor, outdoor, walkways, escalators, platforms, stairs up and down) [66].

Legion is able to provide, through maps, charts and tables, the following numerical and graphical outputs: the origin and destination matrix, ingress, egress and occupancy counts, the normalized flow, the speed, the entity and space density, the journey time and the parameters of inconvenience, frustration, discomfort and dissatisfaction [10].

Legion can be used in various planning fields: airport and railway terminals, commercial buildings and areas of urban development, sport and major events.

The most relevant cases of study are: the London Underground; the New York Pennsylvania Station e Tsim Sha Tsui Station (Hong Kong); Sidney, Athens, Beijing e London Olympic Games; Düsseldorf Arena and Rose Bowl Cricket Ground; fire drill at the multi-store building Broadgate West (London); Airport of Gatwick (London), Barcelona, Madrid, Luton and Venezia [65].

5.4. Simtread

Simtread is a pedestrian software developed by Nemetschek Vectors Inc in 2000 and it is implemented by the shortest path model. It can be used for evacuation planning in different contexts: school, exhibition rooms, rail station or during crowded events, such as concerts [67].

In this software it is possible to set, as inputs, some features of each pedestrian (the spatial position, the direction, the maximum walking speed), to define a few obstacles (walls, furniture and areas in which transit is not allowed) and the destination area.

The software provides both analytical and graphical outputs: measurements areas (which means counting pedestrians in a specific area at a certain time), the travel speed, crowd flow rates, flow rate charts in relation to time and the total flow, and data lists containing the position, the direction and the distance of each pedestrian at each time interval [67].

5.5. Simwalk

Simwalk is an agent-based simulation software released in 1990, implemented by the social-force model [68, 69]. It permits to run simulation for traffic management, for evacuation and urban planning and for station optimization in rail, metro and bus stations.

This software permits to define, as input, an agent profile, which describes the attributes characterizing each pedestrian: the activity, the area, the speed, the height, the age and the gender, the mobility restriction (such as backpack, bicycle or scooter, blind, stroller, crutches, dog, drunk, computer, pregnant, ski or snowboard, shopping bag, suitcase, wheel chair, etcetera) and the clothes (swimwear, business, casual, elegant, military, sportive, uniform). Moreover, it is possible to specify, for any walking person, the starting, waiting and arrival time according to the simulation context, which means considering the aspects that influence its time; for example, the opening and closing time of doors in case of train stations or the delay of departures and arrivals in airports [68].

As far as the graphical outputs are concerned, Simwalk allows to obtain density maps (indicating the maximum and minimum density values), load maps (representing the spatial utilization), speed maps (highlighting the percentage loss of speed in relation to the desired one), trajectory maps, agent flow maps (in which the agent color corresponds to the current walking speed) and counter charts. This software is also able to provide output database.

Simwalk is commercialized with a pedestrian database containing reliable pedestrian measurement data gathered all over the world, in order to improve the model calibration phase for any simulation.

Here follow some of the several Simwalk case studies: railway station simulation at Matabiau in Toulouse (France), pedestrian flows at Oerlikon train station (Switzerland), Lyon metro safety simulation (France), punctuality of S-Bahn Zurich (Switzerland), Lima metro evacuation (Peru), arrival area optimization of a French airport, management of crowd flow at Hajj (Mecca, Saudi Arabia), evacuation of a soccer stadium in Luzern (Switzerland) and evacuation of a football stadium in Pennsylvania (USA) [68].

5.6. Anylogic

Anylogic is a simulation software developed by the Anylogic Company and realesed in 2000. It permits to run both macroscopic and microscopic simulations; in particular, the latter consists in an agent-based and discrete-event approach, which follows the principle of the social-force model. This program has been implemented by the GIS technology [70].

As far as the inputs are concerned, the software Anylogic let users define some features regarding pedestrians and their activities: type of pedestrian to generate, comfortable speed, initial speed, diameter, type of pedestrian groups (size, formation, interarrival time, behavior in services), and actions [70].

As result information, the software provides some outputs, in particular statistics (medium, minimum and maximum value) of data set like the queue length and charts (such as bar chart, stack chart, pie chart, plot, time plot, time stack chart, time color chart, histogram, histogram 2D) [71].

Anylogic allows to run simulation in a variety of application field: pedestrian traffic flows, manufacturing, logistics and supply chains, social process and marketing simulation, markets and competition, business process modeling, healthcare and pharmaceutical simulation, warehouse operations and layout optimization, ports and container terminals, and railroads.

This software has been used in a few real case studies, such as English Channel crossing, passenger flow simulation at Frankfurt Airport and for railway station at Sochi 2014 Olympics, and transfer hub passenger flow simulation at Moscow Ring Railway [70].

5.7. Viswalk

Viswalk is an agent-based simulation software developed by PTV Group and released in 2010. It is implemented by the social forces model and it permits to run simulation for planning rail stations, transportation infrastructures, event management and evacuation in case of emergency [72].

One of the inputs required by Viswalk is the walking behavior, which is defined by several parameters, according to the social forces model: the inertia, the influence of the nearest pedestrian on the considered agent, the interaction forces among pedestrians, the anisotropy of forces, the intensity and the typical range of the social force between two agents, the disturbance and the preferred walking side. It is also possible to distinguish different pedestrian types by setting some features, such as the typology (man, woman, agent on a wheelchair or mum and child), the model distribution, the variance of length, width and height and the walking behavior. Moreover, the software can create a few pedestrian compositions gathering groups of different pedestrian types.

As far as the layout inputs are concerned, the attributes of the areas can be defined: in particular the level, the height in relation to the ground coordinates, the thickness and the pedestrian behavior within a certain area. Once the geometry of the study area is set, it is possible to determine pedestrian route decisions (which means assigning different pedestrian typologies to origin and destination areas) and pedestrian static routes, specifying the relative flow for each path [72].

Viswalk permits to determine, as output, the density and the speed for all types of pedestrians in areas, along stairs and ramps; moreover, it allows to define some queue attributes such as the maximum, minimum and average number of pedestrians in a queue, the maximum, minimum and average length of the queue and the maximum, minimum and average time spent waiting in a queue. Besides, this software is able to evaluate pedestrian areas through section measurements (the speed deviation, the number of pedestrians within the area and entering or exiting it, the density, the speed and its X and Y components, the total dwell time, the total distance, the total gained time, the total delay, the desired speed, the time of entering and exiting the section and the number of pedestrians remaining in the section) and the travel time through some quantities like the number and the type of pedestrians, the distance between origin and destination, the delay, the gained time, the speed deviation from the desired one.

It is also possible to obtain graphical output, which means charts representing a few parameters, such as density [72].

Viswalk has been used to verify the acceptability of the flow of passengers in case of expansion of the capacity of the Amsterdam Central Station [72].

Here follow some software that have been developed by a few universities and not commercialized; for this reason, there are some lacks concerning the information about input and output data.

5.8. Simped

Simped is a software developed by the University of Technology of Delft, in the Netherlands, in 2002. It is used for pedestrian simulations in wide areas and, as it is implemented by the benefit-cost model, it is possible to execute microscopic modelings [73].

In order to run a simulation, several parameters have to be set; in particular they concern: the characteristics of infrastructures (length, width and shape), the characteristics of pedestrians (free speed and familiarity with the environment), the characteristics of public transport vehicles (length, number and width of doors), origin and destination areas of both agents and public transport means.

This software is able to simulate even the interaction between pedestrians and vehicles and to distinguish different types of subjects (tourists, business men, etc…) in relation to their walking behavior and, consequently, to their transfer time [73].

Simped permits to determine the disturbance on pedestrians' transfer time due to delays or advances of trains; moreover, it defines the level of service (LOS) according to the average space per pedestrian on a certain route (between an origin and a destination). Besides, this software considers all the possible activities that walking agents can do while they go from origin to destination, for example buying a train ticket [73].

Since input data refer only to the Dutch context, the application field of Simped is quite limited.

5.9. Alpsim

Alpsim is a software developed by the Swiss National Science Foundation in 2003 and it is implemented by a microscopic model. Its peculiarity consists in the fact that pedestrians can perceive the presence of obstacles in the layout and they are able to adapt their route according to the surrounding environment, following the principles of the benefit-cost model.

This software has been developed to model touristic routes in the Swiss Alp areas [74].

6. Discussion and conclusions

In the paper three important issues for pedestrian dynamics have been discussed: detection techniques, mathematical modelling and simulation software.

Detection techniques have been described, pointing out the pros and cons of each technology.

Pedestrian modelling has been treated introducing the working logic of both traditional and innovative models, highlighting even the newest adaptations of each approach.

Finally, simulation software have been overviewed, analyzing their features, potentialities, the needed inputs and given outputs and mentioning some case studies.

The need of facing problems like a more eco – friendly mobility, urban design more suitable for walking people, the management of crowded areas and safety and security of people has led to the development of more and more precise simulation techniques. This is the aim of the most used simulation software: Legion, Anylogic, Pedestrian Dynamics, Viswalk and Simwalk, which implement mainly two kinds of microscopic models, the benefit-cost and the social force models. These approaches require a well-determined type of data structure, which converts into the need of precise information about the single pedestrian Those data can be obtained only by appropriate detection technologies and, currently, the detection methods providing the largest number of required data are video, RGB, infrared and laser techniques. The outputs got through these technologies permit to achieve a high precision in the determination of model parameters and, acting on calibration parameters, a higher reliability in the results provided by pedestrian simulation software.

References

1. P. T. Martin, Y. Feng, X. Wang (2003), Detector technology evaluation, University of Utah Traffic Lab, 2003
2. D. M. Beckwith, K. M. Hunter-Zaworski (1997), Passive pedestrian detection at unsignalized crossings, http://safety.fhwa.dot.gov
3. T. Schweizer (2005), Methods for counting pedestrians, 6th International Conference on Walking in the 21st Century, September 22-23 2005, Zurich, Switzerland
4. K. Teknomo (2002), Microscopic Pedestrian Flow Characteristics: Development of an Image Processing Data Collection and Simulation Model, http://people.revoledu.com/kardi/publication/Dissertation.pdf
5. K. Teknomo, Y. Takeyama, H. Inamura (2000), Review on Microscopic Pedestrian Simulation Model, Proceedings Japan Society of Civil Engineering Conference, Morioka, Japan, March 2000
6. K. Teknomo,Y. Takeyama,H. Inamura (2001),MICROSCOPIC PEDESTRIAN SIMULATION MODEL TO EVALUATE "LANE-LIKE SEGREGATION" OF PEDESTRIAN CROSSING, Proceedings of Infrastructure Planning Conference Vol. 24, Kouchi, Japan, Nov 2001
7. N. Shiwakoti, M. Sarvi, G. Rose (2008), Modelling pedestrian behaviour under emergency conditions– State-of-the-art and future directions, 31st Australasian Transport Research Forum
8. J. A. Charlton, B. Giddings and M. Horne, (2008), A survey of computer software for the urban design process, 9th Design Decision Support Systems Conference (DDSS 2008), 7 - 10 July 2008, Eindhoven, The Netherlands.
9. S. Alexandersson, E. Johansson (2013), Pedestrians in microscopic traffic simulation, Comparison between software Viswalk and Legion for Aimsun, Master of Science Thesis in the Master's Programme Infrastructure and Environmental Engineering, Master of Science Thesis in the Master's Programme Infrastructure and Environmental Engineering.
10. firemodelsurvey.com ,(2007), Computer models for fire and smoke (NON ESISTE L'AUTORE)
11. E. A. S. Miranda, J. G. Y. Carrasco (2011), Pedestrian volume studies, a case study in the city of Gothenburg, Thesis, 2011
12. A. Millonig, G. Gartner, Monitoring pedestrian spatio – temporal behaviour, Austrian Funds for Scientific Research
13. L.M. Brown, A. Hampapur, A. W. Senior, Y.L. Tian, S. Velipasalar (2009), Methods for automatically tracking moving entities entering and exiting a specified region, IBM,05/05/2009
14. I. Pavlidis (2003), Cooperative camera network, HONEYWELL INT INC,27/02/2003
15. I. B. Ozer (2007), System and method for object tracking and activity analysis, VERIFICON CORP., 22/03/2007
16. R. Yamazaki (2009), Object verification device and object verification method, RATNERPRESTIA, 30/07/2009
17. F. Porikli, O. Tuzel (2006), Tracking objects in low frame rate videos, MITSUBISHI DENKI (MITQ-C), 05/10/2006
18. R. Miyamoto, J. Ashida (2010), Pedestrian tracking method and pedestrian tracking device, UNIV KYOTO, 07/01/2010
19. A. Hampapur, Y. L. Tian, Y. Zhai (2012), System and method for model based people counting, INTERNATIONAL BUSINESS MACHINE CORPORATION, 23/10/2012
20. L.M. Brown, A. Hampapur, A. W. Senior, Y. L. Tian, S. Velipasalar (2006), Methods and apparatus for automatically tracking moving entities entering and exiting a specified region, INTERNATIONAL BUSINESS MACHINE CORPORATION, 30/11/2006
21. http://didattica.arces.unibo.it
22. http://unina.stidue.net/
23. M. Shi, Z. Huang (2010), Method for tracking moving object, IND TECH RES INST,23/06/2010
24. Z. Zhang, G. W. Myers, L. Venetianer (2013), System and method for video content analysis using depth sensing, OBJECT VIDEO INC, 18/07/2013
25. M. Harville (2010), Method for visual-based recognition of an object, HP, 09/11/2010
26. http://www.dicar.units.it/
27. K. Nagata, Y. Hisamitsu (2011), Method for detecting moving body, and laser apparatus for measuring distance, IHI CORP, 02/06/2011
28. H. Y. Kim, G. G. Lee H. K. Kim, J. J. Kim, J. Y. Yoon (2009), System and method for estimating traffic using the laser, IUCF HYU, 30/12/2009
29. H. Chao, R. Gupta (2013), Image and video based pedestrian traffic estimation, QUALCOMM INC, 25/04/2013
30. Z. M. Win, S. Mazuelas, Y. Shen (2012), Tracking a body by non-linear and non-gaussian parametric filtering, MASSACHUSETTS INST TECHNOLOGY, 06/12/2012
31. Y. Mutou, H. Hiroshige, K. Shoji (2006), Pedestrian movement route tracking method and system, JR HIGASHI NIPPON CONSULTANTS, 22/06/2006
32. R. Dharmaraju, D. A. Noyce, J. D. Lehman, An evaluation of technologies for automated detection and classification of pedestrians and bicycles, In Automated Detection and Classification of Trail Users
33. D. C. Duives, W. Daamen, S. P. Hoogendoorn (2013), State-of-the-art crowd motion simulation models, Transportation Research Part C
34. A. Abdelghany, K. Abdelghany, H. S. Mahmassani, S. A. Al-Gadhi (2005), Microsimulation Assignment Model for Multidirectional Pedestrian Movement in Congested Facilities, Transoprtation research record. No. 1939 (2005) pp 123-132
35. S. Okazaki , S. Matsushita (1993), A study of simulation model for pedestrian movement with evacuation and queuing, www.anc-d.u-fukui.ac.jp

36. D. Helbing, P. Molnár (1998), Social force model for pedestrian dynamics, arXiv:cond-mat/9805244vl
37. D. Helbing (1998), A Mathematical Model for the Behavior of Pedestrians, arXiv:cond-mat/9805202vl
38. V. J. Blue, J. L. Adler(2001), Cellular automata microsimulation for modeling bi-directional pedestrian walkways, Transportation Research Part B 35 pp 293-312
39. V. J. Blue (2000) , Modeling Four Directional Pedestrian Movements, Transportation Research Board 79 th Annual Meeting January 9-13 2000 Washington D.C.
40. A. Schadschneider, W. Klingsch, U. Klüpfel, T. Kretz, C. Rogsch, A. Seyfried (2008), Evacuation Dynamics: Empirical Results, Modeling and Applications, Encyclopedia of Complexity and System Science
41. L. Buzna (2004), The Pedestrian Flows-Empirical Analysis and Simulations Models, Journal of Information, Control and Management Systems vol.2 2004
42. D. Helbing,I. J.Farkas,P. Molnár,T. Vicsek (), Simulation of Pedestrian Crowds in Normal and Evacuation Situations
43. D. Helbing (1998), Models for Pedestrian Behavior, arXiv:cond-mat/9805089v2
44. M. Bierlaire, G. Antonini, M. Weber (2003), Behavioral dynamics for pedestrians, 10th International Conference on Travel Behavior Research Lucerne, 10-15. August 2003
45. C. Burstedde, K. Klauck, A. Schadschneider, J. Zittartz (2008), Simulation of pedestrian dynamics using a 2-dimensional cellular automaton, arXiv:cond-mat/0102397vl
46. J. Dijkstra, H.J.P. Timmermans, A.J. Jessurun (2000), A Multi-Agent Cellular Automata System for Visualising Simulated Pedestrian Activity, Conference: Theoretical and Practical Issues on Cellular Automata, Proceedings of the Fourth International Conference on Cellular Automata for Research and Industry, Karlsruhe, 4-6 October 2000
47. J. Wang, L. Zhang, Q. Shi, P. Yang, X. Hu (2015), Modeling and simulating for congestion pedestrian evacuation with panic, PhysicaA
48. Y. Chen, N. Chen, Y. Wang, Z. Wang, G. Feng (2015), Modeling pedestrian behaviors under attracting incidents using cellular automata, PhysicaA
49. S. Bandini, M. Mondini, G. Vizzari (2013), Modeling negative interactions among pedestrians in high-density situations, Transportation Research Part C
50. Queuing models and capacity planning, chapter fourteen
51. G.G. Løvas (1994), Modeling and Simulation of Pedestrian Traffic Flow, Transportation Research Board, Part B
52. W.L. Wang, S.M. Lo, S.B. Liu, H. Kuang (2014), Microscopic modeling of pedestrian movement behavior: Interacting with visual attractors in the environment, Transportation Research Part C
53. Roger L. Hughes (2002), A continuum theory for the flow of pedestrians, Transportation Research Part B 36 (2002) pp 507–53
54. R. M. Colombo, P. Goatin, G. Maternini, M. D. Rosini, Macroscopic Models for Pedestrian Flows, inria-00534882, version 1- 10 Nov 2010
55. A. Johansson, D. Helbing, P. K. Shukla (2008), Specification of a Microscopic Pedestrian Mo del by Evolutionary Adjustment to Video Tracking Data, arXiv:0810.4587vl
56. D. Helbing (1998), A Fluid Dynamic Model for the Movement of Pedestrians, arXiv:cond-mat/9805213vl
57. S P. Hoogendoorn, F. v. Wageningen-Kessels, W. Daamen, D. C. Duives, M. Sarvi (2015), Continuum theory for pedestrian traffic flow: Local route choice modelling and its implications, Transportation Research Part C
58. L. Huang , S.C. Wong , M. Zhang, C.-W. Shu, W. H.K. Lam (2008), Revisiting Hughes' dynamic continuum model for pedestrian flow and the development of an efficient solution, Transportation Research Part B journal
59. Y. Jiang, S. Zhou, F.-B. Tian (2005), Macroscopic pedestrian flow model with degrading spatial information, Journal of Computational Science
60. J. A. Charlton, B. Giddings and M. Horne, (2008), A survey of computer software for the urban design process, 9th Design Decision Support Systems Conference (DDSS 2008), 7 - 10 July 2008, Eindhoven, The Netherlands.
61. M. Horne, R. Hill, C. Underwood, (1997), Visualisation of Photovoltaic Clad Buildings, Information Visualization, 1997. Proceedings., 1997 IEEE Conference
62. MassMotion, http://www.oasys-software.com/
63. J.J. Fruin, Pedestrian Planning & Design, Revised Edition Chapt. 4, Elevator World, 1987
64. Pedestrian Dynamics, http://www.pedestrian-dynamics.com/
65. Legion pedestrian simulation, http://www.legion.com/
66. J. L. Berrou, J. Beecham, P. Quaglia, M. A. Kagarlis, A. Gerodimos (2005), Calibration and validation of the Legion simulation model using empirical data, Pedestrian and Evacuation Dynamics 2005, pp 167-181.
67. Simtread, http://www.vectorworks.net/
68. Simwalk, http://www.simwalk.com/
69. A. Steiner, M. Philipp, A. Schmid (2007), Parameter estimation for a pedestrian simulation model, 7th Swiss Transport Research Conference, September 2007, Ascona
70. Anylogic, http://www.anylogic.com/
71. M. Munaro (2009-2010), Simulazione discreta con il software Anylogic. Caratteristiche generali e applicazione ad uno studio oculistico, Tesi di Laurea, Facoltà di Ingegneria – Dipartimento di Tecnica e Gestione dei Sistemi Industriali, Università degli Studi di Padova
72. Viswalk, http://vision-traffic.ptvgroup.com/en-us/products/ptv-viswalk/
73. W. Daamen, (2002), SimPed: a pedestrian simulation tool for large pedestrian areas, In Proceedings of the European Simulation Interoperability Workshop, London, June 2002.
74. C. Gloor, D. Cavens, E. Lange, K. Nagel, W. Schmid, (2003), Pedestrian simulation for very large scale applications. A. Koch & P. Mandl (Eds.): Multi-Agenten-Systeme in der Geographie, Institut für Geographie und Regionalforschung der Universität Klagenfurt, Klagenfurter Geographische Schriften, 23, 167-188.