A state-of-the-art review of multi-agent modelling of crowd dynamic

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Abstract. This paper reviews the multi-agent modelling (MAM) which applied as a platform to simulate the interaction of crowd dynamics. The research and development of MAM related to crowd dynamics can generate specific analytical evaluation, improve the safety level of the pedestrians and the quality operation of the urban space. Furthermore, crowd dynamics have become a major concern for urban space and are mainly constrained imposed by the ever-increasing populations. Consequently, these scenarios causing more attention are paid to the crowd safety in capacity assessment, especially during an emergency evacuation. This paper presents a concise review on the development of MAM over the past few years. The discussion on the state of the art of the multi-agent methods includes the history of the multi-agent method and the development of multi-agent modelling. This paper also discussed the state of the art of multi-agent methods in modelling crowd dynamic by focusing only on the microscopic approach. The advantages of multi-agent modelling approach have become one of the best methodological approaches in analysing and predicting crowd performance in the real world as a substitute for physical experimentation in a current research field.

1. Introduction

Live in society inevitably leads the individual to experience a crowded movement in public area. Public area or environment especially in terminal, shopping mall, stadium, and street with a different classification of crowd dynamic models usually be identified before modelling approach is selected. There are three classifications of crowd dynamics in pedestrian flow models namely, microscopic models, mesoscopic models, and macroscopic models. The selection of crowd dynamics model depends on the way a study is conducted or model detail considered. Currently, microscopic models had gotten attention in modelling the crowd dynamics. Previous researches had proved that the collective behaviour of crowd dynamic at a macroscopic level is due to the emergence of interactions between individuals at a microscopic level [1].

The microscopic models treat individuals in detail and concern with the motion characteristics of the individuals in the crowd. Each individual is tracked as it interacts between other individuals and environments. Many microscopic models have been developed to accurately predict crowd motion and interpret a variety of self-organized phenomena in crowd motion and typical microscopic models include; multi-agent models [2], agent-based models [3], cellular automata models [4], social force models [5] and other particle-based models like DEM-based model [6].

In this paper, multi-agent modelling (MAM) is selected and reviewed as an approach in modelling of crowd behaviour owing to its ability and advantages in a computerized system for simulating the
autonomous interactions that consist of multiple intelligent agents. The development and application of MAM technique in computer technology make pedestrian study in simulation analysis becomes preferable in various situations since MAM approach is one of the best methodological approaches in analysing and predicting heterogeneous humans. Besides, the concept of the MAM system is depending on the agent and the surrounding environment. An agent can be found in three categories namely, active agents, passive agents, and cognitive agents. Meanwhile, environments can be identified in three types of circumstances such as continuous, virtual, and discrete. Agent and environment are closely linked due to the interaction of pedestrian moving trajectory, indirectly produce gradient force, repulsive force, random force, and resistance force between pedestrians (agents) and their environment [7]. MAM according to Mahudin [8], is the development of instruments that can express the dimensionality of crowding activity and relationship of stress and fatigue experience. More example on MAM application can be referred to ‘Timeline Infographic’ in this paper. Furthermore, the fundamental of simulation of MAM and agent-based modelling (ABM) are almost similar, however, MAM can conduct more intelligent and detailed study rather than ABM.

The development of a reliable prediction model such as MAM for crowd dynamics simulations involves the understanding of local interactions underlying crowd dynamics. Hence, the dynamics of crowd motion is mainly driven by local interactions among pedestrians and their surrounding environment. Individual movements can affect the movement of other individual trajectories in widespread moving to maintain individual space as they will experience social forces to oblige with crowd movement [9]. Another research by Moussaid et al. mentioned that crowd dynamic displays a variety of self-organized behaviors that support efficient movement under everyday circumstances [10]. One of the most notable examples is the formation of unidirectional lanes spontaneously in bidirectional pedestrian flow. However, at high density, the smooth flow of pedestrians may deteriorate, creating patterns of movements such as stop-and-go and crowd turbulence waves. As a result, various research methods in MAM of crowd dynamic have been proposed so far to understand how pedestrians interact with each other and environments. Therefore, the history of MAM gathered by previous research can assess the development of MAM to manage the pedestrians’ flow.

A state of the art on multi-agent modelling of crowd dynamic is proposed to focus on the most recent research, describe and summarizes current information, educational trends and discussion on multi-agent modelling of crowd dynamic. This paper also aims to provide a critical observation on multi-agent modelling of crowd dynamic assessment literature produced from the past and may indicate the ideas needed for future research. On the other hand, with the development of multi-agent modelling, this paper can help in improving the operation and safety level at crowded public areas as well as plays a vital role in helping authority, related agencies, and design engineers.

1.1. Crowd dynamics issues
Over the past few years, the issues in crowd dynamics (e.g., crowding activities, crowd disaster and emergency evacuation) have led to many modelling and simulations studies initiated and various improvements were made to address the issues because pedestrian in crowd dynamic is unpredictable. Thus, it is important to understand the fundamental of pedestrian in crowd dynamic due to the pedestrian flow and behavior throughout their complex surroundings. Bouchard et al. indicates that crowd dynamic is a set of actions which derived from people’s intentions, beliefs, knowledge, and perceptions which involves in observing a variety of group which affect the study may be distributed into several categories, among which are polarization, sharing and adding impact enhancements, and the impact of the dominating group [11].

Furthermore, Samson et al. identified crowd dynamic is a research of crowd motion in terms of form and move due to the increasing density of crowds that requires modelling, simulation, and understanding of individual movements of crowd, space and activities [12]. Moreover, tracking pedestrians in crowd movement draws notable attention recently due to its vital and expansive applications such as profiling group dynamic [13]. It is easier to plan effective crowd movement
control in schemes or floor layout to reduce public traffic with the simulation results that lead to an informed design decision [12].

Formerly, crowd dynamic was studied in the areas of crowd activity simulation [14], but several attempts have been made to anticipate the upcoming paths of the crowd in a real situation from the visual perspective. Also, the incredible human capabilities in visualizing the future are mainly driven by the high knowledge of the visual world. This idea can also be done for computer-aided prediction of motion with visual data due to the phenomenon of self-organizing for moving crowd [15].

2. Modelling

There are various methods for modelling and simulating the crowd dynamic implemented which include multi-agent models (MAM) or agent-based models (ABM), the magnetic force models, fluid-dynamic models, social force model, cellular automata models, lattice gas models, game-theoretic models, and approaches based on experiments with animals. In this paper, MAM is selected as its advantages able to come out with a real emergent phenomenon and a description of a system, save time and cost [16].

![Figure 1](image)

**Figure 1.** Schematic diagram of pedestrian flows - intersecting flows (a), bottlenecks (b), and lane formation (c)

An analysis of modelling and simulation of crowd dynamics, self-organized phenomena of pedestrian flows are influenced by various factors such as intersecting flows (Figure 1(a)), bottlenecks (Figure 1(b)), lane formation (Figure 1(c)), shockwaves, counter flows, a ninety-degree corner, and pedestrian shortcomings. While, some analysis pedestrian behavior attributes of such as walking velocity, psychological distance, angle of vision, angular velocity and angle of avoidance are studied or review in the modelling and simulation activity.

Conceptual framework in Figure 2 is a revision from Ewing and Handy [17] on walking behavior in crowd dynamics to create an analysis of MAM of crowd dynamics. The relation of physical features, urban design quality, and individual reaction able to create an overall walking behavior. However, walking behavior of crowd dynamic affecting the election of MAM analysis criteria such as self-organize phenomena and pedestrian behavior attributes. Therefore, self-organized phenomena of pedestrian flows and analysis on pedestrian behavior attributes are mainly examined by the researcher for a good modelling and simulation results.
3. History of the Multi-Agent Modelling (MAM)

MAM of crowd dynamics platforms and frameworks have been developed since the late 90's. Many attempts have been made in designing MAM, this scenario takes agent model, environment and interaction between agents into consideration. Therefore, many researchers from then until now develop a study gap in MAM’s methodology in order to solve critical problems or cases by a selection of the right tools for a relevant finding [18].

According to Macal and North [19] MAM starts with a simulation involving nature movements, namely Swarm, among the first toolkit developed 20 years ago. The basis for multi-agent simulation is agent-based simulation and at the beginning of the agent-based simulation, the study is developed by using discrete event simulation (DES) [19]. Hence, multiple applications have been found in a multi-agent toolkit or system including modelling and simulating of complex systems, smart grids, computer/mobile networks, graphics, transportation, logistics, manufacturing, and GIS. Features such as MAM’s approaches, situations and typical situation of each research have been listed in Table 1.

![Figure 2. Analysis of MAM of crowd dynamic [17].](image)
Table 1. Features of MAM.

| Year | Approaches                          | Situations         | Application                                                                 | Reference |
|------|-------------------------------------|--------------------|-----------------------------------------------------------------------------|-----------|
| 1999 | MAM and GIS                         | Normal             | Virtual urban environment                                                   | [20]      |
| 1998 | MAM                                 | Normal             | Dynamic model of the economy-energy-climate                                 | [21]      |
| 2000 | ABM/MAM                             | Overview           | -                                                                           | [22]      |
| 2007 | ABM and cellular automata           | Normal             | Simulation of Crowd at The Tawaf Area                                        | [23]      |
| 2008 | MAM                                 | Normal             | Mesoscopic; Route choice self-organization; sink propagation value; smoothing relaxation | [24]      |
| 2009 | ABM                                 | Emergency          | Simulation of crowd evacuation                                              | [25]      |
| 2010 | MAM                                 | Normal             | Agents' behavior, and provide insights into the causing factors behind the expansion | [26]      |
| 2010 | ABM                                 | Normal and Emergency | Simulation of emergent behavior                                               | [27]      |
| 2012 | ABM and SF                          | Emergency          | Panic evacuation                                                             | [28]      |
| 2012 | MAM-self-evasive action model       | Normal             | Decision behavior and pedestrian contra-flow                                | [6]       |
| 2013 | MAM                                 | Emergency          | Crowd Simulation, Modeling, Evacuation, Emergency Planning, and Multi-Agent Systems. | [29]      |
| 2013 | ABM and GIS                         | Emergency          | Disaster                                                                     | [30]      |
| 2013 | ABM                                 | Normal/Conflict Bottleneck | Bidirectional flow evacuation and crowd dynamic                              | [31]      |
| 2014 | ABM                                 | Three Scenarios with Differing Complexity | Crowd simulation; decision rules; evolutionary algorithm; gene expression programming | [32]      |
| 2014 | Mixture model of Dynamic Pedestrian-Agent (MDA) | Normal | Decision behavior, crowd control, and traffic management                     | [33]      |
| 2014 | ABM                                 | Emergency          | Group emotion evolution and incidents management                            | [34]      |
| 2015 | MAM                                 | Emergency          | Decision behavior and evacuate simulation.                                  | [35]      |
| 2017 | MAM                                 | Games              | Massively Multi-player Online Role-Playing Games                             | [2]       |
| 2018 | MAM                                 | Normal             | Simulation with combining game development technologies and crowd behavior   | [36]      |
| 2019 | MAM                                 | Normal             | Robust face detection and multi-face tracking                                | [37]      |

4. The development of MAM
The development of MAM’s research can be found in academic as well as in industrial studies. In the early 90s, MAM studies were limited only to certain fields such as social science and transportation. Nowadays, MAM studies covering various fields such as social science, economics, ecology, political
science, socio-cultural and technological and more. Table 2 below show the example of MAM application in various field.

| MAM Application                                      | Field                  | Reference |
|------------------------------------------------------|------------------------|-----------|
| Switching action model                               | Social science         | [35]      |
| Learning collective crowd behavior                   | Social science         | [33]      |
| Group emotion studies                                | Social science         | [34]      |
| Multi-room and multi-floor building                  | Social science         | [28]      |
| Humanitarian assistance                              | Humanities             | [30]      |
| Modelling urban expansion                            | Social science         | [26]      |
| Pedestrian contra-flow                               | Social science         | [6]       |
| Pedestrian counter flow through bottlenecks          | Social science         | [31]      |
| Robust multi-face tracking                           | Social science         | [37]      |
| Large areas with utility-based behavior models        | Social science         | [36]      |
| Online or computer games                             | Computer technology    | [2]       |
| Marketing research                                   | Economics              | [38]      |
| Real Time, Resource Allocation, Scheduling, Optimization and Controlling in Industrial Applications | Transportation engineering | [39]   |
| Revenue management                                   | Economics              | [40]      |
| The landscape epidemiology of foot-and-mouth disease in South Africa | Ecology | [41] |
| Aedes aegypti mosquito population                    | Ecology                | [42]      |
| Assess the impact of agricultural policies           | Agricultural/Applied science | [43] |
| Traffic and pedestrian modeling                      | Transportation engineering | [3]   |

Timeline infographic provides a visual representation of events that helps better overview the history to a development process. Therefore, timeline infographic on MAM of crowd dynamic is stated in Figure 3 in order to facilitate the MAM of crowd dynamic development for over 20 years. There are various methods in conducting a multi-agent modelling of crowd dynamic study since 1990 till now. Lately, it can be ascertained that the number of researchers on emergency cases is increasing. This is because, building operation and safety level of pedestrian are the main issues if any emergency incidents occurrence (e.g. fire, accidents, structural failures, chemical spill, nuclear accidents, traffic accidents, bomb threats, terrorism, nuclear disaster, or viral outbreak) and other natural disasters (e.g. eruptions of volcanoes, tropical cyclones, floods, earthquakes, tsunamis or wildfires/bushfires). Emergency incident may happen due to crowd evacuation in panic and unexpected occurrence to exit, simultaneously may lead to injury, loss of life damage to property and environment. According to Tajedi et al., little attention is given on the study of the egress facilities effect, towards the pedestrian movement during the emergency evacuation [44] as this egress facilities or emergency evacuation can be analysed through modelling and simulation of MAM.
4.1. Potential and advantages
Macal [45] has reviewed the potential of MAM in the Sackler Colloquium of the National Academy of Sciences with focused on suggestion and challenge of MAM and simulation revolution of social science development needed to encounter (1) superior intervention of uncertainty analysis structure, (2) standardization of models to data, (3) evolve methodologies for a models to response an instance of questions or problem solving, and (4) demonstrating phenomena appearing beyond simple computer graphics. The development of computer technology using MAM of crowd dynamics analysis becomes practical and proficient because MAM is interesting approach as it offers the ability to model pedestrians of various agents. To develop of MAM based on study by Macal and North, the structure of a MAM need a combination of elements (1) agents, their attributes and behaviours (crowd dynamics), (2) relationships and interaction of agents in topology areas defines the reason for interaction (3), the environment of agents as they live in and interact with the environment and other agents [19].

5. Conclusion
This paper has examined the MAM approach applied as a platform to study the interaction of crowd dynamics, by providing history, background and the development of MAM in connection to the assorted disciplines and a community that conducts modelling and simulation research. In addition, this paper has presented the development of MAM over the past few years. In addition, the development of MAM in crowd dynamics research may require analytical computational methods in modelling simulation studies and also covering various fields. The result from crowd dynamic modelling and simulation will become reference information to the related engineers in designing...
walking infrastructures (e.g. shopping mall, sidewalk facilities, stadium, crosswalk facilities, etc.). Contrarily, with the development of multi-agent modelling of crowd dynamic can provide an analytical evaluation of the quality of public urban spaces, help to improve the buildings' operational efficiency, improve pedestrian safety and injury risk.

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