

**ENHANCED BIO-INSPIRED ALGORITHM
WITH PEDESTRIAN SIMULATION FOR
SPATIAL LAYOUT DESIGN**

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FOR SPATIAL LAYOUT DESIGN**

by

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LIST OF ABBREVIATIONS

USM	Universiti Sains Malaysia
ABC	Artificial Bee Colony Algorithm
GA	Genetic Algorithm
ABM	Agent-based Model
SFM	Social Force Model
LTCFs	Long-Term Care Facilities
CA	Cellular Automata
DE	Differential Evolution
CSS	Charge Search System
PSO	Particle Swarm Optimization
EBGA	Elitism Based Genetic Algorithm
ACO	Ant Colony Optimization
AHBO	Artificial Honey Bee Optimization
SOS	Symbiotic Organisms Search
RS	Rank Selection
RWS	Roulette Wheel Selection
TS	Tournament Selection
SUS	Stochastic Universal Sampling
APC	Affinity Propagation Clustering
CTM	Cell Transmission Model
CFLP	Construction Facility Layout Problem
FLP	Facility Layout Problem
BFO	Bacterial Foraging Optimization Algorithm
CRO	Coral Reef Optimization Algorithm
SOS	Symbiotic Organisms Search Algorithm
PT	Pythagorean Theorem
DA	Dijkstra's Algorithm
ANOVA	Analysis of Variance

**ALGORITMA BERINSPIRASIKAN BIO YANG DIPERTINGKAT DENGAN
SIMULASI PEJALAN KAKI UNTUK REKA BENTUK SUSUN ATUR
RUANG**

ABSTRAK

Kemunculan proses reka bentuk bantuan komputer berautonomi telah meningkatkan reka bentuk susun atur ruang yang konvensional dengan menambah baik reka bentuk susun atur dan struktur untuk kegiatan ekonomi, pengaruh budaya, memenuhi fungsi keperluan, mudah diakses dan selamat. Walau bagaimanapun, ruang kemudahan yang telah dipertingkatkan mempunyai isu dalam penggunaan ruang disebabkan oleh pertindihan, lebihan beban, dan pembuangan objek didalam ruang ketika proses pengoptimuman. Tambahan lagi, susunan objek kebiasaanya berdepan dengan permasalahan posisi dengan elemen susun atur ruang yang sediaada untuk mencapai piawaian reka bentuk ruang. Keselamatan pejalan kaki juga telah menjadi permasalahan kritikal walaupun terdapat kemajuan teknologi di dalam process reka bentuk. Kebanyakan permasalahan pengurusan orang ramai yang timbul pada masa kini melibatkan kesukaran bagi pejalan kaki untuk keluar dari ruang ketika berlakunya kecemasan dan akan mengakibatkan kecederaan yang tinggi. Oleh itu, penyelidikan ini bertujuan untuk membina susun atur ruang secara autonomi yang optimum untuk meningkatkan penggunaan ruang dengan berkesan tanpa menjejaskan piawaian reka bentuk dan meningkatkan pergerakan pejalan kaki, terutamanya ketika berlaku kecemasan. Penyelidikan ini telah mencadangkan integrasi algoritma pengoptimuman yang separa dan lengkap, Algoritma Koloni Lebah Buatan (ABC), dan Algoritma Genetik (GA) untuk membentuk algoritma

ABC-GA bagi penumpuan berkelajuan tinggi dalam mempertingkatkan penggunaan ruang yang mematuhi piawaian reka bentuk ruang. Integrasi ini telah mengeksploitasi ciri pengoptimuman dan mencapai fungsi pelbagai objektif, mengekalkan maklumat lalaran masa lalu, meneroka susunan susun atur baharu, mengeksploitasi binaan susun atur yang lebih meyakinkan, dan mengimbangi penyelesaian ekstremum. Integrasi separa algoritma ABC-GA yang dicadangkan telah mencapai penghunian optimum bersama piawaian reka bentuk kerana objek telah memenuhi 99.33% daripada had beban susun atur. Kebolehcapaian ruang dan keselamatan susun atur juga telah dipertingkatkan dengan mencadangkan pendekatan pengesahan susun atur yang menggunakan simulasi pejalan kaki yang hampir realistik untuk menjangkakan tingkah laku pergerakan dan strategi membuat keputusan oleh manusia dengan lebih tepat semasa kecemasan. Penyelidikan ini telah memperkenalkan integrasi Model Berasaskan Ajen (ABM) dan Model Tekanan Sosial (SFM) untuk membentuk simulasi pejalan kaki berasaskan ABM-SFM. Peningkatan ini telah menambah baik trajektori pejalan kaki berdasarkan kecerdasan manusia yang realistik dalam mencari jarak laluan terpendek dan arah pergerakan ketika bertindak balas terhadap kesan ketumpatan ketika memilih jalan keluar. Masa pemindahan, jarak perjalanan, dan pemilihan pintu keluar bagi simulasi pejalan kaki berasaskan model ABM-SFM telah terbukti setanding dengan pendekatan simulasi semasa dan eksperimen pergerakan keluar manusia yang sebenar semasa kecemasan. Oleh itu, penyelidikan ini telah mereka bentuk susun atur yang lebih selamat dengan penghunian ruang yang optimum sambil memenuhi piawaian reka bentuk ruang dan mengutamakan pergerakan pejalan kaki untuk langkah keselamatan dan mengurangkan kecederaan. Hasil penyelidikan ini memberi kesan yang lebih

bermakna terhadap penggunaan ruang, kecekapan, dan keselamatan secara keseluruhan untuk mempertingkatkan kehidupan pejalan kaki.

ENHANCED BIO-INSPIRED ALGORITHM WITH PEDESTRIAN SIMULATION FOR SPATIAL LAYOUT DESIGN

ABSTRACT

The emergence of the autonomous computer-aided design process has enhanced the conventional spatial layout design by improving the layout design and structure to be economically driven, culture-influenced, functionally fulfilling, accessible, and secure. However, the enhanced facility layout has suffered from the space occupancy issue due to the overlapping, overloaded, and discarded spatial objects during optimization. Moreover, the objects' arrangement often faces the positioning issue with the existing spatial layout elements to meet the space design standard. The safety of pedestrians has also become a critical problem despite the technological advancement in the design process. Many crowd management issues nowadays involve the difficulties of pedestrians evacuating from a layout during emergencies and causing high casualties. Hence, this research aims to construct an autonomous spatial layout arrangement optimization that can effectively maximize space utilization without compromising the design standard and enhance pedestrian mobility, particularly in emergencies. This research proposed the partial and complete integration of bio-inspired optimization algorithms, the Artificial Bee Colony (ABC) algorithm, and the Genetic Algorithm (GA) to form the ABC-GA algorithm for high-speed convergence in optimizing space occupancy that complies with the layout design standard. The integration has exploited the optimization features and achieves multi-objective functions, retains past iterations information, explores new layout arrangements, exploits promising constructed layouts, and

balances solution extrema. The proposed partial integration ABC-GA algorithm achieved the optimal occupancy within the design standard as the objects had occupied 99.33% of the layout's load limit. Space accessibility and safety of the layout are enhanced by proposing the layout validation approach that utilizes the near-realistic pedestrian simulation to predict human movement behavior and decision-making strategy during emergencies accurately. This research has introduced the integration of an Agent-based Model (ABM) and Social Force Model (SFM) to model the ABM-SFM-based pedestrian simulation. This enhancement improves the pedestrian's trajectory based on realistic human intelligence in finding the shortest path distance and movement direction while responding to the density impact on the egress selection. The evacuation time, travel distance, and exit selection of ABM-SFM model-based pedestrian simulation have proven to be on par with the current simulation approaches and real evacuation human movement experiments during emergencies. Therefore, this research has designed a significantly safer layout with optimal space occupancy that meets the space design standard while prioritizing the pedestrians' movement for safety precautions and minimizing casualties. The outcome of this research significantly impacts the overall space usability, efficiency, and safety, greatly enhancing pedestrians' lives.

CHAPTER 1

INTRODUCTION

1.1 Background

In recent years, many closed-area incidents have occurred due to poor crowd management, which has led to panic and resulted in injuries and casualties. The crowd issues happened due to the pedestrians' entrapment inside the closed area, causing difficulties in accessing the exit point during evacuation and becoming the main factor that caused the high casualties occurrence (Dong, Chen, & Duan, 2015; R. Liu, Jiang, & Shi, 2016; Lu et al., 2017; Tcheukam, Djehiche, & Tembine, 2016; X. Zhang, Coates, & Ni, 2017). Numerous incidents occurred due to the complex layout structures and interior arrangement, the narrow passageways, large crowds, the lack of air circulation systems, and the poor evacuation assistance (X. Du, He, Mao, & Rao, 2018; F. H. Hassan, Swift, & Tucker, 2014; Sime, 1995; Tcheukam et al., 2016; F. Wang, 2021; Wong, Wang, Tang, & Tsai, 2017). Recently, in Malaysia, a great tragedy has occurred as a religious school burned down at dawn, claiming the lives of 25 people (Jay, 2017). The fatal tragedy has occurred due to the entrapment of the victims behind the barred window, and the burned-down space only has a single exit point that has been blocked during the incident (Jay, 2017). The victims have been found piling on top of each other in the corner of the room.

The other tragedy has been the entrapment of a family of four in their house due to the failure to evacuate during a fire incident that has caused a total death toll (2017). In West London, there has been a great fire at the Grenfell Tower in June 2017 that has caused the loss of 72 persons (Booth, 2018). Furthermore, there are also some incidents that involve the high physical collision of the victims, such as

fire combustion that had blocked some of the egresses and caused the stampede of the customers by pushing and shoving themselves at Station Nightclub in Rhode Island in 2003 and the overflow of the crowd for new year's eve celebration at Address Downtown Hotel in Dubai (Grosshandler, Bryner, Madrzykowski, & Kuntz, 2005; Lu et al., 2017; Yamin, Al-Ahmadi, & Muhammad, 2016). Based on the observation of these incidents, during the panic situations, the pedestrians failed to escape from a building in time because of wrong exit selection, failure to avoid obstacles, and having heavy physical collisions and pressure. The victims of the dreadful incidents are believed to have been safe if there have been other egress points and proper layout arrangements that have led toward the available egress.

Based on Zong and Jiang (2016) and Helbing and Johansson (2009), the unorganized and massive movement of the crowd during panic situations can be controlled by reducing the number of clogging regions and also the pressure at the clogging region. The clogging region can happen at the narrow pathways and exit points. Hence, a pedestrian can meet the movement limitation due to the unaccommodating layout, especially in a big crowd. The essential human movement control that is consistently implemented is using the barricade and adding the exit points. However, the existence of the barricade and the addition and expansion of exit points has some limitation in term of design aesthetics and space limitation and cause the weak fortress. Hence, to overcome the limitation and to manage the crowd, previous research has been carried out by Sime (1995), X. Zheng, Zhong, and Liu (2009), Sarmady, Haron, and Talib (2010), Y. Sun (2013), F. H. Hassan et al. (2014), Tcheukam et al. (2016), Wong et al. (2017), and X. Du et al. (2018) on the importance of crowd movement control, spatial layout structural design and arrangement, optimized evacuation route plan, pre-planning simulation, realistic

crowd emotion imitation, fire event evacuation and many other solutions for mitigating the severe casualties due to the panic crowd and fatal events in the closed area building.

Based on the analysis and findings, it is important to design a feasible spatial layout for a closed area building to assist the pedestrian movement flow, especially during an emergency. Figure 1.1 shows the interrelation between the layout arrangement and pedestrian movement factors that are able to affect the safety of pedestrians during a panic situation and are applicable to solve the crowd management issue.

Based on Figure 1.1, crowd management features have been refined and classified as; 1) geodemography setting that represents the geographical setting and the demographic setting, 2) entity that represents the emergency education that has been given to increase the awareness of the crowd, and the crowd behavior for movement flow as for direction, reaction, and speed, 3) structure design that represents the structural and functional layout design and the design of emergency warning system, and 4) communication that features the news broadcast and the social network services platform (Y. Chen, Cai, Li, & Zhang, 2015; Hall, 2011; Huixian & Shaoping, 2016; X. Jiang, 2015; Lu et al., 2017; Pluchino, Garofalo, Inturri, Rapisarda, & Ignaccolo, 2014; Yan, Han, & Li, 2016; Zong & Jiang, 2016).

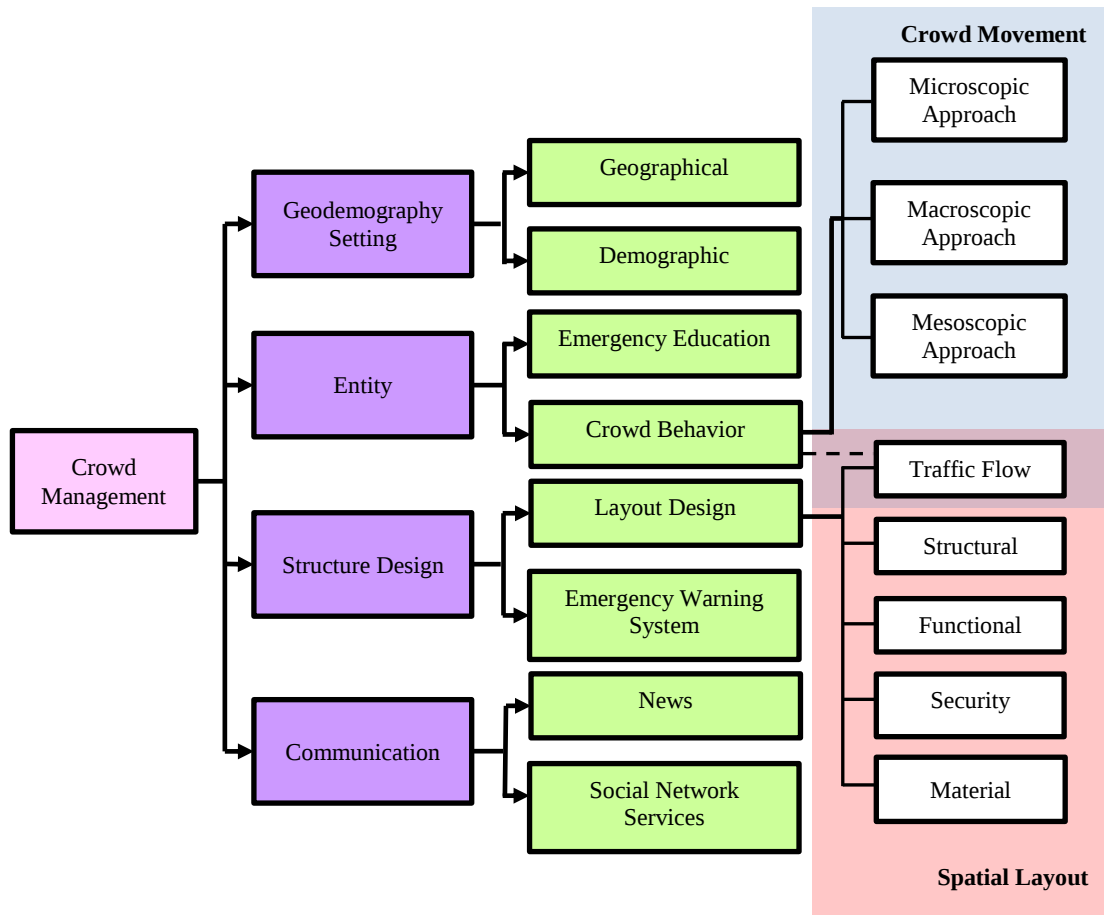


Figure 1.1 Overview of Crowd Management Features and the Relation between the Spatial Arrangement and the Pedestrian Movement

Based on Figure 1.1, the movement behavior of the pedestrian is a subset of spatial layout design for the crowd's reaction towards surroundings. The movement behavior can be classified based on the three grouping levels. The microscopic pedestrian behavior is the discrete approach that focuses on the self-organization movement approach, the macroscopic pedestrian behavior is the herding approach that focuses on a group of the crowd moving together, while the mesoscopic pedestrian behavior is the deliberative group's approach that focuses on the similarity in purpose and goal of the crowd while moving.

Spatial layout design is the physical arrangement of elements (e.g., furniture, appliances, and more) in space. It has become a necessary practice, as important as

the housing structure building and planning process. The conventional design method has been employed to construct the previous layout design that has primarily followed the standard design procedures and has been minimally influenced by cultural and economic needs (Arnolds & Nickel, 2013; Mustafa & Hassan, 2013). However, the computational aided layout design has been introduced as the autonomous technique to assist the design process for more robust, up-to-date, and urban design that meets the functional, cultural and artistic needs. This technique comes in handy for expert and novice interior designers to integrate the updated design with standard design rule (Indraprastha & Shinozaki, 2012; Regateiro, Bento, & Dias, 2012). There are many researchers working on autonomous layout design (Anjos & Vieira, 2017; Bénabès, Bennis, Poirson, & Ravaut, 2010; Chemim, Nicolle, & Kleina, 2021; Z. Guo & Li, 2017; Kubalík, Lažanský, & Zikl, 2002; J. Liu, Zhang, He, & Jiang, 2018; McKendall & Hakobyan, 2021; Rasheed, Hirsh, & Gelsey, 1997). This autonomous technique is taken part as the computer-aided design concept that never aims to replace the interior designer's intelligence and professionalism. The computer-aided design is able to facilitate the interior designer's decision-making in the early stages of the design process.

Nowadays, the autonomous spatial layout design has been improved by integrating the layout design standard with the space's users or functionality needs. Based on previous research by Rom, Palgi, and Isaacson (2022), the research analyzes the Long-Term Care Facilities (LTCFs) layout on planning the optimization of spatial layout arrangement that benefits the residents and caregivers, while research by W. Cao and Dewancker (2021) has evaluated the nursing home needs on planning the feasible spatial layout that can optimize the layout to accommodate the elderly by balancing the layout design and the wayfinding experience. There is also

research by MacAllister, Zimring, and Ryherd (2019) on the exploration of hospital layout to find the satisfaction of patients and medical practitioners in optimizing the travel distance, location, bed arrangement, and room arrangement at the hospital. To overcome the high-risk factor of infection in a laboratory layout, there is research by Zhijian Liu et al. (2020) that optimizing the laboratory layout arrangement in assisting the dispersion of bioaerosol to disinfect the pollutant particles.

The spatial layout arrangement is not limited to the elements only. There is also research on the rooms' arrangement in the large layout plan by Z. Guo and Li (2017), in which the research proposes the method of optimization of space usage in generating the optimal number of rooms in the layout. Based on the optimization of layout arrangement, there are a lot of parameters that have been focused by the researchers, such as: cost, travel distance, space occupancy, spatial usage balancing, and many more to assist the designers hence had created another challenge in finding the balance between the need and the desire of designing a spatial layout.

Based on the current incidents discussed and the technological advancement in spatial layout design, despite the enhancement on the cost, travel distance, space occupancy, and spatial usage balancing, the safety of the inhabitants still has become one of the facility layout problems to date as the pedestrians still faced a significant threat during evacuation in a panic situation that is resulting in great casualties. Hence based on these findings, the current enhancement of the computational aided process in designing the spatial layout must also meet the safety purpose to reduce the difficulties for the pedestrian during an emergency. Hence, in these recent years, there are some researchers proposed the optimization of the computation process for designing a feasible spatial layout that aims the safety design to assist the pedestrian

evacuation process (F. H. Hassan et al., 2014; Huixian & Shaoping, 2016; Lu et al., 2017; Zhao et al., 2017; J. Zhu, Li, Li, Wu, & Zhang, 2017).

These researchers' enhancement has demonstrated the importance of achieving a scalable, reliable, and accurate design for constructing a pedestrian-friendly and safe spatial layout. The previous findings have shown that the spatial layout arrangement has a significant impact that can influence, control, and navigate pedestrian movement (F. H. Hassan, 2013; Huixian & Shaoping, 2016; Miao, Lv, & Zhu, 2012; Shukla, 2009; Tcheukam et al., 2016; Wineman & Peponis, 2010; Zong & Jiang, 2016). Lewin's Equation supports these findings in human behavior interactions with surroundings as Equation 1.1;

$$B = f(P,E) \quad [1.1]$$

where **B** is the behavior or reaction, **P** is the pedestrian and **E** is the environment. This equation is made for human psychological reaction toward social and cultural forces. Based on equation 1.1, it is proven that the spatial layout of the environment also plays a great effect on human psychological reactions (Kihlstrom, 2013; Sime, 1995).

1.2 Motivations

In recent years, the closed area building has been one of the crucial spaces responsible for tremendous incidents (Booth, 2018; Jay, 2017; Lu et al., 2017; The Star Online, 2017). The incidents caused many injuries and deaths due to the challenging moments of panic that led to the entrapment of pedestrians. Based on previous research finding, pedestrian entrapment, especially during panic situation, is highly affected by the difficulty of escaping from the layout during evacuation process (Helbing, Farkas, Molnar, & Vicsek, 2002; Huixian & Shaoping, 2016;

Sime, 1995; Tcheukam et al., 2016). The findings from the previous research show that crowd management and layout design play a significant role in ensuring pedestrian safety during evacuation. Therefore, it is imperative to have closed area spaces that have a good layout arrangement and comply with security building standards for accommodating pedestrians and facilitating traffic flow, particularly during emergency situations.

Research conducted by Sime (1995), Helbing and Johansson (2009), Huixian and Shaoping (2016), F. H. Hassan (2016), Jia, Yue, Tian, and Yin (2017), and R. Wang, Zhang, and Yue (2017) have proposed the utilization of pedestrian movement simulations as the tool to assist the right authorities, building developers, and interior designers in managing, designing and validating the development of secure layouts that can prevent accidents and anticipate emergencies. By exploiting the simulations, the professionals can better understand the pedestrians' movement behavior and decision-making through various environments and manipulate the knowledge to improve safety measures. The pedestrian simulation can be the instrument for identifying potential hazards and proposing effective strategies to mitigate risks. This approach can promote safer and more secure environments for all individuals. Therefore, simulating the near-realistic pedestrian movement will significantly improve the accuracy of feasibility and safety of spatial layout.

Computer-aided layout design has been introduced for solving the facility layout problem by aiding the conventional design process to construct a variety of layout designs, and it is able to decrease the planning cost and the time consumption (Anjos & Vieira, 2017; Indraprastha & Shinozaki, 2012; McKendall & Hakobyan, 2021; Regateiro et al., 2012). Previous studies have proposed various design

approach methods and shown significant findings while highlighting the importance of optimal layout structure and functionality in ensuring pedestrians' smooth traffic flow and safety (F. H. Hassan et al., 2014; Helbing & Johansson, 2009; Huixian & Shaoping, 2016; Jia et al., 2017; R. Wang et al., 2017). However, despite the technological advancements in aiding the design process and customizing a feasible layout, the suboptimal layout arrangements can still hinder pedestrian movement and traffic flow in the layout.

The ineffective layout design caused a tremendous number of entrapment incidents in the layout during emergencies (Yixuan, 2022). Research by Yixuan (2022) has highlighted the significant impact of optimizing interior resources' allocation and occupancy within the layout. This approach can improve the overall quality of life and the environment rather than focusing solely on the layout structure and functionality. The arrangement and allocation optimality are the new approaches to ensure the traffic flow and the safety of the pedestrians in the layout. However, based on the previous research, the optimality of the layout has come with several disadvantages that caused the non-standard layout design and limitation on the space occupancy (Anjos & Vieira, 2017; Bénabès et al., 2010; Chemim et al., 2021; Z. Guo & Li, 2017; Kubalík et al., 2002; J. Liu & Liu, 2019; J. Liu et al., 2018; McKendall & Hakobyan, 2021; Rasheed et al., 1997; Yahya & Saka, 2014). Hence, it is necessary for the computer-aided layout design to exploit the suitable optimization method for constructing the high occupancy elements' layout while adapting the architecture building design policy in constructing the space arrangement.

1.3 Research Problems

Facility layout has grown in complexity and scale, the pedestrian movement has become extremely intricate. Hence, the pedestrian safety has become the major concern especially during evacuation process during emergencies. From a holistic perspective, pedestrian safety encompasses several factors that include the accident prevention, traffic flow and the reduction of potential hazards. Hence, the facility layout optimization shows the correlation with the improvement of pedestrian safety in constructing the safe pathways. Various approaches have been proposed to mimic realistic human movement modeling, especially in simulating evacuation behavior and movement. Researchers have established pedestrian simulation models to re-create the situation to reach the realistic movement of pedestrians that involves many kinds of target objects as the obstacle parameters in the layout and varieties of movement transition and navigation approach for mimicking the pedestrian movement, reflex, and decision-making (F. H. Hassan, 2016; Huixian & Shaoping, 2016; Miao et al., 2012; H. Wang, Wang, Hu, & Liu, 2016). The near-realistic pedestrian movement is important to ensure the accuracy of the simulation.

The pedestrian simulation design requires precise imitation of individual characteristics and decision-making involving interactions and movement navigation, especially for predicting pedestrian movement during panic situations (Mohd Ibrahim, Venkat, & Wilde, 2017; Pan, Han, Dauber, & Law, 2007). However, most studies focus on the separate characteristics and research problems causing unrealistic human decision-making and behavior, leading to inaccurate pedestrian modeling. Research by F. H. Hassan (2013) proposed the Cellular Automata (CA) model as the pedestrian simulation discrete modeling approach. This research does

not encompass the global interactions of pedestrian modeling as it utilizes dynamic local neighbor interactions to avoid physical collisions while navigating with predetermined movement directions for global interactions, resulting in long travel distances.

Research by R. Liu et al. (2016) has proposed the Agent-Based Model (ABM) as the discrete modeling approach with selective local neighbor interactions that force the movement through the static obstacles in the layout while avoiding collision with other pedestrians who act as dynamic obstacles. R. Liu et al. (2016) implemented the dynamic global interactions model, the Social Force Model (SFM), that affects movement navigation to find the less clogged exit point. However, in the existing models, there is no interaction between the human eyes-view and intelligence in decision-making, as the pedestrians will stick to the initial selected exit throughout the evacuation process. Hence, this approach lacks accuracy as realistically, humans will keep updating their status for every time step to reach the suitable, less clogging, and shortest path toward the nearest exit. Based on the proposed idea by F. H. Hassan (2013) and R. Liu et al. (2016), both simulations can imitate the near-realistic pedestrian movement but lack of accuracy. It is vital to improve pedestrian modeling to promote realistic dynamic local and global interaction for developing a pedestrian simulation.

The positioning of the walkways, emergency exits and gathering places must be planned in designing a layout to reduce the potential of physical collision and congestion. However, whether the construction sites, manufacturing plants, office complexes or public spaces, the arrangement of physical components within a facility plays a crucial role in determining overall space productivity and

functionality. There are a lot of research has been developed to solve the facility layout problem, aiming to find the optimal design by focusing on the several parameters such as cost, travel distance, space occupancy and spatial usage balancing (Besbes, Zolghadri, Affonso, Masmoudi, & Haddar, 2020; Lim, S.G, & Izui, 2016; J. Liu & Liu, 2019; L. Ma et al., 2022; Rahbar, Mahdavinejad, Markazi, & Bemanian, 2022; Turanoğlu & Akkaya, 2018).

Research by Anjos and Vieira (2017) has highlighted an enhancement of the facility layout problem using mathematical optimization to overcome the optimal layout solution in a reasonable compute time. Research by J. Liu and Liu (2019) has utilized the Ant Colony Optimization (ACO) approach in optimizing the unequal area facility layout and space occupancy for department formation. Turanoğlu and Akkaya (2018) research has implemented Bacterial Foraging Optimization (BFO) to optimize the layout for material handling cost. Research by Z. Guo and Li (2017) has introduced spatial occupancy optimization using an agent-based topology finding system to maximize the number of rooms in the layout based on the solution limitation; layout structure and size. However, one of the critical aspects that really garnered extra attention in recent years is the impact of the layout arrangement on the traffic flow and crowd safety. The arrangement of the objects in the layout can impact the pedestrians' visibility and surroundings awareness that able to ensure the pedestrian safety.

Research by Bénabès et al. (2010) has enhanced the optimal spatial arrangement by using Genetic Algorithm (GA) and a Separation Algorithm to introduce the space accessibility concept. Research by Rahbar et al. (2022) has hybrid the deep learning computation and Agent-Based Model (ABM) to optimize

the layout arrangement for space assessment and spatial usage balancing. Hence, the optimization of layout objects' arrangement have a great impact on shaping the pedestrian movement as the pedestrians will always make local interactions to avoid collision and finding the best destination through the global interactions.

The previous research on layout optimization has highlighted the findings on the issues of overlapping layout objects, low space occupancy, and random location of the objects' placement (Anjos & Vieira, 2017; Bénabès et al., 2010; Chemim et al., 2021; Z. Guo & Li, 2017; Kubalík et al., 2002; J. Liu & Liu, 2019; J. Liu et al., 2018; McKendall & Hakobyan, 2021; Rasheed et al., 1997; Yahya & Saka, 2014). Hence, it is important for the optimization algorithms to solve multi-objective problems while involving large number of variables and complex constraints. The facility layout optimization requires to balancing multiple objectives for minimizing the number of overlap objects to improve the space occupancy and maximizing the layout quality to meet the layout standard design. The optimization algorithms also must have ability to do solution space exploration and exploitation for ensuring the layout arrangement is truly optimized. Thus, it is important to find the suitable optimization method for adapting the requirements and characteristics in arranging the objects for a feasible layout design and ensuring the pedestrian safety.

The optimal layout arrangement will able to assist the pedestrian movement especially during panic situations (F. H. Hassan, 2016; F. H. Hassan et al., 2014; Helbing, Farkas, & Vicsek, 2000; Helbing et al., 2002). Research by Rahbar et al. (2022) has mentioned the validation of the optimized layout by using the footprint heatmap to find a practical layout for optimizing the space assessment, while research by L. Ma et al. (2022) has combined the ventilation multi-zone model and

spatial flow impact factor in finding the better layout in reducing the risk of infection in large space buildings and ensuring the public health safety. Based on the previous study, it is essential to validate the optimization layout based on the case study. Based on these findings, it is important for a closed area building to have a layout arrangement that is based on the space design standard that able to assist the pedestrian movement flow and navigation, especially during the evacuation process in a panic situation.

Research by F. H. Hassan (2013) has highlighted the use of pedestrian movement simulation for highlighting the impact of pedestrian movement in the spatial layout as the validation of the safety layout design construction. Research by Helbing et al. (2002) has highlighted the impact of the layout design on the pedestrian movement characteristics by simulating the pedestrian simulation with obstacle in front of the exit to divert the moment and reduce the pressure. Hence with the computer-aided process, these research trends highlighted the importance of manipulating the correlation between pedestrian movement and spatial layout design to validate the safety of the layout.

Based on the research problem highlighted, research aims to optimize and enhance the autonomous spatial layout arrangement with the bio-inspired optimization model for obtaining the high occupancy of space arrangement that meets the spatial layout design standard and to improve the pedestrian modeling for imitating the realistic pedestrian movement in pedestrian simulation for validating the spatial layout design in constructing a feasible layout that is safer and able to increase the pedestrian movement flow, especially during the evacuation process.

1.4 Research Questions

- i. How to improve pedestrian modeling using the microscopic approach for constructing a near-realistic pedestrian movement simulation to validate the spatial layout design?
- ii. How to exploit bio-inspired algorithms to maximize space occupancy while complying with building design standards for optimizing the autonomous spatial layout arrangements?
- iii. How to enhance the optimized layout arrangements using population-based multi-objective evolutionary algorithms to achieve effective optimization results?

1.5 Research Objectives

This research aims to optimize the construction of a spatial layout design with the incorporation of enhanced pedestrian movement simulation for resolving the safety of the layout in reducing pedestrians' casualties during a panic situation. Hence, the research objectives of this crowd management solution in the closed area building are as follows:

- i. To construct a near-realistic pedestrian movement simulation by integrating the Agent-Based Model (ABM) and Social Force Model (SFM) for modeling the dynamic behavior and human-like decision-making on local and global interactions with density estimation.
- ii. To optimize the autonomous spatial layout arrangement with multi-objective functions and a solution acceptance rule using the Artificial Bee Colony

(ABC) algorithm and Genetic Algorithm (GA) to maximize the number of layout elements.

- iii. To propose the integration of the Artificial Bee Colony (ABC) algorithm and Genetic Algorithm (GA) for optimizing layout elements' space occupancy for fast premature convergence, balance searching method, and balance solution extrema.

1.6 Research Scope

This study focuses on pedestrian modeling for constructing the near-realistic pedestrian simulation and spatial layout design for auto-generate the layout's elements' arrangement. The near-realistic pedestrian simulation is important for mimicking human intelligence and behavior. Thus, it will be able to assist the future layout design in validating the elements' arrangement. The result of the pedestrian simulation will be the estimation of evacuation time (s) and travel distance (m). The result of the pedestrian simulation is unable to be accurate but approximate due to the probability of the location of the pedestrians being spawned in the layout. Hence the pedestrian simulation will be generated 10 times to find the highest accuracy of the evacuation time and travel distance.

The spatial layout design will be optimized in this study to find the highest occupancy of the elements' allocation in the layout while implementing the multi-objective function; 1) non-overlapping and no elements exist in less than 1.2 m from the walls and doors of the layout. The layout arrangement process will have the optimization limitation as the solution acceptance rule to ensure the number of elements generated in the layout will not exceed the number of the element being loaded into the spatial layout. The result of the auto-generated layout arrangement

will be the number of elements available in the layout after the 1.2 m walkways from the doors and walls are cleared.

This research will manipulate the spatial layout of DKG31 at the School of Computer Sciences, Universiti Sains Malaysia (USM), as the training layout for generating the elements' arrangement.

1.7 Research Contributions

- i. Developing an enhanced pedestrian movement simulation by enhancing the Cellular Automata (CA) with the integration of ABM and SFM methods to form ABM-SFM pedestrian simulation for mimicking human intelligence in decision-making and realistic reactions during a panic situation.
- ii. Designing an autonomous spatial layout arrangement with Artificial Bee Colony (ABC) algorithm and Genetic Algorithm (GA) with multi-objective functions and solution acceptance rule to achieve the standard space design with optimal number of layout elements.
- iii. Constructing high element occupancy of automatic spatial layout design by optimizing the selection process and exploitation phase in the ABC algorithm with GA approach to form ABC-GA spatial layout arrangement method.
- iv. Proposing the optimal spatial layout arrangement with preferable pedestrian movement flow to ensure the safety of the pedestrians during panic situation for evacuating..

1.8 Overall Correlation View of the Thesis

Table 1.1 shows the correlation between the problem statements, research questions, research objectives, methods proposed and contributions of this research

Table 1.1 The Correlation between the Problem Statements, Research Questions, Research Objectives, Methods and Contributions

	Problem Statement	Research Questions	Research Objectives	Support Literature	Chapter	Methodology	Research Contributions
1.	The existing microscopic approach cannot construct the near-realistic pedestrian simulation due to the inaccuracy of the integration of pedestrian behaviors within the panic environmental context.	How to improve pedestrian modeling using the microscopic approach for constructing a near-realistic pedestrian movement simulation to validate the spatial layout design?	To construct a near-realistic pedestrian movement simulation by integrating the Agent-Based Model (ABM) and Social Force Model (SFM) for modeling the dynamic behavior and human-like decision-making on local and global interactions with density estimation.	F. H. Hassan (2016) Huixian and Shaoping (2016) Miao et al. (2012) H. Wang et al. (2016)	Chapter 4	Enhancement of the pedestrian microscopic simulation: 1) Movement behavior and direction 2) The shortest distance movement 3) The effect on clogging region.	Develop ABM-SFM pedestrian simulation for mimicking the human intelligence in decision making and realistic reactions during panic situation.

Table 1.1 Continued

	Problem Statement	Research Questions	Research Objectives	Support Literature	Chapter	Methodology	Research Contributions
2.	The exploration of bio-inspired algorithms offers a promising spatial layout design for maximizing space occupancy. However, integrating these algorithms effectively with multi-objective functions poses a significant research gap.	How to exploit bio-inspired algorithms to maximize space occupancy while complying with building design standards for optimizing the autonomous spatial layout arrangements?	To optimize the autonomous spatial layout arrangement with multi-objective functions and a solution acceptance rule using the Artificial Bee Colony (ABC) algorithm and Genetic Algorithm (GA) to maximize the number of layout elements.	Helbing et al. (2002) Huixian and Shaoping (2016) Sime (1995) Tcheukam et al. (2016)	Chapter 5	Optimizing the autonomous spatial layout arrangement design with Artificial Bee Colony (ABC) algorithm and Genetic Algorithm (GA) based on; 1) Objective functions: Non-overlapping and design standard (1.2 m of walkways near doors and walls) 2) Solution acceptance rule: ≤ 300 elements in the layout	Designing an automatic spatial layout arrangement with Artificial Bee Colony (ABC) algorithm and Genetic Algorithm (GA) with multi objective functions and space design standard

Table 1.1 Continued

	Problem Statement	Research Questions	Research Objectives	Support Literature	Chapter	Methodology	Research Contributions
3.	The optimization of layout elements' space occupancy is a critical aspect in facility design. With the multi-objective functions, there are challenges and limitation need to be explore on the integration of advance optimization algorithms. However, precise integration strategy remains a research gap in overcoming the identified challenges in optimizing space occupancy.	How to enhance the optimized layout arrangements using population-based multi-objective evolutionary algorithms to achieve effective optimization results?	To propose the integration of the Artificial Bee Colony (ABC) algorithm and Genetic Algorithm (GA) for optimizing layout elements' space occupancy for fast premature convergence, balance searching method, and balance solution extrema.	Anjos and Vieira (2017) Bénabès et al. (2010) Chemim et al. (2021) Z. Guo and Li (2017) Kubalík et al. (2002) J. Liu et al. (2018) McKendall and Hakobyan (2021) Rasheed et al. (1997)	Chapter 5	1) Integrating the local search of the GA algorithm with the local search of the ABC algorithm 2) Optimizing the autonomous spatial layout arrangement design with ABC-GA technique based on; a) Objective functions: Non-overlapping and design standard (1.2 m of walkways near doors and walls) b) Solution acceptance rule: ≤ 300 elements in the layout	Constructing high element occupancy of automatic spatial layout design with ABC-GA spatial layout arrangement method.

1.9 Thesis Organization

This thesis consists of six chapters organized as follows:

Chapter 2: Gives an overview of the related work of focused research; pedestrian simulation and spatial layout design. The chapter discusses the relation between the surrounding scenarios and pedestrian behavior, motion, and interaction. The spatial layout design standard and autonomous approach are also being explored for optimizing the layout arrangement.

Chapter 3: Discusses the methodology of this research, which consists of the theoretical and conceptual frameworks.

Chapter 4: Presents the experimental analysis of the proposed idea for enhancing the pedestrian modeling to construct the near-realistic pedestrian simulation; 1) Pedestrian behavior modeling, 2) Pedestrian pathfinding modeling, and 3) Enhanced simulation validation.

Chapter 5: Presents the experimental analysis of the proposed work for optimizing the autonomous layout arrangement design; 1) Comparing the selected bio-inspired methods, and 2) Optimizing the layout arrangement by integrating the selected methods.

Chapter 6: Summarizes and concludes the thesis and some recommendations on the works.

CHAPTER 2

PRELIMINARIES AND RELATED WORK

2.1 Introduction

This chapter covers a comprehensive related works of two research fields: pedestrian simulation and spatial layout design. The synergy of these domains will unlock the potential solution for enhancing the pedestrian safety and minimizing the fatalities in the closed area space. The pedestrian simulation research covers the case scenario in classifying the pedestrian behavior characteristics based on the surrounding situation for the pedestrian actions, interactions and movements. The identified behavioral characteristics will be the fundamental properties for the pedestrian modeling development that tailored to the panic situation in a closed area.

The spatial layout design research covers two important features: the spatial layout design characteristics and the automation of layout arrangement. The spatial layout design characteristics will cover the fundamental of planning the floor design that involve the shape of the layout grid that can influence the possible pedestrian's transition flow structure and also the layout scaling to meet the human standard size. Besides that, the spatial layout design characteristics also cover the spatial layout design standard that provides the insights on the closed space design's rules for pedestrian safety composition. The autonomous layout arrangement will cover the optimization approach on designing an optimal spatial layout that able to generate a high elements occupancy layout while complying with the standard design rule. The summary of the chapter is given.

Pedestrian simulation characteristics are discussed in section 2.2, while pedestrian modeling for self-organizing movement and interaction during panic

situations is discussed in section 2.3. Spatial layout design characteristics and standards are discussed in section 2.4, and the related bio-inspired algorithms for spatial layout optimization are analyzed in section 2.5. The section 2.6 is discussing on the current related works and the direction pedestrian simulation modeling and autonomous spatial layout design optimization. The summary of this chapter will be discussed in section 2.7.

2.2 Pedestrian Simulation: Near-Realistic Pedestrian Behavior

Nowadays, extensive research has been conducted on the simulation movement of pedestrians in a closed space to discover the crowd behavior that encompasses all of the crowd actions and movement, especially during a panic situation. The research aims to find solutions or insights in reducing the incident likelihood and minimizing the fatalities (F. H. Hassan, 2016; Konstantara, Dourvas, Georgoudas, & Sirakoulis, 2016; Ruiz & Hernández, 2015; Schadschneider, Chraïbi, Seyfried, Tordeux, & Zhang, 2018; H. Wang et al., 2016; Zong & Jiang, 2016). Hence, modeling the near-realistic pedestrian behavior has become vital in developing accurate pedestrian simulations to ensure the model is aligned with real-world scenarios. Such simulation plays an essential role in enhancing the simulation result, reducing the number of casualties, and preventing the incident occurrence. Pedestrian simulation can be developed based on pedestrian behavior modeling that encompasses the pedestrian's characteristics, pedestrian interaction that covers the actions and decision-making, and also the movements (Mohd Ibrahim et al., 2017; Pan et al., 2007). Figure 2.1 shows the detailed distribution of the classification of the pedestrian modeling.

Based on Figure 2.1, the pedestrian modeling for pedestrian simulation can be construct by considering the three important features that cover human's traits and behavior; individual characteristics, interaction and movement. The individual

characteristics of pedestrian can be divided into; psychological and physical characteristics. Psychological characteristics of human can be seen as the level of mental state of a person that can be classify based on the intelligence especially in decision-making, familiarity towards the surrounding that can easily assist the pedestrian to rely on the brain and muscle memory, current life motivation to project the intention, and emotion that show the distinct and unique human personality that can affect towards the adjustment of life, values and self-concept.

The physical characteristic of human can be seen as the body size, weight, height, movement speed, strength, age, gender, visibility range, and body positioning. Both psychological and physical elements are the individual characteristics that become the fundamental in setting up the first attributes in pedestrian modeling as the features of a person are set and develop that can give significant impact on the interaction and movement modeling approach.

Pedestrian interaction is the action taken by a pedestrian based on the current neighbors' influence and surroundings' condition and state. The neighbors' influence is the local interaction of the pedestrians with other pedestrians and obstacles that promotes collision avoidance, decision on the neighborhood transition, and monitoring radius. Whereas global interaction is the impact of the environment towards pedestrian behavior, decision-making, and movement based on the egress effect, congestion effect, and condition pressure. Modeling a pedestrian's decision-making, interaction, and movement requires several principles and procedures by imitating the human's unique, continuous, and realistic behavior.