Using a Hybrid Space Discretisation for Urban Scale Evacuation Simulation

Abstract

The increasing number of past incidents have shown that areas that need to be evacuated during emergencies can be extremely large, comprising of considerable population sizes. As such it is crucial to show that these areas can be evacuated safely. This can be achieved through evacuation trials that comprise of full scale evacuation experiments. However, this approach can become prohibitively expensive and can expose the occupants to risks of injury. Evacuation simulation tools provide a viable alternative for assessing egress safety. It is therefore of paramount importance for evacuation simulation tools to be able to handle the complexity of large scale egress. Egress models typically use one of three methods to represent the physical space in which the agents move, namely: Coarse regions, Fine nodes or Continuous regions. In this work, we have demonstrated how the different spatial representations can be interfaced within a single integrated software tool to represent the movement and interaction of agents. We refer to this model as the Hybrid Spatial Discretisation (HSD) and present its capabilities in allowing users to define different discretisation schemes depending on the granularity of the evacuation results required and in optimising the computational efficiencies for the evacuation simulations.

Keywords: city evacuation, hybrid evacuation model, hybrid spatial discretisation, urban scale egress simulation

1. Introduction

Real incidents which have occurred in the past demonstrate that egress situations can take place over very large areas comprising of extremely large population sizes. Examples include: Hajj disaster (Saudi Arabia 2015) [1], Gorkha earthquake (Nepal 2015) [2], Tohoku earthquake and tsunami (Japan 2011) [3], Chilean volcanic eruption in 2011 (Chile 2011) [4], Love Parade disaster (Germany 2010) [5], Katrina hurricane (USA 2005) [6] and the World Trade Centre disaster (USA 2001) [7]. The coordination and management of the evacuation of large numbers of affected people in areas of such enormous proportions can pose considerable challenges. In order to ascertain the safety of extremely large enclosures, for example when preparing emergency response plans, it is crucial to demonstrate whether these highly populated areas can be emptied quickly and efficiently during emergencies and disasters.

During large scale disasters and emergencies, simply warning the population to evacuate threatened areas is not sufficient, rather warnings become more effective when the affected people are informed about alternative evacuation routes and associated hazards and dangers, as well as safety locations [8]. Information related to the selection of safety locations and appropriate egress routes can be obtained through the use of evacuation simulation tools. Evacuation planners, safety managers, engineers and personnel involved in emergency response planning and design of emergency procedures can use these tools to better understand evacuation characteristics and determine appropriate evacuation routes for example, routes which avoid steep gradients or potential hazardous areas.

In addition to the capability of evacuation simulation tools in providing reliable estimates, it is also vital for these tools to provide results of simulations faster than real time. Faster simulations can assist emergency response personnel by guiding ongoing decision-making during the unfolding of actual egress situations [9]. However, it is particularly challenging for simulation tools to provide detailed evacuation results faster than real time when the size of the environment being modelled is extremely large and complex with a substantial population. All evacuation and pedestrian dynamics models need some way to represent the physical space in which the agents move and interact. Models typically use one of three basic approaches to represent space [10]; a continuous representation of space e.g. Pathfinder [11], a fine network of nodes e.g. buildingEXODUS [9] or Coarse regions e.g. PEDROUTE [12]. Each method has its benefits and limitations for instance, the Continuous approach allows accurate representation of agent movement and interaction but suffers from relatively poor computational performance; the Coarse region allows for very fast computation but cannot represent the agents from an individual perspective. The Fine nodal approach represents a compromise between the 2 extremes whereby it can represent the navigation and interaction of agents while providing good computational performance. While there are agent based evacuation tools which attempt to simulate large scale egress situations as a result of incidents such as earthquakes and floods [13], however, these models use only one of the three approaches to represent physical space in which the agents navigate, therefore limiting the user only to the features and advantages offered by that particular paradigm.

Previously Chooramun et al. [14][15] presented a novel approach, known as the Hybrid Spatial Discretisation or HSD to represent the discretisation of space in circulation and evacuation simulation models. The HSD approach, implemented within the buildingEXODUS version 6.2.0 software, allows enclosures to be modelled using a mixture of Coarse regions, Fine nodes and Continuous spaces and is identified as the bEX-Hybrid (bEX-H). The HSD approach integrates the benefits of the three spatial representation methods and maximises computational efficiency while providing an optimal environment to represent the movement and interaction of agents. For instance, in an ideal application of the HSD approach, the Fine nodal approach would be used to map the majority of the geometry, thus providing good computational performance and representing agent interaction. In parts of the geometry where greater precision is required to model more complex agent interactions, the Continuous regions can be used. Then, in areas where agent movement is homogeneous, the Coarse regions can be used to provide improvements in computational performance.

In this paper, we demonstrate the flexibility and scalability of the HSD approach to simulate the evacuation of an extremely large and complex urban environment using a mixture of spatial representation approaches. In the first instance, we demonstrate the application of bEX-H to the urban environment using the Coarse regions and compare it to the Fine nodal approach. We then show how the bEX-H can be used to create a hybrid configuration by combining both Coarse regions and Fine node networks for representing different segments of the urban geometry and discuss related evacuation simulation results and performance considerations.

2. Software Architecture

The bEX-H makes use of the core architecture of the buildingEXODUS software, which utilises the Fine nodal approach. The buildingEXODUS software has been modified to allow plug-in modules to be included into the core software using a component oriented engineering approach. This architecture provides a platform whereby new functionalities can be independently developed and incorporated into the model as required. The Coarse region and Continuous region are examples of two components which have been developed as plug-in modules for the bEX-H model. Figure 1 illustrates an overview of the system architecture of the Hybrid Spatial Discretisation model.

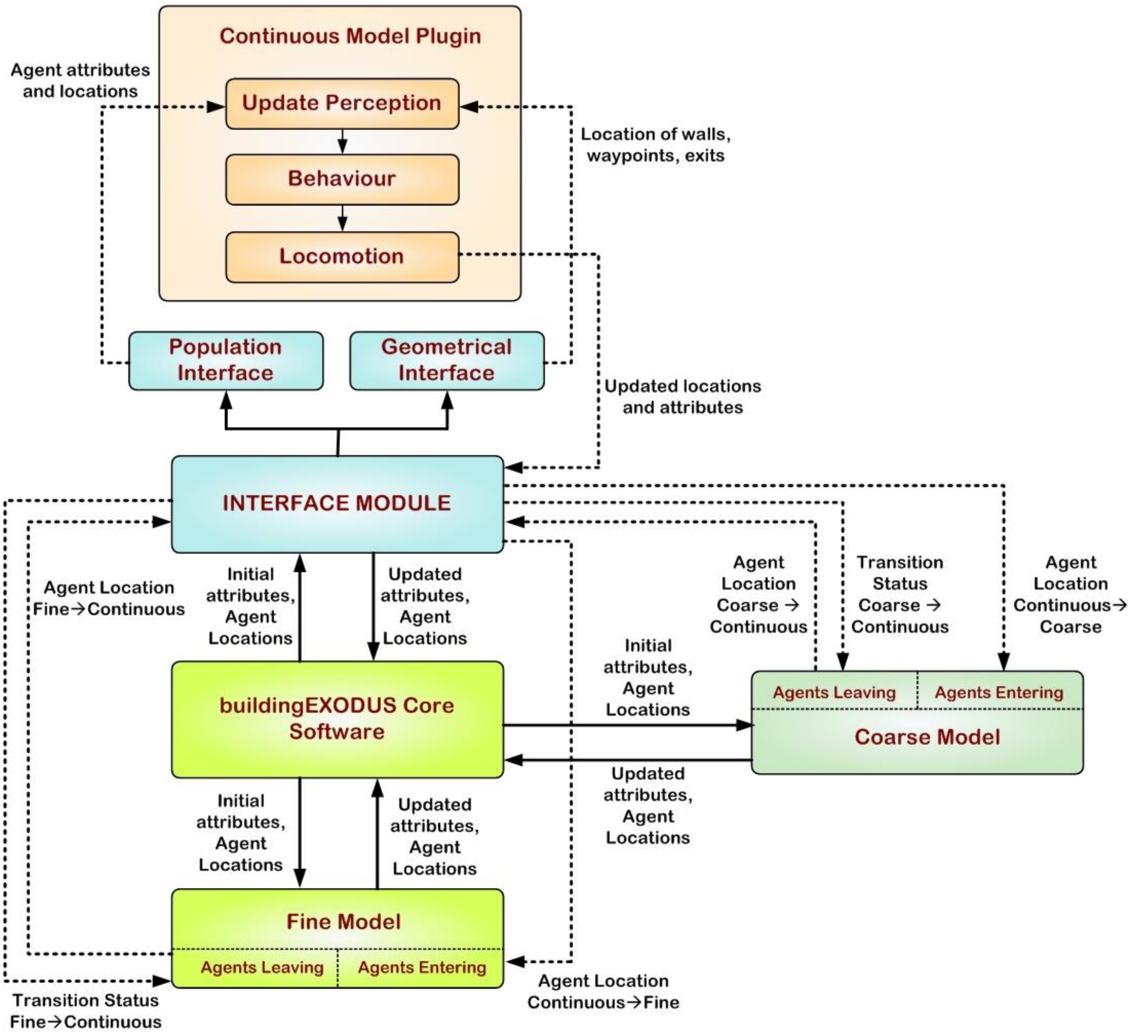

Figure 1 Spatial Discretisation System Architecture

Key:

Agent Location A→B	Position of the agents before they transit from A to B
Transition Status A→B	Boolean flag which confirms whether the agents can physically transit from A to B where A and B represent Fine, Coarse or Continuous.

Agents leaving and Agents entering signifies agents leaving and entering the Fine Node network

The Interface Module is a key component within the architecture and acts as intermediate layer between the buildingEXODUS Core Software and the component modules. The Interface Module is divided into two sub modules namely a Geometrical Interface and a Population Interface which control the enclosure characteristics and the agent model respectively. bEX-H allows simulations to be run using a combination of Coarse regions, Fine nodal networks and Continuous spaces which implies that agents are likely to transit across different spatial types during the simulation. bEX-H incorporates behavioural and movement mechanisms to facilitate the transition of agents across all six possible interface transition regions namely: Coarse region ↔ Fine Node; Fine Node ↔ Continuous and Coarse region ↔ Continuous. The different spatial types are connected to each other via arcs and the endpoints of those arcs are used as waypoints to guide the transition of the agents

When the agents transit from one spatial representation type to another, the agent attributes (e.g. age, gender, body width) are maintained while the experiential attributes (e.g. distance travelled, cumulative wait time) are updated accordingly during the simulation. Moreover, although the graphical output of Coarse regions in bEX-H only illustrates the total number of agents within the node at any point during the simulation, the underlying algorithmic procedures keep track of the individual identities of each agent. Furthermore, the locations of the agents along the arcs of the Coarse region's navigational mesh are also recorded [14]. The navigational mesh is a key data structure behind a Coarse region which allows the creation of non-convex Coarse regions and enables the different spatial types to be linked. Using these methodologies, the HSD model is able to keep track of the agents which have reached their exit points within the Coarse regions, and re-position those agents into the adjacent segment of physical space represented by the Fine node or Continuous region.

3. Suitability of spatial representation techniques

The geometrical construction tools in bEX-H allow the flexibility of manually specifying the hybrid discretisation schemes for enclosures as follows: All-Fine (entire geometry mapped using only Fine nodes); All-Coarse (using only Coarse regions); All-Continuous (using only Continuous regions) and Hybrid (using different combinations of Fine, Coarse and Continuous). However, the choice of a suitable hybrid discretisation scheme is essential in order to optimise computational efficiency and accuracy. In this section, we examine the characteristics of each spatial representation technique and discuss how these can be utilised to map a geometry.

Coarse Region

The Coarse region approach allows the physical space being modelled to be segmented into regions which can represent different sections of the geometry. The representation of enclosures using such regions greatly simplifies the layout of the geometry and such an approach can make it easier to manage large enclosures in simulations, both from the perspective of the user and the model. The agents within the Coarse approach transit from one region to another such that the agent movement within the region itself is not explicitly represented. The flow rates through the Coarse regions are calculated based on Flow to Density equations [12]. In addition, the travel speeds of the agents are adjusted based on the type of regions (e.g. intersection, junction, stairs and escalators) through which the agents are traversing. Coarse models are data driven such that their results can be adapted by introducing different flow to density relationships [16].

In Coarse models, the interaction between the occupants (e.g. overtaking and local conflict resolution) and the interaction between the occupants and the structure (e.g. obstacle avoidance) are not explicitly represented. As such, the low granularity of the Coarse regions provides significant improvements in speed and computational efficiency. Coarse regions can be used where knowledge of detailed agent interaction is not required and also for areas in the far field of the geometry which are not deemed necessary to be explicitly modelled. In addition, Coarse models are most applicable for modelling scenarios where the occupants are expected to show homogeneous behaviour, for instance behaviour of occupants moving in the same direction across a road. This approach is also useful for identifying areas of particular interest for example, areas where maximum flows can be achieved or regions which might be prone to congestion and bottlenecks.

The nature of the Coarse region approach restricts the modelling of regions with simple geometrical shapes which may not adequately represent model complex segments within enclosures. In order to increase the accuracy of the geometrical representation, the Coarse model in bEX-H allows the creation of non-convex regions. Such regions automatically generate an underlying Navigational Graph which in turn provides the necessary information to model the flow of occupants within the Coarse regions[14].

The high computational efficiency of the Coarse region representation makes it suitable for obtaining very quick estimates on the egress situation, while awaiting more detailed information from simulations run in the Fine or Continuous models.

Fine node

The Fine nodal approach allows the creation of geometrically complex layouts and the representation of barriers and internal obstacles which can have a significant impact on the choice of route of the occupants. Furthermore, occupants can be modelled from an individual perspective in the sense that each occupant has a unique location (the occupant occupies the centre location of the node) and their movement can be accurately tracked throughout the simulation. Therefore, it allows the representation of a more diverse population, with each occupant having different traits.

Fine node models demonstrate superior computational performance as compared to Continuous models. This is because the discrete spatial representation allows for faster computation of people to people and people to structure interactions. Since agents in Fine node networks can only navigate to regions occupied by nodes, boundaries and obstacles within the enclosure can easily be modelled by removing relevant nodes and creating gaps of empty spaces around the wall boundaries and obstacles. In this respect, the agents are not required to explicitly perform computationally expensive collision detection checks with the boundaries of the enclosure and internal obstacles. Furthermore, agents in Fine node networks can readily retrieve the neighbouring agents by identifying agents located on surrounding nodes and therefore, computationally expensive spatial search routines are not required. In addition, the Fine nodal structure prevents any form of overlapping of agents and therefore, agents are not required to perform expensive collision detection and avoidance strategies with neighbouring agents. The Fine node model provides good computational performance when modelling agent-to-agent and agent-to-structure interactions in the near field. However, representing agent behaviour based on agents or structural elements that are further away is more computationally expensive. Hence, EXODUS uses a number of "zones", for instance compartments zone, escalator catchment areas and signage VCA [17] to carry out local behaviour calculations. Agents then can access this additional information when navigating within these zones. The Fine node model has been used to simulate external large crowd situations such as for the Beijing Olympics and more recently for the Hajj [18]. For example, on a 3.6 GHz processor with 8 GB of RAM, running a simulation involving between 25,000 and 26,000 agents, with a geometry of 51,500 m^2, required 1.5 hours of computation time to complete [18].

The use of fixed node sizes forces the maximum densities to be limited. This is because the maximum packing density is restricted by the node spacing and the number of neighbouring nodes around each node. For instance, if a node size is defined with an area of 0.25 m^2 and considering that each node can only by occupied by one agent, the maximum density which can be attained at any point within the simulation is 4 persons per square metre. This level of density is considered acceptable for moving and normal static crowds. For example, Oberhagemann [19] found that even at a very slow walking pace, the maximum crowd density observed is 2.5 persons per square metre, and for static crowds, the Green Guide [20] recommends a maximum density of 1.5 persons per square metre in areas that are used for viewing and circulation. Furthermore, several pieces of empirical work have been examined [21-23] that indicate that an individual's movement becomes constrained by the developing crowd at a population density of approximately 4.0 persons per square metre. In addition, an algorithm has been developed [18] to enable the Fine node model to identify the development of the precursors to crowd crush situations.

Continuous region

The Continuous regions allow agents to be modelled using additional physical attributes which are not present in the other spatial representation approaches e.g. varying body widths and turning rate of occupants. Agents modelled in continuous space can also exhibit acceleration, deceleration, explicit overtaking and collision avoidance behaviours. The Continuous representation allows for the prediction of flow rates in non-standard or complex situations (such as contra-flows) since there may not be empirical flow rate data for such situations. In addition, the Continuous model is capable of demonstrating the emergence of certain behaviours and is particular suited for the investigation of behaviours such as lane formation in densely populated cross-flow scenarios.

However, this approach requires far more computational processing power than the Fine node and Coarse region approaches, and is therefore less scalable. Continuous models provide a qualitative improvement when representing movement patterns and paths of agents, when compared to Fine node models. However, from a quantitative perspective, although Continuous models are suitable for predicting flow rates, they are also harder to calibrate due to their increased fidelity.

4. City Block Case

In this section, we demonstrate the application of the HSD approach to an extremely large and complex city block case depicted in Figure 2. This geometry has been selected based on its scale and road network connectivity. Although the HSD approach allows mixing the 3 spatial types, however, for this case, the entire geometry was mapped using only Coarse regions and Fine nodal networks. The use of the Continuous region was not considered for this case as it would not provide the best computational efficiency on an urban scale. In our previous work [14], a preliminary verification of the Coarse model implementation in buildingEXODUS was conducted whereby the Coarse model results were compared against those of the Fine model. The Fine model has been extensively validated in numerous studies [7, 24-27] and was considered suitable for verifying the Coarse model results.

The outer boundary of the city has overall dimensions of 2 km x 2 km connected to a 200 m x 200 m assembly area. The road network comprises of dual carriageway roads of width 7 m coupled with 1.5 m wide pavements on either side [28][29]. The total free space area occupied by the network of roads and the assembly area is 214260 m^2. Moreover, the assembly area comprises of 10 compartments whereby each compartment has dimensions of 40m x 50m and is connected to a 10m wide exit.

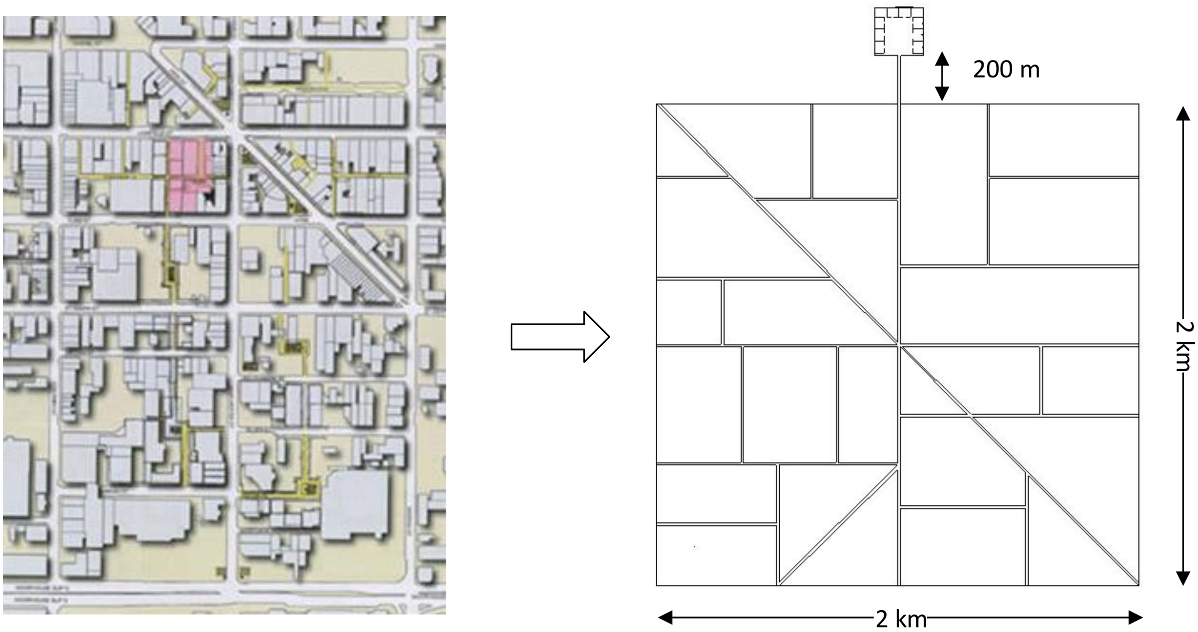

Figure 2 Large City Block geometry; empty spaces represent blocks of buildings surrounded by networks of dual carriageway roads

In the first example, All-Coarse, the geometry was set up so that the entire free space area was modelled using Coarse regions. There are seven types of Coarse regions implemented with bEX-H whereby each type uses the Flow to Density equation but with different parameters. These Coarse regions are namely; Compartment, Intersection, Interchange, Gates, Stairs, Escalators and Travelators. Given the width of the roads being modelled, the Compartment regions were found to be most appropriate, as they represent a general region in which agents enter or exit.

A population of 10 000 agents was initially distributed so that all the roads, with the exception of the 200 m road connecting the city and the assembly area, are occupied. 10% of the agent population was assigned to exit 1 as target, 10 % to exit 2 and same proportions up to exit 10. Furthermore, the agents were assigned instantaneous response times and their remaining attributes were defined as shown in Table 1. In addition, in order to allow the model to predict flow rates rather than be constrained by a predefined distribution, there were no flow rate limitations imposed on the exits.

In the second example, the large case is repeated using the All-Fine configuration. Ten simulation runs were conducted for each case as this was sufficient for our requirements for demonstration purposes. Each repeat simulation involved the same agents located within the same road segments. However, their exact location within the segments was randomised for between each simulation.

Table 1 Evacuee profile attribute default values

Category	**Attribute**	**Unit**	**Default Value**	
			Min	**Max**
Physical	Mobility	-	1.0	1.0
	Age	Years	17	80
	Weight	Kg	40	90
	Gender	-	Both male and female	
	Agility	-	2	7
	Height	M	1.5	2
Psychological	Response Time	S	0	0
	Patience	S	1	5
	Drive	-	5	15
Travel Speeds	Fast Walk	m/s	1.2	1.5
	Walk	m/s	1.08	1.35
	Crawl	m/s	0.24	0.30
	Leap	m/s	0.96	1.20
	Stair-Up	m/s	*	*
	Stair-Down	m/s	*	*
Experiential	Target Exit	-	Nearest Exit	
	Familiarity		Nearest Exit	
	Itinerary		Null	

In the third example, the large case was represented using the Coarse-Fine configuration whereby the geometry was set up so that 71% of the free space area was modelled using the

Coarse region approach and 29% of the free space area was modelled using the Fine node approach, as shown in Figure 3. The Coarse region approach was chosen for modelling the road segments surrounding the buildings in the far field because of its computational efficiency and its suitability for representing the uniform behaviours of the agents, which emerge as a result of their unidirectional motion within these road segments. All the Coarse regions converge into a middle artery road which leads to the assembly area. The middle artery and the assembly area are modelled entirely using a network of Fine nodes in order to account for more complex agent to agent and agent to structure interactions within those areas. The agent population and simulation set up used in the Coarse-Fine configuration was the same as the one used for the All-Coarse and All-Fine configurations.

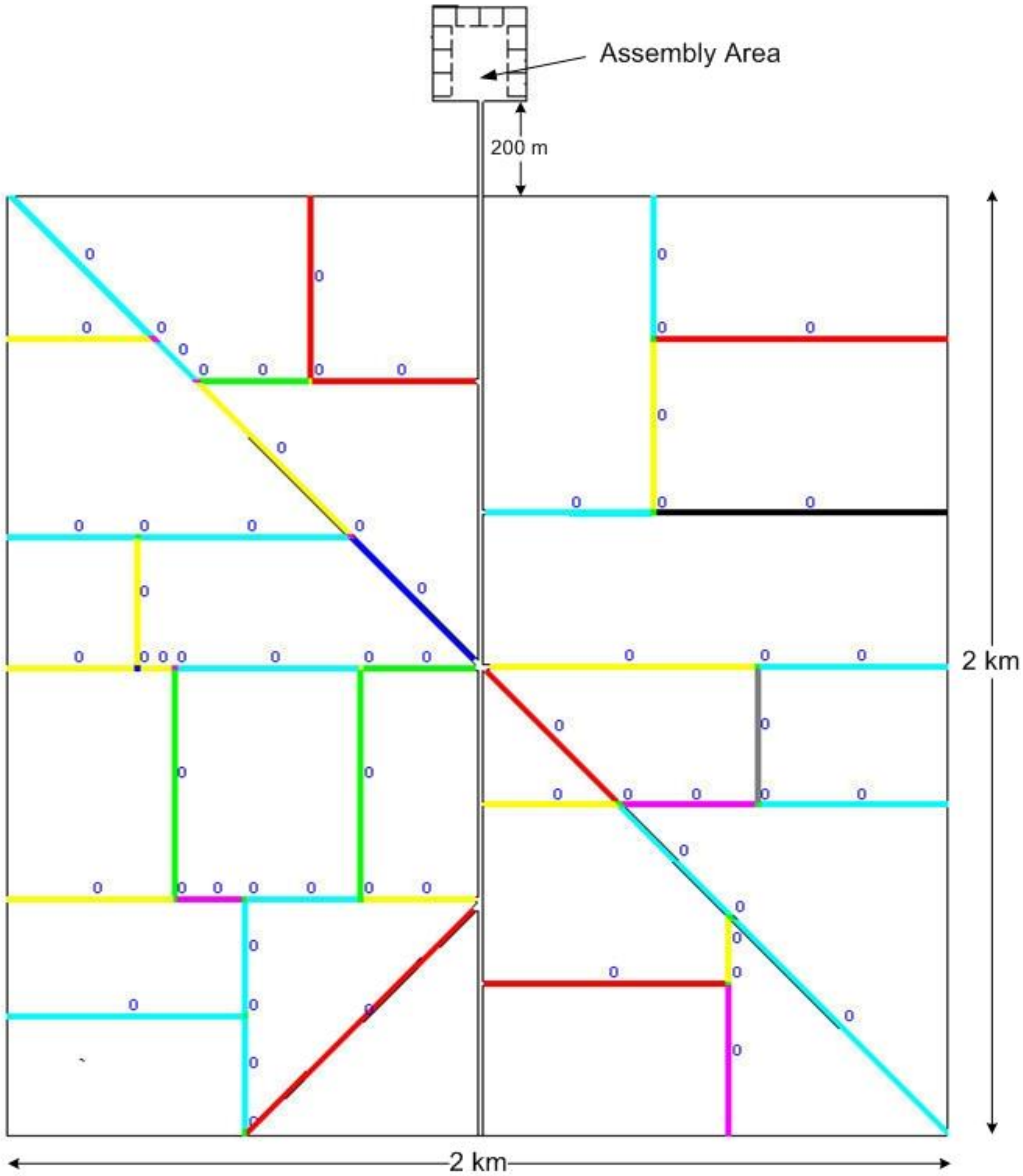

Figure 3 Large City Block geometry; shaded roads represent coarse node approach, unshaded road in the middle of the city leading to assembly area represents Fine node approach.

Given the discretisation strategy used in the Coarse-Fine case and the direction of motion of the agents, the main transition demonstrated by the agents is the Coarse→Fine. When agents traverse from Coarse regions to Fine nodes, they are re-positioned on the Fine nodes which are connected by arcs to the Coarse region as shown in Figure 4. Prior to their transitions, the agents query the transition region to find the density in the space represented by the Fine node. If the density is high such that there are no available Fine nodes to transit to, the agent transitions are inhibited and consequently, the agents exhibit queuing within the Coarse region. In addition, bEX-H features two methods for connecting Coarse regions to Fine nodes as shown in Figure 4. The number of arcs generated using method A is much higher in comparison to the method B and therefore, agents within the Coarse region in method A will have to search for their target waypoint against a larger number of internal paths, thereby reducing performance. Moreover, due to the fewer number of internal paths in method B, this enables the users to better manage the arcs within the Coarse region. In these respects, the method B was preferred in this case.

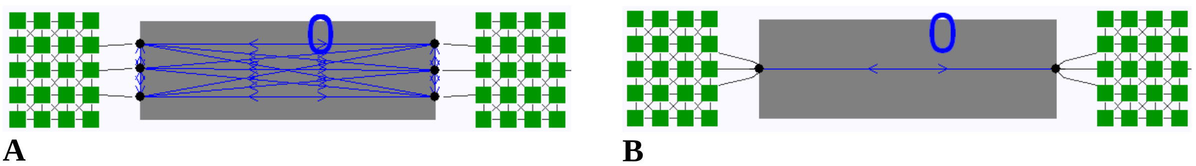

Figure 4 Two methods of connecting a Coarse region (dark region) to set of Fine nodes (2D grid of nodes)

5. Results and Discussion

The evacuation time curves for the All-Coarse, All-Fine and Hybrid cases are shown in Figure 5. These curves represent an average for the 10 repeat simulations. As can be seen both curves demonstrate similar trends. Both cases have been set up precisely in an identical manner and the core software for each case is identical. Nevertheless, differences in the overall evacuation times do exist, as can be seen in Table 2.

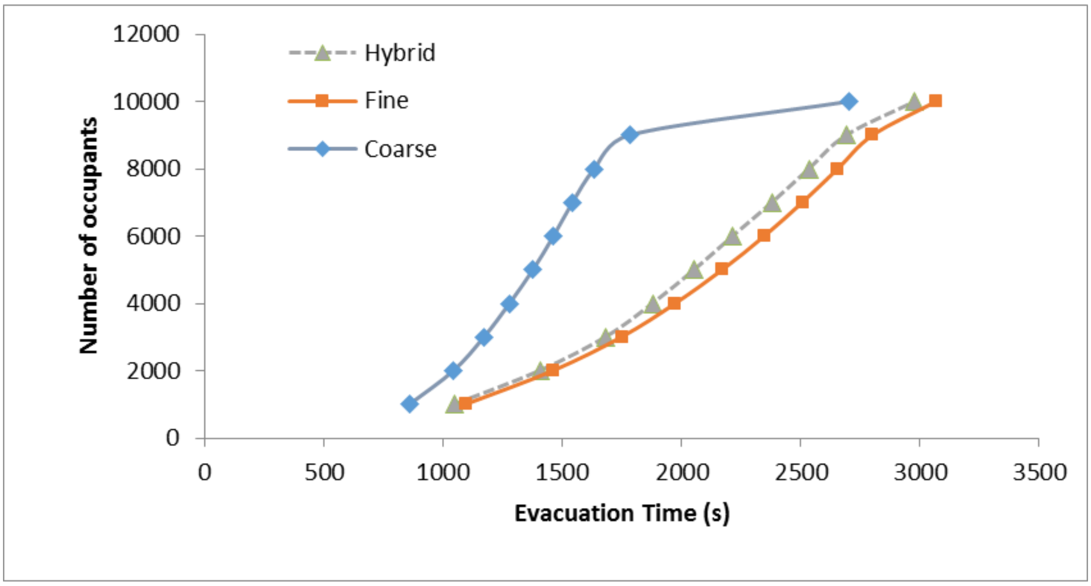

Figure 5 Time taken for a specific percentage of people to evacuate using All-Fine and Hybrid spatial representation

Compared to the average total evacuation time predicted by the All-Fine model, the All-Coarse model predicts an egress time which is 11.9% faster while the Hybrid is 3% faster. The difference in total evacuation times between the All-Fine and All-Coarse models is due to the inability of the Coarse model to explicitly represent agent to agent and agent to structure interactions. As a result, the agents traverse the coarse regions at a faster rate, thereby leading to faster flow rates and consequently faster evacuation times in the All-Coarse configuration.

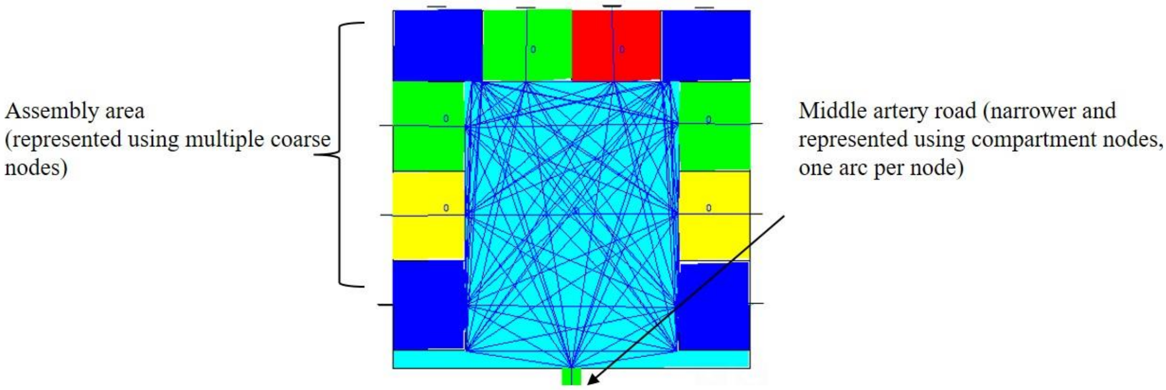

Figure 6 Connectivity of arcs in assembly area and middle artery road

Also shown in Figure 6 is the representation of the Coarse regions in the assembly area and their connectivity to the middle artery road. The assembly area is modelled using multiple Coarse regions. Whereas the middle artery road is narrower and represented using Coarse regions as shown as in Figure 7.

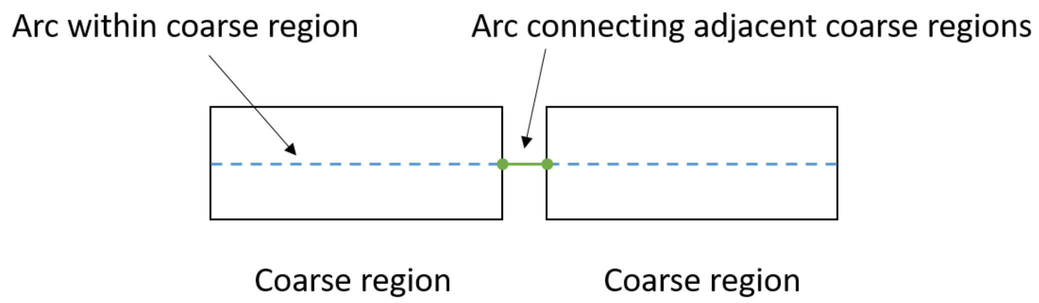

Figure 7 Connectivity of arcs in middle artery road

In the middle artery road, each coarse region is connected to other adjacent coarse regions using only one arc. This results in the creation of a single arc within each coarse region to allow agent movement. With this configuration, any build-up of agents within the single arcs will result in an overall reduction of agent flow rates.

When comparing the All-Coarse and All-Fine curves, it can be noted that in the Coarse model, the flow rate of the agents during the evacuation of the first 9000 agents is higher than the flow rate during the evacuation of the last 1000 agents. During the initial phase of the simulation in the Coarse model, there is no considerable build-up of population density within the single arcs in the middle artery Coarse regions, which results in faster flow rates. However, as the simulation progresses, increased queuing in the single arcs results in agents taking longer to enter the assembly area, thereby reducing the flow rates.

In the Hybrid configuration (Coarse-Fine), the middle artery road and the assembly area are represented using Fine nodes instead of Coarse. As can be seen from Figure 5, the Hybrid and All-Fine curves show similar trends implying that the Hybrid is producing evacuation dynamics which is more comparable to the Fine model. Yet the difference between the average total evacuation times between the Hybrid and Fine can be attributed to the inability of the Coarse regions (in the Hybrid configuration) to explicitly represent agent-agent interactions, thereby leading to faster flow rates and consequently slightly faster evacuation times.

Table 2 Summary of results averaged over 10 simulations

Spatial Representation	**Average Total Evacuation Time (s)**	**Average Run Time (s)**
All-Fine	3068.40	287.1
All-Coarse	2702.99	5.0
Hybrid	2976.82	163.3

The average exit flow rates for each exit for each of the 10 cases are as shown in Table 3 below. The maximum difference in average flow rates for the Fine and Hybrid cases is 5%

whereby the Hybrid model is producing greater average flow rates than the Fine. These results are consistent with the overall average total evacuation time, with the greatest average flow rates being associated with the shortest overall total evacuation times.

Table 3 Average Unit Flow Rate for each case averaged over 10 simulations

Type	Average Flow Rate (persons per second)									
	Door 1	Door 2	Door 3	Door 4	Door 5	Door 6	Door 7	Door 8	Door 9	Door 10
Hybrid	0.39	0.39	0.39	0.38	0.38	0.38	0.38	0.37	0.38	0.39
Fine	0.37	0.38	0.38	0.37	0.37	0.37	0.36	0.36	0.37	0.37

Table 4 below illustrates the average distances travelled by 10 random agents in the Fine node model and the corresponding distances covered by the same agents in the Hybrid configuration. It can be noted that the distances travelled by the agents in the Fine and Hybrid cases are very similar. Although it is expected that the distances travelled by the agents cannot be exactly the same in the Fine and Hybrid due to evolving agent-agent and agent-environment interactions, however, viewing the extremely large size of the geometry and the differences in movement mechanism (in the transition regions), the comparable distances, based on inspection, show that the Hybrid model is producing very similar evacuation dynamics to the Fine model.

Table 4 Distance travelled by agents in Fine and Hybrid configuration

Agent	Gender	Age	Weight (kg)	Distance travelled (m)	
				Fine	Hybrid
A	Male	31	72.15	750.22	749.22
B	Male	27	55.93	750.17	748.14
C	Male	47	72.19	1013.32	1014.29
D	Female	49	73.99	1282.77	1228.05
E	Male	76	73.73	1072.6	1080.94
F	Male	41	55.41	1676.79	1636.77
G	Male	40	65.49	2123.84	2081.74
H	Female	36	58.25	2245.67	2205.78
I	Male	27	55.66	2418.3	2431.01
J	Female	20	83.25	2649.47	2667.08

Also shown in Table 2 are the average run times for the 10 repeat simulations for each case. The Hybrid model produces the fastest run time of 163.3 s which is 43.12% faster than the All-Fine model. This significant speed up is due to the superior computational speed offered by the large proportion of Coarse regions in the Hybrid configuration.

In the light of the results shown in Figure 5 and Tables 2, 3 and 4, the HSD approach is seen to provide a substantial improvement in the run times of the simulation whilst maintaining the accuracy of the Fine nodal approach. The computational benefits offered by this approach make it suitable for the simulation of egress in extremely large environments. In addition, the results demonstrate that the algorithmic procedures employed in modelling the transitions of the agents across the interface regions operate consistently.

6. Conclusions

In this paper, we have presented the HSD approach, a novel technique which allows egress simulations to be run using a mix of spatial representation methods namely Coarse regions, Fine nodes and Continuous regions. The HSD approach was implemented within the buildingEXODUS software as it featured a sophisticated plug-in architecture which is conducive for the implementation, testing and integration of new functionalities. Each of the spatial representation methods have their respective strengths and limitations, however, the strategic combination of these methods into a single Hybrid model allows the benefits of all the methods to be harnessed. This accounts for the high flexibility of the Hybrid model, which makes it adaptable to a range of user and simulation requirements. For instance, to cater for severe time constraints and allow decisions to be made in the fastest time possible (e.g. during actual evacuation scenarios), the Hybrid model can be run in the All-Coarse configuration as it provides the highest computational performance. To cater for the testing of evacuation procedures, especially for extremely large environments (e.g. urban areas), the Hybrid model can be run using a combination of Coarse regions and Fine nodes. This Coarse-Fine configuration provides improved computational performance on extremely large scale geometries whilst allowing the modelling of people-people and people-environment interactions where mostly required. Using Continuous regions for such large scale geometries would not be appropriate due to the large computational overheads that would be incurred. To cater for moderately large geometries such as multiple storey buildings and tunnel stations, a hybrid configuration comprising of all three spatial types can provide improved accuracy over an all-Coarse configuration but without incurring the large computational overheads of the all-Continuous.

When using the HSD approach, the choice of modelling different sections of the geometry using different spatial types is user-based. To facilitate the optimal use of the HSD approach, we have provided recommendations on the suitability of each spatial type for different terrains and scenarios. For instance, Coarse regions are suitable for modelling uniform behaviour and adapt well to regions for which calibration data was collected. Fine node models can be predictive in areas with non-uniform behaviour such as junctions and escalators but they are not as sensitive to spatial dimensions as the continuous spatial representation. The Continuous approach can be used to demonstrate emergence of behaviours such as lane formation and for predicting flow rates at pinch points and exits.

In this work, we have presented the application of the HSD approach to an extremely large and complex city block environment of 2 km x 2 km. The flexibility and scalability of the HSD approach to handle urban environments is demonstrated in evacuation simulations involving 10 000 simulated agents. In this geometry, the areas in the far field are represented using Coarse regions, which constitute 71% of the entire free space area and the remaining 29% are represented using Fine nodes. The HSD approach is shown to produce results of similar trend to that of the All-Fine model, whilst providing a substantial speed up of 43.12%. Moreover, in order to handle the transition of the agents across the Coarse regions and Fine nodes, an interface module was implemented. This interface module uses the underlying Navigational Graph of the Coarse regions to guide the agents across the Coarse-Fine transition regions.

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