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Project Title: Reliable multi-scale modelling of crowd dynamics for disaster prevention

1. AIMS and BACKGROUND

AIMS: The proposed project will develop a rigorous methodology for computational modelling of crowd dynamics under panic conditions. This will significantly improve our capability to predict crowd behaviour during potential emergencies. The methodology will support **real-time modelling based on live event data** as well as **off-line modelling based on data collected from past events**. In this way it will facilitate effective and realistic disaster management during the planning phase as well as during an actual disaster response. In planning applications, the methodology will enable us to perform a realistic safety assessment of different infrastructure options and to compare different evacuation plans for efficiency and safety. During an actual emergency, its real-time capability will allow us to dynamically adjust and optimise a disaster response as the event unfolds. To achieve these aims, the project will develop innovative experimental techniques based on human crowd dynamics and animal dynamics, and it will develop multi-scale modelling methods together with high performance simulation and optimisation algorithms specifically designed for these computational models.

BACKGROUND: Urban growth and the pressures it places on urban infrastructure development are now a major national challenge, world-wide as much as in Australia. By 2050 Melbourne, Sydney, Brisbane and Perth together will house a population which is expected to be similar to the current national population [1]. On an average weekday more than 800,000 people use the Melbourne CBD, and this is expected to grow by more than 3 percent annually [2, 3]. Flinders Street Station, Australia's busiest rail station, now accommodates an average of 100,000 passengers daily and services significantly higher crowds during special events and unexpected service disruptions [4]. Similar growth has occurred in other cities nationally and in major cities in Europe, Asia and North America. Many existing parts of urban infrastructures have not been designed for such a population surge. This has resulted in significant challenges for managing the safety of large volumes of pedestrians in dense urban areas.

A central method to support decision making in urban infrastructure design and management is simulation, specifically the simulation of crowd behaviour. Crowd simulation is now a well-established field of research with a range of commercial software tools available [5]. Yet, many aspects of crowd behaviour are not well understood; specifically, the behaviour of crowds in panic scenarios. This does not constitute only an intellectual gap in our understanding of collective behaviour; it also severely limits the usefulness of crowd modelling for the design of urban infrastructures that are safe in emergencies and of emergency response plans for large scale events. As evidenced by recent crowd disasters [6], panic situations at such events can have catastrophic consequences if they are not managed appropriately. An increased ability to predict the behaviour of human crowds in such scenarios could translate into many lives saved by allowing us to optimise infrastructure layouts and response plans based on realistic assumptions. To make such predictive capability a reality, we need a better understanding of the behaviour of crowds in panic scenarios and a robust as well as reliable modelling methodology. Despite the fact that researchers and practitioners alike are calling for the development of such a framework, systematic studies of panic behaviour and quantitative theories capable of predicting the collective dynamics in such events are still extremely rare. Models which are capable of analysing complex environments, such as major public places, have not yet emerged [5].

Challenges: There are several fundamental challenges for reliable prediction of crowd movement under panic conditions.

- Sparse data: Reliable data is essential for the development of robust models. Base data for crowd movements under panic conditions is extremely rare and sparse [5, 7]. This severely limits the reliability of current crowd models.
- Complex behaviour: Crowd dynamics arises from the interaction of many different individuals' behaviours [8]. Previous crowd disasters have highlighted that understanding these interactions is key to understanding crowd dynamics [9], yet there are no comprehensive studies capturing these phenomena under panic conditions. This restricts the applicability of current models to non-panic scenarios and orderly evacuation.
- Dynamic environments: The environment in emergency scenarios is often subject to rapid and unexpected change. For example, fire or rubble may suddenly block an assumed escape path. A model that assumes a stable, static environment may thus not be applicable in the case of an emergency.
- Uncertain behaviour: It is not safe to assume that actions prescribed by an emergency response plan will be reliably executed. For example, residents may refuse to comply with the evacuation of a particular area. This means that statically optimised response plans may be rendered useless in an emergency [6,10].

2. RESEARCH PROJECT

We will address the fundamental challenges listed above in a number of subprojects that have three specific research aims:

Aim 1: We will develop experimental approaches and data analysis methods to gather better reference data for crowd behaviour in panic conditions.

We will use these methods to establish an improved collection of base data for panic scenarios. To do so we will combine data from a broad range of different systems and identify characteristic patterns that apply across the range.

Aim 2: We will develop mathematical and computational modelling methods that will allow us to predict crowd movement under panic conditions and that can be used to assess the effect of emergency response plans and building layouts to optimise these for safety.

These methods will be based on the analysis of our new experimental data in combination with existing data. While improved base data will allow us to build more realistic crowd models, it is still unlikely that any static model will be sufficiently accurate for a new event under substantially different conditions. This shortcoming will be addressed with the transition to real-time modelling.

Aim 3: We will develop a real-time modelling methodology that can adapt our models dynamically to changing environments and behaviour by taking live data into account as an event unfolds.

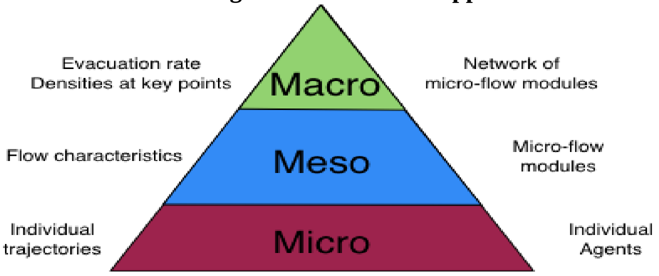
As current crowd modelling methodologies are not suitable for real-time modelling, this poses challenging research questions. To make real-time models possible, we propose to develop a new multi-scale modelling technology. Multi-scale approaches are a standard method of taming complexity in other types of large-scale simulations, such as hydrodynamics [11] and molecular dynamics [12], but they have generally not yet found their way into predictive crowd modelling. A notable recent exception is [13]. However, this is very theoretical work with significant scalability issue and it is not obvious if and how it can be practically applied to realistic real-time predictions of real-world crowd behaviour.

The clear promise for modelling crowd behaviour with a multi-scale approach is evident in recent work which has successfully used such methods to detect anomalies in video recordings of pedestrian movement at very high densities [14]. In contrast to our project, however, this work is focussed on the analysis rather than the prediction of crowd behaviour. Likewise, real-time adaptation of models via data assimilation is successfully used in other complex simulations, for example in hydrodynamic models for flood prediction [15], but has not yet found its way into predictive crowd modelling.

Current crowd models are typically single scale at either the macro or the micro scale. Macro-scale approaches only define the statistical evolution of one or a few macroscopic properties of interest, such as the expected pedestrian density at a given point, typically using partial differential equations [16]. Their major disadvantage is that there is no good way to take complex individual behaviour into account, which limits how realistic these models can be made. For this reason, the majority of practically used crowd models adopt a micro-scale approach, in which the behaviour of each individual is explicitly modelled. These methods are highly flexible and can, at least in principle, be made very realistic [17]. However, this flexibility comes at a price: the approach is typically based on individual-based Monte Carlo simulation or Cellular Automata so that it incurs significant computational cost. This can quickly become prohibitive, specifically in real-time scenarios.

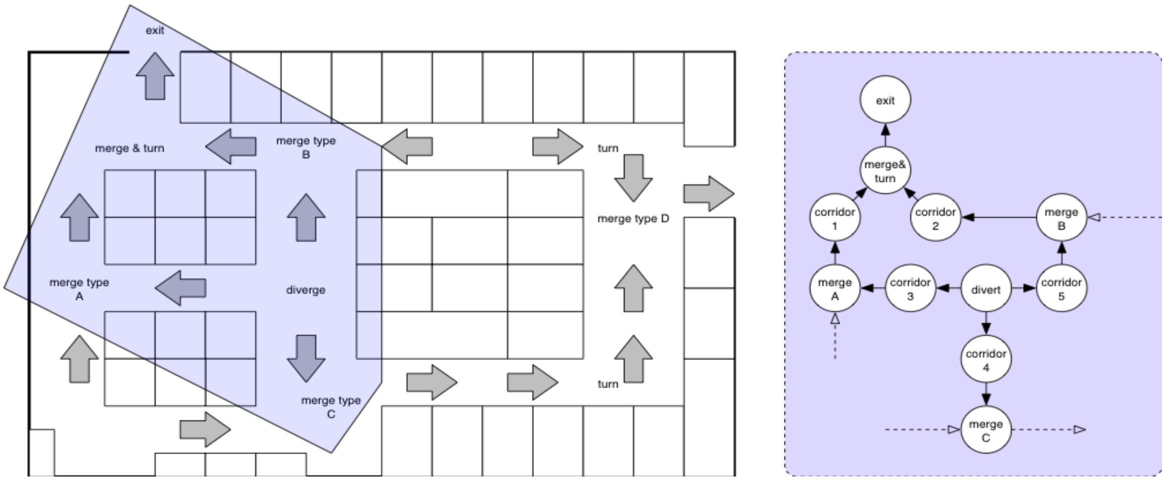
We propose that a fundamental shift in perspective to **multi-scale modelling** is the most promising way to make realistic real-time models possible. More specifically, we plan to develop a multi-level approach in which a new meso-scale takes centre-stage (Figure 1).

Figure 1: Multi-scale Approach



On the meso-scale we will use modules of micro-flows as the new fundamental entity. Each type of micro-flow represents a detailed part of a scenario with a specific flow characteristics (for example, a merging or crossing point of two flows, a bottleneck, such as a door, a straight corridor, etc). At macro-scale we will decompose the overall traffic scenario into a network of these micro-flows (Figure 2). Each micro-flow will be initially modelled at micro-level based on individual behaviour. However, the overall traffic network will be modelled at macro-level utilising only the coarse-grained behaviour of micro-flows. To be able to do so, the project will develop abstraction methods that extract a localised macroscopic flow behaviour from the micro-flow simulations. In this way, multi-level models will be able to combine the flexibility and realism of individual-based simulation with the advantages of mathematical models that can be optimised systematically and efficiently. This new methodology will thus pave the path for realistic real-time models that are of practical use for emergency scenarios.

Figure 2: Schematic of Overall Evacuation Scenario with a Part of the Meso-Macro Network



2.1. SIGNIFICANCE

The proposed project fits squarely into the Strategic Research Priority “Living in a changing environment” as it identifies and develops technological options for urban design and for risk management in the urban environment that allow us to cope with aspects of explosive population growth. The project will deliver a number of methodological and technological innovations. It will:

1. establish fundamental aspects of individual behaviour under panic
2. establish non-human organisms as model systems for systematic study of crowd panic
3. establish experimental techniques to study human subjects in simulated virtual reality escape scenarios
4. develop and deliver the first computational framework for crowd dynamics which allows efficient planning and re-calibration and optimisation as an emergency event unfolds

A wide range of applications will benefit from this. This includes infrastructure design and planning, the management of major events, planning emergency responses and assisting disaster relief agencies. It also has applications to operational planning for security forces where crowd movement is a central concern. Thus, the proposed research project addresses important issues of national and international concern.

Many modelling approaches in the socio-economic and life sciences are based on kinetic particle methods, just like our crowd models. We thus expect that the high-performance simulation and optimisation methods developed in this project will ultimately also benefit these fields.

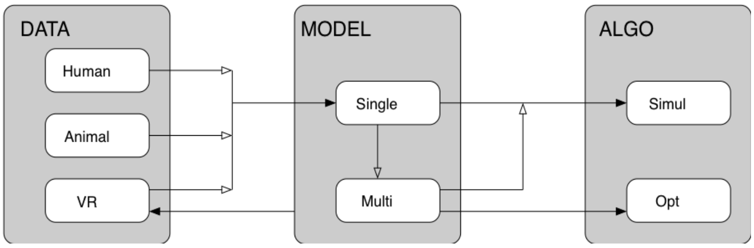
2.2 METHODOLOGY

The project is divided into three major subprojects aligned with the aims of the project:

- **DATA**: These subprojects are concerned with experimental crowd modelling and aim at improving experimental methods and base data. (Aim 1)
- **MODEL**: These subprojects develop a base model from the data established in DATA, utilising as a foundation the prototype model developed by Sarvi in his previous work. (Aim 2)
- **ALGO**: These subprojects develop simulation (ALGO-SIM) and optimisation algorithms (ALGO-OPT) for the modelling framework. The main interface between the MODEL and ALGO projects is the analysis and definition of suitable micro-flows. (Aim 3)

Figure 3 outlines the relationship between subprojects. The project is ambitious in scope. To address all these subprojects, it relies on an interdisciplinary team of CIs and an international partner investigator whose expertise jointly covers all the required areas (for details see Role of Personnel in Section 3).

Figure 3: Project dependencies



2.2.1 Subproject DATA: experimental methods and improved base data

The online characteristic of the proposed modelling approach will significantly increase its predictive power. However, predictive power stands and falls with the accuracy of the base model for the flow characteristics and this can only be made accurate by utilising significant amounts of realistic data. Available real world data is scarce and it is obviously not possible to generate new data by performing experiments under realistic panic conditions. Somewhat problematically, there is no escaping from the fact that no data that can be generated, whether in normal conditions or in laboratory settings, is likely to be fully representative of a real panic scenario.

A possible way forward in this situation is to investigate which dynamic properties are shared by the real world data that are available with other types of traffic flows that are experimentally more accessible. While no single kind of base data (including that of previous events) can give us an accurate representation of a yet-to-be-encountered event, we can have increased confidence that characteristics common to different types of data will also apply to a newly encountered event and scenario.

Three different data sources will be blended to generate the data required for model development. Subproject DATA-HUMAN will analyse video data from real events and existing data from experiments with human subjects (non-panic conditions); subproject DATA-ANIMAL will analyse existing data and generate new experimental data from animal group dynamic (under panic conditions); subproject DATA-VR will conduct detailed observational studies in the Monash immersive Virtual Reality CAVE to obtain improved insights into individual route choice and exit strategy selection behaviour in simulated panic situations.

DATA-HUMAN: human crowd behaviour in high density scenarios (non-panic conditions)

As discussed, there are no comprehensive studies aimed at understanding and capturing the key individual behaviours in panic scenarios. In earlier work Sarvi has identified a number of key behaviours that have crucial influence in panic situations. For example, based on real-world video data of a US in-store stampede his work showed that stampede and crushing can be induced by abrupt turning behaviours [18]. Through further comprehensive real-world data analysis and through trials with humans carried out at Monash, Sarvi also showed that turning movements at corners, merging, and crossing of different pedestrian streams are crucial manoeuvres which need to be captured in any realistic crowd model [7]. In this project we will carry out a detailed analysis of these behaviours. This analysis will be based on comprehensive real-world data that International Partner Investigator Armin Seyfried has generated. Seyfried recently conducted the *world's largest human trial* using 1200 participants over five days in Germany [19]. A broad variety of experiments including turning through different angles, merging, crossing, and exiting from different room layouts were carried out at very high density (7 people/ m^2). Sarvi also has long standing collaborations with the special event group and the emergency team of the Department of Transport, with Public Transport Victoria, and with Metro Train. Through these collaborations the project will have access to many valuable data collections of major public transport stations and of large public spaces during special events, such as New Year's Eve and AFL games.

The richness of these data collections combined means that the proposed project is in an unprecedented position to perform, for the first time, a detailed analysis of the complex manoeuvres that determine crowd dynamics in extremely high density.

DATA-ANIMAL: animal group dynamic data (under panic conditions)

To compensate for the scarcity of panic data, Sarvi and Burd have been developing the use of animal models of crowd panics [20,21,22] to search for commonalities with human pedestrian behaviour [23,24]. Social insects (colonies of the Argentine ant *Linepithema humile*) have been used to measure crowd evacuation dynamics in physical settings corresponding to different architectural layouts of escape areas [20, 25]. Panic was induced using a chemical repellent, causing ants to rush toward exits in the layouts. These experiments confirmed for ant crowds a counterintuitive prediction of human pedestrian models [26], that partial obstruction by a structure slightly “upstream” from an exit would increase rather than impede flow rates through the exit. The obstruction is thought to prevent the formation of transient “frozen” configurations in the crowd that clog the exit. Additional experiments are needed to determine how the size, shape, orientation and placement of such partial obstructions affects individual behaviours and collective flow rates. Sarvi and Burd have also shown that simple allometric scaling of model parameters based on body mass successfully accounts for panic flow characteristics of both humans and Argentine ants [23].

While these results are promising, work to date does not provide a complete understanding of correspondences between the crowd dynamics of humans and animals of different size, locomotion, and social interactions during an emergency situation. It is not yet clear to what extent the simulation models developed by Sarvi [27] have robust predictive capability for humans in novel circumstances. Thus, one objective of DATA-ANIMAL is to test crowd dynamics in panic using a range of animal models that vary in body size, locomotion, and typical crowd size. We propose to use ants, woodlice, and mice as model organisms. The body size and mass of the proposed species are vastly different (woodlice and mice are around 12 times and 230 times, resp., the size of ants). This will provide crucial data to judge how behaviours vary with scale. Through these experiments we will explore if, similar to ant experiments, panic can produce anomalous (and disastrous) dynamics, like the ‘faster is slower’ paradox in which elevated individual speeds during panic reduce the group exit rate through bottlenecks, or the formation of jams at one doorway while another goes unused [26]. Sarvi and Burd have already successfully developed experimental procedures for woodlice and mice. These procedures will be used to carry out experiments that establish woodlice and mice exit behaviour in different chamber layouts and for different exit arrangements. Ant experiments have already been carried out in earlier research of Sarvi and Burd. We will use video tracking methods for individual animals that Sarvi and Burd have developed and successfully applied in previous projects.

DATA-VR: human route choice under pressure in virtual reality

Our third strategy to obtain better base data is to conduct experiments with simulated panic scenarios in virtual reality (VR). While there is no guarantee that the behaviour of human subjects in VR experiments is identical to human behaviour in real panic situations, this will at least provide us with a basic understanding of behaviour under panic conditions. It will specifically help to identify which aspects of individual behaviour in panic scenarios are different from the behaviour during orderly evacuation and it will thus be a significant step for the modelling process. We will test the theories developed from virtual reality observations against the video materials that have been gathered by Sarvi for past real-world panic scenarios [18] and hope to validate them in this way.

The main initial objective of this subproject is to study multiple exit strategies and route choice behaviours of individuals, as these are fundamental aspects of any realistic crowd model. While individual route choice behaviour in normal conditions and during orderly evacuation is an active area of research [28], studies to investigate this under panic conditions are non-existent. We intend to specifically investigate anomalous behaviour at exits, the impact of exit blocking on route choice behaviour, and the impact of signage and leaders.

Monash University has recently installed the *world’s most advanced virtual reality facility* of its type, CAVE2. It provides the largest immersive 3D space to date and sufficient computing power to drive realistic interactive simulations that respond to viewer actions and movement. Current game engine technology [29] makes it reasonably straight forward to implement immersive simulations in which human subjects interact with simulated agents. Latest developments in virtual reality infrastructure (Virtuix Omni) make motion capture possible for subjects that run (on the spot) and can turn in any direction. This generates a far more immersive and realistic experience, and it mitigates the physical space constraints imposed by a VR cave. We will use a combination of these technologies to conduct experiments in which human subjects participate in realistically simulated emergency situations and interact with simulated agents in real-time. The behaviour of the simulated agents will be based on the fundamental movement patterns identified in DATA-HUMAN and DATA-ANIMAL and driven by the models developed in MODEL (see Section 2.2.2). In this way we establish an incremental improvement cycle for our models: the VR experiments will help us to test models and to deliver new insights into the individual behaviour that in turn will be used to shape and refine the model.

2.2.2 MODEL: realistic crowd behaviour model for panic conditions

The empirical data obtained in DATA will be used to build a model of crowd behaviour in two stages. Initially, we will design a single-scale, individual-based model at micro-level (MODEL-SINGLE). The second step will be to restructure this model as a multi-scale model (MODEL-MULTI) by devising mechanisms to identify relevant micro-flow types together with their flow characteristics and methods to decompose the single-scale model into a network of micro-flows. The two steps will be tackled separately to split the representational issues (defining an *accurate* base model) from the technical issues (finding an *efficient* representation of the model).

MODEL-SINGLE: The modelling will be based on preliminary research by Sarvi in which he has developed a prototype model of crowd behaviour under panic for simple situations [27]. In Sarvi's pilot studies, this model called CPM (Crowd Panic Model) has shown to be applicable to both human crowd behaviour and to the movement of ant colonies as a model system. Following a standard approach to micro-scale crowd modelling [30], individuals are modelled as Newtonian 'particles' on which a variety of forces act. These can either be real physical forces, such as those experienced when pushed by other individuals or when pressing against a wall, or they can be virtual forces, such as the intention to move in a particular direction. The motion of each individual *j* is then defined by a Langevin equation:

$$\frac{dx_j}{dt} = F(X,t) + \xi_j(t)$$

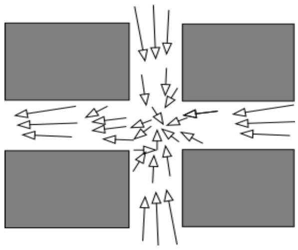
where $F(X,t)$ integrates the forces acting on *j* and ξ_j captures random influences and uncertainty. The crucial modelling step clearly is to identify and define a set of forces that correctly reproduce the collective dynamics. Sarvi's approach is unique in that it utilises a combination of methods including animal dynamics and pedestrian dynamics [21]. However, currently this model can only capture very simple scenarios (such as evacuation under panic from a room with one exit). We will extend this approach to facilitate more complex crowd dynamic movements such as crossings of several streams of pedestrians, merging and diverging, and turning using methods developed by Sarvi in earlier work [7,25].

MODEL-MULTI: We will develop methods for the decomposition of a crowd traffic scenario into a network of micro-flows. The first step is to identify suitable micro-flow types. While some special local scenarios (such as crossings of different streams of pedestrian flow) obviously require a distinct micro-flow type, this may not be clear in all cases. We will investigate whether recent methods used in crowd surveillance to discover unusual behaviour [14] can be extended to segment a scenario into different micro-flow types. To identify different regions of behaviour, these methods use the so-called "finite time Lyapunov exponent", basically a measure of how quickly flow behaviours diverge. While [14] introduces this method to identify diverging behaviour of individuals, we expect to be able to also use it to identify divergence from an expected base behaviour. This will be achieved by first normalising the recorded flow field with an expected flow field. Like our proposed approach, these methods rely on a force-based Newtonian particle model, so that they are well-suited to integration with the proposed methods.

We will specifically aim to identify types of flow behaviour that are common across human and animal experiments. In this way we hope to establish more evidence that certain species are valid model systems for human crowd behaviour. The pilot studies by Sarvi and Burd [22] give us confidence that this will be possible at least to some degree. However, it is crucial to identify in detail which particular aspects of human crowd behaviour can be modelled in this way, and which constraints apply to such modelling. So far there have been no studies addressing this question in a systematic way. Success in this part of the study will also mean that we will have established a way for much simpler, cheaper, and more efficient experiments with crowd behaviour.

Micro-flows will initially be modelled via individual-based simulation using the same methods as for the entire model in MODEL-SINGLE. This will allow us to flexibly incorporate individual-based aspects into the model and thus to achieve realistic simulations. Ultimately, however, we are interested in macro-scale properties, such as the overall speed of evacuation (defined by the time it takes for the expected density of individuals to reach zero). The second step thus will be to define methods to encapsulate and abstract micro-flows in such a form that they can be more efficiently computed and be connected into the overall flow network. In doing so, we will effectively lift the micro-level to the meso-level. Consider a junction point of three pedestrian streams. The behaviour at the junction point (Figure 4) locally exhibits a complex turbulent dynamics. However, we observe that at some distance from the crossing we can again assume a steady state flow, the magnitude of which is determined by the properties of the flow at the crossing. Thus, if suitable scales are chosen (in space and time) we can abstract away from the details of the turbulent behaviour at the crossing. Instead we model the crossing as a 'black box' micro-flow module that is characterised by a response function relating inflow, outflow, transit time (and possibly additional parameters). We expect that such response functions can be extracted from the simulation data via Equation-free Analysis, a technique that Meyer has previously successfully used to automatically find functions that coarse-grain the dynamics of other types of collective behaviour, such as clustering in insect and robot swarms [31,32]. We will extend these techniques to be applicable to pedestrian crowd flows.

Figure 4: Local Flow Bottleneck



2.2.3 ALGO: efficient simulation and optimization algorithms for real-time crowd modelling

We will address the question of efficiently computing our models in two subprojects. ALGO-SIMUL will develop high performance simulation methods for individual-based micro-scale models, ALGO-OPT will develop efficient computational methods for the macro-level networks and for using these to optimise design choices, response plans, etc.

ALGO-SIMUL: Regardless of the fact that we are proposing to move to a multi-scale model, we clearly cannot fully dispense with individual-based micro-scale simulations. Firstly, smaller individual-based simulations will still be needed to determine the behaviour of the micro-flows before they can be abstracted into response functions. Secondly, our approach will benefit from being able to fully simulate the entire scenario at micro-scale, even though this will not be used for the real-time applications. This is because the abstraction of the scenario into a network of micro-flows is indeed only an approximation of the real model and full reference data can only be obtained by full micro-scale simulation. Since this will also require parametric studies we will need to develop micro-scale simulation algorithms that are scalable, efficient and fast.

Fortunately, Meyer has already developed ultra-high performance simulation techniques that can be used as the basis of this. These methods were originally developed in a previous ARC project (DP110101413) to simulate the collective spatial behaviour of large self-organized biological groups, such as bacteria colonies and ant colonies. The models for these systems are fundamentally based on the same modelling paradigm that we will use for the proposed crowd model. The simulation system Inchman (see http://www.csse.monash.edu.au/~berndm/inchman/) developed in DP110101413 is capable of simulating any large system of agents whose behaviour is defined by systems of Langevin equations. It achieves several orders of magnitude speed-up over conventional individual-based simulations [33]. This has already enabled Meyer's team to perform large scale parametric studies of unprecedented size [34]. However, this approach will have to be extended to be applicable to human crowd models. Most fundamentally, a human agent is not as simple as, for instance, bacteria, and its movement can normally not be controlled by a Markovian (memory-less) system. However, in the panic context it can be expected that only a limited (and simple) form of memory is used. Since a process that uses only limited discrete memory is equivalent to a Markov process with a more complex state space, we are confident that this approach can be extended to the proposed crowd models. The key to this is that Meyer's approach already allows context-dependent switching between different Langevin-defined behaviours by combining these with state transition systems.

ALGO-OPT: An important use of our models will be to support decision making by assessing different options for building layout, evacuation plans, etc. Pure individual-based simulation models are not well suited to this task. This is because there is generally no systematic way to predict how given choices influence the dynamics that unfold in an individual-based simulation. Parametric studies or trial & error are the only ways forward. The computational complexity of these is problematic at the best of times even for the static once-off optimisation of, say, a building layout. It clearly renders impossible dynamic decision support that takes real time data into account during a live event.

We thus need to move to a type of model that allows systematic and efficient optimisation of scenarios. The proposed multi-scale approach paves the path for this. Once the overall scenario is decomposed into a network of micro-flows and these micro-flows are coarse-grained into response functions, many decision support tasks can be framed as combinatorial optimisation problems [35]. Consider the example of designing an optimal (maximum efficiency) escape route. In principle, this amounts to choosing a multiple-source, single sink graph (assuming one exit) whose edges are available corridor segments etc., such that the overall transit time is minimal. We can use response functions (obtained from MODEL-SINGLE) to give us the expected transit time for a single path segment as a function of the pedestrian density at this point. We can thus use the response function as a cost function for each path segment. The problem of choosing the optimum escape route now amounts to a combinatorial optimisation problem in a transport network. Another example is the optimal choice between different options for a building layout. By including different design options as alternatives in the macroscopic network graph, the problem can be handled as a constraint choice problem [36].

The optimisation of transport networks is a very well understood field [35] and efficient optimisation algorithms are available for many types of problems. Specifically, recent advances in network optimisation algorithms have resulted in efficient optimisation algorithms for networks with general convex cost functions [37,38] which we expect to be suitable for our problem. The biggest research challenge from an algorithmic perspective will be to design extensions of the above mentioned network optimisation algorithms for generalized cost functions such that they can be used for adaptive online optimisation. As algorithms exist that are based on incremental-improvement strategies, we have confidence that this will be possible. Adaptive network optimisation algorithms will allow us to handle changes in the environment (for example, a corridor becoming blocked amounts to a node in the graph being removed) as well as uncertain behaviour of individuals (by modifying the micro-flow response functions).

We are in a unique position to address this aspect of the project as the Monash Caulfield NICTA lab with which Meyer collaborates hosts a large number of optimization experts, arguably the largest pools of optimization expertise in the country.

3. ROLE OF PERSONNEL (**MS**=CI Sarvi, **BM**=CI Meyer, **MB**=CI Burd, **AS**=PI Seyfried)
The investigators and their associated research teams are internationally renowned for their work on crowd modelling (MS, MB, AS), modelling and simulation of collective behaviour (BM, MS), collective behaviour in animal groups (MB), and combinatorial optimization (BM). The CIs have been collaborating for several years. MS and MB have numerous joint-publications in crowd and animal modelling and joint PhD supervisions. BM and MB have active collaborations in collective behaviour of animals and joint PhD supervisions. MS and AS have a history of collaboration at international level and serve together on several scientific committees.

The team and their collaborators bring together substantial expertise in engineering, computer science and biology covering all relevant aspects of the project. This puts the team in an ideal position to tackle this interdisciplinary challenge.

MS will be the main driver of the project and responsible for the overall coordination. The fundamental modelling framework, which is the core of the project, will be developed in very close collaboration between all researchers. BM will drive the computational parts of the project, i.e. the development of high performance simulation and optimization methods. MB will focus on experimental methods and be closely involved in all other parts of the project that are not of a purely computational nature. AS will contribute domain expertise and his valuable data set collected recently. He will closely collaborate on experimental aspects and consult on the modelling and simulation aspects. We are planning extended exchange visits to ensure a tight collaboration with AS.

The project requests funding for two research fellows (RF1, RF2). RF1 will focus on the experimental stage including infrastructure for VR experiments. We require a candidate with expertise in crowd dynamic and virtual reality and the ability and willingness to acquire expertise in animal and human experiments from MS, MB, and AS. RF2 will focus on the development of high performance simulation and optimization methods and must have expertise in scientific computing and software engineering. Both RFs will be involved in the modelling aspects.

We hope to engage several postgraduate students in this project as well as Honours students. This will ensure that we are building a continuing base of expertise for crowd modelling and management in Australia. We are seeking funding for two PhD students. These will be directly associated with the work of RF1 and RF2, respectively.

All investigators will draw upon their extensive international and national collaboration networks. Specifically, we will work with Prof David Abramson, University of Queensland, a world-renowned expert on parallel and grid computing, on the distributed optimization algorithms of our multi-scale models; and with members of the NICTA Caulfield lab who provide an unparalleled pool of expertise for combinatorial modelling in Australia. Meyer has a long history of successful collaboration with these groups.

The Monash eResearch centre will provide the high-performance computing facilities for this project and the associated technical/programming support. Table 1 fully details the involvement of each individual and the timeline of the project. The total length of the project will be 3.5 years.

Table 1: Time-line and expertise

Subproject	Lead CIs	Others	2015 Q1-Q2	2015 Q3-Q4	2016 Q1-Q2	2016 Q3-Q4	2017 Q1-Q2	2017 Q3-Q4	2018 Q1-Q2
DATA	MS, MB	BM, AS, RF1	■	■	■	■			
MODEL	MS, BM, MB	AS, RF1, RF2		■	■	■	■	■	
ALGO	BM, MS	RF2				■	■	■	■

4. RESEARCH ENVIRONMENT

The project is well aligned with Monash's leading research capabilities. It will contribute to two of these, namely "building resilient cultures and communities" and "sustainable environments". As a cross-disciplinary project it is ideally positioned in the intersection of the research priorities and themes of the faculties to which the two first-named CIs belong:

- "Resilient infrastructures" (Faculty of Engineering, CI Sarvi)
- "Prediction, Preparedness, and Response" (Faculty of IT, CI Meyer)
- "Environmental monitoring, prediction and protection" (Faculty of Engineering, CI Sarvi)
- "Optimisation for Travel, Transport, and Logistics" (Faculty of IT, CI Meyer)

The proposed project will contribute directly to these themes.

PI Sarvi is the director of Institute of Transport studies within the Department of Civil Engineering, which aggregates more than 44 years of experience in cutting-edge transport research and innovation and has a strong track record of successful funding. The department hosts three ARC Future Fellows and two DECRAs.

Modelling, Optimisation & Visualisation is a flagship research area at Monash with a very strong record of achievement. Monash and NICTA jointly operate a research laboratory in Caulfield with Optimisation and Visualisation as its focus. Through these initiatives, arguably one of the largest pools of combinatorial optimisation expertise world-wide is accessible at Monash, including world leading researchers, such as PJ Stuckey, K Marriott, and M Wallace. CI Meyer has a track record of successful collaboration and joint publications with these.

The project team has access to world-class facilities and infrastructure at Monash through the Monash e-Research Centre (MeRC), which supports the proposal. MeRC developed and operates the world's most advanced fully immersive 2D/3D virtual reality environment, CAVE2. It comprises 80 3D LCD panels in an eight metre, 320 degree, curved wall formation. MeRC also provides world-class high performance computing facilities, most prominently MASSIVE, a high performance CPU/GPU cluster dedicated to Visualisation, Modelling, Simulation, and Imaging. It combines accelerated processing power in excess of 170 teraflop with 500 TB high bandwidth storage to give Monash researchers unparalleled capabilities to simulate, capture data, and perform advanced analytics. The proposed project will make ideal use of these facilities. Both CI Sarvi and CI Meyer already have a history of successful collaboration with MeRC. Access to modern laboratory facilities for animal experiments, which CI Burd and CI Sarvi have already used in previous work, is ensured through the School of Biological Sciences.

5. COMMUNICATION OF RESULTS

We will use all traditional ways to communicate our results appropriately, namely by (i) publishing in the appropriate international journals and conferences; (ii) giving seminars nationally and internationally at universities and professional organizations; (iii) organizing satellite workshops in conjunction with national and international conferences; (iv) representing the project in an appropriate form on the world-wide web. We place great importance on the translation of our results into efficient support for meaningful design solutions and policy advice useful at local, state and federal levels. Starting from CI Sarvi's current collaborations we will engage with the relevant local transport authorities and state agencies to raise awareness of the computational decision support methods our project develops. A cornerstone of our strategy is that we intend to release high-performance simulation and optimization software for our modelling approach. This will put other research groups as well as agencies into a position to immediately use the developed methodology.

6. MANAGEMENT OF DATA

All data collected in subproject DATA will be stored for at least 7 years on Department of Civil Engineering data storage which is secure and centrally managed and backed up. Animal and VR data will be also stored on Monash Animal House and CAVE facilities as their standard procedure. Data will be anonymized, collected and handled in accordance with the ethics approval obtained from Monash University Ethics Committee. All CIs frequently obtain ethics permits for their research and are familiar with the procedure and requirements. At the conclusion of the project data will be made available on request.

References

1. Australian Bureau of Statistics. 2013 <http://www.abs.gov.au/Ausstats/abs@.nsf/mf/3222.0> viewed January 2014.
2. Melbourne city user estimates and forecast, 2004-2020. City Research, City of Melbourne publication 2009.
3. Developing Transport Infrastructure and Services for Population Growth Areas, Victorian Auditor-General's Report, August 2013.
4. J. Davies. Beyond the Façade: Flinders Street, More than just a Railway Station. Publishing Sol. 2008. ISBN 978-1-921488-03-0.
5. D.C. Duives, W. Daamen and S.P. Hoogendoorn, State-of-the-art crowd motion simulation models. *Transportation research part C*, Volume 37, December 2013, Pages 193–209
6. D. Helbing and P. Mukerji. Crowd Disasters as Systemic Failures: Analysis of the Love Parade Disaster. EPJ Data Science, 1:7, 2012.
7. N. Shiwakoti and M. Sarvi. Enhancing the panic escape of crowd through architectural design. *Transportation research part C*, Volume 37, December 2013, Pages 260-267
8. A. Seyfried et al. New insights into pedestrian flow through bottlenecks. *Transport Science* 43(3):395-406, 2009.
9. M. Moussaïd, D. Helbing, and G. Theraulaz. How simple rules determine pedestrian behaviour and crowd disasters. *Proc Natl Acad Sci USA* 108(17):6884-6888, 2011.
10. M.J. Chertkoff and H.R. Kushigian. Don't Panic: The psychology of emergency egress and ingress. Praeger, Westport/CT, 1999.
11. B. Engquist, P. Lötstedt, and O.Runborg. Multiscale Modeling and Simulation in Science. Springer-Verlag, New York, 2009.
12. E. Weinan. Principles of multi-scale modelling. Cambridge University Press, Cambridge/MA, 2011.
13. J. Evers. Modelling Crowd Dynamics - A multi-scale, measure-theoretic approach. PhD thesis, University of Eindhoven, 2011.
14. B.E. Moore, S. Ali, R. Mehran, and M. Shah: Visual Crowd Surveillance through a Hydrodynamics Lens. Communications of the ACM 54(12)2011:64-73.
15. C.J. Hutton, L.S. Vamvakeridou-Lyroudia, Z. Kapelan, and D.A. Savic. Real-time modelling and data assimilation techniques for improving the accuracy of model predictions. Scientific report EU-FP 7 Project 244232, 2011.
16. P. Kachroo, S. Al-nasur, S.A. Wadoo, and A. Shende. Pedestrian Dynamics. Springer-Verlag, Berlin, 2008.
17. N. Pelechano, J. Allbeck, N. Badler. Virtual Crowds: Methods, Simulation, and Control. Morgan & Claypool Publishers, CA, 2008.
18. N. Shiwakoti, M. Sarvi, and M. Burd. Consequence of turning movements during emergency crowd egress. In *Transportation Research Record*, No. 2234, 2011, pp. 97-104
19. G. Lammel, A. Seyfried, and S. Bernhard. Large-scale and microscopic: a fast simulation approach for urban areas, 93th Transportation Research Board, Washington D.C., 2014.
20. N. Shiwakoti, M. Sarvi, G. Rose, and M. Burd. A biologically inspired modelling approach for collective pedestrian dynamics under emergency conditions. *Transportation Research Record* 2196: 176–184, 2010.
21. N. Shiwakoti, M. Sarvi, G. Rose, and M. Burd. . Animal dynamics based approach for modelling pedestrian crowd egress under panic conditions. *Transportation Research B: Methodological* 45: 1433–1449, 2011.
22. C. Dias,, M. Sarvi, N. Shiwakoti, O. Ejtemai, and M. Burd.. Investigating collective escape behaviours in complex situations. *Safety Science* 60: 87–94, 2013.
23. N. Shiwakoti, M. Sarvi, and M. Burd. Similar crowd behavior in organisms of vastly different body size. *Journal of Insect Behavior* 27:239–250, 2014. Doi:10.1007/s10905-013-9426-0.
24. N. Shiwakoti, M. Sarvi, and M. Burd. Using non-human biological entities to understand pedestrian crowd behaviour under emergency conditions. *Safety Science* (in press, accepted 25 Jan. 2014).
25. C. Dias, M. Sarvi, N. Shiwakoti, and M. Burd. Turning angle effect on emergency egress: experimental evidence and pedestrian crowd simulation. *Transportation Research Record* 2312: 120–127, 2012.
26. D. Helbing, I. Farkas, and T. Vicsek. Simulating dynamical features of escape panic. Nature 407:487–490, 2000.
27. N. Shiwakoti, M. Sarvi, and M. Burd. Animal dynamics based approach for modelling pedestrian crowd egress under panic conditions. *Transportation Research Part B*, Vol. 45, 2011, pp. 1433-1449
28. G.M. Ramos, W. Daamen, S.A. Hoogendoorn. A State-of-the-Art Review: Developments in Utility Theory, Prospect Theory and Regret Theory to Investigate Travellers' Behaviour in Situations Involving Travel Time Uncertainty, Transportation Review. Volume 34, 2014.
29. http://unity3d.com/
30. D. Helbing and P. Molnar. Social force model for pedestrian dynamics. *Physical Review E* 51 (5): 4282–4286, 1995.
31. H.Hamann, B.Meyer, T. Schmickl, and K. Crailsheim. A model of symmetry breaking in collective decision-making. In Simulation of Adaptive Behavior, Paris, September 2010.
32. M. Vigelius, B. Meyer, and G. Pascoe. Multi-scale modelling and analysis of collective decision making in swarm robotics. Submitted to *PloS One*, February 2014.
33. M. Vigelius, A.Lane, and B. Meyer.. Accelerating reaction-diffusion simulations with general-purpose graphics processing units. *Bioinformatics*, 27(2), 2011.
34. M. Vigelius and B. Meyer.. Stochastic simulations of pattern formation in excitable media. PLoS One, 7(8), 2012, doi:10.1371/journal.pone.0042508.
35. C.H. Papadimitriou, K. Steiglitz.. Combinatorial Optimization - Algorithms and Complexity. Dover Publications, Mineola/NY, 1982.
36. K. Marriott and P.J. Stuckey. Programming with Constraints. The MIT Press, Cambridge/MA, 1998.
37. S. Boyd and L. Vandenberghe. Convex Optimisation. Cambridge University Press, New York, 2008.
38. L.A. Vegh. Strongly polynomial algorithm for generalized flow maximization. Accepted for ACM Symposium on Theory of Computing (STOC), 2014. Available as preprint: arxiv:1307.6809