Crowd safety: prototyping for the future

Summary report showing how the science for “pedestrian flow” can keep up with demographic change

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| FIRE SAFETY ENGINEERING | LUND UNIVERSITY |

The project is financed by Brandforsk

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Lund 2020

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Abstract
This report presents the final output from the project *Crowd safety: prototyping for the future*. The research includes a scoping study focusing on determining primary parameters for pedestrian movement and experimental results on movement in various conditions that focus on movement speed, contact distance and movement behaviour. A parametric model for predicting movement is presented based on this research and finally a road map is proposed that outlines the relevant steps for future research on pedestrian movement and human behaviour in a hazardous situation.

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Preface

The report represents the summary report relating to the research project *Crowd safety: prototyping for the future* aiming at presenting a novel approach to describe and model pedestrian movement in fires. The report describes the outputs from the project including a scoping study of literature in the field of interest, a summary of the experiments performed, a prototyping model to predict pedestrian movement and a roadmap presenting ideas related to future research within the area of pedestrian movement in the case of a fire. The report also briefly addresses the link to human behaviour in fire, as movement is in fact a result of how humans perceive the situation if an emergency has occurred.

The work was initially led by Professor Daniel Nilsson until he was appointed to a position at University of Canterbury, New Zealand. In the final stage Senior Lecturer Håkan Frantzich acted as project leader. The major contributions have been made by Dr Pete Thompson at Autodesk and Lund University, Dr Denise McGrath at University College Dublin and by Professor Daniel Nilsson. Dr Karen Boyce, Ulster University, has also significantly contributed to the work, and has also acted as external reviewer, an appreciated task also performed by Dr Rita Fahy at the National Fire Protection Association (NFPA).

The project is funded by Brandforsk (Swedish Board for Fire Research), grant 200-161. The project was initiated in January 2017 and completed in January 2020.

The project was reviewed by a reference group with the following participants, whose support and contributions are much appreciated:

- Fabian Ardin and Anders Johansson, National Board for Housing, Building and Planning (Boverket)
- Karl Fridolf, WSP Fire & Risk
- Axel Mossberg, Brandskyddslaget
- Johan Norén and Emilia Norin, Briab
- Per-Anders Ohlsson, Säkerhetspartner
- Ville Bexander, Swedish Fire Protection Association
- Mattias Delin and Thomas Gell, Brandforsk

Four students undertaking MSc or BSc thesis work have also been involved in the project:

- Gabriel Larsson
- Jesper Friholm
- Kristjana Doka
- Andreas Hansen

Their contributions are highly appreciated. Finally, the authors want to thank all involved including all participants in the experiments and all persons supporting the experiments.

Executive Summary

Background and Purpose:

In 2016, Brandforsk awarded €68 000 in research funding to the Division of Fire Safety Engineering in Lund University who led an international, interdisciplinary team to carry out the project entitled, "Crowd Safety: Prototyping for the Future" between January 2017 and February 2020. The team consisted of Professor Daniel Nilsson, originally Lund University, later to move to University of Canterbury, New Zealand; Dr. Håkan Frantzich, Lund University; Dr. Pete Thompson, Senior Software Engineer at Autodesk and Dr. Denise McGrath, specialising in the biomechanics of movement at the University College Dublin. Two other important contributors to the project were Dr. Karen Boyce from Ulster University, Northern Ireland and Dr. Rita Fahy from the National Fire Protection Association in the U.S.A., together bringing over 70 years' experience in the field of fire safety to the project.

The goal of the project was to develop a prototype model of crowd flow that could predict crowd flow dynamics across a range of walking speeds by accounting for person-specific variables such as anthropometrics (e.g. height), gait parameters (e.g. step length) and the space a person leaves between themselves and the person in front. The primary purpose of creating such a model was so that the evacuation of building occupants of the future – with predicted higher percentages of older adults, obese people and people with chronic disease – could be achieved in a safer manner, underpinned by an understanding of how mixed ability populations can influence crowd flow. It is now widely accepted that the current design guides do not cater for these demographic changes. A secondary goal of the project was to develop a research roadmap that could guide future endeavours to enhance current modelling approaches. Included in this vision was a pathway for methodological development for the capture and analysis of crowd movement, which was an important element of the project. A third goal relates to experimental procedures and data collection on pedestrian movement. Different experimental techniques were evaluated and novel data were collected and used to improve different versions of the prototype model for crowd flow.

Research Approach:

Desk research, laboratory experimentation in both Lund University (using video capture) and University College Dublin (using wearable optical and inertial sensors), and iterative model development and testing were carried out by the research team. Four Lund University students undertaking BSc and MSc thesis projects, co-supervised by the investigators, worked on various aspects of the research programme. Finally, all investigators developed the research roadmap through a face-to-face workshop and subsequent reviews with external reviewers.

Project Outputs & Conclusions:

A prototype model of single-file crowd flow based on demographics, biomechanics and visual response/adaption was produced, that can be used to predict flow rates for different population types. It is termed the "movement adaption model" and it has been shown that it can easily be integrated into a computer model, potentially producing more realistic flow rates than existing algorithms. The research results were used to quantify peak single-file flow rates, and illustrate the relative impact of demographics on flow rates for different population cohort types.

	Cohort			
Estimated flow rate from prototype equations & simulations	**"Adult"**	**"Elderly"**	**Adult/ Elderly 50:50 mix**	**"School children"**
Peak single-file flow(people/sec)	**1.14**	**0.72**	**0.88**	**1.24**
Proportion of "Adult" flow rate	**100%**	**63%**	**77%**	**109%**
Proportional difference from "Adult" flow rate	0%	-37% (lower)	-23% (lower)	+9% (higher)

In addition, a research roadmap has been presented focusing on three areas a) identifying the primary parameters of crowd movement across a wide variety of contexts and data collection related to these primary parameters b) tackling the methodological challenges in capturing crowd movement using current and next generation sensing and data science approaches and c) producing integrative modelling frameworks that can accurately predict mixed crowd movement dynamics. A limitation of this work is that it focuses on single-file crowd movement, however the approach developed is scalable to wider, more congested flows as more empirical data is produced from these contexts, as outlined in the roadmap.

Publications from the project are listed below:

Type	***Year***	***Title***
BSc Theses	2018	Hansen A, "*A scoping review for the parameters of crowd movement*". Fire Safety Eng. Lund University, Lund.
	2019	Larsson G & Friholm J, "*Evaluation of measurement methods for determining individual movement in crowds*". Fire Safety Eng. Lund University, Lund.
MSc Thesis	2019	Doka K, "*Advanced Parametric testing of Evacuation Modelling for Different Population Groups Using BIM-Generated geometries*", IMFSE MSc thesis, Ghent University.
Project report	2020	Nilsson D, Thompson P, McGrath D, Boyce K, Frantzich H (2020). *Crowd safety: prototyping for the future. Summary report showing how the science for pedestrian flow can keep up with demographic change*. Report 3231, Lund University, Lund.
Conference workshop	2017	McGrath D, Thompson P, "*An analysis of human biomechanics and motor control during evacuation movement*", Presented at the International Association of Fire Safety Science 12th International Symposium workshop "New approaches to evacuation modelling". University of Lund.
Conference paper	2018	Thompson P, Nilsson D, Hansen A, Boyce K, McGrath D, "*Crowd movement, Demographics and Biomechanics: developing a fundamental understanding, and approach to modelling", Proceedings of the 9th International Conference on Pedestrian and Evacuation Dynamics",* Lund, Sweden.
Journal paper	2019	Thompson P, Nilsson D, Boyce K, Molloy M, McGrath D, "*Exploring the biomechanics of walking and crowd 'flow'*". Submitted to Fire and materials *(manuscript FAM-19-0288)*.
Journal paper	2020	McGrath D, Thompson P, Frantzich H, Goulding, C, Nilsson D, Boyce K, A kinematic analysis of interactions between pedestrians in single-file unimpeded and interrupted locomotion" – submission planned for "Human Movement" journal
Journal paper	2020	Thompson P, Frantzich H, McGrath D, Friholm, J, Nilsson D, Boyce K, "Understanding biomechanical interactions between pedestrians in congested flow" - submission planned for Fire Safety Journal or Safety Science.
Journal paper	2020	Thompson P, McGrath D. Nilsson D, Boyce K, Frantzich H, "*Developing a movement-adaption analysis of crowd flow for future generations*." submission planned for "Fire Safety Journal"

Sammanfattning (summary in Swedish)

Utifrån det faktum att demografiska förändringar i befolkningen har kunnat identifieras i de många länder har det ifrågasatts om de underlag som beskriver personers förflyttning är giltiga. Personer som för ett trettiotal år sedan tog fram information om tex gånghastigheter i trappor anser själva att deras material inte är lämpliga att använda. Naturligt vore kanske att genomföra nya experiment för att få mer uppdaterade data och sådana insatser sker också. Det finns dock andra sätt att hantera den förändring som observerats och det är att utgå från med grundläggande fysiska faktorer som kontrollerar hur fort en person går i olika situationer, dvs att utgå från en biomekanisk modell där modellen är oberoende av experimentella förutsättningar men istället baseras på egenskaper som är knutna till individen och dennes förutsättningar samt påverkan från omgivningen. Rapporten sammanfattar arbetet som genomförts i projektet och mer detaljerad information finns i publikationerna som tagits fram under genomförandet. Målet har varit att utveckla ett nytt sätt att modellera personers förflyttning samt att sammanställa kunskap och data om personers förflyttning som även passar det nya sättet att modellera förflyttning. Slutligen har ett mål varit att peka ut färdriktningen för framtida forskning inom området.

Arbetet inleddes med en litteraturgenomgång som genomfördes som en sk scoping review. Det innebär att litteratur som identifierat genomgått en gallring baserat på bestämda kriterier för inkludering eller exkludering. Slutligen har 35 artiklar använts för att identifiera 22 primära parametrar som antas utgöra de viktigaste för att beskriva var dom påverkar personers förflyttning.

Ett andra steg har varit att utveckla en modell som beskriver personers förflyttning baserat på faktorer som beror på exempelvis personers ålder och längd. Båda dessa ingår som primära parametrar och innebär att modellen kan anta ytterligare variabler som reaktionstid för att anpassa sin gånghastighet, gånghastighet utan påverkan från andra personer och vissa kroppsmått.

Parallellt med modellutvecklingen har en rad experimentella studier genomförs för att kvantifiera parametrar som ingår i modellen som utvecklas. Det innebär att modellutveckling och experiment har skett i flera steg för att modellen ska kunna uppdateras när nya experimentella resultat finns tillgängliga. Samtidigt har modellutvecklingen påverkat vilka variabler som ska undersökas experimentellt. Ytterligare ett mål med experimenten är att utvärdera olika tekniker för att samla in data. Data har samlats in från videofilmer från försöken kompletterat med att försökspersoner använt en s.k. Eye-Track-utrustning. Vidare har försök genomförts med CodaMotion, som registrerar positionen av IR-sändare som placeras på försökspersonernas kroppar, samt accelerometrar som också placeras på försökspersonerna.

Det konstateras att datainsamling med CodaMotion är mycket tidseffektiv men förutsätter att detektorer för IR kan registrera personerna vilket innebär att de inte får skymma varandra. Liknande problem uppstår med videoanalys men där kan en kvalitativ bedömning göras för att ändå få tillförlitliga data. Videoanalys tar dock mycket längre tid att genomföra få det i nuläget kräver manuell hantering av videofilmerna. Experimenten har även resulterat i en stor mängd data kring personers förflyttning.

Slutligen presenteras även en färdplan för vidare forskning inom området. Den är uppdelad i tre kategorier; väsentliga parametrar att forska kring inklusive att kvantifiera, utveckling av metoder för datainsamling samt hur ny kunskap ska kunna resultera i nya modeller eller utveckling av befintliga modeller. Färdplanen redovisar även hur forskningen kring de tre kategorierna bör bedrivas sett ur ett tidsperspektiv.

I det korta skedet handlar det om att med dagens kända teknik samla in data kopplade till situationer med enkel förflyttning och att vidareutveckla de existerande modellerna. På lång sikt handlar det mer om att dra nytta av teknik som inte är fullt tillämpbar i dag (men som finns) för att beskriva komplicerade relationer mellan de primära parametrarnas inverkan på förflyttning. Modellerna är på sikt också kapabla att dra nytta av kunskapen om de samband som experimenten ger upphov till.

Projektet har resulterat i tre examensarbeten, två konferensbidrag, en inskickad artikel till vetenskaplig tidskrift samt minst tre utkast till vetenskapliga artiklar. Vidare har ett följdprojekt initierats.

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1 Introduction

It has long been a desire to describe and understand how people move and how various factors will influence this movement. One of the driving mechanisms behind this desire is the ability to predict pedestrian movement in situations where people gather such as train stations, bus terminals etc. For many years it has been understood that movement is not just a physical phenomenon; it is initiated by a person's desire to reach another position, irrespective of the reason behind this.

The field of fire safety science has historically comprised of two research areas relating to people movement; human behaviour research and physical movement research. This is illustrated by early work by pioneers in the field, for example by the fire investigation in Bryan (1957) exploring human behaviour and by Togawa (1955) investigating subway commuters' movement patterns and velocities. Later it became obvious that the two areas were in fact linked, however much research continues to focus on the two separately.

During the final part of the 20th century a significant amount of research was published either investigating group behaviour or looking at crowd flows and speeds in various locations. Present understanding of pedestrian movement in populated spaces is based on this relatively old data on mainly able-bodied people. The most significant data sets used in the analysis of people movement and evacuation (Hankin and Wright, 1958; Older, 1968; Predtechenskii and Milinskii 1969; Fruin 1971; Pauls, 1980; Ando et al, 1988) are derived from research conducted between the 1950s and 1980s. These datasets are derived from observations of the movement of able-bodied commuters (Hankin and Wright 1958, Fruin 1971; Ando et al, 1988), pedestrians in normal circulation in a range of building types (Predtechenskii and Milinskii, 1969) or during evacuation drills in buildings (Pauls, 1980; Predtechenskii and Milinskii 1969). This early research has formed the basis of our understanding of flow phenomena and indeed formed the basis of design guidance documents worldwide, e.g., in the following original documents the Green Guide (Home Office, 1985), SFPE Handbook of Fire Engineering (Nelson and Maclennan, 1996), PD 7974-6 (BSI, 2004).

They have also formed the basis for the majority of existing evacuation models. Some evacuation models have the capacity to accommodate population characteristics (pertinent to walking in crowded spaces) but crucially, the fundamental data that accurately describes particular populations as they move through the built environment is currently lacking. In addition, the 'grid' nature of the analysis of many simulation models in common use today, such as EXODUS (Galea et al, 1993) and STEPS (Hoffmann & Henson, 1997), dictate that they cannot model parameters such as body size, body sway, potentially limiting their ability to accommodate population characteristics that deviate from the "average" pedestrian. Other modelling strategies are available like Cellular Automata (Lizhong, Weifeng and Weicheng, 2003) and the Social force model by Helbing and Molnár (1995) but most of these do not consider the factors just mentioned, still being used for many design situations.

From existing data sets related to crowd movement, design curves relating speed and flow to density have been derived and have become established in design practice. Indeed, researchers continue to produce new data while still analysing the same relationships, e.g., Peacock et al (2012). However, there exists wide variation between the design curves derived from different data sets which originated in different countries, even though they were collected under similar conditions. For example, the commuter curves presented by Fruin in the USA (1971) and Ando et al in Japan (1988) are fundamentally different from those of Pretechenskii and Milinskii (1969), see Figure 1. Potential explanations for these variations include known demographic differences between countries, e.g., height, age distribution, etc. These types of characteristics are believed to influence movement speed, body sway, body size, etc, which in turn will influence how people move in populated spaces. It is important, therefore, to recognise that these speed-density curves mask the complexity that is inherently involved in movement (Brocklehurst, 2005; Pauls et al 2005, Hoskins, 2011). If we were able to characterise the population in terms of the fundamental parameters governing individual movement in populated spaces, then one would expect a better fit of the data to the design curve for a given population.

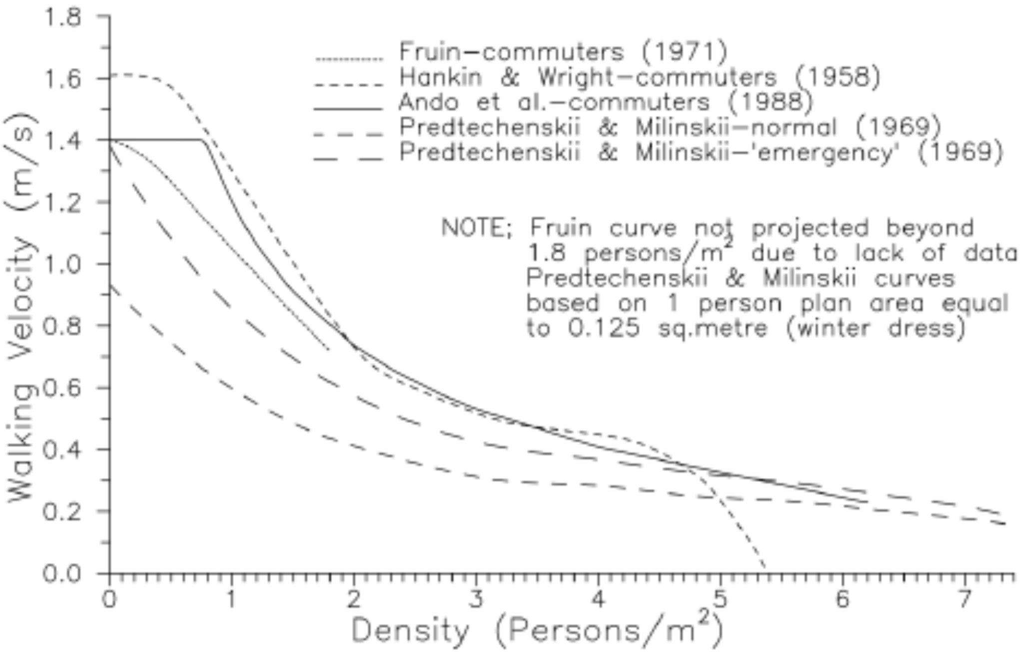


Figure 1. Comparison of Velocity Density Curves Derived from Various Researchers (Thompson, 1994, p 122)

Although the populations from which the most widely used design curves have been derived have not been characterised in detail, it is known that the data was collected for mainly able-bodied working age adults in the 1950s to 1980s. Since that time, building accessibility has changed considerably and today's building populations include people with a range of disabilities (physical, cognitive, sensory), all of which may impact on movement speeds and space requirements (Boyce et al, 2017). The presence of slower moving individuals within an evacuating population is expected to impact the dynamics of evacuation. Those with limited mobility will more often stop for rests (Boyce, 1999), and slow-moving individuals in a populated space may impede crowd movement if overtaking is not possible. For example, 51 % of participants in National Institute of Standards and Technology study of the evacuation of World Trade Centre on 9/11 (Averill et al 2005) suggested that slower moving individuals were a 'constraint to evacuation'.

Globally, we are an ageing society and obesity is becoming more prevalent. The old age dependency ratio (the proportion of adults aged 65+, relative to the remaining adult population) for Sweden (United Nations, 2015) has risen from 18% (1960), to 32% (2015) and is projected to rise to 41% by 2050 and then on to 51% by 2100. Predictions for other countries in Europe, such as the UK, follow similar trends. Age is directly related to a deterioration of physical, mental, neurological functions (Reeves et al, 2008, Kang and Dingwell, 2008), which impacts negatively on individual movement, e.g., speed and stride length. Similarly, obesity has become more common in developing countries (OECD, 2014). Obesity rates have approximately doubled over the last 25 years to 12% in Sweden, 25% in the UK, 35% in the USA and are continuing to increase. Obesity has been shown to correlate with reduced movement speed (Hulens et al, 2003) and increased walking sway (He and Baker 2004), both of which are undoubtedly important parameters related to individual movement in a populated space. Additionally, body size may influence interaction with other pedestrians in crowded situations.

Given these demographic changes, it is therefore impossible to have confidence that the existing design curves are representative of dynamic movement of populations of today and the future. Indeed, the originators of what are widely considered as the most significant North American data sets (Pauls 1980; Fruin 1971) have stated that their data sets are no longer applicable and have asked them to be removed from future design guides (Pauls et al, 2005).

Although, it may be possible to create new design curves for the future, this approach is not believed to be a robust solution (Thompson et al. 2015). A better approach is instead to identify the fundamental or primary parameters governing pedestrian movement in populated spaces and, based on these parameters, develop a new theory based on a first principles approach. This theory could then be tested as part of a computer model and used to provide reasonable predictions of crowd movement of mixed populations, as long as the composition can be accurately quantified in terms of the primary parameters. In essence, this would mean that one universal theory could be used for the entire world, but with different local demographic and occupancy specific parameters.

One of the few models that can assess the influence of potential primary parameters, such as age, individual speeds, and body size, is Simulex (Thompson, 1994). It's implementation of 'inter-person distance' is tested, calibrated, and can be further modified for new equations of movement. Understanding pedestrian movement in a more fundamental way seems, therefore, to be highly important in order to be able to cope with the observed changes.

As mentioned earlier, research on movement and behavioural aspects in evacuation have comprised two fields of research. However, they are highly integrated in terms of creating a holistic understanding of movement. This has been understood for many years for example by research on human behaviour in a modern sense initiated by e.g. Bryan (1957), Wood (1972), Bryan (1977) and Canter (1980).

People's behaviour in a fire is not an isolated phenomenon. Rather it is greatly affected by their normal activity preceding the fire incident. The actions are also not random, and they often follow specific patterns, which are governed by a number of different conditions for the situation (Canter, Breaux and Sime, 1980). Several theories related to human behaviour have been developed which will have an implication on pedestrian movement. One of the most common theories used to describe human behaviour during an evacuation is the theory of behavioural sequences (Canter, Breaux, and Sime, 1980).

What is a common factor in most of the research on human behaviour is the fact that hesitation occurs if the situation is unclear or uncertain. People need to receive enough information and persuasion in order to act. Typically, factors facilitating a safe route selection (e.g. Nilsson, 2009) and for reduction of time taken due to hesitation are investigated (e.g. Proulx and Sime, 1991).

Finally, an aspect expected to be highly relevant is the variation in capability among the general population, not just the change over time. It has been previously mentioned that obesity and the elderly population will have an implication on movement speed. In the same way these factors will have an effect on the behavioural part of evacuation with variation in cognitive capability and variation in the perception of the situation, influencing the decision-making. Research on the elderly and disabled part of the population has gained increased attention and needs to be further included in future research and engineering application.

Common for most research on human behaviour during evacuation is the recognition of the time taken for decisions and implicitly also for movement as that is part of the actions taken during evacuation. Movement occurring in a stressful situation is likely to differ from a normal situation.

Despite the recognition of the potential dangers of using the original data sets, there has been no fundamental research carried out into either the effects of changing population demographics, or the nature and causes of the observed flow behaviours and associated parameters. In addition to the identified changes related to physical movement, recent developments in the human behaviour area must also be considered and the interrelationships between the behavioural aspects and the movement aspects need to be determined. This has reinforced the need to consider a first principles approach to understand pedestrian movement in a populated space.

In order to progress this field, but yet not lose the history, future research should consider the application of biomechanical principles and behavioural aspects on people movement.

The overall aim of this project has therefore been to explore and develop a novel and well-structured scientific foundation for the future study of pedestrian movement in populated spaces. This can be broken down to the following sub-objectives:

i. *determine the current 'state of the art' across multiple research disciplines related to societal change, individual movement and pedestrian dynamics,*

ii. *identify potential primary parameters and associated metrics (such as biomechanical, physiological, psychological), which influence individual movement and interaction in populated spaces.*

iii. *develop a prototype crowd movement model based on primary parameters and a first principle approach*

iv. *evaluate potential data collection techniques, develop experimental procedures, and carry out prototype experiments*

v. *feed the experimental results for these parameters back into a crowd movement simulation model, to evaluate the impact and potential for future simulation approaches,*

vi. *publish the outcomes of experimentation and prototyping and establish a roadmap for the future study of pedestrian movement in populated spaces.*

1.1 Method

The work has been performed in four work packages, an overview of which is given in Figure 2. Initially a scoping study, the state-of-the-art review, was performed to review parameters that are vital for predicting the movement process (WP1). The first phase identified the potential primary parameters governing occupant movement.

The next step in the process combined model development or parametric analysis (WP 2) and an experimental initiative (WP3) to explore different data collection techniques and to provide new input data for continuous model development. During this time a prototype model was developed, refined using new experimental data, and evaluated using data from the literature. Finally, the learning and outputs of these steps, together, informed the resulting roadmap development (WP4).

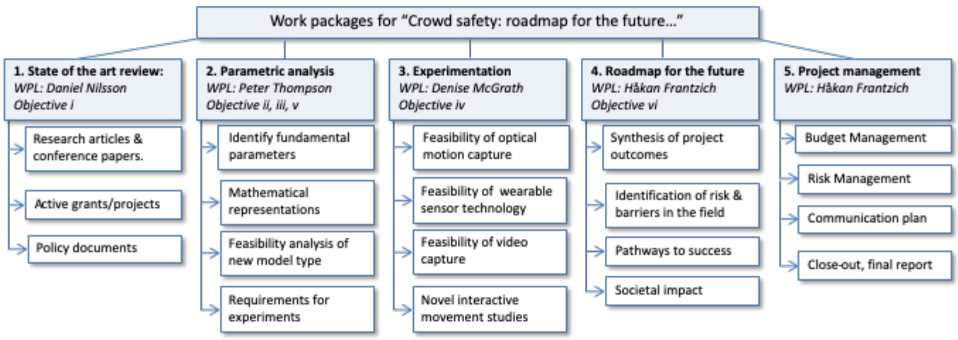


Figure 2. Method overview

As the work process in practice did not follow a linear trajectory, Figure 3 shows how the different steps were inter-related. Most important to mention is the iterative nature of the experimental programme and the model development (parametric analysis and validation). Validation of the prototyping model is an integrated part of this iterative process.

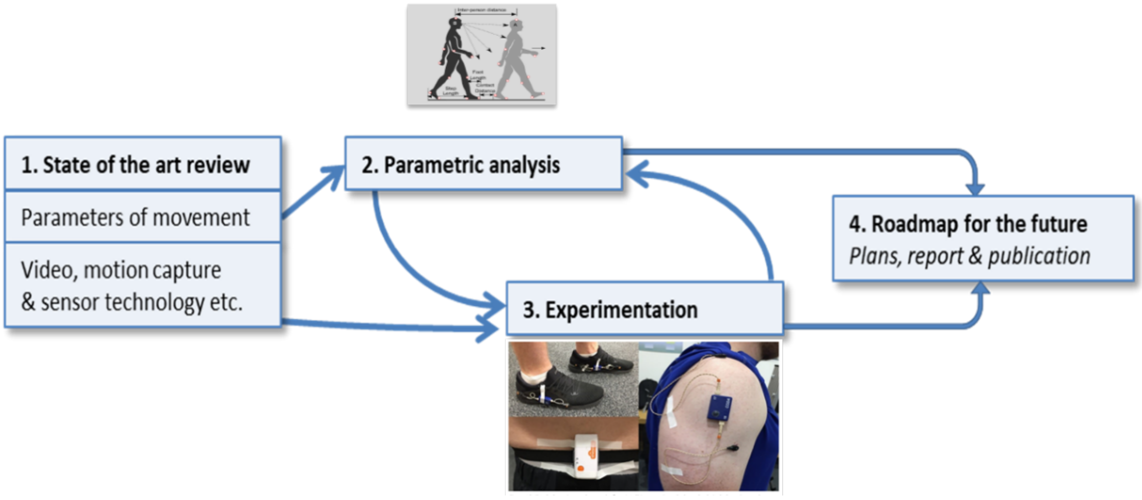


Figure 3. Process of project development indicating inter-relationships of work steps.

The method and the work process will be further explained in the next section which also summarises the outcomes of the project.

2 Project development

The project has been carried out in a number of steps (Figure 4). Before the project began some preliminary experiments (denoted as "Treadmill tests" in Figure 4) were conducted and a prototype model for pedestrian movement was created (First approx. model in Figure 4), both are described in Thompson et al (2015). The prototype model was developed as a set of basic calculation algorithms. This work was the foundation of the project.

The state-of-the-art review was initially conducted to provide information on the range of basic components forming the theory of movement. These components were then presented in terms of the potential primary parameters which were believed to represent factors needed to describe and predict occupant movement.

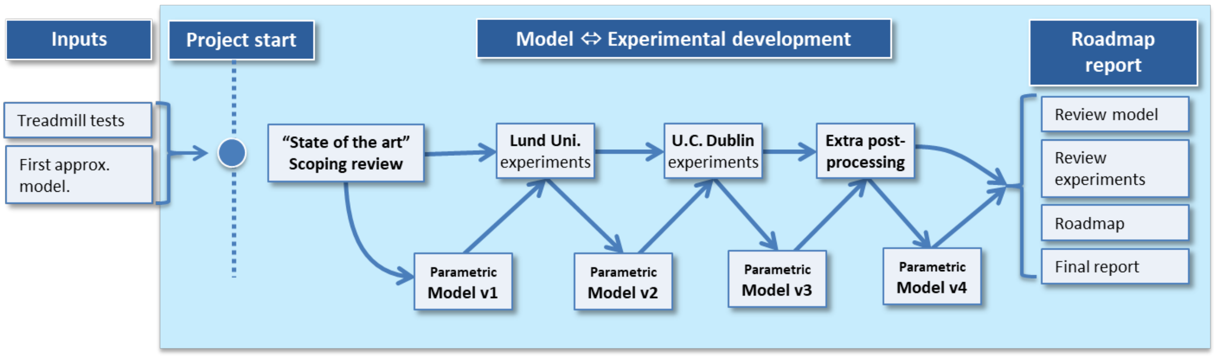


Figure 4. Project workflow.

The next step comprised two parallel processes, i.e. the development of the prototype model and the experimental work. The experiments had two purposes. Firstly, the experiments were designed to inform the model development and, therefore, they were planned in such a way to verify assumptions made in the model and to provide the model with data for its development. Secondly the experiments were designed to investigate various data collection techniques. Different techniques were used at the two experimental sites (Lund University and University College Dublin) and verified with each other, with a view to making future recommendations as to the most appropriate methods to measure and analyse pedestrian movement in the future.

During the course of this research, the model was improved, and the resulting continuously improved prototype model was tested against recently published data. Finally, the experiences gained during the work was synthesised into the roadmap for future research which is the most vital outcome of the project.

The scoping reviews, prototype model, experimental work, and testing the prototype model are published in three student theses, two conference papers and in a submitted journal paper, see summary table in section 2.5. The roadmap is not published elsewhere and is, therefore, presented and explained in the last section of this report.

2.1 State of the art, scoping review

In order to better understand which parameters influence unidirectional crowd movement, a scoping review was performed as a BSc thesis at Lund University (Hansen, 2017) in the initial phase of the project, Figure 5. The scoping review, which adapted the methodological framework presented by Arksey and O'Malley (2005), comprised the following five steps:

1. Identification of the research question
2. Identification of relevant studies
3. Study selection
4. Charting of data
5. Collecting, summarizing and reporting result

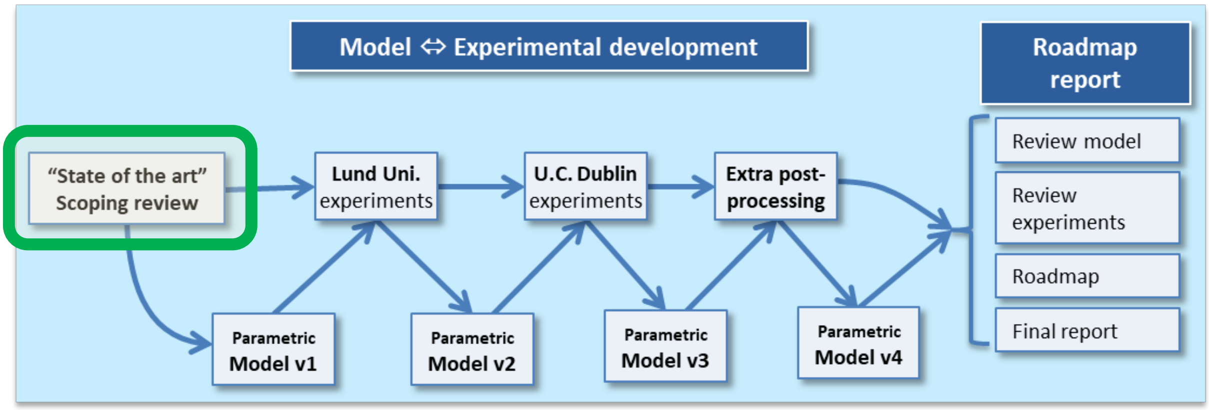


Figure 5. State of the art, scoping review.

The research question, which was identified in the first step (Identification of research question), was

What parameters have an impact on unidirectional crowd movement?

Based on the research question, a list of search terms was specified in the second step (Identification of relevant studies) of the scoping review. These search terms were then combined in four different ways, with the aim of exploring different aspects of crowd movement (see Table 1). Theses combinations, called searches, were used to search for papers in three databases, namely LUBsearch, Scopus and PubMed. The search led to the identification of 4908 papers for consideration in the next step of the process.

Table 1. Aim of the different combinations of search terms (replicated from Hansen, 2017)

Search	Aim
1	Modelling/simulation research about crowd movement
2	Experimental research about crowd movement and the interaction between different individuals in terms of inter-person distance/personal space
3	A combination of Search 1 and Search 2 - the purpose of this search was to get a wider approach and collect any studies which may have been missed in the previous searches
4	Experimental research about crowd movement and the interaction between different individuals in terms of reaction/response

In the third step (Study selection) the 4908 papers were reduced in number using selected inclusion/exclusion criteria. First, any duplicates were removed, which reduced the actual number of papers to 3141. The titles of all these papers were then read and papers were included/excluded based on specified criteria (see Table 1), which reduced the number of papers to 1675. The abstracts of these remaining papers were then read, and papers were included/excluded based on the same criteria (see Table 2), which reduced the number of papers to 524. When reading the abstracts, each paper was given a score for relevance ranging from (1) most relevant to (3) least relevant. Only papers receiving a score of 1 were taken forward. The number of papers receiving the score 1 was 75. All 75 papers were read in full and included/excluded in the final analysis based on the same criteria (see Table 1), which reduced the number of papers to 35.

Table 2. Inclusion and exclusion criteria for the scoping review.

Inclusion criteria	**Exclusion criteria**
• Articles that focus on the physical aspects of human movement in unidirectional crowd movement will be included • Experimental, modelling/simulation, reviews and discursive/commentary articles will be included • Modelling/simulation studies have to be based on real human data, or when an artificial situation is set up and the subjects are filmed without their knowledge, or laboratory based human data.	• Articles dealing with bidirectional or/and counter flow will be excluded • Pure animal studies will be excluded • Articles that do not mention human anatomical or biomechanical movement parameters will be excluded • In vitro studies will be excluded • Articles not in English will be excluded

In the fourth step (Charting of data), all remaining 35 papers were read in full and data was extracted using a data extraction sheet. The data extraction sheet is a spreadsheet in which each row represents a paper and each column represents a characteristic of the paper. One of the characteristics in the data extraction sheet is the parameters influencing crowd movement identified/mentioned in the paper.

In the fifth and final step (Collecting, summarizing and reporting results) the results were summarised in a report (Hansen, 2017). One of the outcomes of this report is the identified parameters (see Figure 6). These identified parameters were used in subsequent phases of the research.

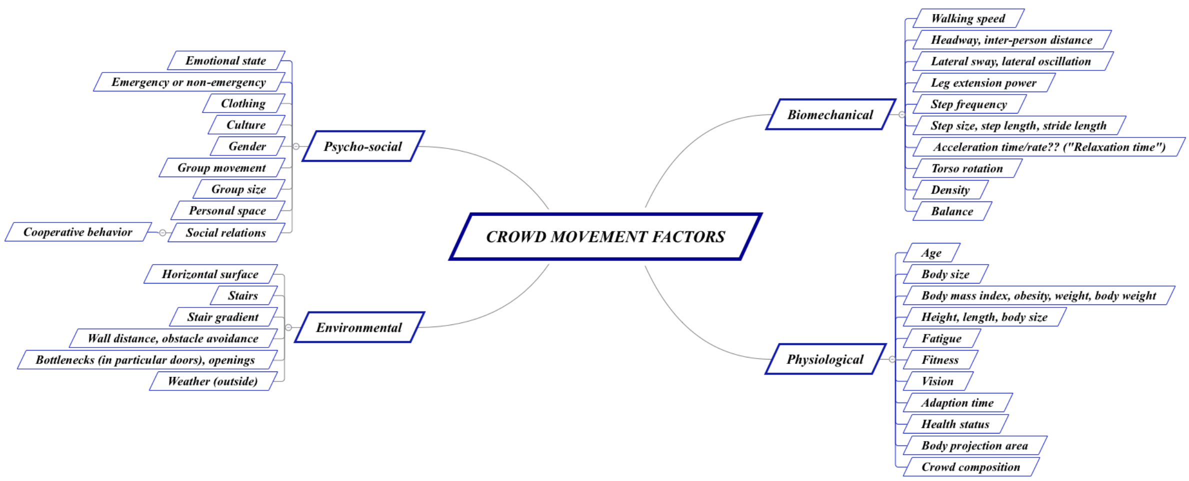


Figure 6. Parameters identified in Hansen (2017)

The process and outcomes of the scoping review were presented at the Pedestrian and Evacuation Dynamics (PED) conference in 2018 (Thompson et al, 2019) and sparked much interest and keen debate. It should be noted that a PhD study at the University of Munich (Bosina, 2018) also investigated the literature for crowd movement factors, where a number of similar factors were identified. The study went on to create some "fit" curves for movement, which it then calibrated to the results available. The main differentiation in the approaches between that study and this project is that here, after identifying primary parameters, the intentions are to quantify each individual parameter (and its variation), to create a core understanding of the different bio-mechanical and cognitive factors, and combine them into an analytical form which will not require further calibration.

2.2 Initial parametric analysis (starting the model development)

The first investigation of crowd flow analysis to use biomechanics and response to pedestrian movement was presented at the Human Behaviour in Fire symposium by Thompson et al (2015). The principles laid out in that initial investigation were combined with the wider knowledge gained from Hansen's (2017) scoping review (outlined in the previous section) which considered a more complete set of parameters extracted from the most recent literature. Essentially, the modelling approach considers the derivation of inter-person distance (aka headway), as the sum of the physical space taken up by the action of pedestrians stepping forward and a buffer between potential points of contact with a person in front, i.e. the contact buffer. The contact buffer may increase with speed, so the time to adapt to the movement of a person in front (adaption time) was identified as a key component along with step size, step length, and stride length considerations.

These terms and the basic principles for the parametric analysis are presented in the following section 2.2.1 "Terms and basic principles used in the parametric modelling". The repeated testing of this model informed the experimental investigations by highlighting parameters which could be used to mathematically describe the movement and the contact "adaption time" processes at play. The findings from the Experimentation section 2.3 enabled the development of the model into basic formulae, from the initial version described here in section 2.2.2 into the more advanced model described in the later section 2.4. The formulae thus derived were then implemented in the computer model Simulex for testing of different populations to test the effectiveness that this prototype analytical model could demonstrate in an advanced computer simulation model, with mixed demographics.

This process of iteratively developing increasing levels of sophistication for the model as the experiments developed, is illustrated graphically in Figure 7.

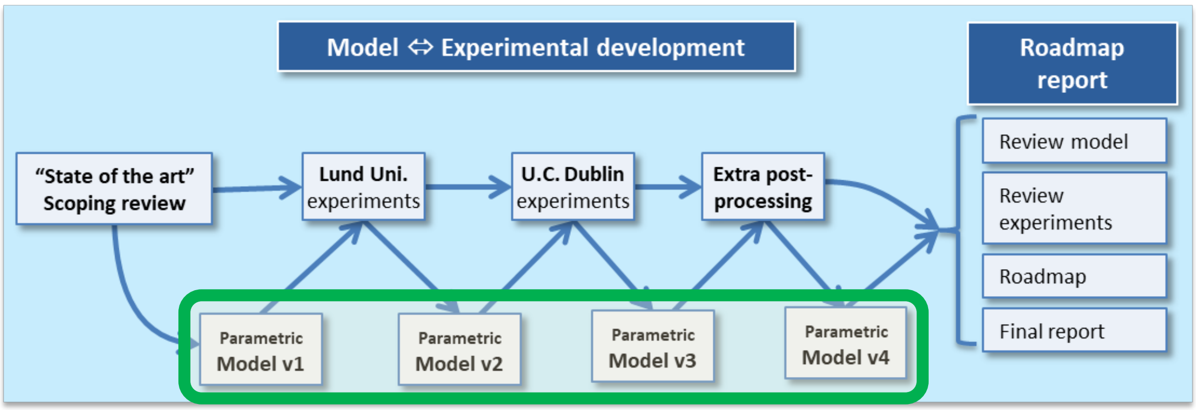


Figure 7. The process of parametric analysis and model development

2.2.1 Terms and basic principles used in the parametric modelling

The first version of the model that was initially outlined by Thompson et al. (2015) combined the science of pedestrian biomechanics with anthropometric data into a basic predictive model for crowd flow analysis. Figure 8 illustrates the main parameters, considered in this approach, to deconstruct the components of individuals walking, one ahead of the other. From initial literature studies, it was clear that the standard measure "step length" (heel-strike-to-heel-strike) was reduced with walking speed in congested space, and that there was a free space gap between instantaneous potential points of contact (heel/toe), which we named the "contact buffer".

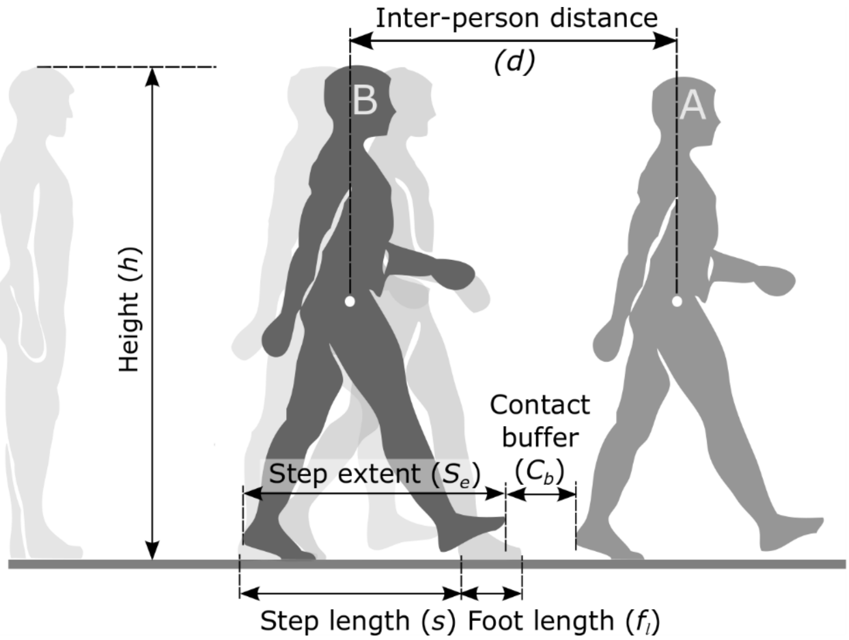


Figure 8: Components of pedestrian movement (left), and movement in congested space (right)

The analysis of step length was refined after the scoping review and experimentation was later used to verify parametric trends and values for groups in two different locations.

The experimental work undertaken in this project focussed on single-file parametric analysis in order to reduce the number of variable parameters, to optimise the chances of successful outcomes, to use this as a platform for future analyses and to inform the formation of the roadmap. The scope of this project was to illustrate how demographics could be incorporated into a prototype model and focussing on single-file crowd-flow enabled us to focus on a narrower set of parameters in greater depth.

Each iteration of the mathematical model, for single-file analysis, observed the basic relationship described in Equation 1. The derivation of inter-person distance, by summing the extent of space occupied by the stepping process (step extent) and the buffer between the nearest points of potential contact (contact buffer), guided the formation of the parametric model. This model may be referred to as the "movement adaption" model for crowd movement. The terms presented in Table 3 have been used to describe the set of parameters being used in the initial mathematical model, presented in this section.

Inter-person distance = | *Step extent* | *Contact buffer* |

$$d = s_e + C_b \quad [1a]$$

Step extent is a proportion of step length ∴

$$d = A(s + f_l) + C_b \quad [1b]$$

Table 3. Summary of terms and units in the prototype model.

A	=	factor for step extent, as a proportion of step length + foot length
C_b	=	contact buffer (m)
$C_{b(min)}$	=	minimum contact buffer when people are queuing at standstill (m)
d	=	inter-person distance between centroid of Person 1 and centroid of Person 2 (m)
F	=	proportion of step length/height (men=0.415, women=0.413, children =0.40)
f_l	=	foot length for people of equal demographics (m)
$f_{l[n]}$	=	foot length of person n, allowing for footwear (m)
h	=	height of person (m)
L	=	stride length - distance between successive strikes of the same heel (=2 × s) "left heel, then right heel, then left heel distance on floor" (m)
s	=	step length - distance between successive heel-strikes to the floor of a person walking "left heel, then right heel distance on floor" (m)
s_e	=	"step extent" of a walking person, defined as the horizontal distance between the rearmost point of the rearmost heel and the foremost point of the foremost foot (m)
s_u	=	unimpeded step length for people of equal demographics (m)
T_a	=	contact adaption time (time to accommodate movement adaption for a person in front) (s)
v	=	forward velocity of person at any given walking speed (m/s)
v_u	=	'unimpeded' (preferred) forward walking velocity of a person (m/s)

2.2.2 First version of model

The initial movement adaption model required the derivation of step length for different walking speeds. A relationship for the stride length (which is double the step length) vs walking speed was investigated by Tanawongsuwan and Bobick (2003) while investigating gait analysis as a form of person identification. An equation representing the outcome of that research was introduced by Thompson et al in 2015 and is described in Equation 2. This relationship forms the "step extent" when multiplied by the factor A (which represents the proportion of the full step length and foot length to consider from the step cycle). Figure 9 shows a sample screen image of the Tanawongsuwan and Bobick tests, and Figure 10 illustrates the relationship of stride length vs walking speed.

$$\frac{s}{s_u} = \left(\frac{v}{v_u}\right)^{\frac{5}{9}} \qquad [2]$$

Figure 9. Still side-view image of Tanawongsuwan and Bobick tests

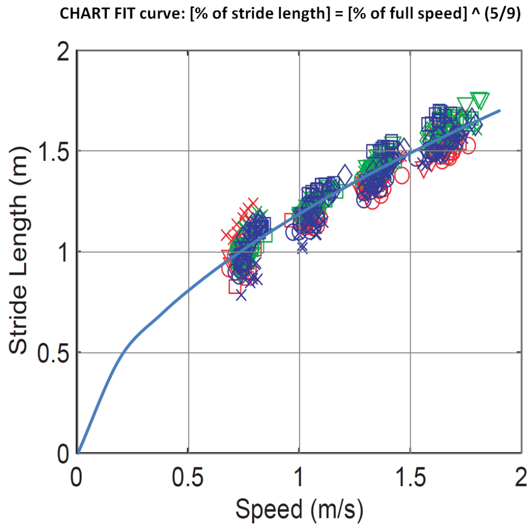


Figure 10. Stride Length vs Speed from **Eqn.[2] plotted as solid line for a "fit"*

It was also postulated that the contact buffer could be derived from the sum of the minimum contact buffer (when the people were "queuing" at standstill) and a basic response time, similar to the first stage of detect and response in traffic analysis, described in the Handbook of Road Technology (Lay, 2009).

Inter-person distance = | *Step extent* | *Contact buffer* |

$$d = A.\left(s_u\left(\frac{v}{v_u}\right)^{\frac{5}{9}} + f_l\right) + (C_{b(min)} + T_a \times v) \quad [3]$$

This early form of the model was revised in later iterations. The contact buffer was revised to take a different form after further investigation. However, the initial equation is laid out above in Equation 3 to illustrate the early draft form. It also used an approximate value for the estimation of factor A=0.8.

This early form of model was improved later, but the base approach of evaluating "step extent" and "contact buffer" held true throughout the project. The model development combined the fixed physiological parameters and dynamically changing variables laid out in Table 4, which were highlighted for investigation through the experimentation stages.

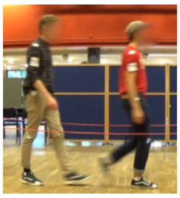
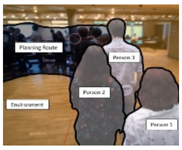
Table 4. Parameters targeted for experimentation, from initial modelling & analysis

"Fixed" physiological parameters (demographics)	**Dynamically changing variables (for experimental investigation)**
• Individual height, h • Foot length, f_l • Unimpeded walking speed, v_u	• Step length, s • Walking speed, v • Inter-person distance, d • Step extent, s_e • Contact buffer, C_b

2.3 Experimentation

A set of experiments were included in the project aiming to a) collect data relevant for the model and b) evaluate different data collection techniques. Data on inter-person distance and its proposed component parts were collected in different contexts and using different techniques, i.e. video analysis of movement at different densities and analysis of single-file flow at high resolution using a motion capture system. The video analysis experiments were conducted at Lund University in Sweden and the motion capture experiments were conducted at University College Dublin in Ireland. In addition, the video analysis experiments in Lund were complemented with an eye-tracker device on one of the subjects to identify what they looked at during motion. The experiments in Dublin were also complemented with a second technique for motion capture, i.e. inertial sensor units attached to the subjects. Table 5 provides a summary of all experiments performed in the project and some notes and insights gained.

Table 5 – Summary of experiments conducted

Location	**Equipment**	**Studying**	**Notes**	**Insights**
Lund (Oct 2018)	Video 	Single file	• Seven density levels • Video cameras side view • Video cameras plan view	• Time-consuming analysis • Large amounts of data • Can analyse outcomes for parametric modelling • Need to cross compare against Codamotion sensor
		Double files (approx. 1.5×file wide)	• Three density levels • Video cameras side view • Video cameras plan view	
	Eye-track (ET) 	Areas of focus	• ET on one subject • Seven combinations wrt ET subject height and others' heights	• Good to determine what subject looks at • Potentially useful for determining route selection • Efficient data management
Dublin (Dec 2018)	Codamotion (3D optical motion capture) 	Single file	• Five different gait speeds • ~12 meter walkway • Markers on both feet and shoulder, enabling measurement of inter-person distance, step length, step extent and contact buffer, to a resolution equivalent to 1/10th of a pixel in a 50 Megapixel camera • Two conditions: one "steady-state" walking, one where there were interruptions	• In healthy young adults, inter-person distance (i.e. measured shoulder to shoulder) increases with increasing speed. • This increase in distance is derived more from increased step extent than contact buffer • There were no differences in trends between steady-state and interrupted walking, with step extent showing a greater difference between conditions than other variables.
	Inertial sensors 	Single files	• A single inertial sensor unit attached to the lumbar spine, containing an accelerometer, a gyroscope and a magnetometer • Not a line of sight technology, thus has the potential to estimate stride length (to 2% error, Xing et al 2017) and body sway of many individuals walking in a crowd • Protocol as above with simultaneous data capture	• Training data and physical characteristics needed to enhance the accuracy of measurement.

2.3.1 Lund Experiments

The primary objective of the experiments performed at Lund University, Sweden, Figure 11, was to investigate the relationship between walking speed and the step distance and contact distance components which together comprise the inter person distance, i.e. to collect data for the parametric studies. The secondary objectives were to evaluate the capability of the data collection techniques and explore the most relevant way to express the experimental results. The experiments are fully described in Larsson & Friholm (2019) from where all the illustrations in this section from the experiments are copied (with permission).

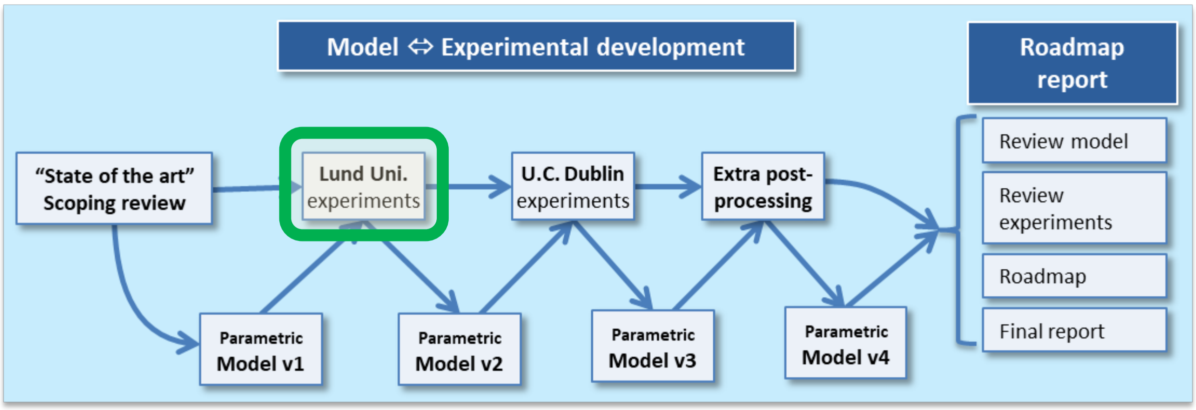


Figure 11. Lund experiments in project workflow.

The distance between individuals was defined as the inter person distance, i.e. the distance from the centre of one individual to the centre of the person in front, see Figure 8. In addition, the closest distance between two individuals, i.e. the contact buffer was also measured. The experiments were conducted in a laboratory with participants who were informed about the conditions and purpose. In addition, one of the participants was equipped with an eye tracking device to enable us to capture what that person was looking at during the experiment. The eye tracker was worn by different persons during the experiments in order to capture any differences between, for example, individuals with different heights. The walking speed and all distances deemed important were measured after the experiment using video analysis techniques. The eye tracking data was analysed using a dedicated software.

2.3.1.1 Description of experiment

In total 59 persons participated in the main series of experiments. A pilot test with 14 participants was performed to test the experimental procedure. All results presented relate to the group of 59 participants.

A majority of the 59 participants were students at the technical faculty at Lund university. The rest were friends of the research staff or friends of those. It must be assumed that many of the participants knew each other. The age ranged between 17 and 29 with a mean age of 20 years. There were 22 female and 37 male participants. All participants were free from mobility issues and provided informed consent to participate in the study. Markers were attached to each participant; heel, toe, knee, hip, shoulder and at the centre of the head, all located to be visible from the side. Anthropometric data such as height, shoe length and leg length (tibia and os femoris) were recorded from each participant.

The experiments were recorded using video cameras recording the measurement area horizontally from two sides and also from above. The camera located above the measurement area was used to record body sway and also to assist in identifying the participants in the high density scenarios. All cameras recorded in HD resolution. In addition to the video cameras, one participant wore an eye tracking device, Tobii Pro eye tracking glasses. The eye tracking device was worn by different participants, depending on the scenario conditions, to identify what the person was looking at. The intention was to investigate if the adaption of walking speed could be related to what the person was looking at.

In all the tests the participants were asked to walk as they would normally do for the number of people present (the current occupant density) without overtaking. The tests had two variations, single- and double file. The double file was approximately 1.5 times the width of the single file path which enabled the participants to walk side by side, however with a slight offset in the direction of walking. The participants were located in a zig zag pattern in the double file experiments. The walking pathway is illustrated in Figures 12 and 13. The order of persons were changed between different experiments.

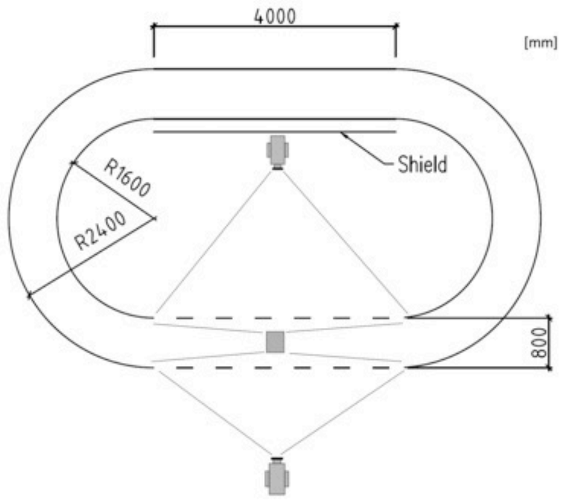


Figure 12. Schematic illustration of the pathway.

Figure 13. Photo of the experimental set-up.

All participants were equipped with an identification tag to enable the determination of any relationships between the participant's walking behaviour and some basic biomechanical data collected before the experiments started. In total 20 different experiments were performed and recorded. The variation between experiments were due to walking pattern (single file or double file), the density or inter-person distance, and the height of the three closest persons in front of the person wearing the eye tracking device. The height of the persons in front of the person wearing the eye tracker was considered either short or tall relative to the height of the subject wearing the eye tracker. Different height combinations were included in the experiments.

The subjects were told to walk as they would normally do given the conditions and that they should walk in a single file or to use the space available (double file). To adjust the distances, or the occupant density during the experiment, different numbers of subjects were allowed into the pathway. The density in the double file experiments (four experiments) varied between 2.4 p/m^2 to 3.6 p/m^2 and in the single file experiments it varied between 0.7 p/m and 2.9 p/m (16 experiments). The density values represent the conditions at the point of movement observation, see area with dashed lines in figure 12.

2.3.1.2 Results

As the video analysis technique was found to be rather time consuming, only a few scenarios were fully investigated with respect to walking speed and inter-person distance. The eye tracking data was investigated for all but the single file experiments. The sampling frequency for the video analysis was between five and eight measurements per second. It was decided that the analysis should consider the location of seven points of interest of the two persons being analysed, i.e. a person ahead and a person behind. The locations were hip, posterior, anterior and both heels and both toes. The posterior and anterior coordinates were used to identify the shortest contact buffer, i.e. the closest free space between the two persons being analysed.

Figure 14 illustrates an idealized description of two persons passing in front of the camera with identified locations of four of the most important body points. The two persons are assumed to walk with a constant speed of 0.5 m/s. From the illustration it is possible to identify the inter-person distance directly. Figure 14 illustrates the location of the heel and hip for two persons walking directly after each other at a constant speed and with a constant distance, both moving their legs in the same manner. The hip position on the two individuals (black sloping lines) moves linearly over the figure as the speed is constant but with a two second difference in time passing a fixed point in the room. The slope of the black line indicates the instantaneous walking speed.

The heel location on each individual will move from behind the person to ahead of the person, and then back again, during a complete step cycle, seen as the variation of the red line over the black line. The contact buffer can be derived as the horizontal difference (expressed as time) between the points on each individual which are closest to the other individual. Inter person distance can also be identified from the graphs.

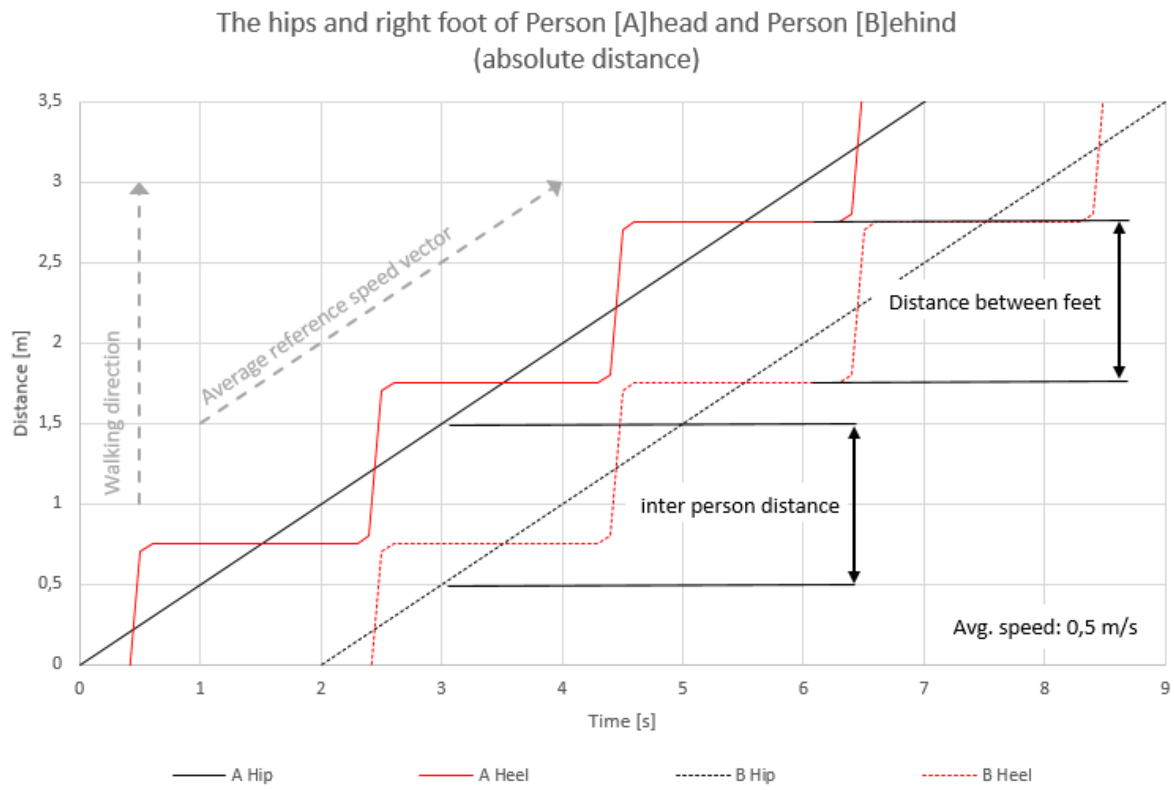


Figure 14. Schematic illustration of the location of the hips and the right heel on each of the two participants. The figure is not a result from an experiment but illustrates the principle for presenting data.

As the contact buffer was initially assumed to determine the preferred walking speed it was identified in each of the scenarios. The contact buffer can, therefore, be extracted from the information regarding the locations of the points of interest, i.e. toe and heel positions for the participants. Figure 15 shows one example of how the contact distance can be presented, in this case the distance between the foremost toe on the person behind (B) and the rearmost heel positions for the participant ahead (A) in one of the scenarios analysed. The same information is presented in Figure 16 but in this case as the absolute difference between the two participants.

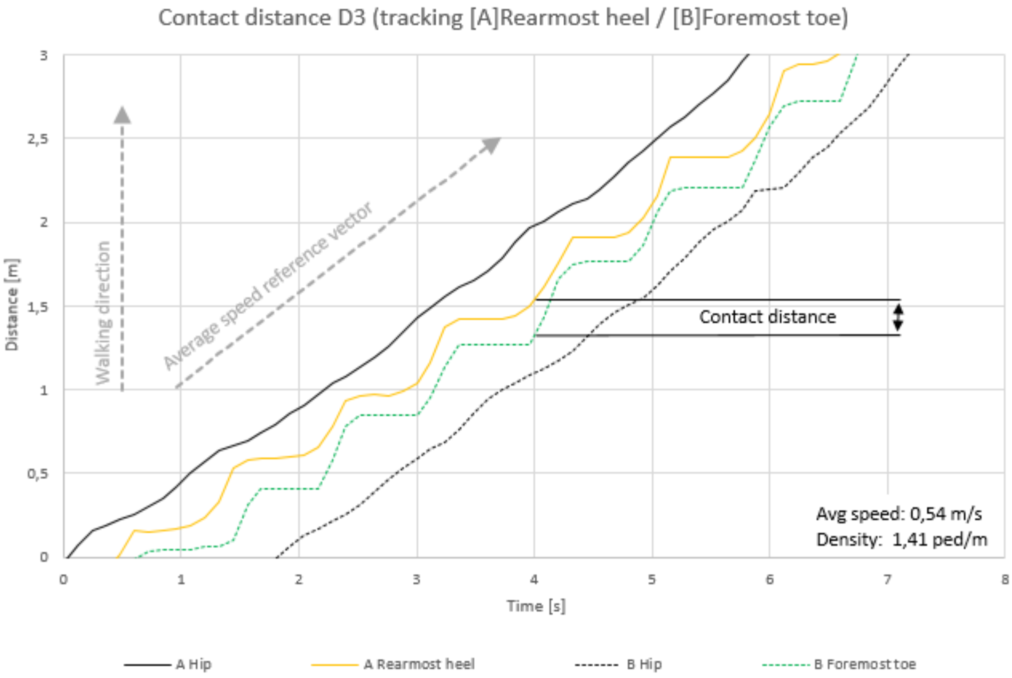


Figure 15. Analysis of the contact buffer between two individuals in scenario D3.

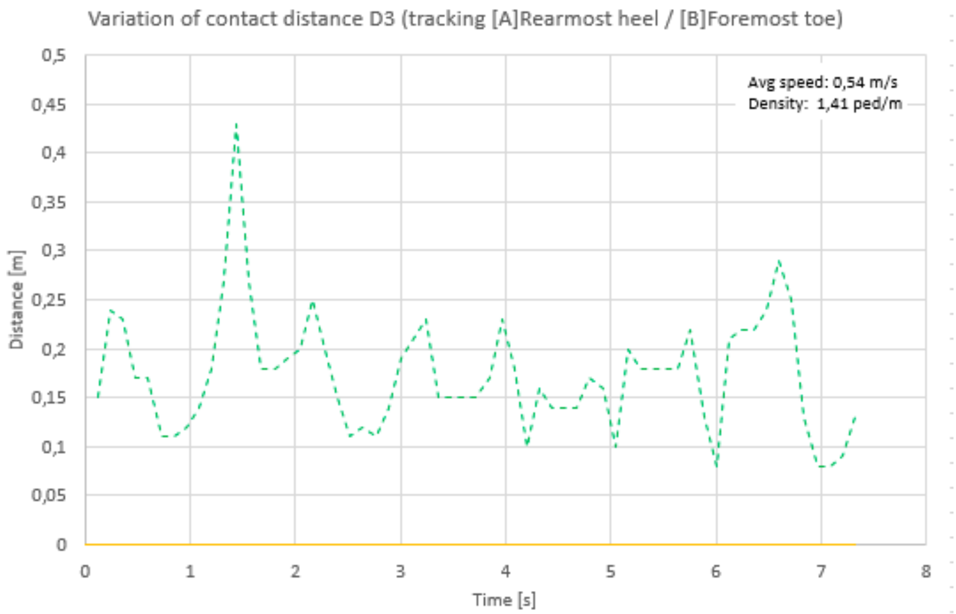


Figure 16. Contact buffer between two individuals in scenario D3 but in relation to the rearmost heel of the person ahead (yellow line).

The eye tracking information was useful to determine what the participants were looking at. The intention was to evaluate what determined the walking speed, i.e. if the focus points would be of any significance. It was concluded that there is a small difference between tall and short people regarding what they focus on. As could be anticipated during high densities the persons (both short and tall) mostly focused on the environment as they were planning their route. Both tall and short persons also focused to a less degree on the persons in front of them. The short persons looked at different body parts on the person in front while the tall person typically focused on the head of the persons in front. The short person looked mostly on the closest person in front but the tall person looked more on the second person in front. The difference on which of the persons in front, the tall and short person focused on is less for the tall person. It seems that the eye tracking experiments should be included in further studies to enable stronger conclusions in relation to movement speeds.

The video analysis technique provided important information for the parametric model which was considered to be of sufficient accuracy. The benefit from the analysis is that it is possible to adjust the measurements for any imperfections in the recorded data which yields a high validity. However, using the video analysis technique is very time consuming and more tailormade software needs to be developed in order to have a rational analysis procedure.

2.3.2 Dublin experiments

A laboratory experiment using optical motion capture and wearable technology was undertaken in the movement analysis laboratory at the University College Dublin, Ireland, Figure 17. The value of this work was in producing high resolution, high accuracy measurement of the components of inter-person distance as defined by the movement adaption model. This work built on our previous research using optical motion capture to understand movement behaviour as participants walked on a treadmill (Thompson et al, 2015). We advanced this work in this study by instrumenting four individuals at a time with markers, walking overground in single file. The scientific questions underpinning this study were as follows:

- Can we show empirically that inter-person distance equates to step extent + contact buffer?
- What is the relationship between changes in inter-person distance, step length, step extent and contact buffer, with changes in walking speed?
- Does inter-person distance, step extent and contact buffer differ when people are walking in a steady-state predictable condition versus an unpredictable condition (for the same walking speed)?

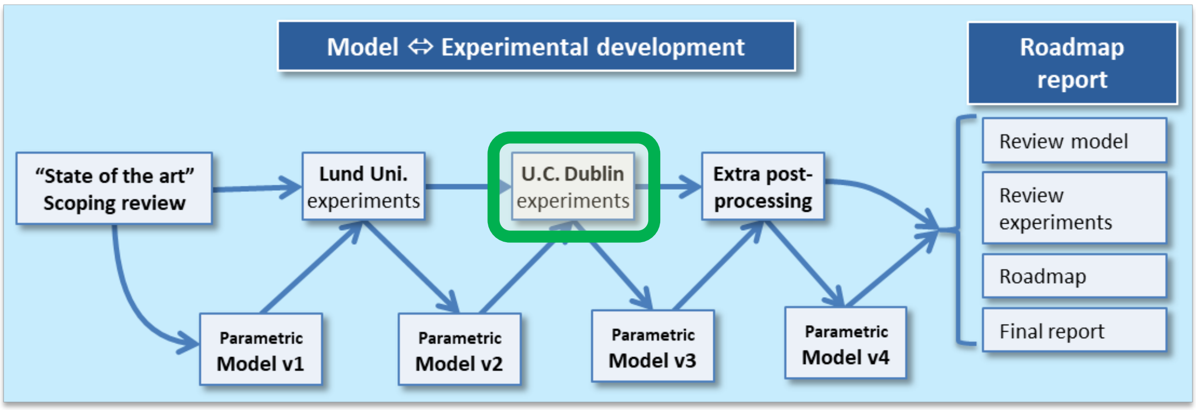


Figure 17. The Dublin experiments.

2.3.2.1 Description of experiment

A total of 16 participants were recruited, 9 female, 7 male aged 31.5 yrs +/- 6.7. All participants were free from mobility issues and provided informed consent to participate in the study. A Cartesian Optoelectronic Dynamic Anthropometer (CODA) motion capture system was used in this study which consists of transmitters i.e. active markers, receivers and data analysis software. The active markers are attached to anatomical areas of interest and the receivers can locate the 3D coordinates of the markers as long as they are within the receivers' field of view. In our experimental set-up, three CODAmotion receivers were aligned and synchronised to capture the maximum number of steps from a unilateral view.

Four participants came to the laboratory at a time for one testing session, with four testing sessions in total. Anthropometric data such as height, shoe length and leg length were recorded from each participant. Preferred walking speed and reaction time using the ruler test were also recorded. Two markers plus battery pack were attached to the outside of the right shoe and the inside of the left shoe. The weight of the battery pack and the markers themselves were low and did not influence the participants' movement. The markers were attached laterally on the heel, 4 cm from the end of the shoe and at the 5th (right side) and 1st metatarsal (left side) heads. One marker was attached to the shoulder's acromion process and another attached to a point mid-way between the shoulder and lateral epicondyle of the elbow.

There were two experimental conditions – condition A, where participants walked in single file in steady-state walking for ~12 meters and condition B, where participants walked in the same formation but with ad hoc stoppages while walking. In condition A, participants walked at 5 different walking speeds: 0.2 m/s, 0.5 m/s, 1.0 m/s, 1.3 m/s, 1.7 m/s. Walking speed and distance between participants were controlled using two research assistants placed in front and behind the four study participants. The person in front listened to a metronome through earphones that corresponded to the required walking speed. This researcher practiced extensively to walk as naturally as possible and as accurately as possible for each speed. The second researcher walked behind the four study participants to create a presence behind the last study participant, without encroaching on their space. Each walking speed was performed twice and all trials were randomised. Participants were told to walk normally throughout, and not to overtake. In condition B which came after condition A, participants walked at 0.5 m/s, 1.0 m/s, 1.3 m/s walking speeds and during each trial the researcher at the front stopped abruptly at random points along the 12m walkway. Each walking speed was repeated three times to ensure that enough walking cycles were captured in total, allowing for when the "stop" came early in the trial with reduced data being recorded in that instance. Again, all walking trials were randomised.

2.3.2.2 Results

The main differences between the experiments undertaken in Lund and in Dublin was the resolution and precision of the data collected. In principle the experiments, although using another experimental setup and procedure, should provide almost the same results. A comparison between Figures 16 and 18 (below) reveal the qualitative differences between the curves generated from the video analysis technique versus the optical motion capture system. The experiment conditions are similar with respect to walking speed between the Lund experiment (D3) and the Dublin experiment (B1.9). No manual data analysis was needed with the optical motion capture system, removing the error associated with subjective judgements of anatomical positions in the video analysis.

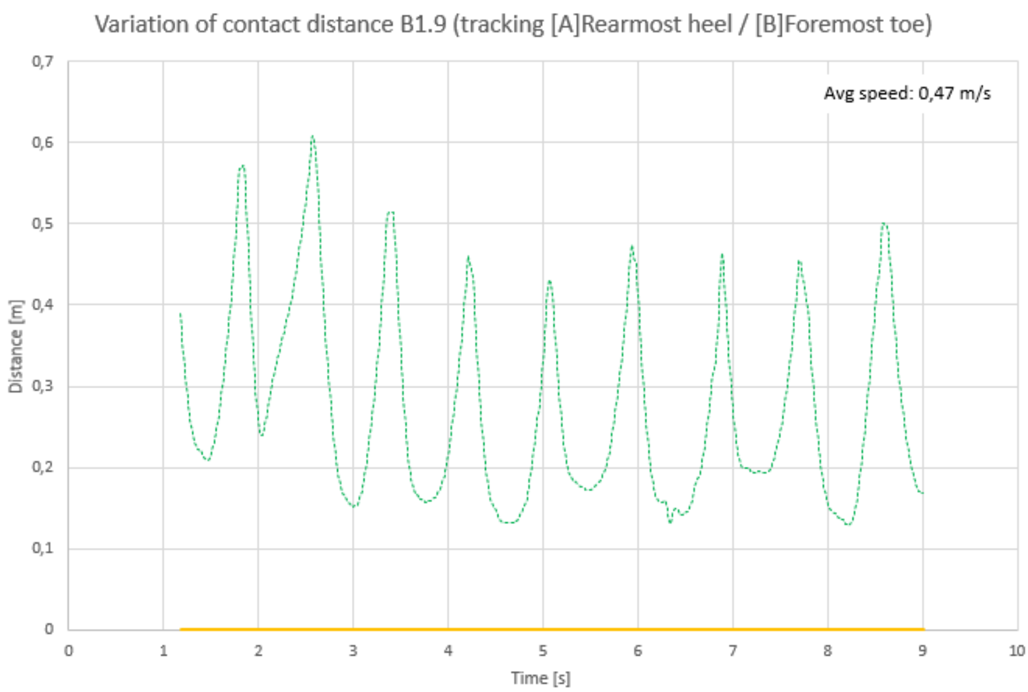


Figure 18. Dynamic variation of contact buffer with step cycle (optical motion capture)

The results confirmed that inter-person distance (measured from the shoulder marker on one person to the shoulder marker to another) can indeed be represented by the sum of step extent and contact buffer using empirical data, Figure 19, cf. Equation 1a. Differences in the outcome variables were not significantly different between steady-state and interrupted walking, although further post-processing is underway to statistically validate this observation. For the purposes of this report, data from both steady state and interrupted conditions were pooled in Figure 19 below. The figure shows that inter-person distance (as measured shoulder to shoulder), contact buffer and step extent increased with walking speed, and that the increase in the contact buffer was more pronounced at greater speeds.

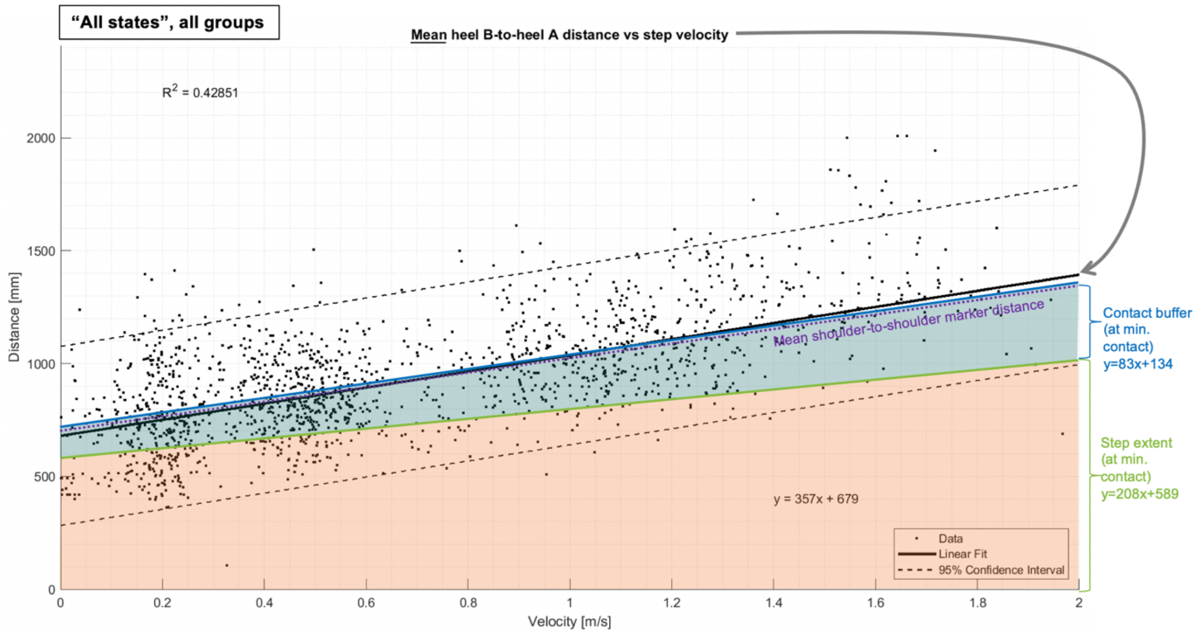


Figure 19. Step extent and contact buffer as a function of walking speed.

2.4 Advancing the parametric analyses, version by version

We learned the following lessons from the experiments, which fed directly into progressing the analytical model:

1. The sum of the maximum step extent S_e and minimum contact buffer $C_{b(min)}$ were reasonable predictors of the inter-person distance at any given speed.
2. The Step extent increases approximately linearly for higher speeds, but is better described with a "power" relationship, of the form described for step length by Wang et al (2015), later used in Eq 4.
3. The minimum contact buffer is approximately equal to the inverse of the maximum density minus the foot length
4. The contact buffer increases with walking speed, so can be expressed, at least in part, with a time element.

The terms presented in Table 6 have been used to represent the full set of parameters being used in the more advanced equations for the parametric modelling. The modelling contains a larger number of variables than the initial analysis and evolved through the project, having gained a deeper understanding of the dynamic components from the experimentation phase.

Table 6. Summary of terms and units in the evolved movement adaption model. Parameters above the solid line, and shaded are the same as in Table 3 and new parameters added are presented below the line.

A	=	factor for step extent, as a proportion of step length + foot length
C_b	=	contact buffer (m)
$C_{b(min)}$	=	minimum contact buffer, at stand-still with minimum inter-person distance d_{min} (m)
d	=	inter-person distance between centroid of Person 1 and centroid of Person 2 (m)
F	=	proportion of step length/height (men=0.415, women=0.413, children =0.40)
f_l	=	foot length for people of equal demographics (m)
$f_{l[n]}$	=	foot length of person n, allowing for footwear (m)
h	=	height of person (m)
L	=	stride length - distance between successive strikes of the same heel (=2 × s) "left heel, then right heel, then left heel distance on floor" (m)
s	=	step length - distance between successive heel-strikes to the floor of a person walking "left heel, then right heel distance on floor" (m)
s_e	=	"step extent" of a walking person, defined as the horizontal distance between the rearmost point of the rearmost heel and the foremost point of the foremost foot (m)
s_u	=	unimpeded step length for people of equal demographics (m)
T_a	=	contact adaption time (time to accommodate movement adaption for a person in front) (s)
v	=	forward velocity of person at any given walking speed (m/s)
v_u	=	'unimpeded' (preferred) forward walking velocity of a person (m/s)
b	=	body depth: whichever is the maximum of torso depth or foot length (m)
d_{min}	=	minimum inter-person distance (inverse of maximum density when movement stops) (m)
d_t	=	threshold of inter-person distance where a person "behind" first slows down for a person in front (m)
$s_{u[n]}$	=	unimpeded step length for person[n] (m)
ρ	=	single-file crowd density (persons/metre)
ρ_{max}	=	maximum single-file density (persons/metre)

The previously defined variables (in Figure 8) have been complemented with new variables defined in Table 6 and are illustrated, graphically, in Figure 20.

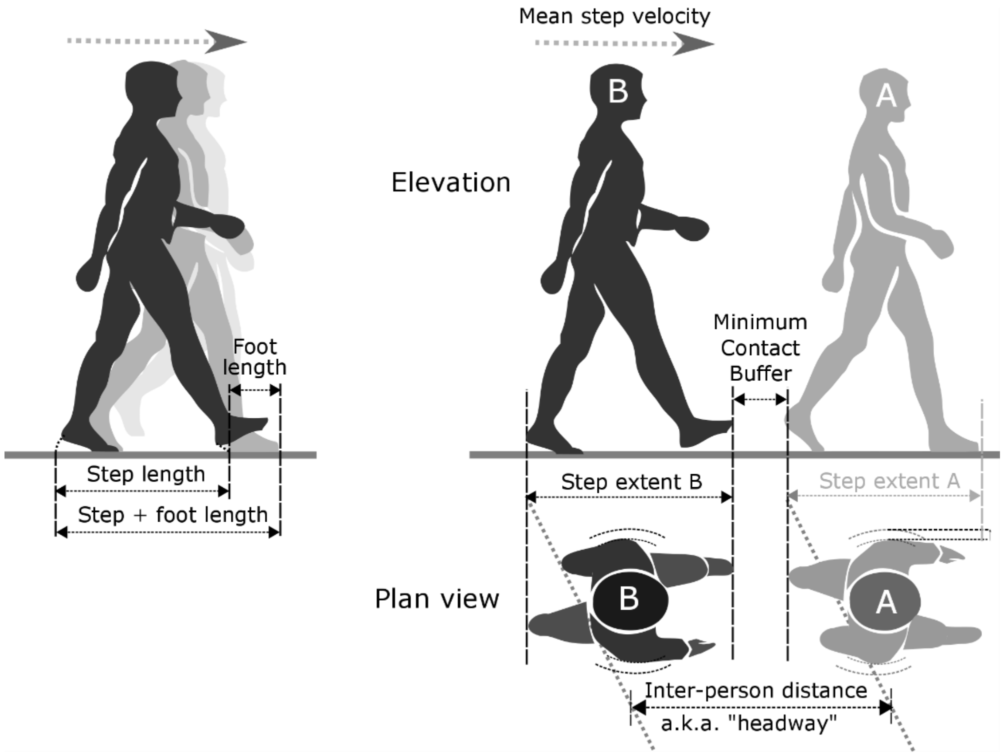


Figure 20. Components of pedestrian movement (left), and movement in congested space (right).

2.4.1 Developing second and third version of the model

The model transformed through multiple iterations, as literature was studied in greater detail and experimental outcomes were considered.

After the scoping review, a more exact analysis for step length was used, as described in Thompson et al. (2019), Eq. 4.

$$s = s_u \left(\frac{v}{v_u}\right)^{0.631} = h \times F \left(\frac{v}{v_u}\right)^{0.631} \qquad [4]$$

Experimental outcomes using the Codamotion sensors at University College, Dublin (see section 2.3.2) verified that different individuals observed variations of this relationship, but that it was still reasonable to include these in a statistical average. One of the most important outcomes of the experimentation was that the sum of the “maximum” step extent and “lowest” contact distance during the step cycle gave a good estimation for average inter-person distance for a group at a given speed with similar demographics. The maximum “step extent” at unimpeded walking speed was estimated to be 92% of the step length and foot length.

The experiments also indicated that the following relationships held true for the contact buffer, laid out in equations 5a and 5b.

For walking velocity where the adaption time is the dominant component for contact buffer

$$C_b = (v \times T_a) \qquad [5a]$$

Where the minimum comfortable inter-person distance is the dominant component for contact

$$C_{b(min)} = d_{min} - b = \frac{1}{\rho_{max}} - b \qquad [5b]$$

Therefore, over multiple iterations of testing, the equations 1, 3 and 4 were combined with the step-cycle factor and person demographics to derive a more complete form of the model, which produced a more complete form of the "movement adaption model", as laid out in equations 6a and 6b.

Step extent		*Contact buffer*
Step	*Foot*	

Walking with contact buffer above the minimum:

where $C_{b(min)} < v \times T_a$

$$d = A\left(s_u\left(\frac{v}{v_u}\right)^{0.631} + f_l\right) + (v \times T_a) \qquad [6a]$$

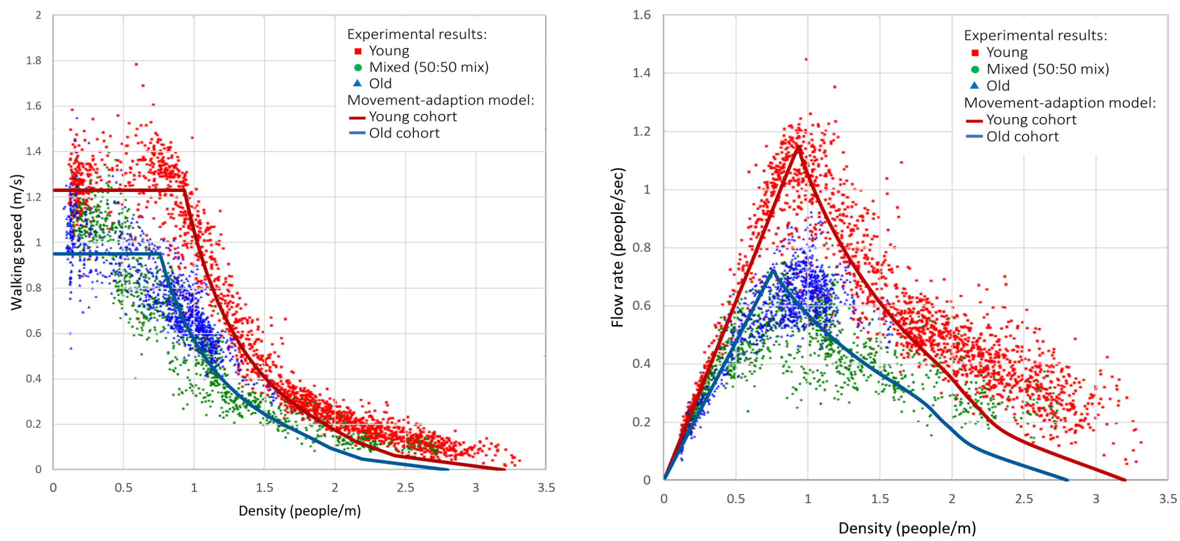
At standstill or low speeds where contact buffer determines personal space: $C_{b(min)} >= v \times Ta$

$$d = A\left(s_u\left(\frac{v}{v_u}\right)^{0.631} + f_l\right) + \left(\frac{1}{\rho_{max}} - b\right) \qquad [6b]$$

Relating inter-person distance to single-file flow density

$$\rho = \frac{1}{d} \qquad [7]$$

Note that this form of model gave a reasonable agreement with the results laid out in the Cao et al experiments, Figure 21, referenced in Thompson et al (2019). An interesting observation is that the movement in the mixed population seems to be governed by the slower population.



(a) Velocity vs density

(b) Flow rate vs density

Figure 21. Comparing the movement adaption model with the results in Cao (from Thompson et al. (2019)). Young is 16-18 years and old is 45-73 years.

2.4.2 Parametric analysis of third version in a simulation model

The third version of the movement adaption model, described in Equations 5a to 6b, was used for a stage of "parametric analysis and testing" where the equations were implemented in a computer model (Simulex) and then tested with a series of batch simulations for different population groups. The results were compared to experimental outcomes carried out by Cao et al (2016).

2.4.2.1 Implementation in Simulex

The primary Simulex function "`SpeedForNearBodies(…)`" already contained a function to assess the walking speed of a person, in relation to the forward distance to the closest person ahead. The implementation of the Equations took the following form (as item 4) in the overall logical sequence of assessing speed:

1. The angle of direction of movement is defined from the "ideal" pathway navigation system,
2. The "ideal" angle is adjusted left or right if less congestion is available in that direction
3. For that angle, the forward inter-person distance for "person behind" to the nearest person ahead *'d'* is calculated.
4. The 'desired velocity' for the "person behind" is calculated by inverting equations 6a or 6b (if d-b < minimum contact buffer) to be calculate 'v' in terms of inter-person distance *'d'*.
5. The algorithm adjusts the existing velocity to the 'desired velocity' but limits the change to within the acceptable range for the person's acceleration or deceleration range. Normally, that acceleration/deceleration adjustment is +/- 10% of the normal (unimpeded) speed for any 0.1 second timestep in algorithms established by Thompson (1994).

The movement-adaption form of the "`SpeedForNearBodies(…)`" function was also enhanced to read in the updated parameters for two "demographic types" (for Young adult students and Elderly adults) which were added to the Simulex data sets in the populations definition file. The parametric values for these "demographic body types" are listed in Table 7.

Table 7: Parameters used in Simulex for batch testing of the movement adaption equations.

Components	Parameter	Symbol (units)	"Young"	"Elderly"
Step & Foot	Height	h (m)	1.64*	1.62*
	Unimpeded walking speed	v_u (m/s)	1.23*	0.95*
	Step extent factor	A	0.92	0.92
	Foot length (as shoe length)	fl (m)	0.28#	0.28#
Contact buffer	Contact adaption time	T_a (s)	0.218~	0.548~
	Max. single-file density	ρ_{max} (P/m)	3.3*	2.8*

** data from Cao et al (2016) data.*
+ average of male and female step length:height ratio from Hatano (1993)
 # a representative foot (average shoe size) 250mm from Armitage (2018) with allowance for 30mm for shoe heel/toe
~ uses simple reaction times for ages 18 & 65 from Woods (2015), adding 0.309s for older adults from (Thompson et al, 2015).

The "demographic body types" were implemented as 3 'population' groups (with distributions of demographics): "Students [bio]", "Elderly [bio]", and "Mix [bio]". Student & Elderly groups only used single demographic body types, and the "Mix" population group consisted of a 50/50 even mix of Young & Elderly.

2.4.2.2 *Batch testing of the model*

A student with the International Masters for Fire Safety Engineering course studied the implementation of version 3 of the movement adaption using the adapted version of Simulex (Doka, 2019). This study ran simulations of different population groups through different geometries, with the intention of comparing results of the simulations against “real” experimental test results described by Cao et al (2016).

The population groups were run with 100 individuals being evacuated through the sample “unit” tests described in the IMO (2016) tests for analysing ship evacuation models. The tests were run with each population set, and also with the equivalent population sets operating with the standard Simulex evacuation algorithm, which uses a simple linear relationship for speed vs inter-person space.

In all, with the various combinations, 12 different population groups were used for simulations and a total of 530 simulations were executed in various batch simulations. The results were harvested and analysed for the statistical averages of flow rates and evacuation times across each batch of simulated runs, Figure 22.

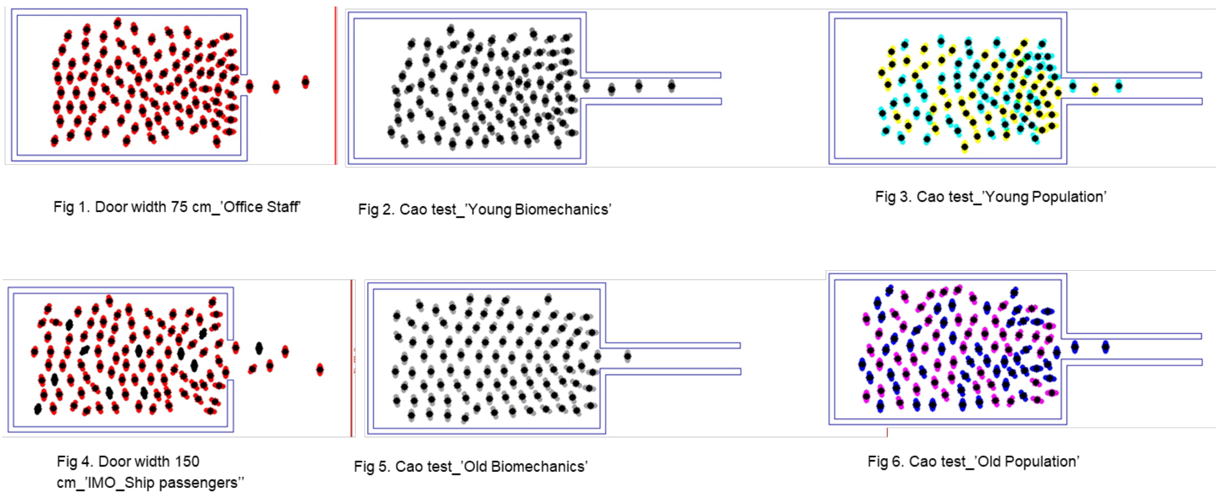


Figure 22. Sample screen images from Simulex being used in the parametric batch testing.

Overall, the outcomes of this study can be summarised thus:

1. The movement adaption model is not overly sensitive to geometry variation when implemented in the Simulex algorithm (part of the validation process).
2. The flow rates across multiple doorways rose approximately linearly (as expected).
3. The model flow rates were sensitive to demographic variation, with the “young” students showing higher flow rates than the elderly.
4. The population group tests for the movement adaption model produced results for flow rates which were closer to the flow rates in the Cao et al tests, when compared to the established, simpler Simulex algorithms.
5. The 50:50 mixed population showed a flow rate only slightly higher than for 100% elderly, yielding similar results to the Cao et al tests as well.
6. Overall the results were very encouraging, and showed significant improvements in accuracy, when Simulex used the new movement adaption model, Figure 23.

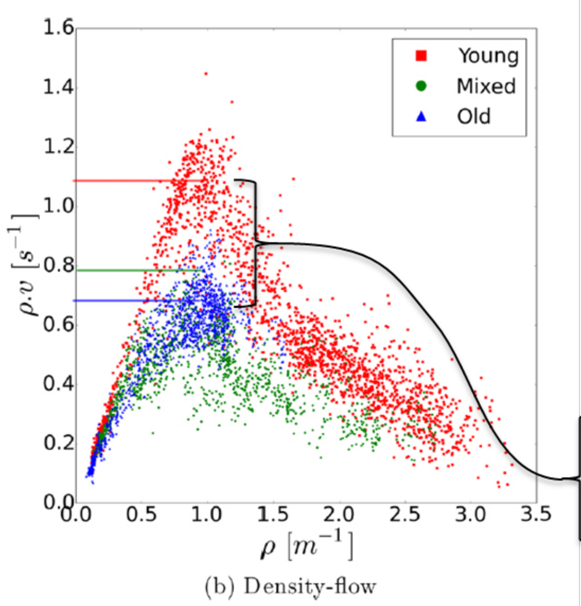


TABLE 1. FLOW RATE RESULTS FROM THE CUSTOMISED POPULATION

Population Type	Flow Rate [ppl/s]
Cao_Young	1.01
Cao_Elderly	0.72
Cao_Mix	0.79

TABLE 2. FLOW RATE RESULTS FROM THE BIOMECHANICS POPULATION

Population Type	Flow Rate
Students [bio]	1.11
Elderly [bio]	0.69
Mix [bio]	0.84

Figure 23. Comparison of model implemented in Simulex vs Cao experiments in Doka (2019).

The overall outcome of the project (after reviewing the results of all the batch simulations) was that the movement adaption model could be implemented in a computer simulation model and gave better agreement with experimental data than the pre-established algorithm form (a simple inter-person distance vs speed curve) described by Thompson (1994).

2.4.3 The (potential) fourth version of the movement adaption model

Through several observations in the experiments both in Dublin and Lund, there was frequent "overlapping" of steps – especially at high densities, as highlighted in Figure 24 below.

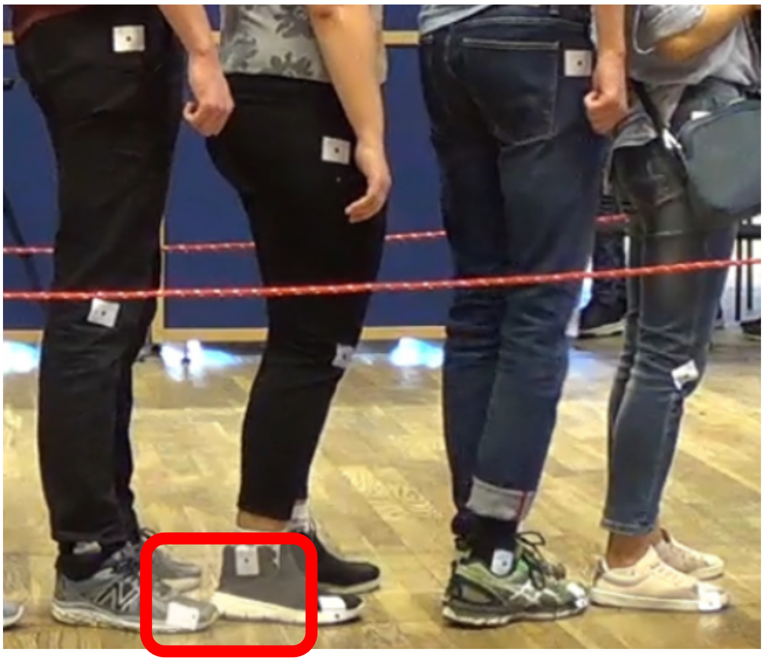


Figure 24. The overlapping steps between the gait cycles of two people.

This "overlapping" has not been accounted for in the previous versions of the model, and it is as yet unclear whether it is best evaluated as a percentage of the step length or (more likely) better estimated as a fixed value “allowable step incursion” which may be around 20 – 50 mm. This is one of the areas of study in some additional post-processing activities, which may continue beyond the original scope of this project.

When the value for overlapping is established then it is likely to be implemented by using an additional proportional factor P_o (proportion of step to use, allowing for overlap, possibly of the order ≈0.98) or a fixed step overlap value (F_o) of 20 – 50 mm. The potential implementation into a fourth version of the mathematical model is best represented in the following (potential) equations:

Inter-person distance	*Step extent*	*Contact buffer*

$$d = P_o(A \cdot s + C_b) \quad \textit{(where } P_o \approx 0.98m?\textit{)} \qquad [8a]$$

<u>*OR*</u>

$$d = (A \cdot s + C_b) - F_o \quad \textit{(where } F_o \approx 0.03m?\textit{)} \qquad [8b]$$

The development of this new “step overlapping” factor is continuing, and requires additional post-processing work, which will extend beyond the timeframe of this project. However, it does highlight the success of the experimental investigations of the project, and the fact that these forms of deep investigation are, now, for the first time possible with a more accurate level of understanding.

2.5 Outcomes: prototyping for the future

The project has produced a significant amount of new experience, experimental results and a novel approach to modelling based on biomechanical and demographical information. Tables 8 and 9 summarise some of the more important new insights and publications respectively. In order to synthesise this information and structure the outputs systematically a road map for future studies is presented in the following section.

Table 8. A summary of lessons learned from the project

Lessons learned from the project	
Work package	Lessons/outcomes
Parametric analysis	• Was effectively used to guide experimental investigations. • Was capable of supporting iterations to improve sophistication. • The primary parameters used for the model seem to be correct, as the different demographics results compare well with real-world results. • Has produced the first model for crowd movement, based on demographics, biomechanics and visual response/adaption. • Can be used to potentially predict flow rates for different population types. • Can easily be enhanced for more sophisticated parameters in the future. • Is likely to form the basis of future research & developments.
Experimentation	• Lund video tests, using Kinovea analysis were successful but laborious • Video analysis has potential for crowded situations. • Eye-tracking was interesting but inconclusive, as the gaze was usually in the distance. Needs further basic research to develop the technique. • CodaMotion sensors analysis in Dublin gave the most accurate results and deepest insights to movement. • Inertial sensors were less successful in terms of inter-person calculations as a frame of reference is required, however they may be useful for applications where body sway is being investigated • Video analysis and CodaMotion system provide similar type of results, fully comparable. • Gave much deeper understanding of underlying biomechanical process of gait cycle during walking in congested space. • Gained a much deeper understanding as a result of multiple forms of experimentation. • Both techniques produced large amounts of data, with the opportunity for further post-processing.
For simulation	• The movement adaption model can be easily integrated into a computer model. • Produces more realistic flow rates than longer-established algorithms. • Accurately accommodates different demographics (and mixes of populations) with realistic outcomes.

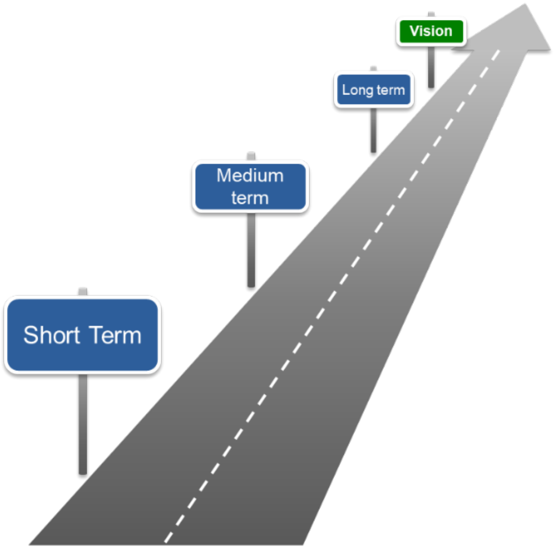
Table 9. Project outputs.

Type	Title, authors	Date
BSc thesis	A scoping review for the parameters of crowd movement, Hansen A, at. Fire Safety Eng. Lund University.	2018
BSc thesis x 2	Evaluation of measurement methods for determining individual movement in crowds, Larsson G & Friholm J, at Fire Safety Eng. Lund University	2019
MSc thesis	Advanced Parametric testing of Evacuation Modelling for Different Population Groups Using BIM-Generated geometries", Doka K, Lund University & University of Ghent.	2019
Conference workshop paper	An analysis of human biomechanics and motor control during evacuation movement, McGrath D, Thompson P, Presented at the International Association of Fire Safety Science 12th International Symposium workshop "New approaches to evacuation modelling". Lund University.	2017
Conference paper	Crowd movement, demographics and biomechanics: developing a fundamental understanding, and approach to modelling, Thompson P, Nilsson D, Hansen A & McGrath D, paper presented at Pedestrian Evacuation Dynamics conference, Lund.	2018
Journal paper	Exploring the biomechanics of walking and crowd 'flow', Thompson P, Nilsson D, Boyce K, Molloy M & McGrath D, full journal paper submitted to Fire and Materials	2019
Journal paper	McGrath D, Thompson P, Frantzich H, Goulding, C, Nilsson D, Boyce K, A kinematic analysis of interactions between pedestrians in single-file unimpeded and interrupted locomotion" – submission planned for "Human Movement" journal	2020
Journal paper	Thompson P, Frantzich H, McGrath D, Friholm, J, Nilsson D, Boyce K, "Understanding biomechanical interactions between pedestrians in congested flow" - submission planned for (not decided)	2020
Journal paper	Thompson P, McGrath D. Nilsson D, Boyce K, Frantzich H, "*Developing a movement-adaption analysis of crowd flow for future generations*." submission planned for "Fire Safety Journal"	2020
Further funding leveraged	Post-processing of remaining single file experimental data collected by Friholm and Larsson (2018).	2020
On-going Collaboration	A PhD student has been recruited at Ulster University, collaborating with UCD for the continuation of this work, focusing on older demographics and pedestrians with walking aids	

3 Road map

The final work package of the project involved the development of a roadmap, i.e., a way forward, based on the results of previous work. The roadmap was derived by the project team using a mix of brain-storming, group discussions and “critical friend” validation approaches. The following key research areas deemed relevant for creating structure for future work were identified;

- what parameters to investigate and what data to collect
- how to collect new data
- how to implement into models for the prediction of pedestrian movement.



For each of these key research areas, a vision was formulated. The primary parameters, earlier identified, are aspects relevant for pedestrian movement and future research should focus on increasing the knowledge of those parameters. It is believed that these parameters are the primary ones governing movement and that they need to be included in pedestrian movement during evacuation. The parameters may not be self-evident, but were identified in the scoping review, see section 2.1.

As significant progress in the area relies on experimental data, different data collection techniques and experiments have been reviewed. Some of these techniques are already available and can be used today, but novel techniques will most likely need to be developed. Therefore, the roadmap is limited to methods available today and those that can be foreseen in the near future.

The roadmap also specifies the desired development of modelling of crowd movement. The starting point of the road map is the enhancement of existing modelling approaches.

The three key research areas of the road map are presented individually (horizontally). Still, it must be recognized that there is a relationship between the key areas. Collecting data is based on the existence of a relevant data collection techniques. In the same way, model development is depending on collection of relevant data. Figure 25 provides an overview of the roadmap, which is presented more in detail in Figure 26. The road map provides a statement of the vision for each of the three key areas and suggestions of what should be considered in the short, medium and long term. These aspects are further elaborated and explained in the text following Figure 26. We envision that medium and long term phases will incorporate previous developments, rather than disregard them.

The road map is to be seen as a structure which indicates what research needs to be done, but it does not claim to be exhaustive. Each "cell" in the road map is further explained in the text below Figure 26.

Development phases	Time frame				
	Key research area	**Short term**	**Medium Term**	**Long Term**	**Vision**
	What parameters to investigate	Quickly obtainable data	Parameters to be evaluated in the near term (more complex parameters)	Relationships between the parameters	… for the understanding of parameters and quantification of data
	How to collect data	Techniques already established in the field	Techniques not used in our field (but established in other fields)	Development of novel techniques	… for data collection techniques
	How to implement in models	Expansion of existing model approaches	Adding more in-depth parameters and rules to models	Refine models with further in-depth parameters & rules	… for the model and the model framework

Figure 25. A brief description of the content of the road map.

<table>
<tr><th>Key research area</th><th>Short term</th><th>Medium Term</th><th>Long Term</th><th>Vision</th></tr>
<tr>
<td>What parameters to investigate
• Physiological (e.g. age, body size, vision, health status and fitness)
• Biomechanical (e.g. step length, gait, headway, walking speed)
• Environmental (e.g. stairs, weather, smoke)
• Psycho-social (e.g. emotional state (stress), emergency, culture, relationships, and group behaviour)</td>
<td>Basic movement aspects in the horizontal plane:
• Cohorts (e.g. elderly, disabled)
• Anthropometrics (height, body size, BMI)
• Laminar and wider flow
• Simple Reaction Time
• Avoidance actions
• Personal space</td>
<td>Relationships of more complex parameters
• Stress
• Smoke
• Health & fatigue
• Cultural aspects, groups
• “Stop & go” flow
Vertical movement
• Stairs
• Ramps</td>
<td>Inter-relationships of parameters
• Behaviour-driven movement
• Stimulus vs stress
• Counter-flow
• Turbulent flow</td>
<td>Combine an in-depth knowledge and quantification of the primary parameters of movement and provide a scientific understanding of the inter-relationships between those parameters.</td>
</tr>
<tr>
<td>How to collect data
<table>
<tr><th>Environment / Method</th><th>Lab</th><th>Field (real-world)
Controlled</th><th>Field (real-world)
Uncontrolled</th></tr>
<tr><td>• Eye-track</td><td>✓</td><td>✓</td><td>×</td></tr>
<tr><td>• Video/image analysis</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>• Optical motion capture</td><td>✓</td><td>×</td><td>×</td></tr>
<tr><td>• Inertial sensors</td><td>✓</td><td>✓</td><td>×</td></tr>
<tr><td>• VR and AR</td><td>✓</td><td>✓</td><td>×</td></tr>
<tr><td>• Mobile phone tech.</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>• Questionnaires / interviews</td><td>✓</td><td>✓</td><td>✓</td></tr>
</table></td>
<td>Newly established techniques in our field:
• Video analysis
• Optical Motion Capture

Explore other technologies for crowd flow:
• Virtual Reality (VR)
• Eye-tracking</td>
<td>Techniques not yet established in our field
• Automated video analysis
• Stress-measurement (e.g. sweat, oxygen)
• Augmented Reality (AR)
• Accelerometers
• Mobile phone tracking</td>
<td>Advanced data analytics techniques
• Smart building sensors
• Machine learning to collect data
• Big data – harvest points from large data sets</td>
<td>Identify and develop experimentation and data gathering techniques, in different controlled and uncontrolled “real-world” scenarios, which can be used to provide a wide body of knowledge to inform and validate in different contexts for different populations.</td>
</tr>
<tr>
<td>How to implement in models
• Mathematical formulae
• Spreadsheet(s)
• Computer simulation (microscopic, macroscopic flow etc.)</td>
<td>Formulae & spreadsheet
• Add physiological params (e.g. elderly, children)
• Wider flows, body sway

Simulation, enhancements
Implement in other stand-alone models</td>
<td>Formulae & spreadsheet
• Add psycho-social params (e.g. stress)
• Additional kinematics

Simulation, new platforms
Implement in other integrated models, e.g. BIM</td>
<td>Behaviour-driven simulation
• More advanced use of behavioural rules & decision making on movement & route</td>
<td>Provide a framework for crowd dynamics to model mixed populations in emergency and non-emergency conditions, where crowd movement results from simulating a set of primary parameters of movement.</td>
</tr>
</table>

Figure 26. The roadmap structure and suggested topics.

In the following sections, each of the three key research areas of the roadmap are described. For each key research area, the vision is first explained, which is followed by a discussion of the nature of the future anticipated work. The nature of the work in the short, medium and long term is described separately. Naturally, the proposal below should be viewed only as a suggestion, and research shall not be limited to the factors described - the road map is only intended to guide, rather than dictate, future research.

3.1 What parameters to investigate

The primary parameters are the ones believed to govern movement of individuals in crowds for specific situations. A number of primary parameters have been identified and quantified in the project for horizontal movement, but more research is needed to identify additional primary parameters for horizontal movement, as well as vertical movement. In addition to being identified, these parameters also need to be quantified, i.e., data needs to be collected.

3.1.1 Vision

The vision of the first key research area (1. *What parameters to investigate*) is to provide a description and a quantification of relevant primary parameters, which influence how individuals move in crowds for different settings. Furthermore, the vision is to identify and quantify interrelationships between the primary parameters, which must be considered in future research efforts.

3.1.2 Basic movement aspects (short term)

The short-term focus should be on obtaining biomechanical data for simple situations, e.g., single file movement but also wider flow movement on horizontal surfaces at relatively low densities where laminar flow is expected. This means that data on parameters such as walking speed for various density/occupancy conditions and for people with different demographical characteristics are prioritized, i.e. different cohorts. This is done in order to better understand the physiological aspects of movement. Currently, data on children, students, adults and elderly are available, but these data have to be validated as a first step. For design purposes, there may also be a need to update the traditional fundamental diagrams, i.e. correlations between flow rates or walking speed and occupant density for different cohorts, also reflecting demographic change. There is, thus, a need to consider these historically known and used parameters as they, most likely, will still be used in the near future for modelling and design.

Furthermore, there is a need to focus on parameters that have recently been identified as important for characterising individual movement in crowds. Of particular interest is how age and anthropometrical variables, e.g., body dimensions (height, BMI, etc) influence movement. Typical variables to investigate are preferred distances between persons, standard reaction time, preferred walking paths and factors determining the route choice, i.e. collision avoidance.

In the short term, movement conditions would typically be simple continuous movement without sudden interruptions and little disturbance from the environment, i.e., laminar flow at relatively low densities in non-complex physical environments.

3.1.3 Relationships of more complex parameters (medium term)

In order to further progress the knowledge on occupant movement, the next step adds a layer of complexity. Simply put, the basic primary parameters from the short-term are combined with parameters making the description and prediction of movement more advanced, e.g., by introducing smoke or by increasing the stress level to more realistically simulate evacuation. Smoke is an example of an environmental primary parameter that is expected to lead to increasing complexity and increased stress levels.

Other aggravating factors needing attention relate to demographic aspects, e.g., using walking aids, fatigue in relation to age, assisted escape, families evacuating with small children or with children in strollers. The implications of possible cultural factors may also be considered in the medium term.

More complex environments will need to be considered, e.g., vertical movement on stairs and ramps.

In addition, ascending evacuation, where fatigue is likely to influence movement, should be included. Medium term research should cover more complex movement characteristics, e.g., higher densities where 'stop and go' flow occurs.

3.1.4 Inter-relationships of parameters (long term)

It is obviously most challenging to provide clear guidance for the long term research, as it is the most difficult to predict. Research in the long term should focus on the forces driving the physical movement from one location to another in a crowd. Furthermore, research should explore how different primary parameters influence each other and how pedestrians move in more complex situations, which include highly congested crowds or merging situations. Turbulent flow, which occurs at high densities when bodies touch, and counter flow with collision avoidance are areas that need to be studied in order to understand the reasons behind individual movement behaviour in crowds. The relation between stimuli and stress is also a factor that needs to be included for a more complete understanding of movement phenomena.

The complex situations studied in the long term are likely to introduce additional aspects that need to investigate to further the understanding of the primary parameters. Macroscopic factor may be dominant over factors which the individual has control over. Understanding these situations is needed in order to fully understanding people movement.

3.2 How to collect data

In order to enable collection of data on primary parameters, suitable data collection techniques and methodologies need to be used. Some techniques and methodologies have been tested and developed in the project, but more research is needed in this area

3.2.1 Vision

The development of data collection techniques is essential for progress. Empirical data is the link between the theoretical aspects related to the primary parameters and the direct application in terms of modelling. Therefore, this second key research area must look at the other two parts in the road map (rows in the matrix) simultaneously. The vision for the second area is to identify and develop techniques and methods by which this data can be obtained, I.e. how to do the data collection. It is a significant research frontier in this research field, where accurate, high resolution calculations of distances between people and body parts are required.

3.2.2 Newly established techniques in our field (short term)

Data collection in the field of fire evacuation has a long history. Two-dimensional video analysis (filming from above) has been the primary approach to collect data on crowd movement, as large numbers of people can be observed at the same time. Recent development has enabled the use of virtual simulation techniques, in particular Virtual Reality (VR), for both behavioural and biomechanical studies. VR represents a substitute for a physical environment and is classified here as laboratory experiments. When using VR, the physical movement of an individual can be studied as the person moves in a virtual crowd. In the short term, focus should be placed on further developing crowd movement VR experiments, e.g., exploring data collection techniques, developing experimental procedures and validation against physical laboratory experiments.

Advances in technology have also enabled the application of three-dimensional optical motion capture (MOCAP) systems for higher resolution measurements of people movement. In the short term, experimental procedures incorporating this technology to collect data on crowd movement should be developed. Procedures need to be developed both for physical and VR experiments. Wearable technologies for the kinematic and kinetic analysis of movement, such as inertial sensors and pressure sensors, have also been used to understand movement in crowds. In the short term, inertial and pressure sensors need to be tested and results compared to those of optical MOCAP approaches

3.2.3 Techniques not yet established in our field (medium term)

Recent research carried out by members of our team has demonstrated the potential of using machine learning techniques to estimate the density of crowds through image processing of CCTV footage in a sport stadium, in addition to the application of artificial intelligence to learn from past crowd patterns. The technique can potentially be extended to also track individuals on a more detailed level, which has not been undertaken to date.

Augmented reality (AR), which may be seen as an extension of Virtual Reality, should be explored in the medium term as a way to explore crowd movement in field settings. This would create an opportunity to add extra layers of complexity and a complement to experiments performed in VR.

Other potential techniques are wearable sensors that collect biological data, such as heart and respiratory rates and perspiration. These sensors can be worn in controlled experiments where behaviours during emergency are of interest. The wearable technologies could be integrated with mobile phone technologies that, to date, have not been exploited to any great extent for crowd flow.

3.2.4 Advanced data analytics techniques (long term)

In the era of Internet of Things and smart buildings, future work in this field will undoubtedly leverage ambient sensors e.g. sensors on turnstiles, doorways, integrated with on-body sensors and image processing from video to create much deeper understanding of crowd flow in many different contexts. It is the integration of multi-modal data that will enable sophisticated modelling of crowd dynamics in the future. In the long term, big data and machine learning (Artificial Intelligence) leveraged through the many "Smart City" initiatives around the globe would enable massive collection and analysis of data on crowd movement. This will require open source data sets and pooling of intersectoral resources and expertise through "open innovation" infrastructures.

3.3 How to implement in models

In order to implement new and accurate models, data needs to be available which supports the basic assumptions in the models. The new data sets should be collected through experiments in line with the second key research area in the road map. The initial implementations, in base mathematical form can be tested and refined for uniform cohorts, in spreadsheets. Ultimately, these mathematical forms can then be implemented for multiple and "mixed" cohorts in computer simulation models.

3.3.1 Vision

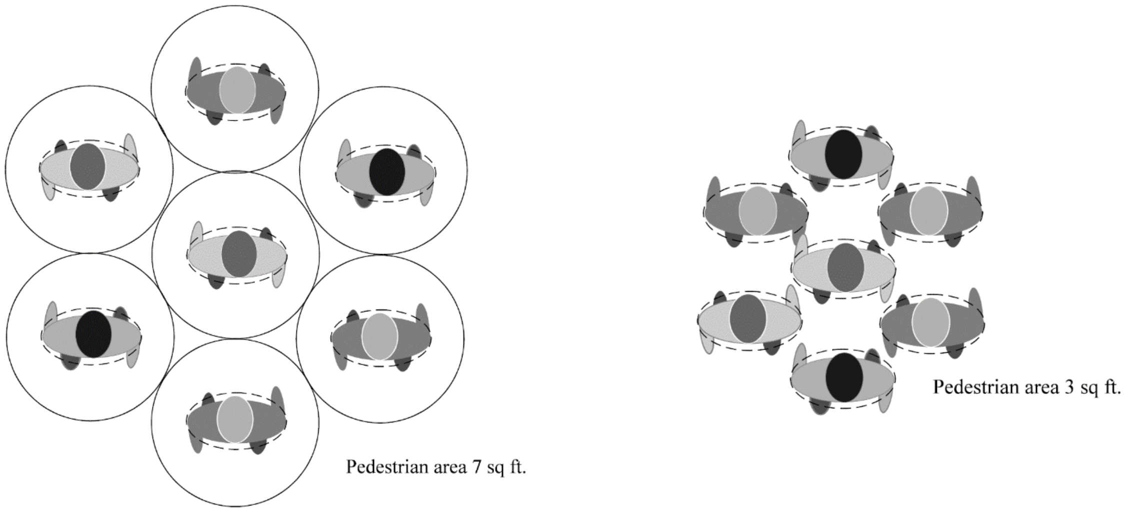
The vision is to expand the framework for crowd dynamics to model mixed populations in emergency and non-emergency conditions, where crowd movement emerges from a set of primary parameters of movement in different scenarios. It is the belief of the research team that if these parameters are well understood and quantified, then the resultant analytical model should not require further calibration. However, testing and verification of outcomes must always be observed.

3.3.2 Formulae & spreadsheet, simulation enhancement (short term)

The current formulae involve the use of biomechanical parameters for young and elderly adults, but we should also establish similar parameters for other cohorts such as children and possibly elderly of different ages, with/without walking aids and some representation of mixed ability populations. In addition, other parameters from short term data collection can be implemented – Body Mass Index (level of obesity), a wider set of Simple Reaction Times and a wider set of values for minimum personal space for different cohorts.

The primary limitation of the existing prototype model is that it is for single file movement. The additional parameters for wider, multi-lane and bidirectional flow should be considered as part of the next phase of model development. In fact, additional experiments for "1.5 times" lane flow were carried out within the project, but time has not been available to carry out the necessary post-processing of the data. This would be prioritised for future research. It is likely that for wider flow, we will need to consider "body-sway", "body width", in conjunction with the identified conditions when contact with the torso or arm would take precedence over potential stepping contact. Consequently, while we currently have two phases of movement described in Equation 5a (foot-contact distance determined by adaption time) and Equation 5b (foot-contact distance determined by comfortable distance) it is likely that an additional phase of movement would be considered where distance between torso or arms would be the determining factors as lateral incursion to the walking cycle becomes important.

It should be noted that Fruin's (1971) study observed a statistically meaningful representation of wider flows in the form of radial "touch zones" where people are packed approximately in circles of potential contact. These "zones" are illustrated in Figure 27. Indeed, it is important to note that the potential "touch" contact approach was highlighted by Fruin to be a determining factor 50 years ago, but only now are the equipment and numerical processing capabilities available to quantify these linear or radial contact zones.



The 18" radius "no touch zone" (low density) The 12" radius "Touch zone" (high density)

Figure 27. The "touch zones" defined by Fruin (1971) for wide area flows

$$D = \frac{1}{d^2\sqrt{\frac{3}{4}}} \qquad [9]$$

Where D= occupant density (people/m²), and d = Inter-person distance (m).

Note that if people do consistently observe this radial spacing arrangement, then the linear forward inter-person distance can be related to occupant density as shown in Equation 9, through basic geometric analysis, described by Thompson (1994). This geometric relationship can be combined directly with Equations 6a and 6b (which use inter-person distance) to simply convert inter-person distance to approximate density. It does allow us to project the current model to a wider flow, mathematically, but this approach must be augmented by gathering the analytical knowledge required when the lateral incursions to a pedestrian's forward path at densities shown in the "high density" configuration in Figure 27.

To support modern, advanced computer simulation models and complex population demographics, individual movement behaviour for single file and wider flows need to be predicted. This requires data and knowledge on how the individual itself moves and what governs this movement. The movement analyses described within the experiments and equations in this project should be expanded to include wider flow movement parameters. These implementations should be published and made available in a form which can be implemented in other simulation models.

3.3.3 Formulae & spreadsheet, simulation new platforms (medium term)

In the medium term it should be possible to implement some of the psycho-social aspects such as emotional state (stress), emergency, culture, relationships, and potentially group behaviour factors. Similarly, the effects of smoke (visibility and associated stress) should be considered using the optical density values, and potentially cross-linking with the Fractional Effective Dose model of smoke toxicity. Also, the presence of environmental parameters such as smoke around the pedestrian, or in their field of vision, will have consequential effects on their decision-making processes, and the kinematic processes which include walking speed and direction of movement.

Additionally, in the medium term, the more advanced simulation models may be hosted within modern integrated platforms, such as Building Information Models or Virtual Reality software systems. While it is already technically possible to do to some extent, there appear to be no moves to do so from software developers yet. This may be because the fire safety engineering community is taking some time to adopt these more recent developments in 3D design and visualization, and it is that adoption will be the driving force behind requests for simulation models to become more integrated.

3.3.4 Behaviour-driven simulation (long term)

The psycho-social parameters (such as stress, culture), which will require additional investigative work to mathematically (and algorithmically) model in a reliable way, should be developed in the long term. It is important to note that the more complex parameters require more complex rules and equations for models. It is important that these rules and equations should be open, published, tested and validated with complementary experimental work. The computer models available on the market have some degree of behavioural modelling, but the rules by which these are defined and implemented are often “closed” and the degree to which they are tested and “validated” is often unclear. It is crucial to maintain transparency in the future for the derivation and implementation of these rules.

4 How to use the research in practice?

It is important to consider how this "fundamental" type of pedestrian movement research may ultimately be applied within design guides and life safety regulatory codes. Currently, most prescriptive regulations around the world, such as NFPA 101 (2018) and UK MHCLG (2019) use a standard design flow rate for an aggregate "adult" population of 1.33 people/metre/second (or 80 people/metre/minute), which is based on numerous real-world flow rate measurements during the mid-to-late 20th century, such as those from Hankin & Wright (1958). The ultimate goal of our research vision would be to:

- support the confident prediction of flow rates which could be used in prescriptive codes for different cohorts (with different demographics), and also to
- describe the movement in forms similar to those outlined in Equations 5a and 5b, which could be implemented within microscopic computer simulation models.

The intention is to enable all forms of calculation or simulation to support different pedestrian groups with different demographic parameters.

4.1 Potential implementation for design guides and regulatory codes

It is possible to use the single-file step extent & contact buffer analysis (proposed in this report) and extrapolate it into wider flows if we assume that the radial packing illustrated in Figure 27 is statistically valid. As stated above, the extrapolation of these equations to wider flow does not account for body sway, lateral incursion or potential changes to gait patterns in the wider channel context, but they can provide a useful comparison relative to a benchmark. Therefore, as a way of demonstrating the potential implementation, Table 10 shows how design flow rates might be derived and adjusted relative to the standard aggregate value of 1.33 people/metre/second.

Table 10. Examples of potential design flow rates, from prototype equations

	Cohort			
Parameters & calculated predictions	**"Adult"**	**"Elderly"**	**Adult/ Elderly 50:50 mix**	**"School children" (11 yrs. old)**
Height h (m)	1.64	1.62	1.64, 1.62	1.42
Normal walking speed V_u (m/s)	1.23	0.95	1.23, 0.95	1.27
Max. Density (p/m)	3.2	2.8	3.2, 2.8	3.5
Adaption time T_a (s)	0.218	0.548	0.218, 0.548	0.210
Foot Length (m)	0.27	0.27	0.27	0.22
Step Extent Factor A (at V_u)*	0.85	0.85	0.85	0.85
Peak single-file flow(people/sec)	**1.14**	**0.72**	**0.88**	**1.24**
Percentage of "Adult" flow rate	**100%**	**63%**	**77%**	**109%**
Percentage difference from "Adult" flow rate	0%	-37% (lower)	-23% (lower)	+9% (higher)

**Factor A, linearly decreasing from 1 (at standstill) to 0.85 (at unimpeded walking speed) has been highlighted as a more accurate representation for the dynamic walking cycle, as part of recent post processing activities at UCD.*

The parameters in Table 10 are a combination of demographic data selected from Hankin & Wright (1958), Ando (1988), Woods (2015), Cao et al (2016), IMO (2016), and Wang et al (2018) to predict single file flow rates with Equations 5a and 5b. The proportional difference for the "elderly" and "school children" cohorts, relative to the value for the "Adult" population are shown to highlight the impact of demographics on flow rates. These values require further research and validation for the wider context (to reflect lateral positioning, overtaking and different dynamics), but the principles can potentially be used to derive recommended proportional adjustments for design flow rates for different populations, once the factors for wider flow are confirmed with further research. The predicted trends (41% lower flow for elderly and higher flow for children) align well with the lower single file flows observed for elderly by Cao et al. (2016) and higher predicted flows for children observed by Hankin & Wright (1958). In addition. one current shortfall with regulatory guidelines is evident with the International Maritime regulations (2016) where detailed demographics data are published for the ship passengers, but the regulations persist with a 1.33 people/m/second flow due to the lack of published data for different cohorts. These guidelines could easily be updated with more realistic (e.g. 41% lower) flow rates for the elderly passenger cohort.

4.2 Potential implementation for computer simulation models

In this project, computer analyses for both post-processing of the experimental data and testing equations in the computer model Simulex have been implemented. The equations laid out in this study enable a set of demographics parameters to be converted into aggregate cohort flow rates or movement algorithms for individual people. Therefore, the methods enable different population types to be considered in all forms of pedestrian modelling, in the context of life safety:

a) There are now a documented set of input parameters defined for any analytical method to consider movement for different cohorts.

b) Older, “flow capped models” computer simulation models can use design flow rates for different demographics. For example, these could be used within EXODUS (Gwynne et al 2005) or STEPS (Mott Macdonald 2020).

More advanced “microscopic” simulation models, such as PathFinder (Thunderhead Engineering 2014) and Simulex (Thompson 2003), can use Equations 6a and 6b with individual profiles for modelling, and run unit tests as demonstrated in Section 2.4.2: "Parametric analysis of third version in a simulation model” to validate the implementation of the equations for movement. They should demonstrate changes in overall flow with values of a similar magnitude, using the unit test approach illustrated in the IMO unit tests.

5 Conclusions and next steps

The overall aim of this research was to develop a novel and scientific foundation for the future study of pedestrian movement in populated spaces. The main objectives were to identify potential primary parameters and associated metrics which influence individual movement and interaction in populated space, to evaluate potential data collection techniques and develop experimental procedures, to conduct prototype experiments to explore the identified parameters and to use the results to inform the development of a prototype model of movement based on a first principles approach. This work was intended to form the basis for the establishment of a roadmap for the future study of pedestrian movement in populated spaces. It is the first step in the development of more advanced, emergent models of crowd movement with the potential to accurately represent diverse population demographics now and in the future.

5.1 Outcomes and conclusions

The first stage of this research comprised a scoping review of the literature to identify biomechanical, physiological, psycho-social and environmental parameters known to influence unidirectional crowd movement. A number of these parameters and their interrelationships were subsequently explored in horizontal plane during the experimental stages of this project and informed the development of the prototype model. However, it is recognised, as noted within the roadmap, that they require significant further investigation in the short, medium and longer terms in order to fully and accurately inform future modelling efforts.

The experimental work in this study had two main purposes i.e. firstly to quantify and explore the relationships between some of the primary parameters (identified in the scoping review) and secondly, to evaluate the capabilities of the different experimental techniques and how to best visualise and convey the experimental results. The main findings with respect to the former (for healthy young adults) were:

- inter-person distance (measured from the shoulder marker on one person to the shoulder marker to another) can be represented by the sum of step extent and contact buffer,
- inter-person distance increased with increasing speed,
- the increase in inter-person distance is derived more from increased step extent than contact buffer, but the increase in contact buffer is more pronounced at greater speeds;
- there were no significant differences with respect to inter-person distance, step extent or contact buffer for a given speed when people were walking in steady-state (predicable) compared to interrupted (unpredictable) walking. This may be due to the highly functioning perception-action capabilities of the study participants. Future work with elderly will investigate similar relationships. Step extent showed a greater difference between conditions than other variables.
- the maximum step extent at unimpeded walking speed was estimated to be 92% of the step length and foot length.

Two data collection techniques were explored in this study i.e. optical motion capture and video analysis. Both produced large amounts of data with the opportunity for post-processing and, importantly, both were capable of producing similar results which were fully comparable. However, for single flow experiments, optical motion capture seems the most promising, giving more accurate and precise results, with the potential for a much deeper understanding of the underlying biomechanical process of the gait cycle.

The video analysis was found to be extremely time consuming and laborious in comparison to the optical motion capture system which did not require any manual data extraction; the latter also removed the error associated with subjective judgements of anatomical positions required in the video analysis.

Notwithstanding, it is expected that optical motion capture will pose significant difficulty in analysis of movement in wider flows and therefore it is important that more effective data collection using video footage and more efficient data analysis of same is developed in the future.

Other data collection techniques used in the experimental work involved the use of eye-tracking and use of inertial sensors. Eye-tracking data, whilst interesting, was limited and inconclusive with respect to factors influencing gaze. Inertial sensors were investigated as a means to estimate inter-person distance and stride length. Without a frame of reference (for example created by fusing wifi signals and ambient sensors) is it not possible to estimate inter-person distance. On-body sensors may be useful for applications where body sway is being investigated. Additional post-processing is underway to investigate the potential of wearable technologies to accurately estimate step length/extent.

The scoping review and the outcomes of the experimental work informed the development of a prototype movement adaption model, the first of its kind to consider crowd movement from first principles based on an understanding of biomechanics, demographics and visual response/adaption time.

New equations (6a and 6b) have been formulated for single-file flow and have been tested in a spreadsheet and cross-checked against other researchers' experiments, with very encouraging results. The project has indicated that the equations are capable of supporting iterations to improve sophistication and can easily be further enhanced as our understanding of the primary parameters and their inter-relationships improves. The equations also have the potential to be further expanded for wider flows to produce demographic-specific flow rates for regulatory guidance in the future.

The movement adaption model equations were additionally implemented, in prototype form, in the computer model Simulex. Once again there was a good correlation between observed flow rates and experimental outcomes. This has demonstrated the potential for the formulae to be fully implemented in advanced computer models and the potential to support the long-term vision of an emergent model of movement for mixed ability populations in emergency and non-emergency conditions.

A road map for future research has been presented here. The roadmap provides some direction in terms of research initiatives needed from a short-term to a long-term perspective. It suggests what parameters need to be investigated, how data might be collected and how our new understanding might be implemented in models for future generations.

5.2 Next steps

The next, practical steps to begin to deliver on this roadmap and the vision for the research have been discussed in sections 2.4.3, 3.1, 3.2 and 3.3. Extra funding has been procured through the SFPE fund for further processing of the Lund experimental data. A newly developed software was used to automatically processes video footage in terms of inter-person distances. UCD has also leveraged a resource in collaboration with the Insight Centre for Data Analytics at University College Dublin for further post-processing of results. Therefore, the prioritized studies for this research may be summarized in the following blocks:

1. Expand the post-processing of Lund video experiments to quantify the 1.5x lane flow movement, to compare against the single-file results, and thus inform the changes in contact buffer and movement that occur in wider flow scenarios.
2. Enhance the parametric model formulae to include the 1.5x lane flow outcomes, and propose the next experiments for wider sets of lane flows.
3. Carry out experiments similar to UCD and Lund tests with different demographics: specifically, elderly and children.
4. Carry out sets of wider flow tests: 2x and 2.5x lane flow tests.
5. Review and update the formulae for both the wider tests and the different cohorts.
6. Create a set of suggested design guidance values for speeds and flow rates for different cohorts, derived from the enhanced equations, and validated against experimental data.

One specific strength of this project was that the research team captured a variety of perspectives outside of the academic arena. Regular reviews and input to our research progress (and plan updates) from a reference group comprised of industry and regulatory stakeholders. Our industry partner (Pete

Thompson representing Autodesk) has been a principal contributor to the research and analyses. This has been an important guiding perspective throughout. Dr Rita Fahy, an external reviewer from NFPA, provided feedback at various junctures, offering views from the regulatory and long-established research perspectives.

The team also understands the value of knowledge exchange between the researchers and the potential users of the research and will continue to champion this as a priority in our respective fields of influence. There will certainly be specific use cases where, for example, the majority of building occupants are known to have limited mobility due to specific disabilities. These use cases could drive the research in particular directions, further expanding the model which could then be considered in design guides and computer simulation models allowing for a more user-centric approach.

It is also important that in these next steps in the research we continue to combine inputs from different disciplines, such as sports and health science, data science and sensor development. This mixture of disciplines and background ensures the ongoing input for new experimental techniques which ultimately produce results and outcomes that can be implemented in the real world. Leveraging inter-sectoral collaborative opportunities for sharing data sets and other research processes and products will accelerate progress in this field so that we can deliver up-to-date, evidenced-based design guidance for future, more diverse populations.

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