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Development and evaluation of a model for supporting accessibility analysis in buildings

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MAI (Computer Engineering)

Declaration

I hereby declare that this project is entirely my own work and that it has not been submitted as an exercise for a degree at this or any other university.

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Abstract

"People of diverse abilities should be able to use buildings and places comfortably and safely, as far as possible without special assistance"[1]. Currently the evaluation of accessibility in buildings is conducted using, largely, manual methods. Advancements in portability and affordability of devices capable of generating and evaluating point clouds indicate that modern technology can now be used in place of these traditional methods. This thesis sets out to design a model for the evaluation of accessibility in buildings that would lend itself to being implemented using these technologies. The model is intended to assist professionals in their analysis of buildings while also providing laypersons with the wherewithal to conduct their own assessments. The aim of the development is to improve upon current models in the areas of usability, incorporating efficiency, cost effectiveness and satisfaction. An application for Google Tango was developed to implement the model, to demonstrate its viability and test its proposed benefits. The model was evaluated by a mixed user group of professionals and laypersons. Though the results of the evaluation were inconclusive overall, in terms of meeting the research aim, they were indicative of there being value in developing the model further.

Acknowledgements

There are many people who deserve to be acknowledged for their contribution to this work chief among them my supervisor, Dr. Kris McGlinn, whose wisdom was fundamental to the development of this thesis and my mother, Dr. Mary Hyland, whose continued support and guidance was crucial in helping me implement my ideas.

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Nomenclature

x	Distance	Metres (m)
θ	Angle	Radians (rads)
CAD	Computer Aided Design	
ISO	International Standards Organisation	
LDM	Laser Distance Meter	
OT	Occupational Therapist	
SUS	System Usability Scale	
TCD	Trinity College Dublin	
TLS	Terrestrial Laser Scanner	
UI	User Interface	

1 Introduction

1.1 Motivation for Research

In recent times, awareness of issues concerning equal opportunities and equality have increased dramatically. A major example of this is an increased recognition of the need for appropriate physical access to buildings. The issue of building accessibility is one that dates back to, at least, "the late 1950s in Holland, [when] the government assisted in constructing a village for 400 severely disabled people."[2]. At that time, accessibility was seen as being primarily an issue for those involved in new builds and developments, with the application of Barrier Free design which later evolved into Universal design. "The more generalised concept of accessible design emerged in the 1970s and promoted the incorporation of accessible solutions into the general design of products, services and environments." [3].

Trinity College Dublin (TCD) has gone to great lengths to incorporate these accessible solutions into its own services and environments[4]. As an historic university, the campus features many buildings which were designed before modern accessibility issues were a consideration, meaning much work has been required to retroactively assess these buildings for accessibility. To date, such work has largely involved manual methods of assessment which, by their nature, are time consuming and tedious, some requiring the "occupational therapist bring along a manual, a number of paper-based data collection forms … a folding ruler, a pen and paper ... and possibly also a camera"[5]. Awareness of this situation led to the question of whether a new model could be developed based on the power of modern technology which, with appropriate implementation, would be capable of completing such assessments more efficiently than through traditional techniques.

Such a model is something which could have a widespread impact on disability access and a potentially revolutionary effect on the way that people interact with physical environments. It could save occupational therapists time and money in the completion of assessments and follow-up, in turn saving time and money for those availing of these essential assessments. It is also believed that the model could be cheap enough and simple enough for anyone to use it and share the results. This could ultimately lead to those responsible for commercial buildings more actively considering the accessibility of their property by completing nonessential assessments, as doing so has been shown to have multiple financial benefits. Not only does increasing the accessibility of a commercial building increase the potential customer base but proper implementation of user centred design can lead to better customer experiences for all. A member of the National Disability Authority, interviewed as part of this research, referred to a case study in Barcelona, whereby improving access provisions for buses sped up overall embarkment and disembarkment to such a degree that the system experienced an efficiency increase equivalent to the addition of one extra bus per-route.

If these assessments of commercial property were successful enough to become accepted practice among all property owners, this could, in turn, lead to increased awareness of access needs among the public more generally. If the model were to achieve these aims, it would impact positively on the way that those with specific access requirements are considered and provisioned for.

1.2 Research Aim and Objectives

The aim of this thesis is to address the following research question: What level of usability can a model to support accessibility analysis in buildings achieve, whilst being cost-effective? Usability is estimated by looking at three core aspects; effectiveness, efficiency and satisfaction as proposed by the International Standards Organisation (ISO), under their Usability Standard [6].

The specific objectives of the research are:

1: To conduct a State-of-the-Art review of current practices for assessing accessibility. To then identify key requirements for assessing accessibility through analysis of the strengths and weaknesses of current approaches.

2: To design a model to assess accessibility which can be used by both novices and experts in the field.

3: To implement and evaluate the resulting model to determine if it has met the key requirements of being usable by accessibility assessors.

2 State of The Art

2.1 Building Assessment Methodologies

2.1.1 Approach in Ireland

In Ireland there are a range of approaches to the assessment of accessibility in buildings, the most consistent of which is the Disability Access Certificate[7]. This certificate is a requirement when planning new builds or renovations in non-residential buildings. It is acquired by having an architect or engineer review the drawings of the work to be completed and establishing that they are in line with relevant provision in the national building regulations, referred to as Part M[8]. This sets out guidance on the minimum level of provision to be made, for people to access and use a building, in that building's design and construction. These minimum levels of provision are generally highly specific, often detailing the exact measurements required, although some are subjective.

The National Disability Authority also recommends that existing buildings, not completing renovations, carry out access audits to establish how well they are performing in terms of access, and to improve accessibility where required [9]. Currently, it is advised that these audits be completed by a person who has received training in access auditing, using some method of recording information, a measuring tape (to measure door width, risers, landings etc.) and a digital camera. Other recommended tools are a Grad level or gradient measuring device (to measure slopes), a door pressure gauge, a light meter, an induction loop tester, a sound meter and a temperature recording device (hot water)[10] but these are rarely used in practice. Furthermore, there are no formal requirements for how, or by whom, an audit should be completed nor that it be completed at all.

The final aspect of building assessment in Ireland is home assessments to establish that a residence is suitable for the needs of a specific person with a disability. These are completed by occupational therapists (OTs) who will visit homes to ensure they are suitable for the residents within them. The primary difference between these assessments and others is that they will not be looking to ensure a home reaches a particular standard, rather that it is suitable for the individual who lives there. Where renovation is required, they will be aiming for the maximum accessibility at the minimum cost. As with accessibility audits, measurements will be taken in the physical environment as there would very rarely be technical drawings to work off. It is remarkable that while there are courses available in housing assessment, there is no accreditation and nor is there a recognised common approach. This research found that many OTs have developed their own consistent approach which they use in all assessments (this will be discussed further in chapter 5).

2.1.2 Novel International Approaches

No evidence was found to suggest that Ireland's approaches are significantly less developed than those in other countries, though there has been research into the development of ways to improve on existing methods. One such piece of research devised an assessment model, based on Swedish accessibility standards, named "the Housing Enabler"[11]. In a follow-up study, software was developed to take the results of this assessment and analyse the data, producing an accessibility score[12]. Subsequently, the paper-based assessment forms, that are central to the Housing Enabler, were adapted into a digital format by Svarre et al.[5], who created a prototype Housing Enabler app. The app was directly based on The Housing Enabler Screening Tool[13], a reduced version of The Housing Enabler, with a simpler algorithm for developing the accessibility score. The app aimed to "decrease time use, minimize data entry errors and facilitate communication with other ICT [Information and Communication Technologies] tools and documentation systems"[5]. However, it still required manual data input and offered little more than could be accomplished by digitally scanning a completed screening tool, in terms of facilitating communication. It gathers standardised data which is highly specific to the calculation of the score (see the checkboxes in Figure 2.1). While the app allows notes to be taken that are likely to include useful measurements, these cannot be interpreted for other uses.

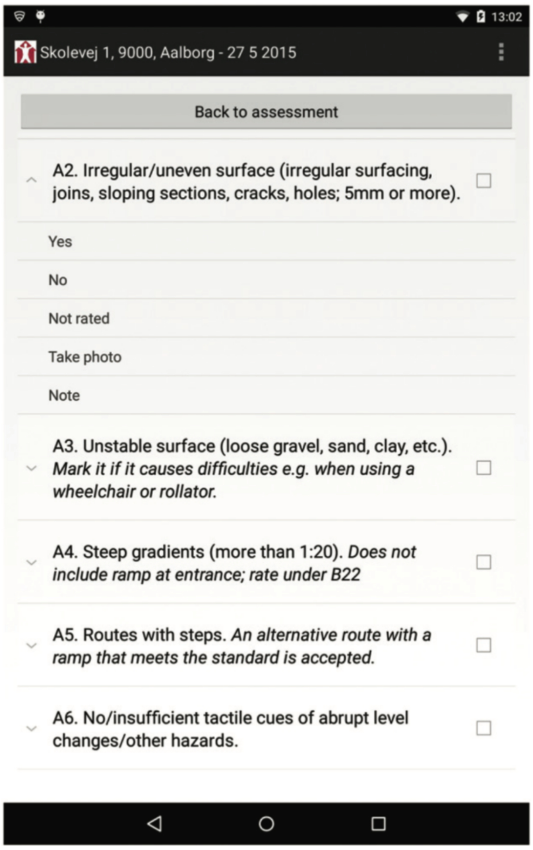

Figure 2.1 – Housing Enabler prototype app in Use[5]

As can be seen, the research studies discussed above followed a developmental trajectory. The main improvements added by each new piece of research are outlined table 2.1 below.

Table 2.1 – Comparison of novel systems

Reference	Improvement
[11]	Introduced objective standards of accessibility
[12]	Automated score calculation
[13]	Reduced complexity of assessment
[5]	Reduced data entry errors and improved communication

2.2 Building Assessment Technology

This research found many examples of tools and technology that are currently being used in building assessments or are suited to being used for this purpose. These technologies can be broadly divided into two categories, those that collect data and those that analyse data, with some technologies capable of both.

2.2.1 Data Collection Technology

Fundamental to all assessment approaches are tools used to collect the data. The most basic of these, and most prevalent, is the ruler. In the case of building assessment this is most often a retractable measuring tape[14]. This tool has many benefits such as being low cost, portable, and easy to use but its accuracy is limited by the frequency of the marked graduations, as well as by dependence on the individual user's ability to read them. Furthermore, it provides no means to easily store the data collected, requiring the user to bring a separate tool for this, which can be cumbersome as measuring takes two hands to use and users may have other tools also. Often measurements are written down in paper format. Occasionally users will bring a digital storage device, such as a tablet, but these are often too restrictive in how they let the user store data, or simply are not available.

A direct alternative to measuring tapes are laser distance meters (LDMs)[15]. These devices use laser beams to measure the distance to an object. They do this by sending a narrow beam towards the object and measuring the time it takes for it to reflect off the object and return to the sender. Given that the beam travels at the speed of light, this time can be evaluated to estimate the distance. Due to the high speed of light, measuring this time precisely is very difficult, which limits the accuracy of the device to within a few millimetres. However, these devices are still more accurate and easier to use than measuring tapes, particularly for areas that may be obstructed, but they come at a greater cost. Furthermore, they do not address the issue of data storage. Despite generating the measurement in a digital format, this cannot necessarily be exported to other devices for analysis and must often be recorded on paper instead.

Both measuring tapes and LDMs can struggle with collecting data on angles. Although theoretically possible by measuring rise and run, it can be awkward and inaccurate. There are specific low-cost tools designed to make angle measurement easier, but as they are used very infrequently, they have not been considered here.

Laser technology is also used in Terrestrial Laser Scanners (TLSs)[16]. However, rather than simply measuring the time it takes for the emitted laser to return, these systems use a more accurate triangulation algorithm (See Figure 2.2). The system shines a laser on the subject and uses a camera to observe where it hits the object. This provides the system with enough information to very accurately measure distance, and it can do this for many points in quick succession. This allows these systems to model entire buildings in a few hours, by simply outputting the position of each point, defined relative to some fixed point. These points are denoted by their 3D coordinates and the collection of them is known as a point cloud[17].

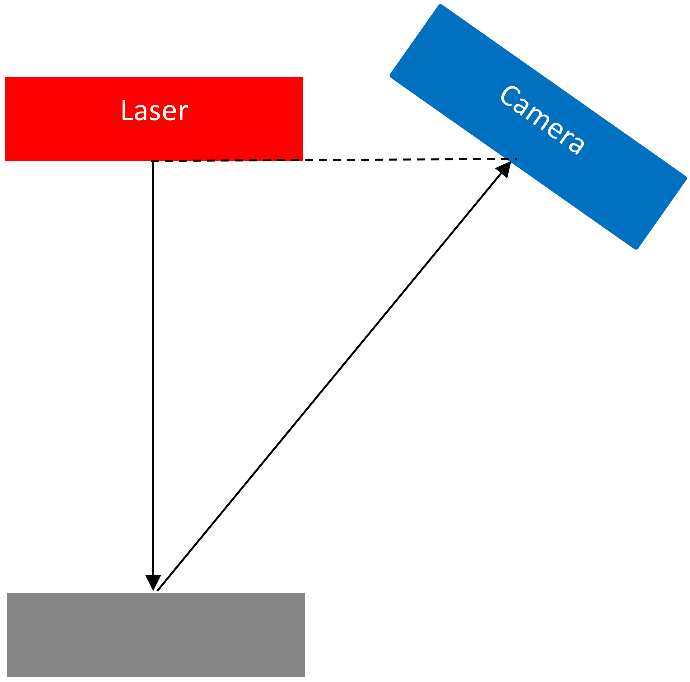

Figure 2.2 - Diagram of Triangulation

The negatives of TLSs are that they cost tens of thousands of euro and can be very difficult to use. They not only feature complex interfaces, but require the user to regularly move them after they have scanned all in their line of sight. Although some of these systems have 360° field of view they still must be disassembled and moved to compensate for occlusion.

There are other novel, laser scanners that seek to address this difficulty of use by making the scanners portable. Research carried out by Lehtola et al.[18] compared several such devices. It found the most accurate device to be a trolley-based solution from NavVis[19]. However, as this is a wheeled platform, it is restricted to mainly flat surfaces. Another device tested in this research was the Zebedee[20], a scanner that is now commercially available as the ZEB-REVO[21]. This device is highly portable, simply requiring the user to hold the scanning head in one hand and strap the data logger across their shoulder. It also has the ability to easily interact with the point cloud being generated, using the integrated tablet, in real time.

Although specific pricing for these devices could not be established, it seems unlikely that they cost less than TLSs.

Optical systems offer a cheaper alternative to laser scanners for 3D imaging. These are compared in Table 2.2 (drawn from a paper by Li [22] which has more detailed information on these systems). Many of these devices combine their optical sensors with motion tracking to make area mapping more straightforward. This is the case with the ZED camera[23]which is a low-cost stereoscopic peripheral. However, it is only accurate to the nearest centimetre and it requires a high-powered computer to achieve real time processing. Another low cost peripheral capable of 3D mapping is the Structure Sensor[24]. It uses structured light technology, is designed to work with an iPad and is accurate to a few millimetres. The Google Tango platform [25] also offers low cost 3D mapping on mobile devices, although rather than coming as a peripheral, Tango is incorporated into several consumer smart devices. These devices use either structured-light imaging or time-of-flight cameras, depending on the model, with accuracy similar to that of the Structure Sensor.

Table 2.2 – "Comparison of 3D Imaging Technologies [in 2014]"[22]

CONSIDERATIONS	STEREO VISION	STRUCTURED-LIGHT	TIME-OF-FLIGHT (TOF)
Software Complexity	High	Medium	Low
Material Cost	Low	High	Medium
Compactness	Low	High	Low
Response Time	Medium	Slow	Fast
Depth Accuracy	Low	High	Medium
Low-Light Performance	Weak	Good	Good
Bright-Light Performance	Good	Weak	Good
Power Consumption	Low	Medium	Scalable
Range	Limited	Scalable	Scalable
APPLICATIONS			
Game		X	X
3D Movies	X		
3D Scanning		X	X
User Interface Control			X
Augmented Reality	X		X

The data collection tools and technologies discussed above each offered their own benefits which are outlined in Table 2.3 below while Figure 2.3 provides a visual comparison of the tools.

Table 2.3 - Comparison of Data Collection

Reference	Form Factor	Easy to Use*	Accuracy	Cost (€)	Output
[14]	Handheld	x	mm	<10	None
[15]	Handheld	x	mm	<100	Distance
[16]	Stationary Mounting		um	>10,000	Point cloud
[19]	Trolley Mounting		um	>10,000	Point cloud
[21]	Handheld‡		um	>10,000	Point cloud
[23]	Handheld‡	x	cm	<1,000	Point cloud
[24]	Handheld	x	mm	<1,000 †	Point cloud
[25]	Handheld	x	mm	<1,000	Point cloud

* *Does not Requires technical expertise*
‡ *Requires external data logging device*
† *If purchased without iPad needed for function*

Figure 2.3 - Clockwise from Top Left: Measuring Tape[26]*; LDM*[27]*; TLS*[28]*; NavVis*[29]*; Zeb-Revo*[30]*; Zed Camera*[31]*; Structure Sensor*[32]*; Google Tango*[33]

2.2.2 Data Analysis

Data analysis technology has been an active research area for several decades, resulting in a substantial literature, and research outputs more generally. While an exhaustive review of all works relating to analysis in buildings would be beyond the scope of this thesis, it does include a review of the most relevant materials. Early computer models and methods for accessibility analysis in buildings were outlined by Han et al. [34]. They further developed on this research by showing that building accessibility can be assessed by simulating the motion of a wheelchair along a specified path in a building model [35]. In this work, the analyst determines targets within the building that need to be accessible and the programme identifies potential routes, while identifying hindrances along them.

More recently, research was carried out to integrate the analysis of accessibility into the object-orientated, 3D based Computer Aided Design (CAD) tools, Revit and ArchiCAD as a plugin [36]. The focus of this research was on making the analysis more immediately available to address the perceived insufficient application of universal design in the planning of new buildings. Although this tool successfully improved availability, the extent to which it was improved was hampered by the niche status of 3D CAD tools, which are not used for the majority of developments. The work of Han et al. was also built upon in a 2016 paper, which modelled the kinematics of the upper body of a wheelchair user “to determine the accessibility of handling elements like doors, windows, etc.” [37]

The data analysis technologies discussed here each offered their own benefits which are outlined in the table below.

Table 2.4 - Comparison of Data Analysis

Reference	Improvement
[34]	Developed computer assessment of physical environment
[35]	Demonstrated computer accessibility assessment
[36]	Improved availability of accessibility assessment
[37]	Improved accuracy of accessibility assessment

3 Design and Implementation

3.1 Methodology

In the design of the model the first step was to establish the non-functional requirements that would support the singular functional requirement, to assess accessibility in buildings. These would shape the model and form the basis of the following evaluation. Some of the requirements had already been laid out in the research question while others were established by reviewing the state of the art. An initial model was then developed based on these requirements. This model underwent an iterative design cycle in which it was implemented and evaluated repeatedly so it could be refined.

3.2 Non-functional Requirements Gathering

In reviewing the state-of-the-art, it is apparent that 3D data is a significant feature. Not only do each of the data analysis tools considered depend on having 3D data files, but most collection devices looked at can generate data of this form. Furthermore, one of the issues identified with the Housing Enabler systems (See section 2.1.2) their lack of interoperability, could be in part addressed were they to base the score on a 3D data format. Currently the measurements taken during the assessments are not fully utilised as they are obfuscated by the accessibility score. Were these measurements derived from a point cloud they could, for example, be transferred, with context, to CAD systems to be used to help plan renovations. All of this would indicate the advisability of using 3D data in this research.

Another consistent trend coming from the state-of-the-art is the compromise between accuracy and ease of use. This can clearly be observed in the comparison of data collection but can also be seen by comparing the automatic accessibility assessment tools in Section 2.2.1 with the manual tools identified in 2.1.2. The automatic tools are simpler to use by virtue of not requiring extensive, laborious manual measuring, but they can only tell if an environment is physically navigable by someone in a wheelchair. There are much more nuanced criteria in the Housing Enabler tools that allow them to produce a score that more accurately quantifies accessibility.

Both systems are striving to improve levels of usability, but it is impossible to say which has been more successful in achieving this. Levels of usability can range from high to low with both systems, with the independent variable being the circumstances in which the systems are being used (e.g. establishing how well a wheelchair user could function in their home). It is intended that the model being developed here will show improvements in its level of usability, regardless of circumstances, which will be defined by the user. Usability should be offered to both experts, interested in accessing accurate reporting efficiently, and non-experts, requiring a system simple enough to encourage them to take on such work themselves.

As is evident from Chapter 2, many of the systems in place today are low cost and highly portable, requiring little more than a simple ruler to use. Alternative technologies have been identified that can perform similarly well in terms of cost and portability, while enabling the objectives previously stated for the model. These technologies should be prioritised in the model to minimise disruption, thereby accelerating adoption.

Finally, as can be seen, there is a very broad range of people potentially involved in building assessment and it cannot be assumed that they all have access to systems capable of gathering or effectively analysing 3D data. The model should therefore represent an end-to-end system that gathers its own data, which it then processes and outputs some report.

Table 3.1 - Model Non-functional Requirements

Number	Name
1	**Broadly Useable**
2	**Cost-Effective**
3	Use 3D data files
4	Portable
5	Low cost
6	Encompass end-to-end system

3.3 Version 0.1

The requirements established for the model were effective in that they were generally explicit enough to make design choices trivial. However, the requirements of usability and flexibility necessitated more complex design choices. Making these choices involved revisiting the state of the art. It had been noted that while the automated accessibility assessment systems were useable for some use cases the manual approaches were useable for others. It was therefore decided that the most straightforward solution would be to directly build on both approaches. The core of the design of Version 0.1 of the model was as a system that would allow users to easily create a 3D scan of an area, and then calculate if a wheelchair could access it automatically. This core functionality would then be extended by the ability to manually enter other data which the system could not collect automatically, allowing those experienced in the field of accessibility analysis to leverage their expertise to generate an accessibility score, based on that developed by Iwarson for The Housing Enabler Screening Tool [13]. These interactions are described by the use case diagram, activity diagram and class diagram in Figure 3.1, Figure 3.2 and Figure 3.3 respectively.

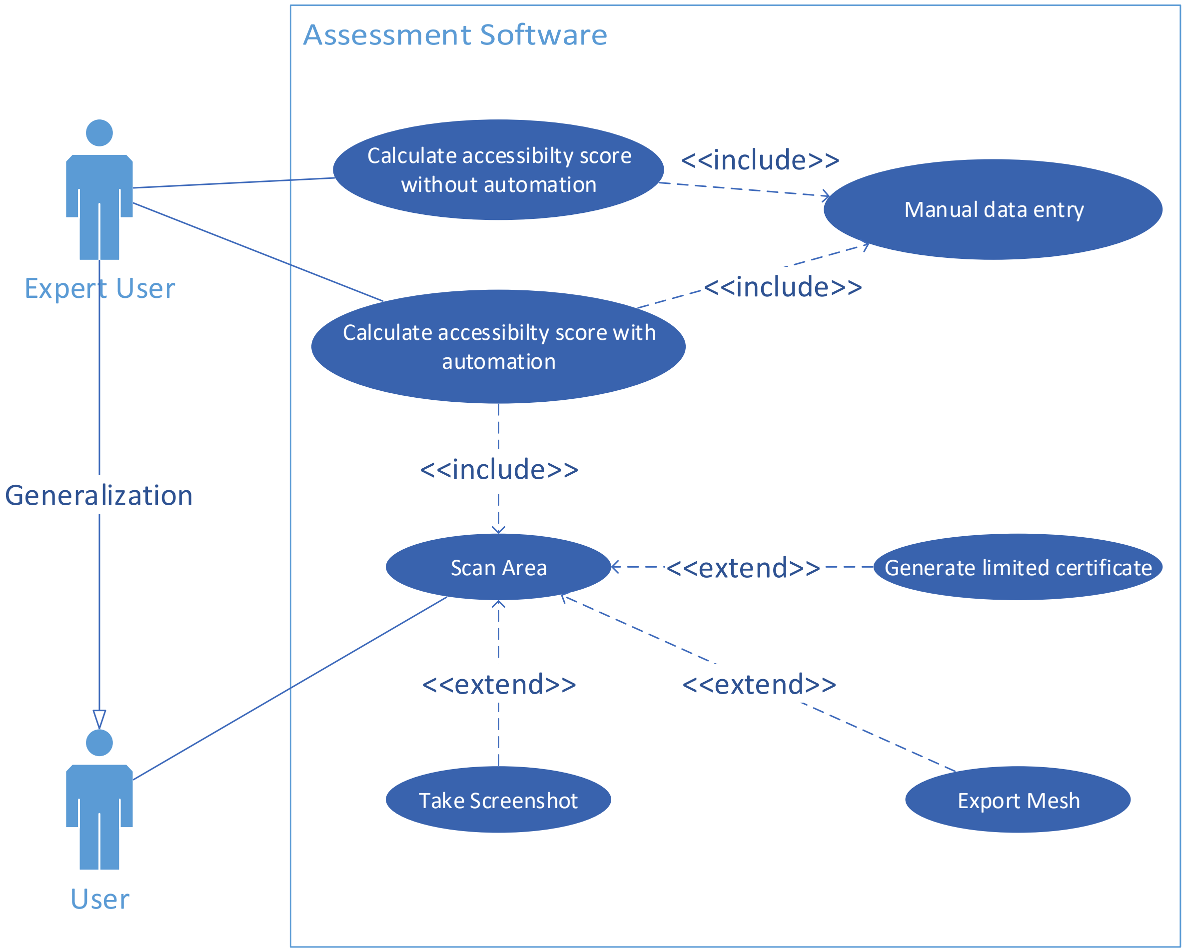

Figure 3.1 - Use Case Diagram of Model V0.1

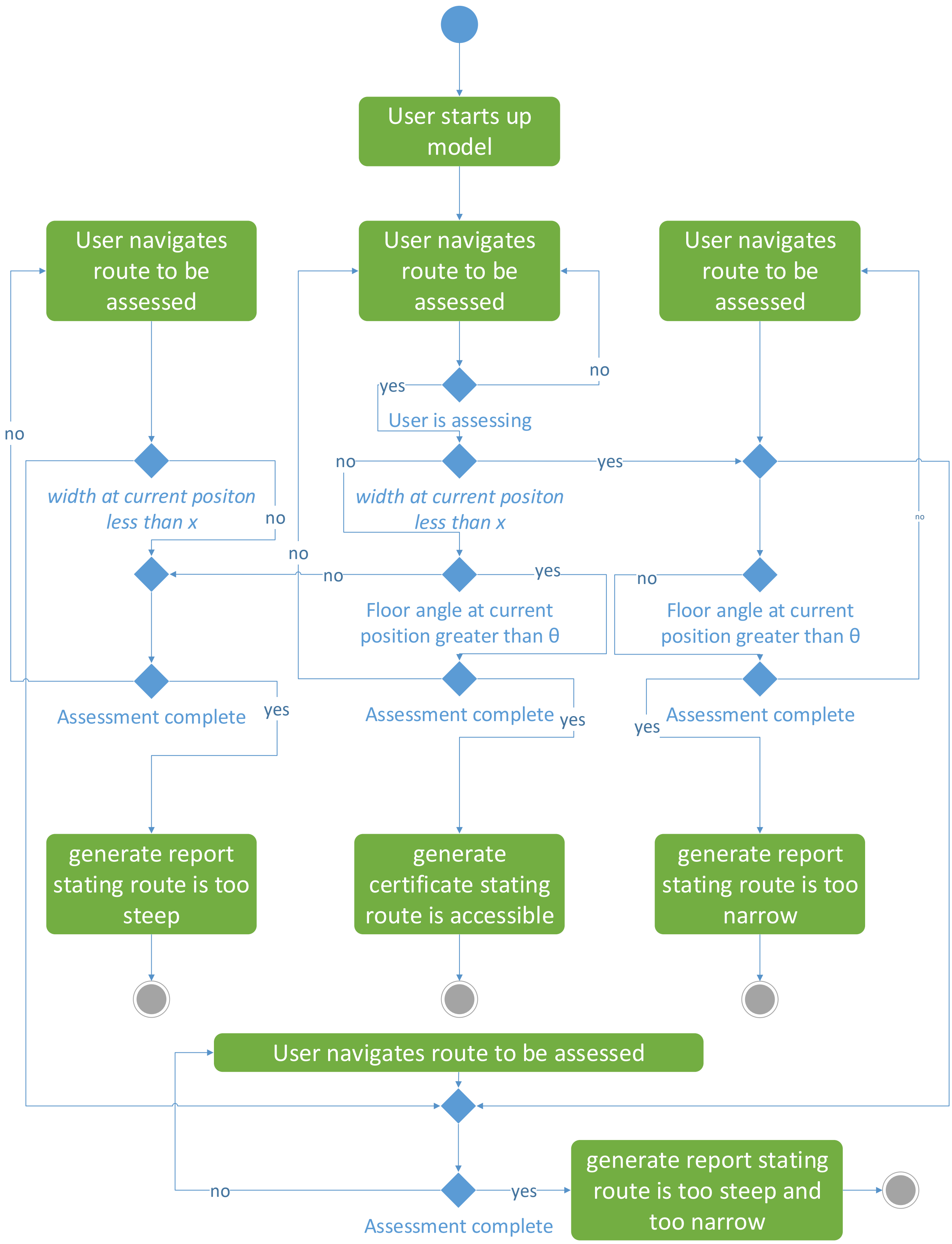

Figure 3.2 - Activity Diagram of Model V0.1 for Generic User

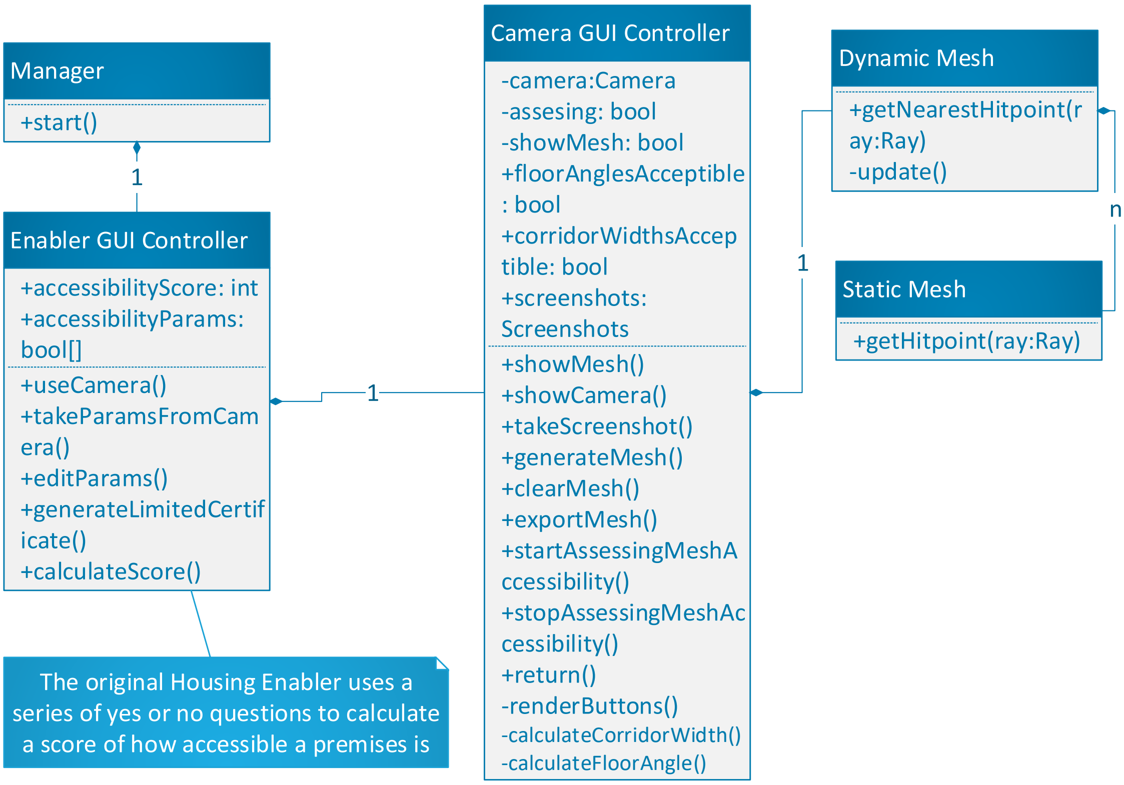

Figure 3.3 - Class Diagram of Model V0.1

Version 0.1 was implemented on Google Tango using Unity, as this was a cost effective and accurate way of testing its capabilities. However, upon implementation, several flaws were identified, the most significant of which was that the fully automated design was not intuitive in practice. This was largely because Tango was only able to add features to the mesh that passes through its field of view. A user would have to accommodate this before scanning, to make sure that each area of the mesh to be scanned would be complete. Simply navigating the route, with the model running on the Tango once prior to scanning was usually enough of an accommodation, but even that was found to be cumbersome. Furthermore, the researcher noted a desire to interact with the model as it scanned. Passively letting it scan, with no control or effect on the result or process, therefore went against natural intuition. This is discussed further in Chapter 5.

3.4 Version 0.2

Based on the findings associated with developing and running Version 0.1 of the model, a second iteration was developed. The second version omitted the ineffective automated scanning, and this allowed it to function as an almost direct extension of the established Housing Enabler prototype app[5], which already featured many of the chosen model requirements. The new model, however, uses the Housing Enabler Screening Tool[13] question set, as opposed to the original Housing Enabler[12] question set used in the Housing Enabler prototype app. The new model added to that app the ability to use point cloud measurements to answer prompts, rather than measuring with an external device and entering these measurements manually. The manual data entry is still enabled by the model if required, as is the ability to take notes and photographs of the area being assessed, all of which can be seen in the use case diagram (*Figure 3.3)*, as well as the class diagram (*Figure 3.4)*.

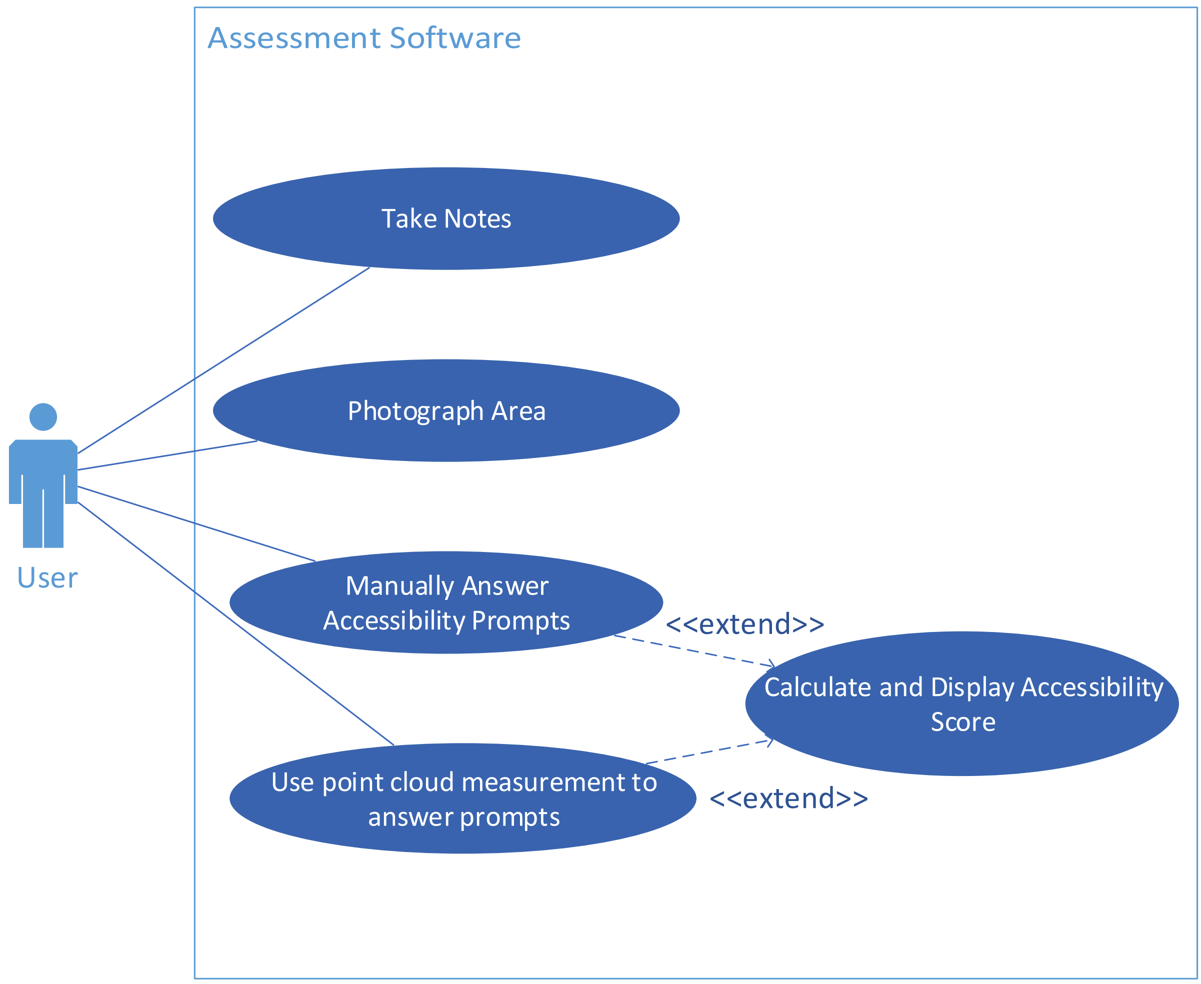

Figure 3.3 - Use Case Diagram for Model V0.2

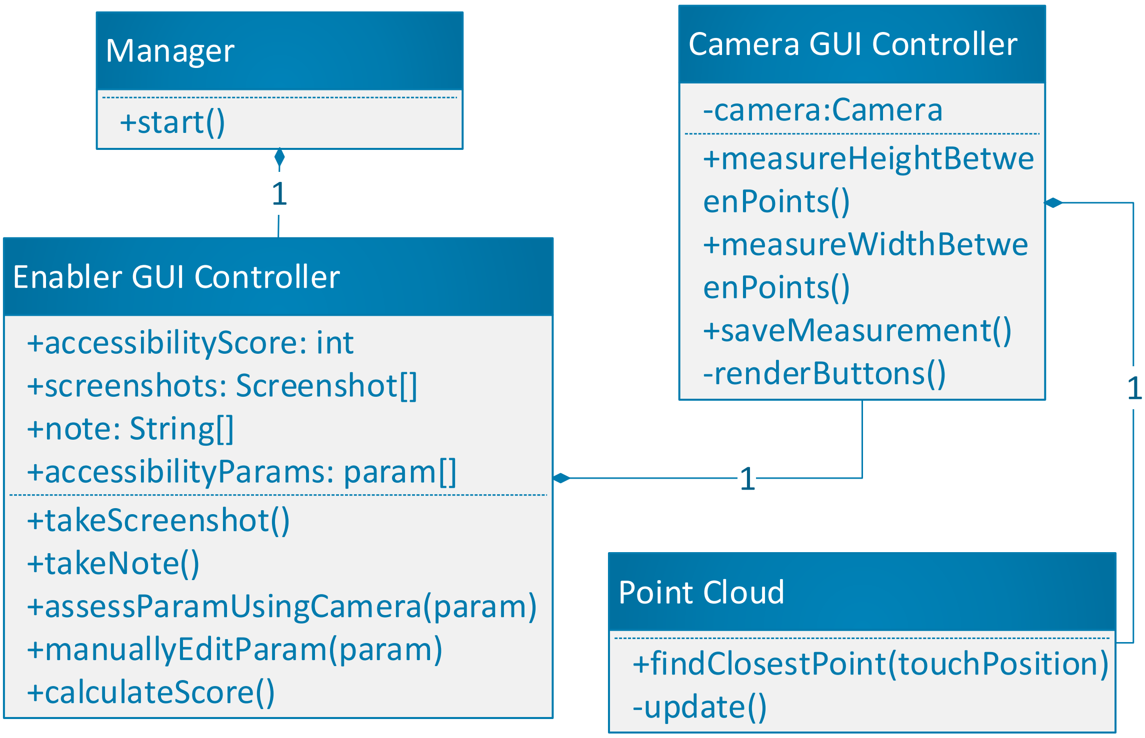

Figure 3.4 - Class Diagram for Model V0.2

If a user elects to use point cloud measurement they will be presented with a visualisation of what is currently visible by the camera. They will be prompted to select two points on the screen which will lead to the isolation of the points in the cloud most closely matching where they have selected. With these points, measurements will be calculated relevant to the parameter being assessed.

The sequence diagram (*Figure 3.5*) shows how this interaction works for one specific example, which is shown in Figure 3.6. In this example a user is attempting to find out if the variations in floor height in a building are appropriate for a wheelchair. They are testing if the height variations currently in place conform to the specified height variation. They have selected two points on the ground and the height between those points will now be calculated. If this height exceeds the accessible height outlined, this parameter will be marked as false and further scanning will be disabled. If the height does not exceed what's specified, the parameter will be marked true. This means that once a full sweep of the building is completed, if the parameter is still marked true, that is the case for the whole building.

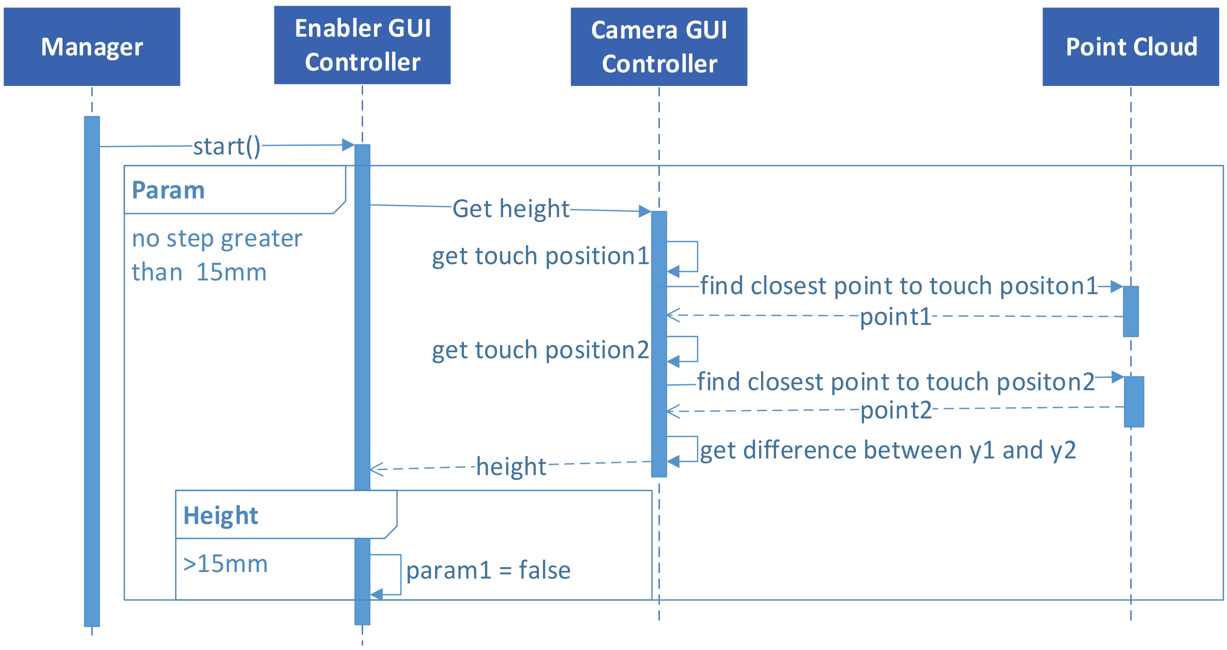

Figure 3.5 - Sequence Diagram for Model V0.2

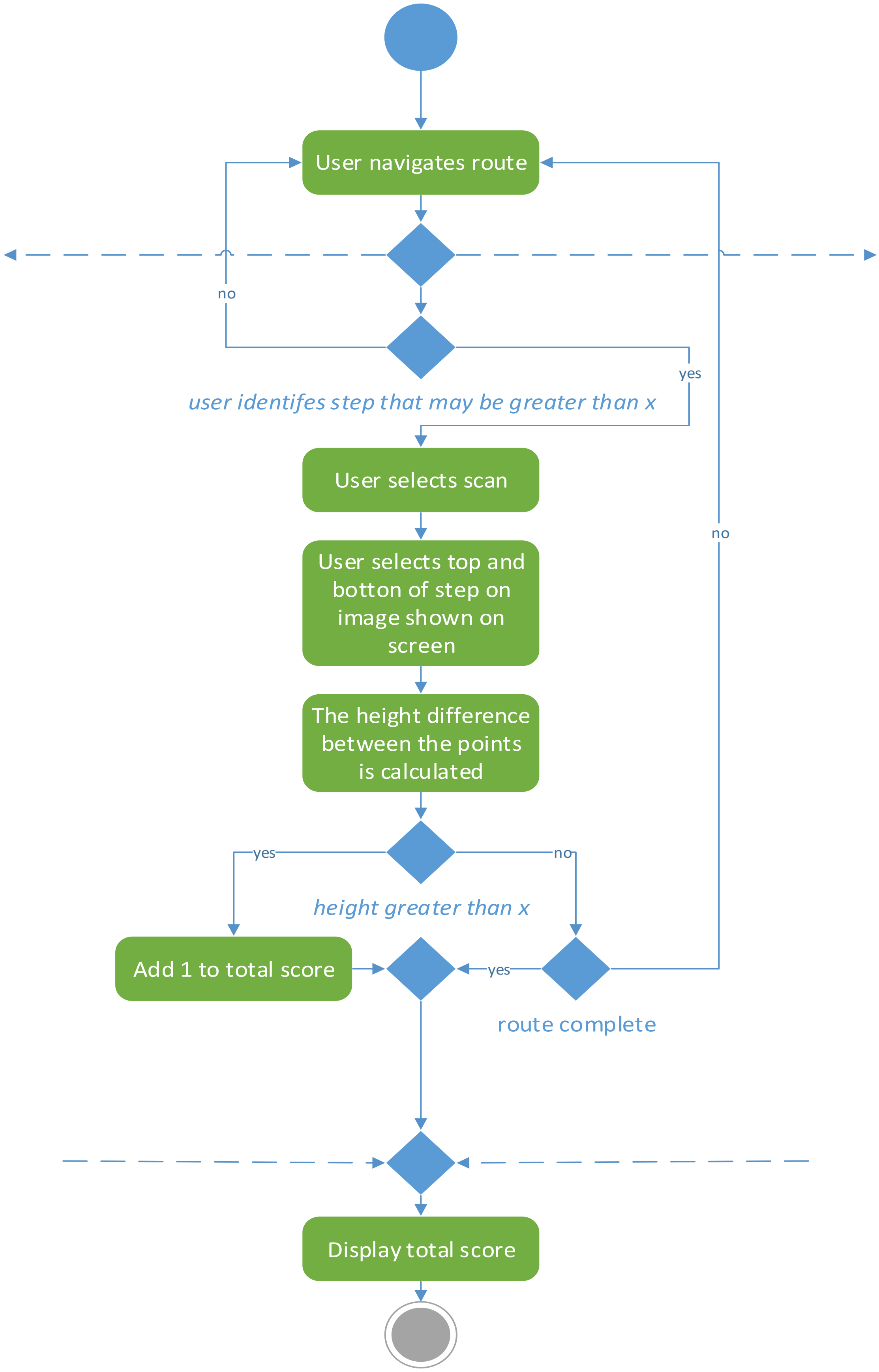

Figure 3.6 - Activity Diagram for Model V0.2

3.5 Model Implementation

Both models were implemented on the Yellowstone tablet of the google Tango platform. Devices on this platform were identified as the best technology to implement the models because they are low cost, integrate the hardware needed for data collection & analysis in a single unit and, as android devices, have user experiences familiar to most people. The Yellowstone tablet specifically was chosen as it was already in the possession of the School of Computer Science and Statistics in TCD.

Although applications can be developed for Tango using Java, C and Unity, as google has released APIs for all three tools, Unity was selected as the best tool to implement the models. Unity was selected because, despite being free to use, it “is a powerful cross-platform game development environment and runtime engine supporting a wide range of platforms”[38].

A major benefit of using Unity was that it came with several example applications that could be adapted to implement the models. The “Experimental Mesh Builder with Physics” programme provided a dynamic meshing algorithm that helped in the development of an implementation of model V0.1 while the “Point to Point” programme did the same for point clouds and model V0.2.

Both implementations only incorporated the aspects of their respective models necessary for evaluation purposes. The implementation of model V0.1 had no UI and the reporting was limited. The implementation of model V0.2 considered only two features from the Housing Enabler Screening Tool, internal steps greater than 15mm and internal doors less than 76cm and had no additional features.

3.5.1 Limitations

Initial attempts to develop for Tango using Unity proved extremely difficult. Google began to reduce the support for Tango last year (2017)[39] and so many versioning errors were encountered early on. In March of 2018 they removed all support from the Tango project, redirecting all official support webpages to other technologies. This made finding information to solve problems that were encountered very challenging and was associated with persistent system errors which skewed evaluation results.

4 Evaluation

4.1 Methodology

The two models were both evaluated according to the same methodology, although only the second model completed the full evaluation as preliminary results when evaluating the first model produced enough findings to warrant a second iteration. The aim of the evaluations was to establish if the developed models had achieved the set requirements and, thereby also to answer the research question: What level of usability can a model to support accessibility analysis in buildings achieve, whilst being cost-effective?

The models were implemented on Google Tango prior to evaluation. Through this implementation it was possible to evaluate the model against the requirements of being a low cost (requirement 5), portable (requirement 4), end-to-end system (requirement 6), using 3D data files (requirement 3), based on pre-established specifications alone. The evaluation focused on using the implementation to examine levels of usability in terms of efficiency, cost effectiveness and satisfaction, as defined by the ISO Usability Standard [6].

The evaluation consisted of two phases. The first was a formative evaluation that set out to evaluate the first iteration of the model design against the usability criteria. This was followed by a summative evaluation which involved user testing, for which quantifiable metrics were developed to be associated with each aspect of the Usability Standard.

4.1.1 User group selection

User validation was a central element of the development of the model and involved a total of nineteen participants. These were made up of seven experts and twelve laypersons and were selected for participation in a number of ways.

The laypersons were recruited informally, through person-to-person contact by the researcher. Six of them were current TCD post-graduate students from the School of Engineering. The remaining six consisted of one bank employee and five graduates from a range of disciplines and universities (engineering in DCU, international relations in DCU, cultural studies in IADT, business in DIT and computer science in NCI).

The recruitment of expert participants involved a more formal and rigorous approach. Following analysis of the numbers working in the field, the target was to recruit between seven and ten such participants through a process of self-selection. In the first instance OTs working in the field of housing assessment in Dublin were identified. They were contacted directly and individually by personalised email, outlining the research project and inviting them to participate in assessment of the model. The initial response was very low and follow up emails were sent. Direct personal contact was also made with the National Disability Authority with an invitation to participate. Subsequently, these initial contacts were followed up with more generic email contact with Private OT organisations, Dublin City Council and the universities with departments of OT requesting that they would circulate mass emails about the research and the call for participants.

4.1.2 Formative Evaluation

The formative evaluation was carried out by the researcher directly after implementation. It involved assessing the accessibility of nearby routes whose accessibility was intuitively known, such as stairs and courtyards. The intention was to evaluate the level of usability against the traditional methods of assessing accessibility, in terms of effectiveness, efficiency and satisfaction, to make progressing to user testing worthwhile. This comparison with traditional methods was entirely subjective.

4.1.3 Summative Evaluation

The summative evaluation, which involved user testing, was designed to gather quantitative data on effectiveness, efficiency and satisfaction while also gathering qualitative data on the research more generally. As stated previously, the quantitative data would primarily be used to evaluate the usability and efficiency of the model while the qualitative data would give context to the quantitative, aiding in the estimation of cost-efficiency, amongst other things.

This data was to be gathered by having participants assess the accessibility of a simulated environment. Efficiency would be measured by the time it took each participant to complete the assessment while effectiveness would be quantified by the number of accessibility considerations for which the participant's assessment results matched the expected result. Satisfaction would be measured by having the participant complete the System Usability Scale (SUS)[40], shown in Figure 4.1. This scale was designed as a means of comparing usability of systems for widely different applications. However, for systems with similar applications, it provides an effective way of collecting test level satisfaction. It asks users to answer ten questions by giving scores from one to five. These scores are then used in an algorithm to produce a score out of a hundred, measuring the total satisfaction. After the quantitative data had been collected, and the physical testing was complete, the qualitative data was gathered by conducting a semi-structured interview.

The assessment was run with both the developed model implementation and a control with the order in which participants used each tool alternating between participants to avoid bias.

System Usability Scale

© Digital Equipment Corporation, 1986.

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

Figure 4.1 - System Usability Scale[41]

4.2 Design and Implementation

4.2.1 Scenario

To implement the user testing an environment was designed consisting of a route with some features that can pose challenges to those with specific access requirements. The route had three doorways and two steps, some of which were specifically designed to be close to the limit of accessibility. Participants were asked to measure these features for width and height respectively to establish if the route was accessible.

The environment was developed by working with the robotics department in TCD. They were able to provide ad hoc lab space of approximately 8 m^2, including one accessible entrance way. Within this space a corridor was mapped out in tape which entered through the door then turned 90 degrees and continued straight for approximately 4 m. The simulated corridor was 1.3 m wide, in accordance with guidelines on widths for accessible corridors, although participants were not asked to consider this.

Figure 4.2 - The Artificial Route Used for User Testing Set Up in One of the Testing Spaces

This space was than furnished with temporary walls and plastic sheeting to represent doors and steps. The first obstacle, on entering through the accessible entrance way, was a plastic sheet of 2mm, representing an accessible step. This was followed by a step of approximately 20mm which, according to the Housing Enabler screening tool, is not an accessible internal step, as it is greater than 15mm. The temporary walls were at the end of the corridor and had two markers each, to represent either side of two doorways. The first of these was approximately the same width as the corridor, and so highly accessible, the second was 74cm across, less than the 76cm required by the Housing Enabler screening tool.

To provide a control to compare against for model V0.2, which was tested in this scenario, the default screen that displays when running the application was printed. Participants were asked to manually measure features using a measuring tape and then use that information to complete the worksheet by ticking the relevant boxes on the sheet using a pen.

C. Indoor environment	NOTES	Rating
General	*Assessment of C1–C4 is linked to the concept of "necessary housing functions", meaning that all doors leading to these places are included in the screening, but not those leading to other housing functions/ areas.*	
C1. Steps/thresholds/differences in level between rooms/floor spaces (more than 15 mm).		☐ **Yes** ☐ **No** ☐ *Not rated*
C3. Narrow passages/corridors in relation to fixtures/design of the building (less than 1.3 m).		☐ **Yes** ☐ **No** ☐ *Not rated*
C4. Narrow doors (less than 76 cm clearance).		☐ **Yes** ☐ **No** ☐ *Not rated*

Figure 4.3 - Testing Sheet Given to Participants During Control Tests

A camera was placed in the corner of the lab which recorded all tests and interviews in both audio and video. This majority of the data from these tests was gathered by reviewing the footage although timers and audio recordings were also set up on separate devices as backups.

4.3 Results

4.3.1 Formative Evaluation

As mentioned previously formative evaluation of the model V0.1 resulted in several findings that led to the development of model V0.2. The informal testing of this model found the implementation to be faster to use, and similarly accurate, to taking measurements manually with a measuring tape, while cutting out the need to carry cumbersome equipment, such as a measuring tape, pen and paper. Furthermore, it enabled the researcher to objectively judge the accessibility of an area, as it proposed clear standards to be met. This contrasts with attempting to follow the current practices used in Ireland, where no standards exist, thus judgement must be subjective.

However, the model was not without fault, as the implementation was found be to be temperamental, with system crashes not uncommon. Furthermore, it appeared to be less accurate than traditional tools. The implementation was shown to have an uncertainty of approximately $\pm$3mm with perfect use, based on the observations of this research, where as a traditional ruler has an uncertainty of $\pm$0.5mm with perfect use. Ideally the model should improve upon the accuracy of a measuring tape. However, it was possible that it would be more accurate in practice, where perfect use cannot be expected.

4.3.2 User Testing

The user testing produced a substantial amount of quantitative data, the most significant results of which are shown below in Table 4.1. A more detailed breakdown of this data can be found in Appendices A, B, C and D.

Additionally, some of the non-expert users had time available to complete the analysis a second time allowing for any improvement to be observed. The most significant results of this observation are shown below in Table 4.2. A more detailed breakdown of this data can also be found in Appendices A, B, C and D.

Table 4.1 - Result comparing Usability of Control and Implementation

Comparison	Participant Group	Control			Model Implementation		
		Efficiency (minutes)	Effectiveness (%)	Satisfaction (SUS score)	Efficiency (minutes)	Effectiveness (%)	Satisfaction (SUS score)
Mean	All participants	02:21	84.21	69.8	04:02	89.47	61.54
	Expert Participants	02:06	83.33	74.29	04:10	91.67	63.57
	Non-Expert Participants	02:29	85.71	64.58	03:58	85.71	59.17
Minimum	All participants	00:35	50	47.5	01:26	50	45
	Expert Participants	01:09	50	47.5	01:26	50	45
	Non-Expert Participants	00:35	50	50	02:08	50	50
Maximum	All participants	05:06	100	92.5	08:57	100	77.5
	Expert Participants	03:16	100	92.5	08:57	100	77.5
	Non-Expert Participants	05:06	100	77.5	07:55	100	75

Table 4.2 - Usability Results for Participants Repeating the Assessment with the Implementation

Comparison	Model Implementation		
	Efficiency	Effectiveness	Satisfaction
Mean	01:28	91.67	70.42
Minimum	01:05	50	57.5
Maximum	02:02	100	85

5 Discussion

The extent to which the model met the set requirements can be examined using the results obtained during the implementation and evaluation. As previously stated, some of these requirements can be judged based on pre-established specifications alone. The model used 3D data files (requirement 3) and it is clearly an end-to-end system (requirement 6), as demonstrated during the evaluation where no other tools were needed to complete the assessment. Furthermore, while a tablet was used in this evaluation, the Tango platform extends to smartphones and so such a device could equally have been used to run the developed application. Given that the average Irish adult carries a smartphone with them at all times, this means not having to carry additional equipment (requirement 4).

Assessing if the model meets requirement 5, that it be low-cost, is less clear as the concept is subjective – what is low-cost to a commercial property owner can be expensive to a self-employed health professional. Starting from the premise that Tango devices, such as the one used here, are available from €200, it would seem this should be entirely affordable for the property owner and also manageable for the OT, on the basis that it equates to an average fee for a single assessment. For the layperson, wishing to use the system in their own home, it is likely to be a rather expensive option, and they would likely require some financial support to purchase it.

5.1 Usability of Model

Broad usability was identified as the primary requirements for the model developed in this research (requirement 1). In implementing and evaluating the model, data was gathered in line with the ISO Usability Standard (efficiency, effectiveness and satisfaction) to help inform to what degree the model succeeded in achieving this requirement.

5.1.1 Efficiency

The efficiency data recorded indicates that the model's use of 3D scanning technology is a slower method of data collection than the use of a measuring tape. There are, however, some qualifiers to those results which must be considered.

Deficiencies in the implementation must be taken into account as they had a clear impact on the time it took participants to complete the assessment. The Tango device used was prone to malfunction, primarily due to the absence of continued support from Google. This was a factor external to the work of this research, but it interfered significantly with all applications on the device, including that which implemented the model. Frequently, during the testing process, these malfunctions necessitated that the device be examined by the researcher which, obviously, distorted the final testing time. The interruption would likely have distracted the user, as would other malfunctions in which the researcher was not involved, making it difficult to accurately compensate for the delays that were specific to the implementation.

Nonetheless, given the scale of the efficiency disparity between the model and control, there is insufficient evidence to suggest that the comparative results were affected by the substandard implementation. There is, however, evidence to suggest that the comparative results were also affected by the brief nature of the evaluation. Users who repeated the assessment did so in vastly reduced times, improving upon the average time set with the control. It is true that the repeat testing was ad hoc as a result of circumstances and that therefore the evidence is anecdotal, rather than scientific. However, it seems reasonable to extrapolate that it is likely that participants repeating the control assessment would also have improved their times. This indicates that the testing could have been improved upon if a repeat test was built in to the original assessment process. While one aim was that the model be user friendly, its efficiency will ultimately depend on how it is used by those who are familiar with it. Given that the results show the participants were not given adequate time to become familiar with the model in the initial test, it would seem a longer form test, of larger or more numerous routes, would be needed for the collected data to provide a sufficiently accurate comparison of the model and control.

For truly representative quantitative data on the efficiency, full scale trials are required. Not only would these address the familiarity issue identified but also the wide variety of features and challenges - such as obstruction when measuring, something which was only established as an issue during the evaluation process – that cannot be fully accounted for in a test environment.

Furthermore, full scale trials would serve to establish how the model can improve post-assessment efficiency. For example, the communication and storage of assessment results was a problem identified by many OTs interviewed, with some indicating they scan every document into their computer following assessments, indicating that the new model's digital format could greatly improve efficiency in this regard.

Another major issue for expert users affecting the usability of current methods, outside the assessment itself, was the time it took to get to assessment locations. This leads to lower than ideal productivity. Some of the OTs interviewed indicated that a great deal of their time is wasted in transit and they wished for a model that could remove the need for them to always have to visit clients' homes. While meeting this requirement is beyond the scope of the model in its current form, as it is not designed to replace OTs and for them to apply their knowledge remotely they would need a full model of the home. Nevertheless it is certainly an area for future research and development. However, even as it stands, the model could impact the amount of travel time to some extent, by minimising the need for re-assessment.

5.1.2 Effectiveness

The issue of excess transit impacting usability can also be seen as one of effectiveness. Interviews conducted as part of this research indicated that the need for building or home re-visits also occurs because details were missed or forgotten. Another cause of revisits identified was human error where measurements were taken or recorded inaccurately. Currently, if measurements are found to be inaccurate after an OT has left a location, they have no choice but to go back. These are all issues that would be reduced by the structured nature of the model.

With regard to the data gathered as part of this research, effectiveness was the area in which the model compared most favourably with the control. Although based on a small sample set, the results unanimously indicate that the model implementation is more effective than the control. These results are consistent with several observations made about the control, which would affect its ability to be accurate.

Issues with Measuring Tape

Measuring tapes are associated with a range of errors such as manufacturing errors, expansion/contraction with temperature and stretching due to tension. While most of these errors are negligible with perfect use, some can become significant when not adequately accounted for, which can easily occur if the user is unfamiliar with the device or it is being used in an awkward scenario. Two such errors are sag and inclination in the vertical plane. If a tape is not supported or kept level these errors will exaggerate the distance being measured.

Parallax, which is the perceived shift in an object's position as it is viewed from different angles, is another source of error when measuring tapes are used imperfectly. If a user does not view a measurement from a point directly perpendicular to the distance to be measured than the reading on the tape will be shifted. In the below image (Figure 5.1) the position of the floor prevents the user correctly aligning their eye with the distance they are measuring, resulting in parallax error.

Figure 5.1 - Using Measuring Tape to Measure A Small Step

Figure 5.1 also demonstrates a different practical error with using some measuring tapes, which is that graduations can be obscured. The metal fitting on this tape is a common feature of measuring tapes but can result in the smaller graduations being ineffective. Similary, marks or damage to tape can affect how measurements can be read from the tool.

Measuring in confined spaces was also noted as an issue for participants and their methods of addressing it frequently lead to further error. Most participants were observed to bend the tape when in confined space so that the tape housing would not interfere with the measurement. The bent tape, however, will indicate a distance different to that which would be found if the tape were kept straight, even if the bend is small. Other participants were seen to measure the length of the housing and then include the housing in the measurement. By introducing a second measurement this approach doubles the effect of the errors inherent in the use of measuring tapes.

Issues with Implemented Model

Errors associated with data collection were also observed in the model implementation. One such observed issue was participants selecting virtual points on the device that did not match the physical points from which they were trying to measure. This was partly the result of participants finding it challenging to be precise as to where on the device they pressed, with some users reporting they felt they would need a stylus or some means of steadying the device to use it properly.

A further reason for participants selecting incorrect points was due to the device offering them insufficient options. The optical system employed by the device could not always gather depth information for it’s entire field of view due to certain lighting conditions and material finishes. This was particularly apparent with a certain sheet of plastic serving as the step in one of the labs used for testing. The step had a slightly translucent finish and the interaction between it and the lighting on that specifc occasion seemed to cause the device difficulty. The device was able to get depth information for a very limited number of points on the top of the step and it appeared the information was innacurate also, with each participant on that occasion producing innacurate measurements of the step. This could indicate a flaw in the broader effectiveness of the model although it is worth noting that the plastic step was used subsequently in a different lab and the original lab was used with other materials and there were no further issues of this kind.

A further issue with the model was also observed in that same lab, which was noted to have a slightly angled floor. When measuring the height of a step, the model encourages users to select any point on the floor and any point on the top of the step, as it does not need the points to be vertically alligned to return an actual measurement. This is because rather than returning the absolute distance between the points the model can use a gyroscope to determine the up direction and then only return that component of the absolute difference (see Figure 5.2). However, this approach assumes that the floor and top surface of the step are perfectly level relative to the gyroscope. If this assumption does not hold, the results can be inaccurate.

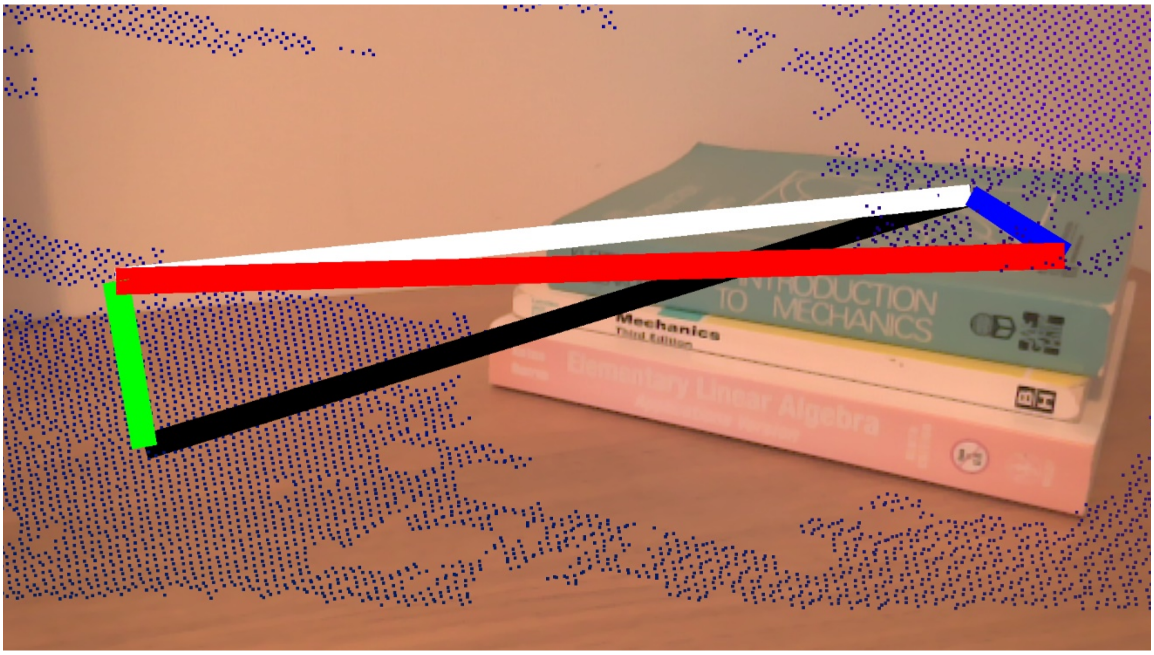

Figure 5.2 - Screenshot of application showing how absolute difference between two points (black) can be resolved into x, y and z components (red, green, blue), with y aligned with real world up direction

Error in Data Analysis

Although both systems were liable to data collection error, only the control demonstrated any element of data processing error. The participants were asked to compare their findings with certain criteria in the control, while the model implementation completed this automatically. Participants were observed to have difficulties relating their observations from the tape to the question posed on the sheet that was provided. The most common error related to units of measurement, with some participants confusing millimetres and centimetres, while some participants seemed to misinterpret the question entirely. These errors are especially noteworthy as the participants were only asked to assess two parameters in this trial. In full housing evaluations there are many more aspects to consider which would create many more oppurtunities for confusion of this kind.

5.1.3 Satisfaction

When compared, the SUS scores recorded in this research seem to indicate that participants were less satisfied with using the model than they were with using a measuring tape, regardless of how the results are categorized. Furthermore, the application was given a lower SUS score than the control by 74% of participants (see Appendix D). Comparing the SUS scores observed here to the scale shown in Figure 5.3[42], based on global averages, indicates that users felt the model had significant issues with regard to satisfaction.

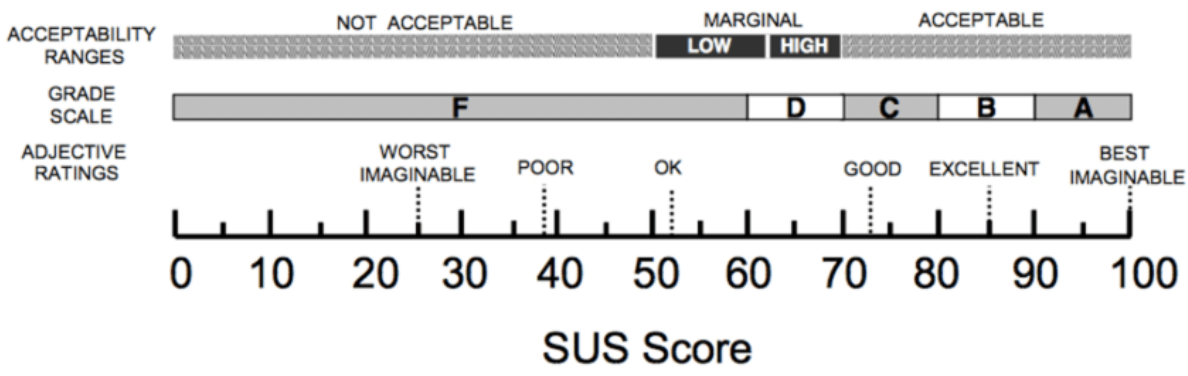

Figure 5.3 - Grading Scale of SUS Scores Based On Global Averages[42]

These results could be considered as an indication that the model is limited in terms of how satisfactory it is to use but they must be considered in the context of implementation being a major factor in the satisfaction rating. As mentioned previously, the implementation hardware used in these tests had issues, unrelated to the model, which resulted in the user experience being consistently interrupted by error warnings and system crashes. Furthermore, the quality of the implementation software had been impacted by time constraints, resulting in it having minimal UI features, for example. The feedback of participants indicated that, had simple features such as tool tips, been included they would have felt much more comfortable with the application.

As with efficiency, the improvement shown between the first and second use of the model must be considered. Once again averages increase with repeat use, indicating that while the learning curve may be an issue, the system is quite satisfactory to use with a small amount of practice. This is consistent with the fact that the majority of non-experts asked said they would rather use the application than a measuring tape if they had to do a full housing assessment themselves.

5.1.4 Summary of Usability

When efficiency, effectiveness and satisfaction are viewed together there is little that can be stated confidently about the usability of the model. The quantitative data on efficiency and satisfaction is inconclusive, when the failings of the implementation and limitations of the evaluation are considered. However, the data on effectiveness appears to slightly favour the model in comparison to the control. As this data has been collected from both experts and non-experts in the field of accessibility, the model could be said to have achieved the requirement of being broadly useable. However, a more realistic conclusion to draw is that further testing will be required to investigate the broad usability of the model. This is especially true as, during the evaluation, further use cases and potential improvements to the evaluation were established, which will be developed upon in Chapter 6.

5.2 Cost-Effectiveness

It could be argued that the cost-effectiveness of the model is inextricably linked to its usability, particularly efficiency - “time is money” as one user interviewed said. Therefore, it’s not possible to be definitive as to whether the model is cost-effective until these aspects are further investigated.

However, the indictors of cost effectiveness that are available are generally positive. The system being low cost will mean that if the model can offer even a slight improvement in efficiency over traditional methods, it will represent better value and the model being portable will increase the possibility of use.

One area in which the model could be highly cost-effective is that of hospitality, as it will give hosts the ability to assess their own facilities and publicise accessibility, resulting in financial gain through increased business. This is especially true when it is considered that an accessibility auditor may charge €1200 to perform the same work that can be accomplished using the model.

The model could be also be cost-effective for disabled people to use for the same purpose. Many people with disabilities share their experiences online for the benefit of others in similar situations. The accessibility scores output by this model could be a way for them to share information about hospitality facilities which they could then use when searching for accommodation. This would allow them to expand their searches and find better value in the market. Currently many of those with special accessibility requirements will, regardless of cost, return to the same destinations that have previously provided for them, rather than risk going somewhere new which may not be able to meet their needs. Furthermore, the model is fully usable by someone with a disability, unlike a measuring tape, for example.

At present, the most significant argument against the model being cost effective is the lifespan of the tools. Most tools used in this area are designed to be hard wearing. A traditional measuring tape can be used for many years without issue. This is not the case with many smart devices, such as those on the Tango platform. The tablet that was used in these tests, for example, is almost unusable despite being a mere four years old. Furthermore, if a device like this is dropped or impacted in some way it, unlike a measuring tape, can require costly repairs.

5.3 Other Research Outcomes

Along with establishing to what degree the requirements for the model were met the evaluation also produced a number of other outcomes.

5.3.1 Interest in Future Work

The most significant of these was the establishment of interest in the future of this work. All of the test participants were positive about the research and saw some potential in the model, with the reasons being varied.

Some experts were interested in how it could reduce the amount of paper they use, while others were particularly interested in how it could help minimise the cumbersome nature of the current assessment process. This was exemplified by the experience of one participant, who reported assessing an exterior environment in bad weather and low light. She was forced to hold the measuring tape, a torch, a pen and paper which she was attempting to keep away from falling rain.

Interest was also expressed in an element of the model that it inherited from the Housing Enabler Screening Tool[13], the simple yet thorough standardisation of assessment. As mentioned previously many OTs use individual assessment forms and felt that introducing standards could be hugely beneficial to facilitate communication between them. In Ireland a number of OTs can be involved with one patient and this can result in the patient's home being assessed a number of times. A standardised assessment could remove the requirement for multiple assessments of a building. Furthermore, as this model introduces standardised data collection, the relevant measurements of each accessibility consideration would be stored and catalogued for every assessment. This would allow for the sharing of information, which is more detailed than that required by other housing enabler tools, without any extra effort on the part of the assessor. Further benefits of the standardised assessment are discussed in Housing Enabler Screening Tool[13] and its associated works.

The model inherits some aspects from the Housing Enabler prototype app[5] and some users saw great potential in those areas. Participants commented that the very fact that it was a digital tool could make it highly accurate with appropriate implementation. They referenced active features such as integrated tutorials and error checking, that a digital tool enables. They also felt that simply by virtue of it being a digital tool they would expect to make less omissions of data and would trust the output more. This element of trust was developed upon by one participant who felt that a digital tool could make it more difficult for someone to generate intentionally misleading results.

5.3.2 Model Feature Set Critique

In addition to discussing the potential of the model, many participants also offered comments and suggestions on the feature set of the model, the most interesting of which referred to the chosen method of interaction. A number of participants felt they might prefer a system that was more automated and completed the assessment more passively, similar to the operation of version 0.1 of the model. Others stated that they would struggle to trust a system in which they could not be actively involved. It was suggested that a model incorporating the two might be the ideal as, in the words of one participant, "in some ways the passive one can be brilliant, that for a person that isn't techy and isn't getting it accurate and various things, the machine will automatically do that for you … but the active involvement may be of great benefit where people want to get really specific".

Another feature of version 0.1 of the model that was often referenced by participants was the ability to export a full 3D scan from the model. The ideal would be that this would be detailed enough, not just for OTs to use to identify issues, but also for contractors to use, both to quote for and plan renovations. For housing adaptation grants to be approved, it is required that at least three quotes first be obtained. Currently this requires three different contractors to personally measure the space. This is not only invasive for the home owner but can greatly delay the approval of a grant if scheduling times for the measurements to be taken is a challenge. Having a 3D file that could be sent directly to the contractors would be a major benefit in this regard.

A visualisation package that would allow users to virtually overlay the required space or adaptations on the space being assessed was also suggested. Participants spoke of the difficulty in explaining to their clients how a room will appear once it has been made accessible. Correctly conveying that information can be an important factor in advising someone on how they should adapt their home.

5.3.3 Implementation

The evaluation demonstrated the importance of a good implementation to make best use of the model. It was severely hindered by the implementing hardware in this research and so selecting appropriate hardware for future implementations would be a priority.

It would appear that the Yellowstone tablet is no longer a viable option for running the model and so upgrading to a newer device on the Tango platform should be considered. As the newer devices are all smartphones, this would not only improve stability but would make the implementation more portable and perhaps be a form factor with which participants would be more comfortable.

Moving from the Tango platform to the Structure Sensor should be considered. This device was disregarded at first because, when considered in combination with an iPad, suggested for running it, it is more expensive and less compact than any Tango device. However, it compares favourably to Tango in that, not only is it still supported but it is being actively developed. Furthermore, as a standalone sensor, it will not be directly affected by issues with any supporting smart device, theoretically extending its lifespan. This independence from its supporting device could offer further benefit with future iPhones set to be as powerful as current iPads. This could mean that users will be able to attach the sensor to their existing phone which would greatly benefit the usability of the model once implemented.

6 Conclusion

As pointed out earlier in this thesis, currently the evaluation of accessibility in buildings is carried our using largely manual methods and involving tools such as measuring tapes, pens and paper. Surely, there must be a better way? This research set out to answer the question of whether a model could be developed to support efficient, cost-effective accessibility analysis in buildings using modern technology. On a broader level, the aim was to establish if it was possible to develop a model with enhanced usability which made it appealing to both professional and non-professional users, while being more efficient and more cost effective than the systems that are currently in use.

The model was developed, using Google Tango to implement it and test its viability and effectiveness in meeting the aim of the research. It was tested by the researcher and a number of professional and non-professional users. And overall, the test results were inconclusive, in that there was insufficient data produced to determine if it was efficient or cost-effective.

However, the data produced was not entirely discouraging and, with further testing, may yet demonstrate that the model, in its current form, is user friendly, while being both efficient and cost effective. The research was successful in demonstrating interest among the target user group and the potential for the use of a model such as the one developed. It also identified many potential areas of application e.g. official OT use for measuring accessibility; replacing the need for further site visits by professionals where follow-up assessment was required; providing the facility for self-assessment of premises by hotel owners and others in the hospitality industry; and allowing disability activists and others with disabilities to undertake accessibility assessments to share with both their own constituency and the public.

Given the potential that participants observed in the model, and the suggestions that were made on ways in which it could improve, it has been established as a base upon which future work can build. As an iterative design process has been employed up to this point, it would be encouraged that this be continued with further iterations being produced of the model based on what has been established thus far.

6.1 Future Research

One outcome of this research has been to identify several pieces of future research that would build upon the work carried out here. These can broadly be categorised into implementation and evaluation, in the short term, and expansion in the longer term.

6.1.1 Implementation

The evaluation undertaken in this research did not produce conclusive results. But the indications and the user responses were positive, suggesting that there is clear case for further testing. However, prior to any such further testing, the implementation must be improved. As discussed in Chapter 5, this would involve the model being implemented in significantly higher fidelity using more stable hardware, with a newer Tango device or the Structure Sensor as viable candidates.

6.1.2 Evaluation

Once the implementation is complete the issue of how best to evaluate it can be considered. This research indicates that while the metrics were suitable, a larger and more diverse user sample was required. This would ideally include architects and people with disabilities, and would involve completing longer, more detailed assessments than those featured here in order to produce the most accurate usability data. Should it be possible, these assessments taking the form of full scale trials should be considered.

6.1.3 Expansion of The Model

As is evident from the research project, the most recent iteration of the model as presented and discussed here, does not and cannot represent the final version. It is necessary that the design cycle should be continued until it is perfected. While the collection of further data should help identify the development and alterations necessary, through this research, it is already possible to propose a number of possible additions:

- Increased automation should be incorporated into the model. This would help in both the identification of accessibility issues and in the solving of them.
- Incorporating further visualisation tools would be a benefit for communicating solutions, be they automatically or user generated.
- Finally, further improving interoperability should be investigated, perhaps through enabling the generation and export of full building scans.

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Appendices

Appendix A

Key
Control Results
Test Results
Repeat Test Results

Mean Results						
Participant group		All	Non-Expert	Expert	<40 years	>40years
Efficiency (time to complete, mm:ss)	Door 1	00:27.93	00:34.89	00:17.50	00:32.55	00:15.25
		00:58.57	00:54.44	01:06.00	00:50.70	01:18.25
			00:15.00			
	Door 2	00:30.20	00:32.80	00:25.00	00:33.00	00:22.50
		00:47.14	00:35.00	01:03.33	00:37.40	01:11.50
			00:26.75			
	Door 3	00:18.28	00:19.18	00:16.86	00:19.38	00:15.40
		00:47.21	00:50.67	00:41.29	00:46.14	00:50.20
			00:22.17			
	Doors Marked	00:26.32	00:28.67	00:22.29	00:26.14	00:26.80
		00:00.00	00:00.00	00:00.00	00:00.00	00:00.00
			00:00.00			
	Step 1	00:22.37	00:26.30	00:15.83	00:25.25	00:13.75
		01:11.41	01:19.91	00:55.83	01:13.54	01:04.50
			00:14.80			
	Step 2	00:16.41	00:15.90	00:17.14	00:16.00	00:17.40
		00:56.67	00:54.45	01:00.14	00:49.46	01:15.40
			00:26.00			
	Steps marked	00:17.95	00:14.58	00:23.71	00:16.64	00:21.60
		00:00.00	00:00.00	00:00.00	00:00.00	00:00.00
			00:00.00			
	Doors Measured	01:01.83	01:06.91	00:53.86	01:05.85	00:51.40
		01:45.58	01:28.50	02:14.86	01:26.50	02:39.00
			00:45.17			
	Steps measured	00:46.78	00:54.36	00:34.86	00:52.54	00:31.80
		02:17.11	02:29.50	01:55.86	02:16.79	02:18.00
			00:43.33			

	Total	02:21.00	02:29.50	02:06.43	02:27.64	02:02.40
		04:02.68	03:58.00	04:10.71	03:43.29	04:57.00
			01:28.50			
Satisfaction (SUS score)	SUS 1	3.23	2.83	3.57	2.75	4.00
		3.77	3.83	3.71	3.75	3.80
			4.33			
	SUS 2	1.85	1.83	1.86	1.75	2.00
		2.46	2.83	2.14	2.63	2.20
			2.33			
	SUS 3	4.15	3.67	4.57	3.88	4.60
		3.08	3.17	3.00	3.38	2.60
			4.33			
	SUS 4	1.54	1.50	1.57	1.38	1.80
		3.15	3.17	3.14	2.88	3.60
			3.17			
	SUS 5	3.31	3.17	3.43	3.13	3.60
		3.62	3.50	3.71	3.63	3.60
			4.00			
	SUS 6	3.23	3.17	3.29	3.38	3.00
		2.69	2.83	2.57	2.50	3.00
			1.83			
	SUS 7	4.23	4.50	4.00	4.50	3.80
		4.62	4.67	4.57	4.75	4.40
			4.50			
	SUS 8	2.85	3.83	2.00	3.38	2.00
		2.23	2.83	1.71	2.50	1.80
			2.67			
	SUS 9	3.92	3.33	4.43	3.63	4.40
		2.62	2.83	2.43	2.88	2.20
			4.33			
	SUS 10	1.46	1.33	1.57	1.25	1.80
		2.54	2.67	2.43	2.50	2.60
			3.33			
	SUS score	69.81	64.58	74.29	66.88	74.50
		61.54	59.17	63.57	63.44	58.50
			70.42			
Effectiveness (% Correct)	Steps Correct	78.95	75.00	85.71	78.57	80.00
		89.47	83.33	100.00	85.71	100.00

			83.33			
	Doors Correct	89.47	91.67	85.71	92.86	80.00
		89.47	100.00	71.43	92.86	80.00
			100.00			

Appendix B

Key
Control Results
Test Results
Repeat Test Results

Minimum Results						
	Participant group	All	Non-Expert	Expert	<40 years	>40years
Efficiency (time to complete, mm:ss)	Door 1	00:07.00	00:08.00	00:07.00	00:08.00	00:07.00
		00:11.00	00:11.00	00:17.00	00:11.00	00:53.00
			00:08.00			
	Door 2	00:05.00	00:09.00	00:05.00	00:09.00	00:05.00
		00:18.00	00:18.00	00:20.00	00:18.00	00:26.00
			00:21.00			
	Door 3	00:04.00	00:04.00	00:05.00	00:04.00	00:05.00
		00:08.00	00:11.00	00:08.00	00:08.00	00:14.00
			00:08.00			
	Doors Marked	00:01.00	00:01.00	00:10.00	00:01.00	00:13.00
		00:00.00	00:00.00	00:00.00	00:00.00	00:00.00
			00:00.00			
	Step 1	00:05.00	00:05.00	00:11.00	00:05.00	00:11.00
		00:16.00	00:16.00	00:21.00	00:16.00	00:28.00
			00:10.00			
	Step 2	00:04.00	00:04.00	00:08.00	00:04.00	00:08.00
		00:06.00	00:06.00	00:20.00	00:06.00	00:23.00
			00:09.00			
	Steps marked	00:00.02	00:00.02	00:06.00	00:00.02	00:06.00
		00:00.00	00:00.00	00:00.00	00:00.00	00:00.00
			00:00.00			
	Doors Measured	00:15.00	00:15.00	00:24.00	00:15.00	00:24.00
		00:37.00	00:37.00	00:45.00	00:37.00	01:27.00
			00:39.00			
	Steps measured	00:08.00	00:09.00	00:08.00	00:09.00	00:08.00
		00:37.00	00:46.00	00:37.00	00:41.00	00:37.00
			00:19.00			
	Total	00:35.00	00:35.00	01:09.00	00:35.00	01:09.00
		01:26.00	02:08.00	01:26.00	01:26.00	02:13.00
			01:05.00			

Satisfaction (SUS score)	SUS 1	2	2	2	2	2
		3	3	3	3	3
			3			
	SUS 2	1	1	1	1	1
		2	2	2	2	2
			1			
	SUS 3	3	3	4	3	4
		2	2	2	2	2
			4			
	SUS 4	1	1	1	1	1
		1	1	1	1	1
			1			
	SUS 5	1	1	2	1	3
		2	2	2	2	2
			3			
	SUS 6	1	1	2	1	2
		1	1	1	1	1
			1			
	SUS 7	2	4	2	4	2
		4	4	4	4	4
			4			
	SUS 8	1	3	1	1	1
		1	2	1	1	1
			2			
	SUS 9	1	1	4	1	4
		1	2	1	2	1
			4			
	SUS 10	1	1	1	1	1
		1	1	1	1	1
			2			
	SUS score	47.5	50	47.5	50	47.5
		45	50	45	50	45
			57.5			

Appendix C

Key
Control Results
Test Results
Repeat Test Results

Maximum Results

Participant group		All	Non-Expert	Expert	<40 years	>40years
Efficiency (time to complete, mm:ss)	Door 1	01:13.00	01:13.00	00:31.00	01:13.00	00:31.00
		02:31.00	02:18.00	02:31.00	02:18.00	02:31.00
			00:21.00			
	Door 2	01:47.00	01:47.00	00:39.00	01:47.00	00:39.00
		02:36.00	01:24.00	02:36.00	01:24.00	02:36.00
			00:32.00			
	Door 3	01:13.00	01:13.00	00:32.00	01:13.00	00:32.00
		02:09.00	02:09.00	01:30.00	02:09.00	01:30.00
			00:41.00			
	Doors Marked	04:07.00	04:07.00	00:58.00	04:07.00	00:58.00
		00:00.00	00:00.00	00:00.00	00:00.00	00:00.00
			00:00.00			
	Step 1	01:43.00	01:43.00	00:27.00	01:43.00	00:16.00
		04:52.00	04:52.00	02:09.00	04:52.00	02:09.00
			00:20.00			
	Step 2	00:35.00	00:35.00	00:26.00	00:35.00	00:26.00
		04:07.00	02:31.00	04:07.00	02:31.00	04:07.00
			00:47.00			
	Steps marked	00:54.00	00:54.00	00:51.00	00:54.00	00:51.00
		00:00.00	00:00.00	00:00.00	00:00.00	00:00.00
			00:00.00			
	Doors Measured	03:21.00	03:21.00	01:28.00	03:21.00	01:28.00
		04:06.00	02:56.00	04:06.00	02:56.00	04:06.00
			00:56.00			
	Steps measured	02:09.00	02:09.00	00:57.00	02:09.00	00:57.00
		06:10.00	06:10.00	06:07.00	06:10.00	06:07.00
			01:07.00			
	Total	05:06.00	05:06.00	03:16.00	05:06.00	03:16.00
		08:57.00	07:55.00	08:57.00	07:55.00	08:57.00
			02:02.00			

Satisfaction (SUS score)	SUS 1	5	3	5	3	5
		5	5	5	5	5
			5			
	SUS 2	4	4	4	4	4
		5	5	3	5	3
			5			
	SUS 3	5	4	5	5	5
		4	4	4	4	4
			5			
	SUS 4	4	3	4	3	4
		5	5	5	5	5
			5			
	SUS 5	5	5	4	5	4
		5	5	5	5	5
			5			
	SUS 6	5	5	5	5	5
		4	4	4	4	4
			3			
	SUS 7	5	5	5	5	5
		5	5	5	5	5
			5			
	SUS 8	5	5	3	5	3
		4	4	3	4	3
			4			
	SUS 9	5	5	5	5	5
		4	4	4	4	4
			5			
	SUS 10	3	2	3	2	3
		5	4	5	4	5
			4			
	SUS score	92.5	77.5	92.5	77.5	92.5
		77.5	75	77.5	77.5	77.5
			85			

Appendix D

Key
Test Results
Repeat Test Results

Results Favouring New Model (%)						
Participant group		All	Non-Expert	Expert	<40 years	>40years
Efficiency	Door 1	36.84	41.67	28.57	50.00	0.00
			66.67			
	Door 2	21.05	33.33	0.00	28.57	0.00
			50.00			
	Door 3	10.53	8.33	14.29	14.29	0.00
			50.00			
	Doors Marked	100.00	100.00	100.00	100.00	100.00
			100.00			
	Step 1	15.79	16.67	14.29	14.29	20.00
			50.00			
	Step 2	21.05	33.33	0.00	28.57	0.00
			16.67			
	Steps marked	100.00	100.00	100.00	100.00	100.00
			100.00			
	Doors Measured	15.79	25.00	0.00	21.43	0.00
			50.00			
	Steps measured	5.26	8.33	0.00	7.14	0.00
			50.00			
	Total	21.05	25.00	14.29	28.57	0.00
			66.67			
Satisfaction	SUS 1	36.84	33.33	42.86	35.71	40.00
			83.33			
	SUS 2	10.53	8.33	14.29	7.14	20.00
			33.33			
	SUS 3	5.26	8.33	0.00	7.14	0.00
			66.67			
	SUS 4	5.26	0.00	14.29	0.00	20.00
			16.67			
	SUS 5	36.84	25.00	57.14	28.57	60.00
			66.67			
	SUS 6	47.37	33.33	71.43	42.86	60.00
			83.33			

	SUS 7	31.58	16.67	57.14	21.43	60.00
			16.67			
	SUS 8	36.84	33.33	42.86	35.71	40.00
			66.67			
	SUS 9	10.53	16.67	0.00	14.29	0.00
			66.67			
	SUS 10	15.79	8.33	28.57	7.14	40.00
			0.00			
	SUS score	26.32	16.67	42.86	21.43	40.00
			66.666667			