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TESIS DOCTORAL:

TÍTULO
Study of evacuation drills through data collection, dimensional analysis, statistical regression, and IoT technologies

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A los que me aman estando conmigo y
a quienes, en su aparente ausencia, sé que siempre estarán conmigo

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Resumen

Imaginemos que suenan las sirenas de evacuación, ¿en cuánto tiempo estaríamos todos fuera del edificio? Dependerá cuantos seamos (¿1.000 personas o quizás sólo 200?), de las dimensiones y diseño del edificio, y sobre todo de cómo nos comportemos, es decir, el tiempo que tardemos en asimilar que tenemos que salir, en decidirnos a salir, quizás en entretenernos en coger algo, o esperar o convencer a alguien, y otras cuestiones que nos pueden entretener. Es decir, se trata de un sistema con multitud de elementos que interaccionan entre sí.

Las bases de la modelización de la evacuación se establecieron en las décadas de los años 70 y 80 del siglo XX, siendo un desglose analítico del tiempo total a considerar cuando se efectúa una evacuación teniendo en cuenta las diferentes variables que podían influir en cada uno de los elementos definidos. La modelización de todos estos aspectos de complejidad creciente, pasó a ser estudiado con la ayuda de simulaciones por ordenador. Las simulaciones de ordenador son de gran ayuda pero implican un gran esfuerzo en recursos para poder llevarlas a cabo, no evitan la realización de ejercicios de simulacros y no permiten comparar edificios diferentes.

Esta tesis doctoral propone un enfoque diferente, desde una visión holística, como un sistema en su conjunto donde cada edificio sea una caja negra caracterizada con un parámetro adimensional que permita diferenciar edificios distintos, siendo el edificio la variable independiente del sistema mientras que la relación “tiempo de evacuación entre personas evacuadas” es la variable dependiente. De esta manera se pueden comparar las evacuaciones de diferentes edificios.

Una gran dificultad que tiene el estudio e investigación sobre las evacuaciones es recopilar datos suficientes, tanto cuantitativos como cualitativos, de las mismas. En esta tesis se han recogido los datos de simulacros de evacuación de la Universidad de Valladolid durante 10 años. Además se propone un sistema, basado en localización indoor, para facilitar la recogida de datos futuros, válidos para alimentar tanto al modelo propuesto por esta tesis, como para validar otros modelos de estudio.

Esta tesis ofrece un planteamiento novedoso para poder comparar las evacuaciones de edificios diferentes, teniendo en cuenta sus características más relevantes en la evacuación, lo cual, hasta ahora, no había sido posible. El planteamiento teórico se ve respaldado por los datos históricos recogidos y por los datos publicados por otros autores. Además, propone una solución viable para la recopilación de más datos de evacuaciones valiéndose de tecnologías de posicionamiento en interiores.

Palabras clave

Simulacro de evacuación, tiempo de evacuación, análisis dimensional, número adimensional, regresión estadística, localización indoor.

Abstract

Let's imagine the evacuation sirens go off, how soon would we all be out of the building? It will depend how many we are, 1000 people or maybe just 200? It will also depend on the dimensions and design of the building, and above all on how we behave. I mean, the time to assimilate that we have to leave, decide to leave, perhaps delayed by picking something up, waiting for or convincing someone, and other issues that make the exit longer. In other words, it is a system with many components that interact with each other.

The foundations of evacuation modeling were established in the 1970s and 80s, these being an analytical breakdown of the total time when carrying out an evacuation taking into account the different issues that could influence each of the defined components. All these aspects were of increasing complexity and began to be studied with the help of computer simulations. Computer simulations are very helpful, but require a large amount of resources to carry them out. They do not avoid the need to carry out evacuation drills and do not allow comparisons between evacuations of different buildings.

This Ph.D. thesis proposes a different approach, from a holistic view, of a system as a whole, where each building is a black box characterized by a dimensionless parameter that allows different buildings to be differentiated. The building is the independent variable of the system, while the ratio of evacuation time to people evacuated will be the dependent variable. In this way, the evacuations of different buildings can be compared.

One great difficulty concerning the study and research of evacuations is to collect enough data, both quantitative and qualitative. In this Ph.D. thesis, data have been collected from evacuation drills at the University of Valladolid for 10 years. In addition, a new indoor positioning system is proposed to facilitate the collection of future data that could be used to feed both the model proposed by this thesis, and to validate other study models.

This Ph.D. thesis offers an unprecedented approach to be able to compare the evacuations of different buildings, taking into account their most relevant characteristics for the evacuation, which until now had not been possible. The theoretical approach is supported by the historical data collected, and by data published by other authors. Furthermore, it also offers a viable solution for collecting more evacuation data using indoor positioning technologies.

Keywords

Evacuation drills, Evacuation Time, Regression analysis, Dimensional analysis, Dimensionless number, Indoor Positioning System

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Resumen de la Tesis

La Ingeniería Industrial es una rama de la Ingeniería creada en España hace más de 150 años. La Ingeniería Industrial se ocupa de la optimización del uso de recursos humanos, técnicos e informativos, y del manejo y gestión óptimos de los sistemas de transformación de bienes y servicios de una empresa o compañía. Es la más generalista de las ingenierías, con base multidisciplinar, y aúna conocimientos tecnológicos muy diversos, permitiendo la capacitación del profesional de la ingeniería industrial para adaptarse a cualquier sector empresarial. Esta disciplina permite encontrar soluciones a los diferentes problemas que se plantean, tanto de orden tecnológico como económico o de gestión.

En el estudio de la gestión de las emergencias y las evacuaciones en edificios intervienen muchas áreas de conocimiento, tanto del ámbito técnico como del ámbito de conocimiento del comportamiento de las personas. Circunstancias que propician que la investigación científica de estas cuestiones en el marco de la ingeniería industrial puedan ser muy fructíferas, gracias a la citada base multidisciplinar y al diverso conocimiento tecnológico de la ingeniería industrial. Dentro de este marco, la presente tesis doctoral propone un nuevo enfoque a los planteamientos del estudio de las evacuaciones. Con esta propuesta se obtiene una forma de estudio que permite comparar evacuaciones de diferentes edificios y por tanto proporciona una herramienta de mejora continua en el resultado de los simulacros de evacuación. Además ofrece una solución viable para la recopilación de datos de las evacuaciones de forma automática con el uso de tecnologías de posicionamiento indoor, válidos para usarse tanto en el modelo propuesto, como para otros modelos.

R.1 Motivación

En 1997, a través de la regulación de los servicios de prevención en España, la confección de medidas de emergencia en los lugares de trabajo se vinculó a una de las tareas de asesoramiento propias de los técnicos de prevención. No obstante, un plan de emergencias puede ser una cuestión más compleja que simplemente unas medidas de emergencia para los empleados en un centro de trabajo. La redacción y la implantación de los planes de emergencia y evacuación requiere de conocimientos transversales de varios campos de la ciencia y la tecnología. La normativa española contempla las evacuaciones desde varias perspectivas técnicas profesionales vinculadas a la prevención de todo tipo de riesgos, incluyendo el diseño en sí de la construcción (arquitectura, ingeniería civil, etc.), las instalaciones de todo tipo que requiera la edificación (instalaciones eléctricas, instalaciones con inflamables o con almacenamientos de productos químicos, instalaciones particulares como pueden ser las térmicas, otras donde haya riesgos especiales como los nucleares o radioactivos, etc.), la funcionalidad de los edificios (protección civil, espectáculos, educación, residencial, etc.) y demás aspectos relacionados. Todas estas perspectivas están vinculadas o se pueden vincular al ámbito profesional de la ingeniería industrial.

Desde 1997, debido tanto a mis intereses personales como a mi actividad profesional, he estado vinculada y trabajando en los planes de evacuación y de emergencia de diferentes edificios. Empecé por redactar planes de emergencia para centrales hidroeléctricas en los Saltos de Duero, continué redactando planes de emergencias para varias empresas asociadas a la Mutua Fraternidad- Muprespa, y posteriormente redacté, implanté, y mantuve actualizados los planes de emergencia de la Universidad de Valladolid, en un proceso de depuración progresiva con la colaboración de diferentes personas pertenecientes a diversos organismos oficiales, empresas y alumnos en prácticas. La experiencia durante los más de 20 años que llevo trabajando en el tema me sugería que había patrones de comportamiento en los diferentes edificios, pero no tenía herramientas para poder expresar objetivamente lo que intuitivamente se podía vislumbrar, lo que me alentó a investigar y a buscar maneras de poder comparar las evacuaciones de edificios diferentes que pudiera arrojar luz sobre esta cuestión.

En mi vida profesional he tenido interés y motivación personal por buscar herramientas que permitan mejorar los diversos campos que cubren la prevención de riesgos laborales. Realizar esta búsqueda a través de la investigación ha sido una constante en mi vida. He publicado los resultados obtenidos siempre que mis circunstancias personales me han permitido dedicar el tiempo añadido que requieren las publicaciones. A principios de los 2000 detecté que, si bien el sistema de gestión que proponía la legislación para los riesgos laborales era básicamente un sistema de mejora continua, como los sistemas de mejora continua en el ámbito de la calidad, ni el legislador decía como hacer e implantar el sistema de gestión, ni había estudios acerca del tema como los había en el ámbito de la calidad. La normativa de prevención de riesgos laborales había tenido una publicación muy rápida y profusa, entendiendo el sentido de rapidez en comparación con los retos que para la gestión supone adaptarse a las nuevas exigencias normativas de forma eficiente y compatible con los sistemas de gestión ya implantados. Por lo tanto, trasladar las herramientas ampliamente usadas en sistemas de calidad hacia el ámbito de la prevención de riesgos laborales era una brecha de conocimiento por cubrir. En 2002, apliqué uno de los métodos de calidad en producción, el QFD (Despliegue de la Función de Calidad), al ámbito de la gestión de la prevención de riesgos laborales, con resultados positivos, publicados en [Gento et al., 2001] y [Miñambres et al., 2004]. Por razones ajenas a la investigación en sí tuve que interrumpir mi profundización en ese tema en aquel momento. Hoy en día las normas ISO-UNE ya han publicado sistemas de gestión de calidad, medio ambiente y prevención que permiten la integración y la optimización de los esfuerzos de cada una de estas áreas.

Centrándonos de nuevo en el tema específico de la gestión de las emergencias y los simulacros de evacuación que se realizan en los edificios, éstos son una herramienta de mejora de la gestión de las emergencias en el propio edificio. Las propuestas de mejora se basan en el análisis del simulacro, viendo posibles incidencias y puntos débiles, pudiendo, en su caso, compararlo con otros simulacros realizados en el mismo edificio, o como opción alternativa, se podría comparar con la simulación de la evacuación usando uno de los múltiples softwares que hay en la literatura, lo que supone un gran esfuerzo en recursos económicos y de tiempo de las personas que recopilen toda la información que necesita el software.

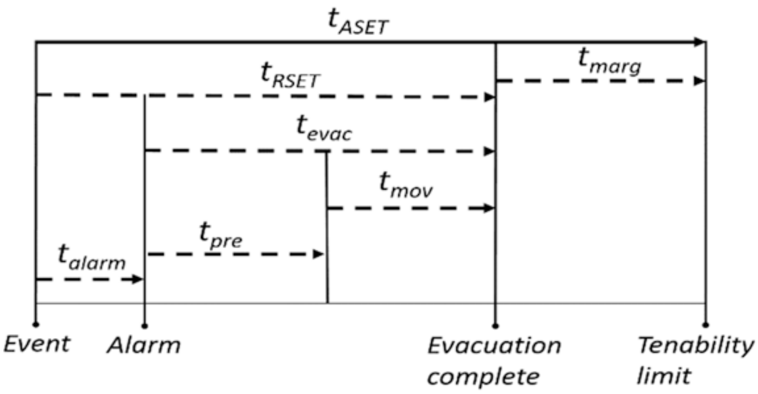

Figura 1: Tiempos en el proceso global de evacuación según [Cuesta et al., 2015]

El núcleo principal de la literatura sobre la que se fundamentan las bases de la modelización de la evacuación se estableció en las décadas de los años 70 y 80 del siglo XX, gracias a estudios realizados por autores independientes en países diferentes (se puede ver una recopilación muy ilustrativa en [Cuesta et al., 2015]). Todos estos conocimientos se constituyeron como parte de lo que se denomina Ingeniería de Seguridad contra Incendios (Fire Safety Engineering) cuyo objetivo principal es garantizar un entorno adecuado durante el tiempo que necesitan las personas para evacuar. Dentro del estudio de las evacuaciones se definieron varios tiempos, como resumen se pueden ver en la figura 1 extraída de [Cuesta et al., 2015].

Como ilustra la figura, lo que se planteó es un desglose analítico del tiempo total a considerar cuando se efectúa una evacuación. El tiempo que se tarda en evacuar un edificio desde que surge un evento que va a requerir de evacuación ($\mathrm{t_{RSET}}$, o Required Safe Egress Time) es la suma de los siguientes tiempos: el tiempo que pasa desde que surge el evento hasta que las alarmas de evacuación saltan ($\mathrm{t_{alarm}}$, que a su vez también podría ser subdividido y estudiado), más el tiempo desde que saltan las alarmas hasta que la gente comienza a evacuar ($\mathrm{t_{pre}}$, que igualmente puede ser subdividido y estudiado), más el tiempo en salir del edificio ($\mathrm{t_{mov}}$, de nuevo también este tiempo puede ser desglosado y hay que tener en cuenta muchos factores en su estudio). El tiempo de evacuación ($\mathrm{t_{evac}}$) es la suma de $\mathrm{t_{pre}}$ más $\mathrm{t_{mov}}$. La suma de estos tiempos debería ser inferior al tiempo disponible para una evacuación segura ($\mathrm{t_{ASET}}$ Available Safe Egress Time): cuanto mayor tiempo de margen ($\mathrm{t_{marg}}$) mayor seguridad. Formalizando las ecuaciones tenemos lo siguiente:

$$t_{\mathrm{RSET}} = t_{\mathrm{alarm}} + t_{\mathrm{evac}} \tag{1}$$
$$t_{\mathrm{evac}} = t_{\mathrm{pre}} + t_{\mathrm{mov}} \tag{2}$$
$$t_{\mathrm{ASET}} = t_{\mathrm{RSET}} + t_{\mathrm{marg}} \tag{3}$$
$$t_{\mathrm{ASET}} > t_{\mathrm{RSET}} \tag{4}$$

La norma ISO/TR 16738:2009(en) (*Fire-safety engineering — Technical information on methods for evaluating behaviour and movement of people* [ISO/TR16738:2009(en), 2009]) contempla diversos aspectos del cálculo de estos tiempos. Igualmente otros organismos, como la Society of Fire Protection Engineering [Hurley et al., 2015], hace diversas consideraciones para los cálculos de estos tiempos.

En todos los tiempos influye el comportamiento humano, como todas las cuestiones que puedan afectar al mismo, y ahí se abre un extenso campo de estudio ya que afecta tanto a cuestiones psicológicas de los individuos (incluida la percepción e interpretación de las diferentes informaciones que puedan estar o surgir en la evacuación) como a cuestiones de comportamiento en grupo, cuestiones culturales, cuestiones asociadas al estado físico de los individuos, etc. (estudios sobre estos aspectos se pueden ver en diversas publicaciones como por ejemplo en [Kuligowski, 2008], [Kuligowski, 2009], [Wang et al., 2021b], [Ding et al., 2021]).

Por otro lado, en lo referente al tiempo de movimiento del grupo de personas sin considerar los aspectos mencionados en el párrafo anterior, este tiempo se ve afectado por las cuestiones físicas del diseño del edificio (distancias a recorrer, posible cuellos de botella, etcétera). Este último aspecto fue estudiado usando modelos de mecánica de fluidos, y es un enfoque que aún hoy en día sigue siendo parte de los modelos actuales ([Gwynne and Rosenbaum, 2016]). Las ecuaciones fueron adquiriendo cada vez más complejidad y el modelado de todos estos aspectos pasó a ser estudiado con la ayuda de simulaciones por ordenador. Las primeras fueron en la década de los 80 del siglo XX, proliferando en la década de los 90 y más allá [Cuesta et al., 2015]. Existe una amplia gama de modelos de simulación por ordenador disponibles para este propósito: [Chunmiao et al., 2012] menciona que hay más de 22 modelos que simulan los procesos de evacuación y el movimiento de multitudes, cada uno con diferentes variantes; [Kuligowski, 2016] proporciona una descripción general de 26 modelos que simulan evacuaciones, cada uno con su ámbito de aplicación y proporciona una guía para realizar y verificar otros modelos de simulación. En la actualidad, los modelos de simulación tienden a incluir nuevas tendencias computacionales, ejemplo [Jiang, 2019] usa Inteligencia Artificial e Internet de las cosas (IoT), [Mohottige et al., 2020] usa las conexiones WiFi para detectar evacuaciones, [Dong et al., 2019] insta al uso de Big-Data para la validación de los modelos de simulación y en la mejora de los planteamientos matemáticos. Pero la aplicación de los avances en nuevas tecnologías no quita para que se busquen nuevos enfoques teóricos como recoge [Ronchi et al., 2019].

Las simulaciones por ordenador no se han usado únicamente para las evacuaciones, sino también para otras cuestiones vinculadas a la seguridad contra incendios o vinculadas a otro tipo de emergencias, como por ejemplo [Gao et al., 2020] usa un modelo computacional para general la posición óptima de las puertas para minimizar las distancias de evacuación, mientras que [Arteaga and Park, 2020] desarrolla un modelo particular para ser aplicado en incidentes con tiradores disparando. También hay una propuesta para el uso en tiempo real como por ejemplo [Mirahadi and McCabe, 2020] o [Mirahadi and McCabe, 2021]. Muy interesante también otras propuestas, para validar modelos empleando escenarios de realidad virtual donde se vería el comportamiento de las personas como en los artículos de [Wang et al., 2021a], o [Moussaïd et al., 2016].

No se ha de olvidar que todo modelo de simulación que se use va a estar circunscrito al ámbito para el que se modelizó, sometido a las hipótesis que se hayan hecho para el desarrollo del modelo, e inevitablemente tendrá las limitaciones asociadas a los modelos predictivos [Cuesta et al., 2015]. Estas limitaciones e incertidumbres son extensibles a modelos cuya resolución no necesariamente esté implementada en un software.

Pero por mucho que avancen los modelos matemáticos y los softwares programados para resolver dichos modelos, no se puede dejar de hacer y utilizar los simulacros de evacuación. La cuestión que los diversos autores se plantean en este punto están ligadas al aprovechamiento de la realización de estos simulacros. [Amos et al., 2019] o [Gwynne et al., 2020] hablan acerca de esta problemática.

Resumiendo, los diferentes softwares tienen el propósito de estimar cómo se puede comportar las personas de un edificio concreto durante una evacuación, pudiendo hacer diferentes configuraciones, y son muy útiles en ese sentido. No obstante, aunque permiten hacer estimaciones de los diversos tiempos diferenciados en una evacuación, no permiten la posibilidad de comparar las evacuaciones reales de un edificio con respecto a otros. La bibliografía ya planteaba esta necesidad. Por ejemplo, [Haghani and Sarvi, 2018] después de un extenso recopilación de estudios experimentales en comportamiento de multitudes dirigido a las evacuaciones concluyen que hay un vacío en la unificación que permita la comparación entre los mismos. Con el planteamiento de esta tesis se pretende abrir un camino nuevo para encontrar formas que permitan comparaciones entre evacuaciones de edificios diferentes empezando por edificios de similares características o de ámbitos que pudieran ser comparables.

La realización de simulacros de evacuación requiere de un gran esfuerzo organizacional de las entidades que lo llevan a cabo. No todas las empresas lo hacen y habitualmente se realiza únicamente en aquellas que se ven obligadas a realizarlo por disposición legal o por compromiso con la seguridad, por la sencilla razón de que realizar esta actividad conlleva la asignación de recursos que tienen un coste. Se parte del coste que supone la paralización de la actividad durante todo el tiempo que dure el simulacro hasta que se puede retomar la actividad normal. A partir de este coste se le van sumando otros como son: los recursos añadidos de organización y desarrollo del simulacro, costes de oportunidad por la parada de la actividad en cierto preciso momento, otros costes por posibles contingencias. Si se quiere hacer una recopilación de datos cuantificables que permitan futuros estudios supone dedicar más recursos al simulacro y por tanto incrementar los costes.

Evidentemente, la realización de simulacros de evacuación tiene beneficios, pero estos tienen un carácter más intangible. Para que los resultados de un simulacro sean de provecho, todos los empleados se han de involucrar e implicar y de la misma manera hay que hacer partícipes a todos los ocupantes del edificio. Igualmente, para poder analizar los resultados de los simulacros hay que contar con recursos extra bien organizados. Estos recursos han de permitir la recopilación de los datos que posteriormente se estudien y analicen para conocer los resultados del simulacro con sus propuestas de mejora. Hasta el momento los recursos que se utilizan para la recopilación de la información son o bien personas observadoras del simulacro situadas en lugares estratégicos, convenientemente instruidas para la observación, o bien de videocámaras igualmente convenientemente situadas. Para lo primero, el valerse de personas observadoras, tiene la dificultad de que debe haber personas convenientemente formadas para ese fin que puedan estar disponibles. Para lo segundo, el uso de elementos de grabación de imágenes (videocámaras) requiere tener las autorizaciones pertinentes para cumplir con lo establecido en la normativa de protección de datos y derechos de las imágenes de cada país, además de que posteriormente las grabaciones han de ser convenientemente estudiadas para recopilar la información. También hay otra opción que es la de pasar un cuestionario a todas o a parte de las personas evacuadas para que den su testimonio. El uso de testimonios y de observadores es de gran valor cualitativo, pero dejan la posibilidad de un indeseable margen de error para la recopilación de datos cuantitativos, en especial cuando la información la dan los propios evacuados.

No obstante, el uso de nuevas tecnologías como las de posicionamiento indoor, IoT, la nube, etc., abren nuevas posibilidades para la recopilación de datos cuantitativos de forma automática, aplicables también al ámbito de las evacuaciones.

R.2 Objetivos

En la motivación de esta tesis se ha mencionado que [Amos et al., 2019] y [Gwynne et al., 2020] plantean diferentes cuestiones vinculadas al aprovechamiento de los simulacros, entre otras, que no haya un consenso global en cómo desarrollar la realización de los mismos. No obstante, lo que sí que tienen todos los simulacros en común es que cuando se realizan, el primer dato que se pregunta es ¿en cuánto tiempo se ha evacuado el edificio? y luego se pregunta ¿cuántas personas se han evacuado?. Después se empieza a preguntar por otras cuestiones cualitativas que pueden influir en los anteriormente mencionados datos cuantificables. La información cualitativa se corresponde con los incidentes dentro de la evacuación y otros datos de interés que quedan reflejados en los informes que se realizan al respecto con vista a mejorar futuros simulacros del mismo edificio.

También se ha planteado en la motivación que hay un vacío en el estudio de las evacuaciones que permita comparaciones entre edificios. Esta tesis pretende abrir un camino nuevo para encontrar formas que permitan dichas comparaciones entre evacuaciones de edificios diferentes, empezando por edificios de similares características o de ámbitos que pudieran ser comparables. Este camino nuevo está fundamentado en datos cuantitativos, aunque se valga de datos cualitativos de cómo se han comportado los colectivos de personas observados en los simulacros de evacuación para comprobar que los resultados obtenidos son coherentes. No obstante, esta tesis no pretende dar justificación o plantear modelos subyacentes de conducta desde un punto de vista sociológico, psicológico o de cualquier otra ciencia social o de comportamiento humano que se vea relacionada con las evacuaciones de los edificios.

La comparación entre evacuaciones de edificios diferentes puede valer de indicador para el análisis de los simulacros y usarse como una herramienta de mejora. Si se consigue un sistema de comparación que no suponga un gran esfuerzo en la obtención de los datos necesarios y realización de cálculos, entonces podría convertirse en una herramienta muy útil para la mejora de los resultados de los simulacros de evacuación, y por tanto de la seguridad de las personas ante posibles situaciones de emergencia en edificios.

Por otro lado, para poder proseguir en el estudio de las evacuaciones, bien dentro de los simulacros, o bien dentro de las propias emergencias, sería muy conveniente tener disponibles más datos de evacuaciones reales. Si además la recopilación de los datos de evacuaciones reales se pudiera obtener de forma automática, esto supondría un avance para la investigación en este campo.

Esta tesis doctoral también tiene como objetivo el planteamiento de un sistema / herramienta para obtener los datos de las evacuaciones en los simulacros valiéndose del uso de tecnologías de localización indoor de bajo coste. Se pretende que el sistema guarde las posiciones en la nube para evitar pérdidas de la información facilitando el posterior estudio. De esta manera se aprovechan las ventajas que ofrecen las tecnologías 4.0, para aplicarlo al campo del estudio y mejora de las evacuaciones y por tanto, de la gestión de las emergencias.

R.2.1 Preguntas de Investigación

En el contexto de los simulacros de evacuación, la primera pregunta es:

¿Es posible encontrar un modelo que permita comparar las evacuaciones de diferentes edificios de forma cuantitativa, obteniendo una predicción y posibilidad de advertir patrones de comportamiento?

La segunda pregunta que se plantea es:

Dado un modelo como el descrito, ¿es posible mejorarlo e introducir un edificio de un ámbito afín pero fuera del ámbito donde se ha estudiado el modelo?

La pregunta inmediatamente subsiguiente a esta, que constituye la tercera pregunta de esta tesis, nace de lo que se ha visto acerca de que una de las principales dificultades que hay en la investigación en este campo es recopilar los suficientes datos con la suficiente calidad cuando se realizan evacuaciones:

¿Es posible obtener más información cuantitativa con tecnologías de posicionamiento o localización indoor con suficiente calidad y con bajo coste, para poder alimentar este u otros modelos de estudio de evacuaciones de diferentes edificios?

Objetivos específicos

Para contestar estas preguntas de investigación, necesitamos llevar a cabo algunos objetivos intermedios, más específicos. La primera pregunta se desdobla en la consecución de dos objetivos:

Objetivo primero: Recopilar datos suficientes de simulacros de evacuación efectuados en edificios diferentes.

Se ha mencionado en la motivación de esta tesis que la realización de simulacros conlleva un importante coste organizacional (supone el parón de la funcionalidad del edificio durante la ejecución del mismo, y la organización de recursos que permitan la recopilación de los datos cuantitativos y cualitativos necesarios para el análisis). Este esfuerzo organizacional propicia que no siempre se hagan simulacros con evacuaciones totales de los edificios, o que cuando se realizan no se cuente con los recursos necesarios para proporcionar todos los aspectos necesarios para poder realizar un análisis metódico y sistémico que permitan estudios más profundos. Además se da la circunstancia que los simulacros son cuestiones que realizan las empresas para cumplir con los mínimos marcados con la obligación legal y para mantener entrenadas a sus empleados para la actuación en caso de emergencia, y no se plantean una recopilación de datos de manera que permita realizar investigación científica en este campo. Esto conlleva que no haya apenas publicaciones científicas con datos suficientes de simulacros de evacuación. Conseguir los datos de un número mínimo de edificios que comparten el mismo ámbito, con un número mínimo de simulacros ha sido un trabajo metódico de muchos años de dedicación.

Objetivo segundo: A partir de los datos cuantitativos obtenidos en el objetivo primero, plantear un método que permita comparar las evacuaciones de los edificios diferentes obteniendo una predicción, comprobar que el método es suficientemente válido con los datos cuantitativos y cualitativos de los edificios disponibles.

Este segundo objetivo ha requerido de un nuevo planteamiento con respecto a lo que había en la literatura de las evacuaciones, y para ello, en este objetivo se han usado conceptos muy arraigados en otros campos de la ingeniería pero no aplicados hasta el momento al ámbito del estudio de las evacuaciones.

La segunda pregunta de investigación da lugar al siguiente objetivo:

Objetivo tercero: Una vez planteado el método mencionado en el objetivo segundo, revisarlo, depurarlo y buscar otros datos de simulacros de evacuación de edificios de otros autores para comprobar si admite o no admite su incorporación al modelo ya depurado.

De forma natural, el tercer objetivo está ligado a la depuración y a la consolidación del modelo con datos independientes de los obtenidos durante el transcurso de la elaboración del modelo inicialmente propuesto.

Finalmente, la tercera pregunta de investigación da lugar al siguiente objetivo:

Objetivo cuarto: Plantear un sistema automatizado de recoger información cuantitativa en los simulacros, acerca de lo que pasa dentro de los edificios empleando tecnologías de localización indoor, que sean asequibles económicamente pero que a la par proporcionen calidad de datos suficiente para alimentar modelos de evacuación de edificios.

Las nuevas tecnologías están para ayudar al avance de la ciencia e inevitablemente el estudio de las evacuaciones es un campo donde se puede aportar mucho con la recopilación automática de datos que la localización de interiores puede proporcionar.

R.3 Metodología

La metodología de investigación de esta tesis ha seguido los pasos clásicos de observación, formulación de hipótesis, comprobación, replanteamiento para la mejora y de nuevo comprobación.

Esta tesis está enmarcada dentro del ámbito de la ingeniería industrial, siendo por tanto bastante transversal tocando temas de muchas áreas de conocimiento. Esto ha propiciado que se hayan usados varios métodos.

La parte de la tesis dirigida a encontrar la forma de comparar los tiempos de evacuación de diferentes edificios teniendo en cuenta el número de personas evacuadas y las diferentes características de los edificios ha requerido de recopilación de datos tanto cualitativos como cuantitativos. Los datos proceden de la observación de casos reales de simulacros de evacuación. La observación de los datos se ha realizado con personas previamente formadas para ello. Los observadores han sido mayoritariamente estudiantes universitarios que hacían prácticas vinculadas a alguna asignatura estrechamente relacionada con emergencias y evacuaciones. Para participar como observadores se requería de una formación previa que le habilitaba para recoger información imparcial de observación del comportamiento de los ocupantes evacuados considerados como grupo. Justo antes de cada simulacro, se llevaba a cabo una reunión con todos los observadores para asegurarse de que supieran qué y dónde hacer, cómo evitar interferir con la evacuación, y como apuntar los tiempos para que todo el mundo tuviera el mismo criterio. Cada observador participó en al menos dos o más simulacros. El número de observadores mínimo de cada simulacro venía dado en función del tamaño y características del edificio a evacuar. Todos los observadores rellenaban un cuestionario con las mismas preguntas básicas, que en esencia han sido iguales en todos los simulacros observados. Acto seguido después de finalizado el simulacro, en el mismo centro se celebraba una reunión con todos los observadores donde se ponía en común todo lo observado (tiempos, conductas, etc.), se aclaraban dudas de interpretación del cuestionario, en caso de que las hubiera, y se recogían los cuestionarios de observación rellenados por los observadores. En las horas subsiguientes se enviaba por correo electrónico el tiempo empleado en evacuar el edificio y el número de personas que había salido a los responsables del centro con el ruego de que se lo comunicaran a todo el personal del centro donde se había realizado el simulacro. El informe de resultados del simulacro, con el análisis cualitativo de cuestiones mejorables y cuestiones que se habían realizado bien, se enviaba a los Decanos, Directores de centros, a los delegados de prevención (representantes de los trabajadores en temas de seguridad y salud) y al resto de miembros del Comité de Seguridad y Salud de la Uva, además de quedar a disposición de la autoridad laboral en caso de que lo solicitara. Este proceso se ha realizado en todos y cada uno de los 47 simulacros de edificios universitarios que figuran en esta tesis doctoral.

A partir de los datos metodológicamente observados y recopilados a lo largo de los años, se ha podido construir el modelo, usando los conocimientos de diferentes campos de la ciencia.

En esta tesis se ha planteado un modelo sistémico para el estudio de las evacuaciones. Se ha pensado un modelo sistémico porque este tipo de modelos no se centra exclusivamente en el estudio de forma analítica de las diferentes partes en las que se puede descomponer el sistema, sino que procede con el estudio del sistema y las relaciones entre sus elementos que lo conforman, es decir, se basa principalmente en entender que los sistemas tienen propiedades distintas a la simple suma de sus componentes. Las definiciones de sistema todavía están en evolución, no obstante una que es bastante clarificadora es la que dice [Ogata, 1980]:

> *"Un sistema es una combinación de componentes que actúan juntos y realizan un determinado objetivo. Un sistema no necesariamente es físico. El concepto de sistema se aplica a fenómenos abstractos y dinámicos, tales como los que se encuentran en la economía. Por tanto, el término sistema debe interpretarse como una implicación de sistemas físicos, biológicos, económicos y similares."*

Desde el entendimiento de los diversos elementos que se pueden diferenciar en una evacuación se ha podido plantear dos bloques principales. Por un lado la influencia de aspectos vinculados al diseño y dimensiones del propio edificio donde se realiza la evacuación, este bloque de parámetros del edificio actuaría como variable independiente frente al segundo bloque. El segundo bloque estaría ligado a los factores humanos que no forman parte del edificio y que con los medios actuales se puedan medir en cantidades numéricas, es decir, el tiempo que se tarda en evacuar una cantidad de personas un edificio. O sea, el segundo bloque estaría compuesto por el tiempo en evacuar y el número de personas evacuadas, y actuaría como variable dependiente del primer bloque (características del edificio). Este razonamiento resulta bastante directo, ya que el diseño y las dimensiones del edificio afectan a los tiempos de evacuación pero el cómo se comporte la gente en una evacuación no afecta, al menos no de forma directa, el cómo esté diseñado cierto edificio y sus dimensiones. Entonces si se tuvieran esos datos, se podría plantear un estudio estadístico mediante un análisis de regresión de manera que ayudaría a entender cómo el valor de la variable dependiente (relación tiempo de evacuación/ número de personas evacuadas) varía al cambiar el valor del bloque de variables independientes (caracterización del edificio).

La clave del problema es conseguir un valor que pueda funcionar como la variable independiente y que sea representativo de cada edificio. Para ello se ha usado un análisis dimensional. El análisis dimensional es una herramienta que permite simplificar el estudio de cualquier fenómeno en el que estén involucradas muchas magnitudes físicas en forma de variables independientes, como ocurre en la parte de la evacuación vinculada al edificio. Como se explicará en el desarrollo de la tesis, las diferentes cuestiones de diseño del edificio que pueden intervenir de forma más notoria en la evacuación son independientes las unas de las otras, por ejemplo, el número de salidas al exterior y la anchura de estas es independiente del número de salidas que tenga cada planta hacia las escaleras, y ambos pueden ser cuellos de botella y retrasar una evacuación, siendo todos aspectos del diseño del edificio.

Resumiendo, se ha planteado un modelo sistémico tratando los datos cuantitativos utilizando un análisis dimensional para la parte vinculada a propiamente los edificios y un análisis estadístico para la parte vinculada a la del comportamiento humano en la evacuación del edificio teniendo en cuenta la caracterización del edificio por el análisis dimensional como variable independiente del sistema. Los datos cualitativos han sido empleados para validar la coherencia de los resultados cuantitativos proporcionados por el modelo.

El otro aporte de valor para el avance de la investigación en el campo de las evacuaciones que aporta esta tesis doctoral es el dirigido a facilitar la obtención de información cuantitativa en las evacuaciones. Con ese fin se plantea el uso de un sistema automatizado para recoger información cuantitativa en los simulacros. Esta parte de la tesis tiene una fuerte componente tecnológica. Para ello se ha utilizado la metodología de investigación definida por [Adrion, 1993]. Este enfoque, denominado método de investigación para ingeniería del software, adapta las fases clásicas del método científico hipotético-deductivo a la Informática. Así consta de cuatro fases diferentes que pueden repetirse cíclicamente hasta la consecución de los objetivos. Las fases son:

(a) Observar las soluciones existentes
(b) Proponer soluciones mejores
(c) Construir o desarrollar la solución
(d) Medir y analizar la nueva solución

R.4 Resumen de contribuciones

R.4.1 Recopilación de datos

Como ya se ha mencionado en la motivación de esta tesis, la realización de simulacros de evacuación en los edificios requiere de un gran esfuerzo organizacional de la entidad que lo realiza. Todos los empleados se han de involucrar e implica de la misma manera hacer partícipes a todos los ocupantes del edificio. Igualmente, para poder analizar los resultados de los simulacros hay que contar con recursos extra bien organizados que recopilen los datos que posteriormente se estudien y analicen para conocer los resultados del simulacro y las propuestas de mejora. En la primera parte de la investigación se recopilaron los datos y la información disponible de los simulacros de evacuación desde 2010 de edificios de la Universidad de Valladolid, pudiéndose recabar la información de 47 simulacros de evacuación de 15 edificios diferentes donde se habían involucrado a más de 19.000 personas en total. Para ello recoger toda esta información de los simulacros, se han necesitado en los mismos un total de 688 personas voluntarias que observaron 646 puntos en los 47 simulacros. En algunos puntos de observación hubo dos observadores. Se tiene además que 12 de los 15 edificios tenían dos o más simulacros, con lo que de estos edificios se podía esperar cierto grado de representatividad de los mismos, mientras que los otros tres edificios de los que únicamente había un simulacro, se han usado como grupo de control. Con la recopilación de esta información se pudo empezar a realizar la investigación sobre los siguientes objetivos planteados.

R.4.2 Planteamiento de un modelo que permite comparar simulacros de evacuación realizados en diferentes edificios obteniendo predicciones

Se ha visto en el punto de motivación de esta tesis los diferentes planteamientos dentro del ámbito del estudio de las emergencias, de las evacuaciones y de otras cuestiones relacionadas con el comportamiento humano en evacuaciones y emergencias. Se ha visto también que las tendencias de estudio de investigación eran principalmente con un enfoque analítico consistente en dividir en partes las evacuaciones, caracterizando cada una de estas en partes diferenciadas para así poder modelar el tiempo de duración de cada una de estas partes.

Es decir, hasta ahora el enfoque planteado en la bibliografía ha sido un modelo dentro de la línea de tiempo, donde se representa el movimiento de personas como una suma de tiempos en los que la complejidad del comportamiento se representa a través de interacciones de agente a agente y de agente a entorno ([Cuesta et al., 2015]). Teniendo en cuenta que la interacción entre esta diferentes partes, que constituyen un sistema, son muy difíciles de poderse modelar, y que hasta el momento, no permitía comparar evacuaciones de edificios diferentes, en esta tesis se ha planteado otro enfoque diferente al que se centra en la línea temporal, y ha planteado un enfoque más holístico. Es decir, se ha abordado un enfoque desde la perspectiva de la teoría general de sistemas planteándolo como una caja negra, donde existen una serie de entradas y unas salidas. Las entradas serían las características del edificio y el número de personas evacuadas, y la salida sería el tiempo de evacuación que se espera para esas entradas, entendiendo por tiempo de evacuación el tiempo desde que se da el aviso de evacuación a todo el edificio (disparo de las sirenas de evacuación en todo el edificio) hasta fin de la evacuación, definiendo de forma general este final cuando deja de salir gente del edificio. No se tienen en cuenta las posibles acciones vinculadas a posibles o eventuales rescates.

La caracterización del edificio se ha realizado mediante un análisis dimensional. El análisis dimensional es un método para reducir problemas físicos complejos a su forma más simple (forma más económicas) antes del análisis cuantitativo o la investigación experimental [Gibbings, 2011]. El análisis dimensional se usa en diferentes campos de la ciencia desde hace mucho tiempo, desde la física, química, matemáticas, hasta la economía. La forma del análisis dimensional no es única y es necesario que la elección de las variables tenga un sentido físico. En esta tesis se ha planteado un análisis dimensional que tiene sentido físico y como se verá, con los datos recopilados y disponibles en bibliografía se ha podido verificar para la tipología de los edificios estudiados. Puede que haya otras formas de análisis dimensional, ya que la teoría nos dice que no es único, pero el estudio de otras posibles formas queda fuera de los objetivos de esta tesis.

Por otro lado era necesario relacionar todos los simulacros de diferentes edificios y para ello la estadística es la mejor herramienta científica de la que se dispone en este momento. El análisis de regresión es un método conceptualmente simple para investigar las relaciones funcionales entre variables: variable (s) dependiente (objetivo) y variable independiente (predictora). Existen varios métodos de análisis de regresión y todavía es un área de investigación activa. Estas técnicas de modelado predictivo tienen numerosas áreas de aplicación, como negocios, economía, educación, finanzas, ingeniería, medicina, meteorología, psicología, sociología, etc.

Llegados a este punto, ¿había alguien más que hubiera propuesto un análisis dimensional y un análisis de regresión para estudiar alguna cuestión dentro de otras áreas de conocimiento? Porque dentro del estudio de las evacuaciones nadie lo había propuesto hasta la fecha. En su trabajo, [Vignaux and Scott, 1999] muestran que, valiéndose de un análisis dimensional, los números adimensionales pueden utilizarse como variables de una regresión. Ellos obtuvieron buenos resultados ya que el análisis dimensional permitía manejar menos valores que los originales de partida, lo que a menudo permitía una interpretación más adecuada. Los ejemplos prácticos que mostraron fue en el área de la ingeniería mecánica. Otros ejemplos prácticos del uso combinado del análisis dimensional y el análisis de regresión se pueden encontrar en el trabajo de [Shen et al., 2014].

El modelo propuesto en esta tesis tiene los mismos puntos fuertes y las mismas limitaciones que lo expuesto en el trabajo de [Vignaux and Scott, 1999].

Valiéndonos de la caracterización de los edificios mediante un número adimensional que fuera la variable independiente y la relación entre el tiempo de evacuación y las personas evacuadas como la variable dependiente, se ha podido hacer un análisis de regresión de los datos recogidos en los simulacros. El uso conjunto del análisis dimensional con un análisis de regresión no se había realizado con anterioridad en el estudio de simulacros pero, como se acaba de mencionar, sí que se había realizado en otros campos de la ciencia.

La validez del resultado de la regresión se comprobó de dos maneras. La primera viendo la coherencia de los resultados numéricos obtenidos contrastándolos con los datos cualitativos de las evacuaciones, y la segunda manera, con los simulacros de los edificios que únicamente tenían un simulacro realizado, igualmente contrastando tanto los resultados cuantitativos, como los cualitativos observados en las evacuaciones. Todos los resultados fueron coherentes.

El trabajo realizado en estas dos primeras contribuciones ha sido aceptado y publicado en PLOS ONE, revista incluida en el JCR, de ámbito pluridisciplinar clasificada como Q1 con un factor de impacto en cinco años de 3,778 en 2020, ver [Miñambres et al., 2020a]

R.4.3 Depuración y mejora del modelo: incorporación de otros simulacros procedentes de bibliografía de autores diferentes

En esta parte del estudio nos planteamos por un lado mejorar el estudio matemático de manera que tenga un mejor ajuste estadístico y, por otro lado, comprobar si había datos publicados de simulacros de edificios de otros ámbitos no universitarios que aportaran la información suficiente como para poder aplicar el modelo planteado.

Referente a la parte matemática del modelo, específicamente en la parte estadística, se vio que con miras a mejorar el análisis y estudio de los datos de las evacuaciones, era muy interesante poder tener disponible la varianza de la relación de tiempos de evacuación frente a personas evacuadas en cada uno de los edificios usados para construir el modelo. En esta reflexión se pudo comprobar que incluyendo este parámetro, el planteamiento matemático era más adecuado además de proporcionar mejores resultados en la realización de la regresión estadística.

Concerniente a datos publicados de simulacros de evacuación de edificios de otros ámbitos, no universitarios, se encontraron cinco simulacros de un edificio dedicado a educación no universitaria de niños menores de edad ([Cuesta et al., 2017b]). Se pudo comprobar que los datos publicados y las condiciones en las que se realizaron los simulacros eran las mismas que las usadas por el modelo. Con esos datos se hicieron los cálculos pertinentes del modelo arrojando resultados muy prometedores que ayudaban a validar la propuesta del modelo, ya que encajaban perfectamente, tanto a la vista del ajuste estadístico, como la explicación cualitativa de la comparación de los resultados observados. Con este trabajo el modelo propuesto se consolida como herramienta muy interesante para comparación de simulacros de edificios que cumplan ciertas características de tamaño y de uso.

El trabajo realizado en esta contribución ha sido aceptado y publicado en Journal of Building Engineering, revista incluida en el JCR, de ámbito de la ingeniería civil y de las tecnologías de construcción y edificación clasificada como Q1 con un factor de impacto a 5 años de 5,146 en 2020, ver [Miñambres et al., 2022],

R.4.4 Uso de localización en interiores (IoT, XtremeLoc y otros elementos tecnológicos) que pueden facilitar recopilación de datos en el futuro

El estudio del comportamiento humano en incendios ha permitido el desarrollo de procedimientos de emergencia y también, como se ha comentado antes, se ha utilizado para modelar el movimiento de evacuación en simulaciones por computadora. Los datos de esos estudios provienen generalmente de los testimonios de personas que fueron recolectados después de la emergencia, y / o en ambientes experimentales controlados. Además, en los ambientes experimentales controlados realizados en los últimos años también se pueden estudiar grabaciones de vídeo. En el caso de los simulacros se realiza a menudo con observadores y con los testimonios de los propios participantes en el simulacro. El uso de testimonios y de observadores es de gran valor cualitativo, pero dejan la posibilidad de un gran margen de error para la recopilación de datos cuantitativos, a no ser que sean personas formadas con criterios unificados para rellenar los cuestionarios de observación, por medio de las reuniones de antes y después del simulacro como se ha realizado con los datos usados en esta tesis, como se ha descrito en el apartado de metodología. El uso de grabaciones de vídeo permite revisar con mayor objetividad los datos pero, se limita al punto de grabación (por lo general únicamente los lugares que se han previsto, no dando una visión general del conjunto). Para cuantificar los datos de número de personas y tiempos en videograbaciones, bien se ha de usar programas capaces de identificar a partir de la imágenes, esos parámetros de forma numérica, o bien se hace de forma manual, o bien se hace de forma combinada. Las tecnologías 4.0, en especial la localización indoor, pueden ser una herramienta muy útil para mejorar todo este proceso, obteniendo mejores datos. Con nuestro trabajo propusimos construir una nueva herramienta para recopilar datos individuales sobre el comportamiento humano en simulacros de evacuación. Los datos obtenidos de esta manera podrían ser utilizados tanto para tomar decisiones en tiempo real por los administradores de emergencias (como rescatar personas) como para realizar análisis en un momento posterior. Esto se realizó con un proyecto financiado por la Junta de Castilla y León, llamado PERIL (Prevention of Emergency Risk by Indoor Localization). Con el proyecto PERIL se comprobó que era factible realizar la localización, recopilar y almacenar la información que permitiera su posterior estudio. Además se podía observar en tiempo real. Este trabajo realizado fue aceptado y publicado en la XIX International Conference on Occupational Risk Prevention ORP2019 [Miñambres and Llanos, 2019]

Además es necesario realizar una propuesta de sistema de localización que sea técnicamente viable y económicamente asumible. Esto implica que la arquitectura del sistema con sus componentes y software ofrezca soluciones suficientemente adecuadas al problema que manejamos.

XtremeLoc es un sistema de localización indoor que es válido para hacer seguimiento de personas allí donde el GPS no es una solución viable bien por coste, o bien porque el sistema no es factible por diversos temas de la limitaciones tecnológicas de la señal GPS. Con este trabajo se describe la arquitectura y las características principales de XtremeLoc, cómo usarlo para encontrar personas y bienes, y su uso para registrar el comportamiento de personas individuales durante los simulacros de evacuación.

Este trabajo realizado fue aceptado y publicado en Proceedings of the International Conference on Localization and GNSS (ICL-GNSS 2020), Tampere, Finland, June 2nd to 4th, 2020. [Miñambres et al., 2020b]

XtremeLoc es una solución rentable para el seguimiento de personas y bienes. Sin embargo, ofrecía una precisión limitada, de alrededor de dos a tres metros. Esto se debía a que la distancia es calculada a través de la intensidad de la señal RSSI (Received Signal Strength Indicator) y esta se ve afectada por diferentes factores como son las atenuaciones debidas a la presencia de obstáculos, y también la orientación relativa de las balizas y antenas receptoras.

Por su naturaleza, el primer factor es difícil de manejar, aunque puede mitigarse mediante la recopilación de varias medidas consecutivas y el uso un filtro Kalman para reducir el ruido.

El segundo factor (el de la influencia de la orientación relativa de las antenas y balizas), se puede estudiar mejor a través de experimentos controlados. En esta etapa se estudió, a través de una experimentación empírica, los resultados del uso de dos conjuntos de diferentes Placas RPi (Placas Raspberry Pi modelos 3B y 3B +) para estimar las distancias a un conjunto de balizas Bluetooth ubicadas a distancias conocidas, con el objetivo es responder a diferentes preguntas necesarias para mejorar la localización:

(a) Cómo la orientación relativa de las Raspberry 3B afecta el valor RSSI asociado a una particular señal Bluetooth;

(b) Cómo la orientación relativa de las Raspberrys 3B + afecta el valor RSSI asociado a una señal Bluetooth en particular;

(c) Cómo la orientación relativa de las balizas afecta sus valores RSSI; y

(d) Si el modelo de propagación esperado de las señales de Bluetooth se correspondía con el experimental, resultados que se obtuvieron utilizando ambos modelos de Raspberry.

El resultado de nuestro experimento mostró un diferencia importante entre los modelos de RPi 3B y 3B+. El trabajo realizado en esta parte de contribución fue aceptado y publicado en las Jornadas Sarteco 2020/2021 [Miñambres et al., 2021].

R.5 Respuesta a la pregunta de investigación y conclusiones

La primera pregunta planteada era:

> En el contexto de los simulacros de evacuación, **¿es posible encontrar un modelo que permita comparar las evacuaciones de diferentes edificios de forma cuantitativa, obteniendo una predicción y posibilidad de advertir patrones de comportamiento?**

Con el trabajo de esta tesis se ha podido comprobar que sí, se pueden encontrar formas para comparar las evacuaciones de diferentes edificios de forma cuantitativa que nos permite la predicción y el estudio de patrones de comportamiento.

Desarrollo: Con esta tesis doctoral se ha encontrado una manera teórica y práctica de comparar los tiempos de evacuación de diferentes edificios teniendo en cuenta el número de personas evacuadas. De esta manera se puede comparar si los tiempos de evacuación son mejores o peores al tiempo esperado dadas las características del edificio evacuado y el histórico de datos disponibles hasta el momento. Se demuestra que el modelo es coherente tanto en su planteamiento teórico, como en la coherencia de los datos proporcionados por el modelo desde un punto de vista tanto cualitativo como cuantitativo, esto último teniendo en cuenta que la variabilidad de la conducta humana es muy grande y que además por las simplificaciones realizadas por el propio análisis dimensional y por valerse también de la estadística, no se puede pretender el 100 por 100 de exactitud. Se trata de un sistema sencillo en su aplicación y con gran aplicación práctica para las personas que deseen comparar los resultados de las evacuaciones del o de los edificios en que tengan interés, con los publicados en esta investigación. Para su aplicación no requiere de grandes inversiones. No obstante, la sencillez de su aplicación no quita la solidez del planteamiento del modelo, que ha tenido en cuenta diferentes campos de la ciencia para su formulación teórica.

La segunda pregunta que se había planteado era:

Dado un modelo ¿es posible mejorarlo e introducir un edificio de un ámbito afín pero fuera del ámbito donde se ha estudiado el modelo?

Con el trabajo de esta tesis se ha podido comprobar también que sí, se ha podido mejorar el modelo inicial depurando la parte estadística y se ha comprobado que el modelo se comporta de forma robusta al introducir un edificio de ámbito afin pero fuera del ámbito universitario, cuyos datos habían sido recogidos y publicados por otros autores. Se ha visto que el modelo seguía siendo válido tanto analizado de forma cualitativa como cuantitativa.

Desarrollo: Se ha comprobado que se podía mejorar la parte matemática del modelo ofreciendo mejores resultados en el análisis de regresion.

También se ha comprobado que funciona tanto con los edificios de ámbito universitario, teniendo estos diferentes funcionalidades (académicas, investigación, administrativas, biblioteca, residencial,...), como con otro edificio fuera del ámbito universitario pero con funcionalidad y características similares a los edificios de ámbito universitario estudiados, cuyos datos han sido recopilados y publicados por otros autores. Esto abre nuevos caminos para encontrar comparaciones entre edificios de otros ámbitos, es decir, si se pone a disposición de la comunidad científica los datos suficientes de los ejercicios de evacuación habituales de diferentes edificios de diferentes ámbitos.

Como tercera pregunta se planteaba lo siguiente:

¿Es posible obtener más información cuantitativa con tecnologías de posicionamiento / localización indoor con suficiente calidad y con bajo coste, para poder alimentar este u otros modelos de estudio de evacuaciones de diferentes edificios?

Con el trabajo de esta tesis doctoral se ha comprobado que se pueden usar tecnologías de localización indoor que permiten recopilar y almacenar la información en la nube, lo que a su vez permite su tratamiento y su posterior estudio. Se ha verificado usando la localización en simulacros reales y mejorando el uso de los componentes del sistema de localización de manera que permita una fiabilidad suficiente conservando un bajo coste.

Desarrollo: Con este trabajo presentado se ha mostrado que el sistema mostrado en el proyecto PERIL permite localizar a los individuos que porten las balizas durante las evacuaciones. En el proyecto PERIL se vio cómo se almacenaba la información de la evacuación en la nube para su posterior análisis, valiéndose del uso de XtremeLoc (solución IPS -Indoor Positioning System- empleada por PERIL), que a su vez ha permitido también mostrar las localizaciones en tiempo real. Además se ha podido mejorar la precisión del sistema en la localización gracias a la realización de un experimento controlado. El experimento ha estudiado el grado de comportamiento robusto de sus componentes frente a cambios de orientación para posiciones iguales.

Chapter 1

Introduction

Industrial Engineering is a branch of Engineering, created in Spain more than 150 years ago (1850). It is the most general engineering, with a multidisciplinary base, which combines very diverse technological knowledge, thus allowing the training of industrial engineering professionals to adapt to any business sector, in order to find the solution to the different problems that arise in technological, economic or management terms. Industrial Engineering (in Spain) deals with the optimization of the use of all available resources, whether human, technical or organizational, and the optimal handling and management of the transformation systems of goods and services.

Many areas of knowledge are involved in the study of emergency management and evacuations in buildings; areas of both a technical field and a field of knowledge of human behavior. These favorable circumstances mean that scientific research on these issues within the framework of Spanish industrial engineering can be very fruitful. Within this framework, this Ph.D. thesis proposes a new approach to the study of evacuations. With this proposal, a form of study is obtained that allows evacuations of different buildings to be compared and therefore provides a tool for continuous improvement in the results of evacuation drills. This Ph.D. thesis also offers a viable solution for collecting more evacuation data using indoor positioning technologies; a solution which is useful for the model proposed in the first part of the Ph.D. thesis and which could also be useful for other models.

1.1 Motivation

In 1997, Spain regulated the activity of the Occupational Risk Prevention Services. Within this regulation, occupational health and safety professionals were entrusted with advising the employer on the emergency measures to be adopted in their work centers. However, an emergency plan can be a more complex matter, more complex than simply setting out emergency measures for employees in a workplace. The drafting and implementation of emergency and evacuation plans requires knowledge that cuts across various fields of science and technology. Spanish regulations contemplate evacuations from various professional technical perspectives linked to the prevention of all kinds of risks, such as those due to the design of the construction itself (architecture, civil engineering, etc.), the installations of all kinds that the building requires, or the functionality of the building (for its use in the education of minors or special education centers, its residential use, mass events, other uses for which emergencies may affect the population in general and/or are subject to civil protection, etc.) and other related aspects. All of these perspectives are linked or can be linked to the professional field of Spanish industrial engineering.

Since 1997, due to my personal interests and my professional activity, I have been linked to and working on the evacuation and emergency plans for different buildings. I started writing emergency plans for the hydroelectric power plants of the Saltos de Duero. I continued writing emergency plans of several companies associated with Mutua Fraternidad - Muprespa, and later I wrote, implemented and kept updated the emergency plans of the University of Valladolid, which have been improved in a progressive process with the collaboration of different people belonging to various official authorities, companies and students of the university itself. The experience acquired during the more than 20 years that I have been working on the subject suggested to me that there were patterns of behavior in the different buildings, but that there were no tools to objectively express what could be glimpsed intuitively. This encouraged me to do some research and look for an approach to compare the evacuations of different buildings that could shed light on this question.

In my professional life, I have had a personal interest and motivation in the search for tools that allow the different fields covered by occupational risk prevention to be improved. Carrying out this search through research has been a constant in my life. I have published the results obtained whenever my personal circumstances have allowed me to dedicate the added time that the publications require. At the beginning of the 2000, I detected that, although the management system that the legislation proposed for the occupational risks was basically a system of continuous improvement, such as continuous improvement systems in the field of quality; this legislation did not say how to make and implement the management system, nor were there studies on the subject like there were in the field of quality. The occupational risk regulations had been published very quickly and profusely, understanding the need for speed, compared to the challenges that management entails to efficiently adapt to the new regulatory requirements, making them compatible with the management systems already in place. Therefore, transferring the tools widely used in quality systems to the field of occupational risk was a knowledge gap to be covered. In 2002, I applied one of the quality methods in production, QFD (Quality Function Deployment), to the field of occupational risk management, with interesting results that were published in [Gento et al., 2001] and [Miñambres et al., 2004]. For reasons unrelated to my investigation, I had to stop my exploration of this topic at that time. To date, the ISO or UNE standards have already published quality, environmental and occupational risk management systems that allow the efforts of each of these areas to be integrated and optimized.

Focusing again on the specific topic of emergency management, and the evacuation drills that are carried out in the buildings, these are a tool to improve the management of emergencies in the building itself. The improvement proposals are based on the analysis of the drills, foreseeing possible incidents and weak points and being able, where appropriate, to compare it with other drills conducted in the same building. Alternatively, the outcome of an evacuation drill could be compared to evacuation simulation using one of the multiple software packages that exist in the literature, which is a great effort in economic resources and time of the people who collect and enter all the information needed by the software.

The main nucleus of the literature on which the foundations of the modeling of the evacuation was established in the decades of the 1970s and 80s (we can see a very illustrative compilation

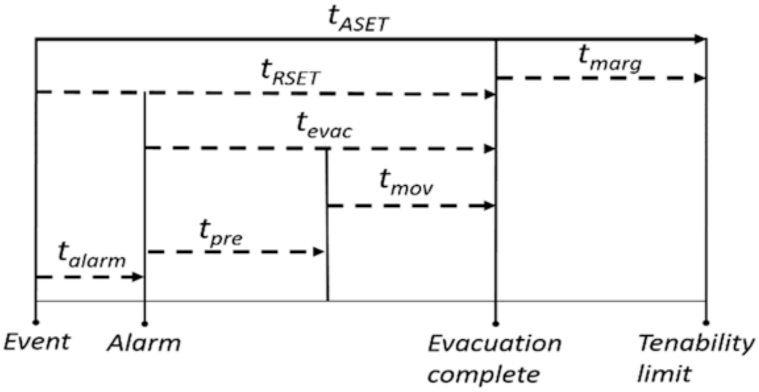

Figure 1.1: Egress time-line model by [Cuesta et al., 2015]

in [Cuesta et al., 2015]). This literature was the basis of what is called Fire Safety Engineering, whose main objective is to guarantee a suitable environment during the time needed by the people to evacuate. Within the study of the evacuations, several timings were defined, such as can be seen in the summary in the figure 1.1, obtained from [Cuesta et al., 2015].

As the figure very well illustrates, what was proposed is an analytical breakdown of the total time to consider when performing an evacuation. The time it takes to evacuate a building from the moment an event requiring evacuation occurs ($\mathrm{t_{RSET}}$ Required Safe Egress Time) is the sum of the following times: the time that elapses from the occurrence of the event until the evacuation alarm goes off ($\mathrm{t_{alarm}}$,this could also be subdivided and studied), plus the time from when the evacuation alarms go off until people start to evacuate ($\mathrm{t_{pre}}$,this time can also be subdivided and studied), plus the time to leave the building ($\mathrm{t_{mov}}$, again this time can also be broken down, and many factors must be taken into account in the study). The evacuation time ($\mathrm{t_{evac}}$) is the sum of $\mathrm{t_{pre}}$ plus $\mathrm{t_{mov}}$. This sum should be less than, the time available for a safe evacuation ($\mathrm{t_{ASET}}$ Available Safe Egress Time), the longer the margin time, the greater the safety ($\mathrm{t_{marg}}$). As equations, it would be the following:

$$t_{\mathrm{RSET}} = t_{\mathrm{alarm}} + t_{\mathrm{evac}} \tag{1.1}$$

$$t_{\mathrm{evac}} = t_{\mathrm{pre}} + t_{\mathrm{mov}} \tag{1.2}$$

$$t_{\mathrm{ASET}} = t_{\mathrm{RSET}} + t_{\mathrm{marg}} \tag{1.3}$$

$$t_{\mathrm{ASET}} > t_{\mathrm{RSET}} \tag{1.4}$$

The ISO/TR standard 16738:2009(en) Fire-safety engineering — Technical information on methods for evaluating the behavior and movement of people [ISO/TR16738:2009(en), 2009], contemplates several aspects of the calculation of these times. Other organizations, such the Society of Fire Protection Engineering [Hurley et al., 2015], also make various considerations for the calculations of these times.

On the one hand, human behavior influences the duration of all the times described in the previous paragraphs. Therefore, the duration of the times will be affected by any circumstance that can modify human behavior. A wide field of study opens up since it affects several questions including the psychology of individuals (including the perception and interpretation of the different information sources that may arise in the evacuation), cultural questions, physical issues of individuals, group behavior issues, and others. Studies on these aspects can be seen in various publications, such as in [Kuligowski, 2008], [Kuligowski, 2009], [Wang et al., 2021b], [Ding et al., 2021]).

On the other hand, as far as movement time is concerned, this is also affected by the physical issues of building design (distances to travel, possible bottlenecks,...). This last aspect was studied using fluid mechanics models, and it is an approach that is still part of current models ([Gwynne and Rosenbaum, 2016]). The equations were becoming more and more complex, and these models went on to be studied with the help of computer simulations. The first computer simulations were in the 1980s, proliferating in the 1990s and beyond ([Cuesta et al., 2015]).

There is a wide range of computer simulation models available for this purpose. For example, [Chunmiao et al., 2012] mentions that there are more than 22 models that simulate the evacuation processes and the movement of crowds, each with different variants; [Kuligowski, 2016] provides an overview of 26 models that simulate evacuations, each with its scope of application, and the paper provides a guide to carry out and verify other simulation models. Currently, simulation models tend to include new computational trends, for example [Jiang, 2019] uses AI and IoT, [Mohottige et al., 2020] uses wifi connections to detect evacuations, [Dong et al., 2019] recommends the use of Big Data for the validation of simulation models and to improve mathematical approaches. However, the application of advances in new technologies does not mean that they do not seek new theoretical approaches, such as those collected in [Ronchi et al., 2019].

Computer simulations have not only been used for evacuations, but also for other issues related to fire safety or to other types of emergencies. For example [Gao et al., 2020] uses a computational model to generate the optimal position of the doors to minimize evacuation distances; while [Arteaga and Park, 2020] develops a particular model to be applied in incidents with shooters firing. There are also proposals for use in real time, for example [Mirahadi and McCabe, 2020] or [Mirahadi and McCabe, 2021]. Other interesting proposals aim to validate models using virtual reality scenarios, where the behavior of people would be observed, as in the papers of [Wang et al., 2021a] or [Moussaïd et al., 2016].

It should not be forgotten that any simulation model used will be limited to the scope for which it was modeled, must hold to the hypotheses that have been made for the development of the model, and will inevitably have the limitations associated with predictive models [Cuesta et al., 2015]. These limitations and uncertainties can be extended to those models whose resolution is not necessarily implemented in the software.

However, no matter how much mathematical models and programmed software advance to solve such models, it is not possible to stop carrying out and using evacuation drills. The question that the various authors consider at this point are linked to the proper use of the realization of these drills. [Amos et al., 2019] or [Gwynne et al., 2020] comment on this issue.

To summarize, the purpose of the different software tools is to estimate how groups of people in a specific building may behave during an evacuation enabling different configurations to be made, which are very useful in this regard. However, they do not allow the possibility of comparing the actual evacuations of one building with respect to others.

The existing bibliography already raises this need for tools to compare behaviors. For example, [Haghani and Sarvi, 2018] conduct an extensive collection of experimental studies on the behavior of crowds in evacuations, concluding that there is a gap in the unification which allows comparison between them. The work of this Ph.D. thesis aims to begin to fill in that knowledge gap. What is specifically intended is to open up a new approach to find ways that allow comparisons between evacuations of different buildings.

Carrying out evacuation drills in buildings requires a great organizational effort from the entity that carries them out. Not all companies do it, and it is usually done only in those that are forced to do so by legal provision or by commitment to safety, for the simple reason that carrying out this activity implies the allocation of resources that have a cost. We start from the cost of the stoppage of productive activity during the entire duration of the drill until normal activity can be resumed. From this cost, others are added, such as: the added resources of organization and development of the drill, opportunity costs for stopping the activity at a certain moment, other costs for possible contingencies. If you want to collect quantifiable data that allow future studies, this supposes dedicating more resources to the drill and therefore to increasing the costs.

Obviously, carrying out evacuation drills has benefits, but these are more intangible. To make the results of a drill useful, all the employees must be involved, and it also implies involving all the occupants of the building. Likewise, in order to analyze the results of the drills, it is necessary to have well-organized extra resources. These resources must allow the collection of data that is later studied and analyzed in order to know the results of the drill with its proposals for improvement. To date, the resources used for the collection of information are either drill observers located in strategic places, duly instructed for observation, or video cameras equally conveniently located. For the first, the use of observers has the difficulty that there must be people suitably trained for this purpose. For the second, the use of image recording elements (video cameras) requires the necessary authorizations, in order to comply with the provisions of the regulations of each country;

in addition to the fact that, later, the recordings have to be conveniently studied to collect the information. There is also another option that is to ask, through a questionnaire, all or part of the people evacuated to give their testimony. The use of testimonials and observers has great qualitative value, but leaves the possibility of an undesirable margin of error for the collection of quantitative data, especially when the information is given by the evacuees themselves.

However, the use of new technologies, such as indoor positioning, IoT, the cloud, etc., open up new possibilities for automatically collecting quantitative data, also applicable to the field of evacuations.

1.2 Objectives of this dissertation

It has been mentioned, in the motivation of this Ph.D. thesis (1.1), that several authors, such as [Amos et al., 2019] or [Gwynne et al., 2020], raise different questions related to the evacuation drills themselves, among others, that there is no global consensus on how develop them.

However, what all the drills have in common is that, when they are carried out, the first question that people ask is "How long has it taken to evacuate the building?", and then they ask, "How many people have been evacuated?". They then begin to ask other qualitative questions that may influence the quantifiable data mentioned above. The qualitative information corresponds to the incidents within the evacuation and other data of interest that are reflected in the written reports made with a view to improving future drills in the same building.

It has also been said in the motivation of this Ph.D. thesis, that there is a gap in the study of evacuations as comparisons between different buildings has not been possible. This Ph.D. thesis aims to open a new approach to find ways that would allow such comparisons, starting with buildings of similar characteristics or scopes that would be comparable. This new approach is based on quantitative data, although it uses qualitative data of the behavior of the people observed in the drills to verify that the results obtained are consistent. However, this Ph.D. thesis does not intend to justify or propose underlying models of behavior from a sociological, psychological or any other social science point of view related to the evacuations of buildings.

Evacuation drill comparisons among different buildings can be used as an indicator for drill analysis and can be used as an improvement tool. If a comparison system is achieved that does not involve a great effort to obtain the necessary data and perform the calculations, then it could become a very useful tool for improving the results of evacuation drills, and therefore of the safety of people in possible emergency situations in buildings.

On the other hand, it would be very convenient to have more up-to-date evacuation data in order to continue advancing in the study of evacuations either as drills, or the emergencies themselves. If, in addition, the collection of real evacuation data could be obtained automatically, it would represent an advance for research in this field.

This Ph.D. thesis also aims to propose a system / tool to obtain evacuation data from drills using low-cost indoor location technologies. The system aims to save the positions in the cloud to avoid loss of information, facilitating their subsequent study. In this way, the advantages offered by 4.0 technologies can be applied to the study and improvement of evacuations and therefore of emergency management.

1.2.1 Research questions

In the context of evacuation drills, the first question is:

Is it possible to find a model that allows evacuations of different buildings to be compared quantitatively, obtaining a prediction and possibility of noticing behavior patterns?

The second question that arises is:

Given a model, is it possible to improve it and introduce a building from a related field but outside the field where the model has been studied?

The question immediately subsequent to this and the third question of this thesis arises from what has been seen to be one of the main difficulties in research in this field, which is to collect enough data of sufficient quality when conducting evacuations:

Is it possible to obtain more quantitative information with indoor positioning system (IPS) / indoor localization technologies and with sufficient quality at low cost to be able to feed this or other evacuation study models from different buildings?

1.2.2 Milestones

In order to answer these research questions, we need to carry out some specific objectives.

First objective: Accumulate sufficient data from evacuation drills carried out in different buildings.

It has been mentioned in the motivation of this Ph.D. thesis that the performance of drills carries a significant organizational cost. It involves stopping the functionality of the building during its execution, and the organization of resources that allow the collection of the necessary quantitative and qualitative data for analysis. This organizational effort means that drills are not always carried out with the total evacuations of buildings, or when they are carried out, the necessary resources are not available to provide all the necessary aspects to carry out a methodical and systematic analysis that allow deeper studies. Furthermore, drills are carried out by companies to comply with the minimum legally requirements and so its employees know what to do in an emergency, and not to collect data in such a way that would allow scientific research in this field. This means that there are hardly any scientific publications with sufficient data from evacuation drills. Obtaining data from a minimum number of buildings that share the same area, with a minimum number of drills, is an achievement because it implies the methodical work of many years of dedication.

Second objective: From the quantitative data obtained in the first goal, propose a method that allows the evacuations of the different buildings to be compared, obtaining a prediction to prove that the method is sufficiently valid with the quantitative and qualitative data of the available buildings.

This second objective has required a new approach from what was in the evacuation literature; and for this, in this objective, different concepts have been used. Concepts that are firmly rooted in the field of engineering, but which had not yet been applied to the field of evacuation studies.

Third objective: Once the method mentioned in the second objective has been completed, it must be reviewed and debugged, and a search must be made for other building evacuation drill data from other authors to check whether or not it can be incorporated into the model already debugged.

Naturally, the third objective is linked to the refinement of the model, and its consolidation with data independent of those obtained during the development of the initially proposed model.

Fourth objective: Propose an automated system to collect quantitative information in the drills, about what goes on inside buildings using indoor location technologies, that are affordable economically but at the same time provide sufficient data quality to feed building evacuation models.

The new technologies are there to help the advancement of science and inevitably the study of evacuations is a field that can be enriched with Indoor Positioning Systems for automatic data collection.

1.3 Research methodology

The research methodology of this Ph.D. thesis has followed the classic steps of observation, hypothesis formulation, testing, rethinking and refinement for improvement and check again.

This Ph.D. thesis is framed within the field of industrial engineering so, by its nature, touches on issues from many areas of knowledge, consequently being quite transversal. This has led to the use of various methods.

The part of the Ph.D. thesis aimed at finding a way to compare the times of evacuation of different buildings, taking into account the number of people evacuated and the different characteristics of the buildings, has required the collection of both qualitative and quantitative data. The data comes from the observation of real cases of evacuation drills. The observation of data has been done with people previously trained for this purpose. The observers have been mostly university students doing internships linked to a subject closely related to emergencies and evacuations. Previous training was required to participate as observers that enabled them to collect unbiased behavioral observation information of the evacuated occupants, considered as a group. Immediately before every drill, a meeting was held with all the observers, in order to make sure they knew what to do and where to be, how to avoid interfering with the evacuation, and how to write down the times so that everyone had the same criteria. Each observer participated in at least two or more drills. The minimum number of observers for each drill was given as a function of the size and characteristics of the building to be evacuated. All observers filled out a questionnaire with the same basic questions which were essentially the same in all the exercises observed. Immediately after the end of the drill, a meeting was held in the same center with all the observers. Everything observed was shared (times, behaviors, etc.) in this meeting, any doubts about the interpretation of the questionnaire were clarified, in case there were any, and observation questionnaires, filled in by the observers, were also collected. In the hours that followed, information pertaining to the time taken to evacuate the building and the number of people who had left was sent by email. The e-mail was sent to those responsible for the center with the request that they communicate it to all the personnel of the center where the drill had been carried out. The report of the results of the drill, with the qualitative analysis of improvable issues as well as issues that had been done well, was sent to the Deans, Center Directors, prevention delegates (union representatives of workers on health and safety issues), and to the rest of the members of the Health and Safety Committee of the UVa, in addition to remaining at the disposal of the labor authority if requested. This process was carried out in each and every one of the 47 evacuation drills of university buildings included in this doctoral thesis.

From these data, methodologically observed and collected over the years, we have been able to build a model using knowledge from different fields of science.

In this Ph.D. thesis, a systemic model has been proposed for the study of evacuations. A systemic model has been considered because this type of model does not focus exclusively on the analytical study of the different parts into which the system can be decomposed, but it proceeds with the study of the system and the relationships between its component elements, namely, it is mainly based on the understanding that systems have properties other than the simple sum of their components. System definitions are still evolving, however, one that is quite clarifying is the one by [Ogata, 1997] that says:

> *A system is a combination of components that act together and perform a certain objective. A system is not limited to physical ones. The concept of the system can be applied*

> *to abstract, dynamic phenomena such as those encountered in economics. The word system should, therefore, be interpreted to imply physical, biological, economic, and the like, systems.*

From the understanding of the various elements that can be differentiated in an evacuation, it has been possible to propose two main blocks. On the one hand, the influence of aspects linked to the design and dimensions of the building itself where the evacuation takes place. This parameter block would act as an independent variable in regard to the second block. On the other hand, we have the second block concerning the influence of aspects linked to human factors that are not part of the building but which can be measured in numerical quantities with current means. Namely, the time it takes to evacuate a number of people from the buildings. In other words, the second block would be composed of the time to evacuate, and the number of people evacuated and it acts as a dependent variable of the first block (building characteristics). This reasoning is quite straightforward, since the design and dimensions of a building affect its evacuation times. Nevertheless how people behave in an evacuation does not affect how the building was designed or its dimensions, at least not directly, because it requires other actions deferred in time to change how a certain building is designed and its dimensions. So, if you have these data, a statistical study could be proposed through a regression analysis; so it would help to understand how the value of the dependent variable (relationship evacuation time / number of people evacuated) varies by changing the value of the block of independent variables (characterization of the building).

The key to the problem is to get a value that can function as the independent variable and that is representative of each building. A dimensional analysis has been used for this purpose. This is a tool that allows the simplification of the study of any phenomenon in which many physical quantities are involved in the form of independent variables, as occurs in the evacuation of the building. As will be explained during development of the Ph.D. thesis, the different design features of buildings that intervene most decidedly in the evacuation are independent of each other; for example, the number of exits to the outside and the width of these is independent of the number of exits that each floor has towards the stairs, and both can be bottlenecks and delay an evacuation, both also being parts of the design of the building.

Summarizing, a systemic model has been proposed to treat the quantitative data using:

- A dimensional analysis of the part linked to the design of the buildings; and
- A statistical analysis of the part linked to the human behavior during the building evacuation, bearing in mind that the characterization of the building by dimensional analysis is the independent variable of the system.

The qualitative data have been used to validate the consistency of the results of the quantitative data provided by the model.

The other contribution worth noting for the advancement of research in the field of evacuations contributed by this doctoral thesis is that aimed at facilitating the collection of quantitative information in the evacuations. For this, the use of an automated system for gathering quantitative information in the drills is proposed. This part of the Ph.D. thesis is a part with a strong technological component. For this purpose, the research methodology defined by [Adrion, 1993] is used. It adapts the specific stages of the classical scientific hypothetical-deductive method to Computer Science. Thus, the software engineering method is composed of four stages that may be repeated, or not, depending on the results achieved. The phases are:

(a) Observe existing solutions,
(b) Propose better solutions,
(c) Build or develop them, and
(d) Measure and analyze the results.

1.4 Document structure

This document is organized as follows. Chapter 2 presents and analyzes the historical data of 47 evacuation drills in 15 different university buildings, both academic and residential, involving more than 19 000 people. We propose the study of the data presented using a dimensionless analysis and statistical regression in order to give a prediction of the ratio between the exit time and the number of people evacuated. In Chapter 3, we propose a refinement of the method to calculate the expected exit times of the previous chapter, which leads to an even better adjustment between predictions and real-world results. We then use this refined model to predict the results of evacuations of a new building, whose use and characteristics are different from those previously studied, and whose data were provided by other authors in the bibliography. Chapter 4 offers a solution to take advantage of the possibilities of indoor positioning technologies and the use of the cloud, applying their advantages in data collection for the study of evacuation drills. Finally, Chapter 5 concludes this Ph.D. thesis, enumerating its contributions, the resulting publications, and some possible ways of continuing this work.

Chapter 2

Towards a model for comparing evacuation drills of different buildings

The time needed to evacuate a building depends on many factors. Some are related to people's behavior, while others are related to the physical characteristics of the building. This chapter analyzes the historical data of 47 evacuation drills in 15 different university buildings, both academic and residential, involving more than 19 000 persons. We propose the study of the data presented using a dimensionless analysis and statistical regression in order to give a prediction of the ratio between exit time and the number of people evacuated. The results obtained show that this approach could be a useful tool for comparing buildings of this type, and that it represents a promising research topic which can also be extended to other types of buildings.

2.1 Introduction

To implement the evacuation of an entire facility requires a great organizational effort, where all the staff is involved. It is crucial to be very careful so as to avoid generating confusion or demotivation among staff or public. In addition, it is not always possible to have enough resources to gather all the data that is desirable. When several evacuation drills have been carried out in a building, safety and security staff usually compare results, but these results are not often comparable to results from other buildings.

This chapter analyzes the historical results of 47 evacuation drills in 15 different university buildings, both academic and residential, involving more than 19 000 persons. We propose the study of the data using a dimensionless analysis and statistical regression in order to give a prediction of the time ratio between exit time and the number of people evacuated. As far as we know, our approach has not been used before in the field of evacuation drills.

The time used in the study is time elapsed from the evacuation alarm to the end of the evacuation. This time, that we call *exit time*, is be the sum of the pre-evacuation time (that is, the time elapsed from the moment when the alarm sounds and when the occupants decide to start the evacuation) plus the movement time.

With the help of the data related to the characteristics of the evacuated buildings, we have calculated a dimensionless parameter associated to each building, that we call the *Characterization of building evacuation (CBE)*.

Given the CBE for a particular building and the number of people occupying it, we are able to calculate an estimated exit time. Comparing this estimated exit time with the real values obtained in evacuation drills, more informed decisions on whether to invest in more training and/or preventive culture of the occupants or to invest in structural improvements of the buildings can be taken.

To build this study, we have analyzed the historical information collected by the University of Valladolid over the last decade from a total of 47 evacuation drills of 15 university buildings, both academic and residential, involving 19 198 occupants and 688 external observers. Most of this information has been used to build the study introduced in this work, while the remaining evacuation drills have been used to validate the obtained results.

We are aware that this study cannot be used directly to compare buildings of other types. Instead, we see this approach as a promising method to compare exit times of buildings that share the same or similar characteristics.

The chapter is organized as follows:

Section 2.2 discusses some related work. Section 2.3 describes the techniques used and the fundamentals our model is based upon. Section 2.4 presents both the structural characteristics of the buildings used to feed the study, and the results of the evacuation drills conducted in them. Section 2.5 shows the details of our study, including the definition of the Characterization of Building Evacuation (CBE), the regression formula obtained from the evacuation drills conducted, and the associated formula for the estimated exit time, $\widehat{Te}$. Section 2.6 compares and discusses the differences between the average exit time obtained in evacuation drills for each of the buildings considered, and the value for $\widehat{\mathrm{Te}}$ returned by the model. Section 2.7 applies the model to a different set of buildings and discusses the results. Finally, Sect. 2.8 concludes our work in this chapter.

2.2 Related work

Published work on different mathematical models of behavior in different emergency situations has increased enormously in recent years. Emergency situations include fire, e.g., [Purser, 2003], terrorist attacks [Li et al., 2017], natural disasters [Serulle and Cirillo, 2017], specific behaviors such as evacuation processes in areas with internal obstacles [Guo et al., 2011], etc.

Regarding the field of human behavior in fire, Kuligowski [Kuligowski, 2015] gathered all the available data, studies and research at that moment, including evacuation dynamics, timing for certain aspects of building evacuations, analysis of the characteristic movements of vulnerable population, and modelling of evacuation movements. More recently, Ronchi et al. [Ronchi et al., 2019] summarized recent findings in the field of fire evacuation modelling of different topics within research disciplines outside fire safety engineering, including Applied Mathematics, and Dynamic Simulation and Biomechanics, aiming to study the feasibility of development and application of modelling methods based on these fields and to discuss their implementation strengths and limitations

Related work also includes results regarding different surroundings:

- Evacuation of buildings of various sizes, from skyscrapers to multi-story office buildings and others, e.g. [Purser and Bensilum, 2001];
- Evacuation of public buildings such as train stations or underground, for example the work by [Haghani and Sarvi, 2017];
- Evacuation of tunnels [Capote et al., 2013, Alvear et al., 2013], etc.

In most of them, where behavior is modelled to predict evacuation time [Tavares, 2009], they use algorithms that require the layout of escape routes in buildings, together with models that can be continuous or discretized in a grid [Li and Han, 2015]. However, as [Lovreglio et al., 2014] pointed out, many of these models are based on the comparison of a single experimental data-set with simulation results. The associated algorithms contain complex methods of calculation for assessing crowd flow, based on equations. Essentially, this consists of calculating the number of people in a specific area, in order to obtain the density, then deriving the speed and flow rate of the crowd. Algorithms, also take into account merging traffic flows, and the resulting changes in density and flow rate. Initially, these tedious calculations were carried out manually, as for example with Predtechenskii and Milinskii equations (as appear in [Hurley et al., 2015]) where the building is segmented into a network of discrete areas, linked with doorway 'nodes' of specific widths. [Haghani and Sarvi, 2018] developed an extensive compilation of all empirical studies carried out to date, both with people and animals, concluding that there is a lack of unification to allow studies to be comparable and reproducible.

In this work, we present the information on evacuation drills conducted by the University of Valladolid during the last decade in different university buildings, both academic and residential, together with the buildings' main characteristics. We also propose the study of the data using a dimensionless analysis and statistical regression in order to give an expected value of the ratio between exit time and the number of people evacuated. We are aware that our procedure for estimating the evacuation time is simpler than other well-established methods described above. However, the main advantage of our proposal is that it facilitates the comparison between the evacuations of different buildings with a method that requires some simple calculations that can be carried out without a great investment

2.3 Our proposal

Holistic view of evacuation drills

In Chapter 1, we have seen how Fire Safety Engineering has raised the problem of evacuations. The approach was analytical, dividing the problem of calculating the evacuation time into parts and studying each of those parts. They approached the division of the parts as the division of the periods of time that they could differentiate and study (time-line model). However, they were aware that, due to the very nature of the problem, which involved the study of human behavior; there are aspects that interact with each other, cross-affecting the parts studied, which causes distortions between the model and the complexity of reality. Computational models aim to solve the equations that model the mentioned interactions. Nevertheless, to date, some of the behaviors that may occur are not completely understood and there is no agreement on the theories to be used to explain certain phenomena ([Cuesta et al., 2015]).

This doctoral thesis proposes a different approach to the study of building evacuations. This approach will allow an estimation of evacuation times based from historical data from building evacuations, in addition to allowing the comparison of evacuations between different buildings.

The idea is to consider the evacuation of a building as a system that is made up of parts that interact with each other in a varied, complex way, and where knowledge from different fields of

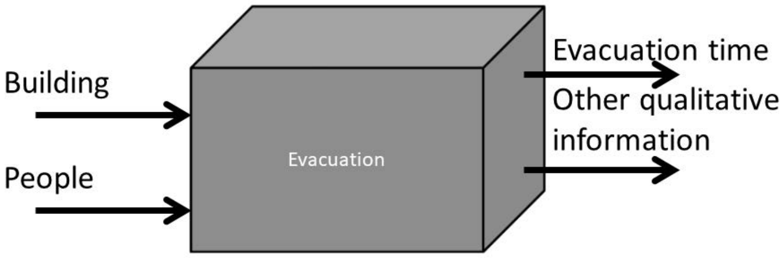

Figure 2.1: Evacuation as a black box

science is needed to understand the interactions. What we want to know about the system is the time to evacuate. This will be the system output.The system would be composed of two main parts. On one side, the building to be evacuated. This building will be defined by a series of physical characteristics that can influence the evacuation. On the other hand, the people to be evacuated. And Here, a quantitative aspect will be differentiated, which is the number of people, and a qualitative aspect, which are a series of physical, psychological, cultural, social characteristics, etc., that can influence people's behavior.

In this way, we focus our attention on the system and its properties rather than the properties of the timeline parts as traditional fire safety engineering studies do. In short, we are applying the approach used generically in general systems theory and we could represent our system as in figure 2.1

The concept of systems was formally introduced in the second decade of the twentieth century in biology by von Bertalanffy (1924), and the concept has been widely applied, either implicitly or explicitly in the entire spectrum of technology and science, be it natural or social ([Forrest et al., 2018]). Since von Bertalanffy raised his ideas until today, the research directions in General Systems Theory have been diverse and prolific, as we can find in [Lin, 2006] and in [Forrest et al., 2018]. The study of systems for their control is a main objective of control and automation engineering ([Ogata, 1980], [Ogata, 1995]). However, the purpose of this thesis only reaches the study of the open-loop system and simply gives some suggestions about the feedback of the system for its future control.

Characterization of buildings through dimensional analysis, regression analysis and its application with dimensional analysis

Dimensional analysis is a method for reducing complex physical problems to their simplest (most economical) forms prior to quantitative analysis or experimental investigation. Dimensional analysis has been used in different science areas, in some of them for a long time [Macagno, 1971]: Chemistry, mathematics, physics (electricity and magnetism, sound, fluid mechanics, etc.), and, more recently, in economics. The Vaschy-Buckingham π theorem, first described in [Vaschy, 1892, Buckingham, 1914] provides a method for calculating sets of dimensionless parameters from the given variables, even if the shape of the equation is still unknown and the choice of dimensionless parameters is not unique. It is necessary that the choice of variables has a physical meaning.

Regression analysis is a conceptually simple method for investigating functional relationships among variables, dependent (target) and independent (predictor) variable(s) . There are several methods of regression analysis and it is still an area of active research. These predictive modeling techniques have numerous areas of application, such as business, economics, education, engineering, finance, medicine, meteorology, psychology, sociology, etc.

Dimensional analysis and regression analysis have not been used together in evacuation studies but they have been used together in other areas. [Vignaux and Scott, 1999] show that, with dimensional analysis, factors without dimension can be used as variables of the regression. As a result, fewer values than the originals are obtained, often offering a more appropriate interpretation. They showed practical examples in the area of mechanical engineering. Other practical examples can be found in the work by Shen *et al.* [Shen et al., 2014]. The model proposed in this Ph.D. thesis has the same benefits and limitations introduced in the work of [Vignaux and Scott, 1999].

The aim of this chapter is to analyze the historical results of many evacuation drills in several different university buildings, both academic and residential. Using this data, we carry out a study that estimates the exit time that can be expected from a particular building, based on both the architectural characteristics of the building and the data collected from previous evacuation drills of this building and others of the same type.

According to [Cuesta et al., 2017a], exit time is influenced by: The layout and distance to be travelled by people; bottleneck points; added times relative to different circumstances and choices; and speed of movement of the people.

We consider "exit time" to be the interval between the moment the sirens start to sound until the moment when no more people come out of the building, the moment that consider to be the end of the evacuation. This interval includes pre-evacuation and movement times.

In order to manage the characteristics of the buildings, we propose the use of a coefficient called "Characterization of Building Evacuations" (CBE). This value is obtained with the help of a formula that depends on a reduced number of measurable parameters of the building. This formula substitutes the need for both a mathematical modelling of all possible routes of evacuation of a building, and a computer simulation of the equations of human behavior based on the planned routes. Our idea was inspired by dimensional analysis, where, instead of solving complex equations, calculations are simplified thanks to the use of previously calculated, dimensionless numbers. For example, in fluid mechanics, these coefficients are calculated for different fluids, in different modes of behavior, and working in a laminar or turbulent regime. As long as it is not proven that variables of human behavior can be considered in the same way as physical magnitudes, the π theorem of Vaschy-Buckingham [Vaschy, 1892, Buckingham, 1914] cannot be applied directly to find the equation that models the behavior of people in the evacuation, which is the product of a regression analysis [Vignaux and Scott, 1999].

As will be seen later, the CBE will be the independent variable that will allow calculating the relationship between people evacuated in the evacuation time, which will be the dependent variable. This estimated relationship can be compared with the real numbers obtained in evacuation drills.

Our dimensionless number considers the following points:

- The distance to be travelled by people. It depends on the design of the building: In general, the bigger the surface, the bigger the average distance to be travelled and the greater the evacuation difficulty. We are aware that, for the same surface, the distance is also affected by other circumstances, such as number of exits, number of floors, number of staircases, or different surface geometries.
- Number of exits: The fewer the number of exits, the greater the possibility of delays and the greater the evacuation difficulty.
- Width of exits: The smaller the width of the exits, the greater the possibility of delays and the greater the evacuation difficulty.
- Points of exit from each floor to the staircases: The higher the number of floors, the greater the possibility of conglomerations at the exits or in the floors and the longer the delays, making the evacuation more difficult. Besides this, the fewer the number of staircases leading to these floors, the greater the possibility of slowing down the evacuation and the greater the evacuation difficulty.

In the following sections, each building is characterized through: Surface area, number of floors, number of staircases, number of exits, and width of the exits. Other parameters could be considered as well, such as staircase widths (that must have a minimum width in accordance with the Spanish regulations of health and safety at work).

Our analysis stopped at this point because we have found that the use of the chosen parameters allows the of a formula that fits very well with the experimental data, as we will see in the following sections.

It is necessary to keep in mind that the aim of this study is not to yield 100% accurate results, but to offer a useful tool to help companies and organizations to know what to expect from the exit times and where they should prioritize their interventions, either by reducing the difficulty of evacuating a building or by training and sensitizing the employees/occupants of the building.

Besides this, the proposed formula for the dimensionless number has been derived from data related to university buildings with the characteristics that are described in this chapter. Future works should check if this formula is valid for the same type of buildings in non-university contexts. We think that it could be suitable as long as most of people in those contexts do not have physical, psychic or social impediments that limit their ability to evacuate, as it happens in university buildings. In the same way, it would be necessary to test if this dimensionless number formula is valid for another type of buildings with different physical characteristics (for example, with greater surface, many more floors, etc.). Chapter 3 will deal with these questions. We believe that this approach is an interesting path in better understand the relationship between building characteristics and exit times.

2.4 Data collection

The University of Valladolid have several buildings in four cities with different sizes, uses and characteristics. Evacuation drills are held periodically as part as of the routine of the university. The drills have been designed for the training of the staff and users, as well as to detect possible problems in the evacuation or detection of emergencies. The process of conducting the drills includes the collection of data and the completion of a report. This report includes exit times, the observers who have participated and where they are located, events and issues to improve. Reports are sent to leaders and unions. In addition, exit times are sent to Deans, Directors and to every employee in the building in the following hours of the drill. These data of evacuation and exit times are those that have been used to perform the present study. The observers were mostly university students who did practical exercises of their university studies with subjects related to emergencies and evacuations.

This study analyzes the historical data of evacuation drills at the University of Valladolid. No evacuation drill has been specifically conducted to carry out this study. A total of 688 persons observed 646 points in 47 drills, with a total of 19 198 people evacuated in these drills. Every volunteer has been an observer in two or more evacuation drills. Observers were trained for their task in order to collect impartial observations of the behavior of the evacuated occupants considered as a group. The qualitative information collected in the questionnaires and in the post-drill meetings has been used to validated the coherence of the data results of the model, as explained in Sect. 2.6. Just before each drill, a meeting was held with all the observers to make sure they knew what and where to do, and how not to interfere with the evacuation.

In each drill, observers are placed at the exits of a building, at the meeting point outside the building, always in places that do not interfere with the development of the evacuation. The observers are provided with questionnaires where they can record the behavior of people in the evacuation, incidents, comments, and observations, as well as the timestamp of each of the possible milestones in the evacuation (when the first/last evacuated person passes through a certain point, etc.). The start time (activation of the evacuation sirens) is used to calibrate the rest of the timestamps collected by each observer. After the drill, the observers attend a second meeting, together with maintenance personnel of the building, to collect together the issues observed, as well as possible incidents during the course of the evacuation.

The historical data available have been divided into two sets. In order to carry out this study, we have used the data of 44 evacuation drills from 12 different buildings. There are between two and five drills from each of the buildings considered. The more evacuation drills from the same building, the less uncertainty concerning human behavior [Lovreglio et al., 2014] and the more representative the results. However, the organizational costs of an evacuation drill are high, so it is not feasible to organize additional evacuation drills to have more data available. The results of the model obtained were then used to analyze individual drills of three additional buildings (as will be seen in Sect. 2.7).

At every evacuation drill, the exit time and the number of people evacuated were measured. Regarding time, we measured the time needed to perform the evacuation, considered from the start of the sirens until the evacuation is considered finished, as well as other intermediate times in order to check the process. The time was recorded in whole minutes, having weighed up the pros and cons of recording the data in seconds. Minutes were chosen over seconds because of the problems of getting observers to record exact times in seconds, mostly due to the need to write the data while continuing with the observation, and the problem of exact calibration of clocks.

Regarding the approximate number of people who have evacuated the building (Np), this number is the sum of all the estimations of people leaving the building using each one of the exits towards the outside, as collected visually by the observers. The figures offered in our measurements are rounded in most cases because the measures are not 100% reliable, due to the fact that observers could pay attention to other qualitative information at that moment. In quantities below 100 persons, the count is more accurate

To build the CBE formula, we have used the following building parameters:

- The average number of exits per floor that can be used as evacuation exits (Ea).
- The sum of the widths of the exits towards the outside of the building (Me).
- Number of different staircases that can be used as evacuation paths (St).
- Number of floors that are usually occupied (F). The floors occupied occasionally for maintenance issues are not included, such as the rooftop of the building if it is only accessed for maintenance operations, or the basement if there are only technical rooms exclusively for maintenance operations.
- Total surface of the parts of the building usually occupied (Sf). In the case of discrepancies among building projects, building maps, and legal registers, the latter are used.

It is interesting to note that the Spanish regulations establish a maximum Theoretical Occupancy (TO) for a given building, taking into account its surface and the type of use for the building. This information is relevant in our case, because the length and width of the evacuation routes are calculated by designers according to the maximum theoretical occupancy allowed. It is also important to note that all the buildings meet at least the minimum safety conditions stated by the EU regulations with respect to emergencies in workplaces, including evacuation signage. The values of TO for each building considered are depicted in Tab. 2.1 Comparing the occupation of the evacuation day (Np) with the Theoretical Occupancy (TO), it can be determined whether the building had high occupation during that day. This, in turn, serves as an indicator of whether the routes might be saturated, and whether the people in the evacuation drill might have felt pressure or stress to evacuate the building. It is also important to note that all the buildings meet at least the minimum safety conditions stated by the EU regulations with respect to emergencies in workplaces, including evacuation signage.

In summary, our model is valid for buildings similar to those considered in our study, that is: Buildings that accomplish EU regulations for buildings with respect to safety in workplaces; buildings of similar sizes to the ones used in our study, both in terms of building surface and number of floors; and buildings with similar uses, that is, we do not consider industrial working places.

Table 2.1 summarizes all the data used for this study, gathered as described above. This table shows the data for buildings with two or more evacuation procedures used to derive the model.

2.5 The study

Based on the aforementioned parameters and how we believe they influence the difficulty of evacuation, we propose the following formula for CBE:

$$CBE = \frac{\sqrt{Sf}}{Me} * \frac{F}{Ea} \tag{2.1}$$

where Sf is the surface of the building, Me is the sum of the widths of the building exits in meters, F is the number of usually occupied floors (as described in the previous section), and Ea is the average number of exits per floor, including floor exits towards the staircases and floor exits towards the outside.

Building	Building characterization parameters						Values measured in each evacuation drill	
Drill	**Sf**	**F**	**St**	**E**	**Me**	**TO**	**Np**	**Te**
EII-SPC 2013-11	14 683	4	3	3	10	3 494	700	9
EII-SPC 2015-10	14 683	4	3	3	10	3 494	700	9
EII-SPC 2016-11	14 683	4	3	3	10	3 494	700	9
EII-SPC 2017-11	14 683	4	3	3	10	3 494	800	7
EII-SPC 2018-11	14 683	4	3	3	10	3 494	500	9
EII-SFM 2015-05	13 185	6	6	4	6.8	3 021	500	5
EII-SFM 2016-03	13 185	6	6	4	6.8	3 021	500	6
EII-SFM 2017-03	13 185	6	6	4	6.8	3 021	800	5
EII-SFM 2018-05	13 185	6	6	4	6.8	3 021	350	4
FC 2013-04	15 107	4	6	4	8.1	1 470	175	9
FC 2016-11	15 107	4	6	4	8.1	1 470	175	8
FC 2017-11	15 107	4	6	4	8.1	1 470	200	6
FC 2018-11	15 107	4	6	4	8.1	1 470	180	5
AFC 2013-04	11 166	4	7	7	11.23	3 131	225	8
AFC 2016-11	11 166	4	7	7	11.23	3 131	600	9
AFC 2017-11	11 166	4	7	7	11.23	3 131	900	5
AFC 2018-11	11 166	4	7	7	11.23	3 131	900	6
ETIC 2010-03	21 009	3	5	8	14.4	3 169	700	6
ETIC 2011-04	21 009	3	5	8	14.4	3 169	700	10
ETIC 2016-03	21 009	3	5	8	14.4	3 169	700	7
ETIC 2017-03	21 009	3	5	8	14.4	3 169	700	6
ETIC 2018-05	21 009	3	5	8	14.4	3 169	500	6
FFIA 2015-05	21 709	6	6	5	25	3 029	1 000	9
FFIA 2015-11	21 709	6	6	5	25	3 029	1 000	12
FFIA 2017-05	21 709	6	6	5	25	3 029	500	6
FFIA 2018-05	21 709	6	6	5	25	3 029	1 000	7
AVIII 2010	22 726	9	4	10	14	3 269	200	8
AVIII 2015-05	22 726	9	4	10	14	3 269	130	7
AVIII 2015-10	22 726	9	4	10	14	3 269	130	10
AVIII 2017-11	22 726	9	4	10	14	3 269	150	12
AVIII 2018-11	22 726	9	4	10	14	3 269	300	8
CMSCF 2016-05	6 514	8	3	4	3.4	145	15	8
CMSCF 2016-11	6 514	8	3	4	3.4	145	50	6
CMSCF 2017-11	6 514	8	3	4	3.4	145	55	4
CMSCF 2018-11	6 514	8	3	4	3.4	145	40	5
BRS 2013-04	2 155	2	1	2	2.01	362	80	4
BRS 2014	2 155	2	1	2	2.01	362	80	4
ETSA 2016-03	13 605	5	8	4	14.8	2 615	350	5
ETSA 2018-05	13 605	5	8	4	14.8	2 615	250	5
CMSCM 2017-05	4 057	5	2	3	4.1	579	50	6
CMSCM 2017-11	4 057	5	2	3	4.1	579	50	4
CMSCM 2018-11	4 057	5	2	3	4.1	579	31	3
LUCIA 2018-05	5 321	3	2	2	3.4	476	64	4
LUCIA 2018-11	5 321	3	2	2	3.4	476	43	3

Table 2.1: Data used to build our model: Buildings with more than one evacuation drill.

Drill	**Avg. Np (ANp)**	**Avg. Te (ATe)**	**(ATe/ANp)*100**	**CBE**
EII-SPC	680	8.6	1.25	16.16
EII-SFM	537.5	5	0.93	17.88
FCMD	182.5	7	3.84	11.04
AFC	656.25	7	1.07	5.38
ETIC	660	7	1.06	5.03
FFia	875	8.5	0.97	6.06
AVIII	182	9	4.95	20.77
BRS	80	4	5.00	30.79
CMSCF	40	5.75	14.38	60.77
CMSCM	50	4.33	8.67	35.31
ETSA	300	5	1.67	5.47
LUCIA	53.5	3.5	6.54	32.18

Table 2.2: Average number of people and exit times, and CBE for the considered buildings.

Ea is obtained as follows:

$$Ea = \frac{St * (F - 1) + E}{F} \tag{2.2}$$

where E is the number of exits from the building, and St is the number of staircases going to the exit or to a main evacuation route.

Table 2.2 shows the value of CBE for all the buildings where more than one drill took place. Average values for the number of people evacuated (ANp) and average exit times (ATe) for each building have been used to perform the corresponding regression analysis. CBE depends only on the structural parameters of the building that influence evacuation time, so it is taken as the independent variable. In this way, the analysis separates the structural issues that influence evacuation times from issues related to human behavior.

When a single drill is done, how do we know if the results of the drill are representative of any evacuation that takes place in the building?

The more evacuation drills from the same building, the less uncertainty concerning human behavior [Lovreglio et al., 2014] and the more representative the results.

Any model that is presented must be built with the most representative values of the buildings under study. For this reason, the collected data set has been divided into two sets: a set with the buildings where data from two or more evacuation drills have been collected, and another group with the buildings where it has only been possible to collect data from a single evacuation drill. The means of the measured values of evacuation times and people evacuated have been calculated and entered in the Table 2.2. Do not forget that CBE is associated with the building itself, and will not change from drill to drill. What can change from one drill to another is the behavior of the people, that is, the evacuation times and the number of people evacuated. The approach to the problem is based on the hypothesis that the buildings are not going to be altered constructively or in their facilities that substantially influence the evacuation from one drill to another. Therefore, what we have is that CBE would be, within a statistical regression model, the independent variable, while the relationship of the evacuation time versus the number of people evacuated would be the dependent variable (since it depends on which building is evacuated).

In order to use CBE to predict the exit time for other buildings, it is necessary to derive a formula that, for a given CBE, returns the value for *(ATe/ANp)*100*, which in turn can be used to estimate the average time (ATe) needed to evacuate a building, for a certain number of persons (ANp). We have chosen a polynomial formula for this purpose. Adjusting the formula to the data shown in Table 2.2, we reach the following expression (see also Fig. 2.2):

$$f(x) = 0.0018x^2 + 0.1218x + 0.4289 \tag{2.3}$$

The value of R^2 for this expression, using the available data, is 0.911. We consider this value good enough to predict the exit time with respect to the population of the building and its ar-

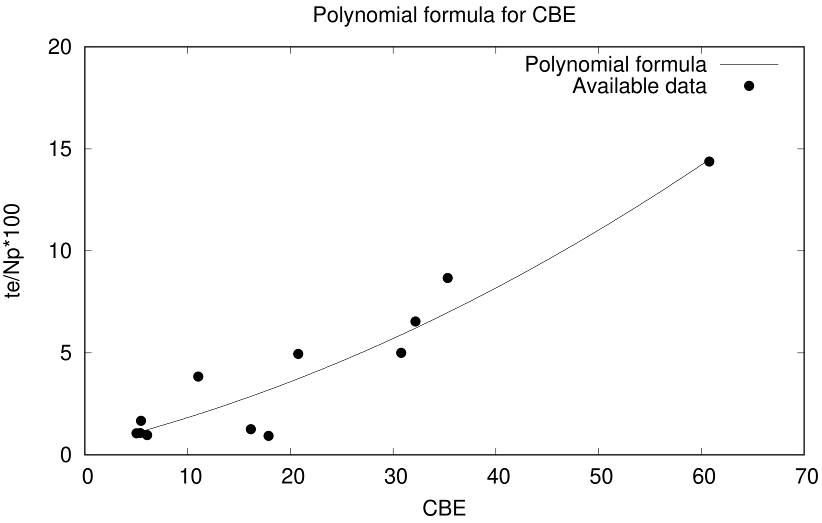

Figure 2.2: Polynomial formula for CBE presented in [Miñambres et al., 2020a], obtained by statistical regression of the available data, with $R^2 = 0.911$.

Drill	**ATe**	$\widehat{\textbf{Te}}$
EII-SPC	8.6	19.49
EII-SFM	5	17.1
FCMD	7	3.64
AFC	7	7.45
ETIC	7	7.18
FFia	8.5	10.79
AVIII	9	6.8
BRS	4	4.71
CMSCF	5.75	5.79
CMSCM	4.33	3.49
ETSA	5	3.45
LUCIA	3.5	3.32

Table 2.3: Evaluation of the CBE model with respect to average exit times.

chitectural characteristics. (Using other families of regression formulas returns a lower R^2 value.) This formula can be used to get estimations of the exit time, $\widehat{Te}$:

$$\widehat{Te} = \frac{Np * f(CBE)}{100} \tag{2.4}$$

In the following sections, we analyze the coherence of the estimations returned by our model in comparison with the real qualitative information, for these and other buildings.

2.6 Goodness of the study

In this section, we compare and discuss the differences between the average exit time (ATe) for each of the buildings considered and the value for $\widehat{\text{Te}}$ returned by the model.

Table 2.3 shows both the ATe and $\widehat{\text{Te}}$ for each building. As we know from the theory of regression analyzes, having a good coefficient of determination R^2 is not enough. In order to check the coherence of the proposed model, we can make the following observations:

EII-SPC and EII-SFM: Evacuation drills in both buildings were faster than the time indicated by the value of their CBE and number of occupants. The reasons may be related to the particular involvement of the center's management of both buildings, as well as the interest and sensitivity shown by both employees and students, partly because safety and protection issues are taught there as part of their academic programs.

FCMD: Evacuation drills in this building were slower than expected according to its CBE. It is consistent with a known difficulty (admitted by the Deans of this academic center) regarding the attitude of many employees of this particular center, who consider the evacuation drills an activity that should not be carried out during working hours and/or during lectures.

ETIC and AFC: Both centers were evacuated in a time very similar to the time estimated by our model. If we examine all the evacuation drills, we can see an evolution in their behavior that is consistent with the actions for the improvement of the preventive culture.

FFIA: People at this building carried out the evacuation in less time than the time expected by our model. The center is known for being particularly involved in this activity. We can see an evolution in their behavior similar to the ETIC and AFC but with a better improvement in the results.

AVIII: This is a student residence, with some spaces hosting other activities. Different directors are responsible of each activity, with different levels of involvement in conducting drills. Almost all drills were done early in the morning, so it does not seem strange that the residents who were still in their rooms needed more time to evacuate the building.

BRS: This is a historic and small building in comparison with the rest of the premises. It is used as a library where librarians are actively involved in risk management activities and have a very effective organization to evacuate students and researchers. These reasons can explain why the effective exit time was shorter than the value predicted by our model.

ETSA: People in this building performed the evacuation in longer times than expected according to our model, not improving their behavior in subsequent evacuation drills. The particular attitude of the occupants of this building towards this subject could have affected the evacuation drills, because they do not complain about the activity but neither do they show active participation in this matter.

CMSCF and CMSCM: Both buildings have the same management, which is very involved with security and safety issues. Almost all the students have attended a seminar on how to act in case of emergency. The results from CMSCM diverges more from the model than those from CMSCF, although it can be seen that the estimated time for the former building is the same exit time as the last evacuation drill of the center. CMSCF behaves as the model predicts.

LUCIA: The model makes a good prediction in this case. It is a building with laboratories, spaces and facilities dedicated to research. Their occupants are researchers with experience in evacuation drills of other buildings.

2.7 Applying the model to other buildings

The proposed model offers a prediction for groups of people of similar characteristics to our population, and for buildings in the range of size and characteristics of the buildings described in this chapter. Comparing the prediction value with the experimental value, we can see whether the people evacuated show a better or worse behavior than the values returned by the model. In the latter case, it would be wiser to invest in improving their knowledge and safety culture, in order to reduce the exit time. If they behave better, then it would be better to invest in improving the building's conditions to further reduce the exit time.

In order to show the effectiveness of our model, we apply it to examine the results of three different buildings where a single evacuation drill has been carried out. These drills and buildings were not used to build the model, because we believe that one single evacuation drill is not enough for the results to be representative.

We use the evacuation drills shown in Table 2.4.

We have followed the same steps as those described in the section 2.4 for the observation of the evacuation drills. In this case, a total of 40 people observed 40 points in these three drills,

Drill	Sf	F	St	E	Me	TO	Np	Te
AETSA 2017-03	3.700	2	2	2	3.2	657	350	9
EMZ1 2013-05	10.810	4	14	14	19.65	3469	975	9
ETSIAP 2011-03	7.633	3	3	2	6	1961	100	5

Table 2.4: Data for a set of buildings with one evacuation drill.

Drill	Te	$\widehat{\text{Te}}$	CBE
AETSA 2017-03	9	11,88	19,01
EMZ1 2013-05	9	6,02	1,51
ETSIAP 2011-03	5	2,91	16,38

Table 2.5: Evaluation of the CBE model with respect to exit times of buildings with one drill. For these buildings, ATe becomes Te (only one datum).

with a total of 1 425 people evacuated. The calculation of their CBE and the comparison with the estimated exit time can be found in Table 2.5. Based on these results, we can make the following observations:

AETSA: The occupants clearly behave better than the prediction of the model. The context is interesting to analyze. AETSA is a building used for delivering lectures of the ETSA school, because ETSA does not have enough classrooms. It was the first evacuation drill for AETSA, but many people have participated in previous evacuation drills of ETSA. Many of them know that ETSA is bigger than AETSA and that ETSA was evacuated in five minutes. This could be an anchoring effect [Tversky and Kahneman, 1974] that has a positive impact in this case, because they do not know that, according our model, AETSA is more difficult to evacuate, being even smaller. In this case, our model suggests that, if we wanted to improve the exit time in this building, then it would be better to invest in the building itself.

EMZ1: Considering the building's characteristics, the exit time forecast seems to be reasonable. Therefore, according to the model, the occupants should improve their behavior. In fact, it was their first evacuation drill and the only drill organized by the Health and Safety Service of the University. This building is one of the two buildings analyzed that are located in a different city, and, for organizational and historic reasons, it is more difficult to involve people in procedures organized remotely from the University headquarters. In this case, the model confirms our impression: If we wanted to improve the exit time in this building, it would be better to invest in improving safety culture.

ETSIAP: As happened with the previous building, the exit time forecast is reasonable to achieve and, according to the model, the occupants' behavior still has room for improvement. It was also their first evacuation drill, and ETSIAP is the other building located in a different city, but not in the same city as EMZ1. The process to involve people in procedures organized remotely from Valladolid is also difficult.

In short, we have found that all the results have a qualitative coherence with respect to the collected data. The quantitative deviations observed between real and predicted results are consistent with the different behavior patterns of each group of people in each building.

2.8 Conclusions and next work

We conducted an innovative regression analysis of the evacuation drills of some buildings in our university campuses. The regression analysis has been drawn by analyzing the relationship between the exit time vs. the number of people evacuated in the evacuation drill for each building, a value that we relate to a dimensionless parameter that we have called the Characterization of Building Evacuations (CBE). The CBE can be calculated using simple structural parameters of the building, making the model easy to use. CBE is a dimensionless value that only depends on the characteristics of the building and is completely independent of the behavior of the people involved. We have proposed a polynomial formula that fits the values with sufficient goodness, complementing the study with an exhaustive qualitative analysis that leads to consistent results.

The main added values of our model are the following: First, given a certain building whose CBE number can be calculated, and given the number of people in an evacuation drill, our model returns an estimated exit time. The relationship between the estimated and real times can be used to guide activities to improve the latter. If the estimated time is shorter than the measured time, it means that people behave worse than expected. This would suggest that it might be better to invest in improving people's behavior than investing in improving facilities to ease the evacuations. On the contrary, when the estimated time is longer than the measured time, it would suggest that it might be better to invest in the facilities to further ease the evacuation.

Second, this form of study can be used to analyze and compare the dimensionless number of other buildings of a similar size and characteristics (number of floors betweeen 2 and 9, surface between 2 000 and 23 000 square meters). It should be taken into account that the model was designed to be used with buildings that satisfy the legal minimums established in European regulations on safety in workplaces (regarding signage, expedited evacuation routes, etc.), and also with a population that does not, in general, present big disabilities.

Finally, our study can be easily used without significant investments. It is a very simple model that a professional can use just by collecting the indicated data, making a few calculations and comparing the results with the results obtained in their own evacuation drills.

Our next work includes improving the estimations given by this proposal, thus allowing to take better strategic decisions about evacuation subjects. To do so, in the following chapter we will further refine the study with more data, more buildings and more evacuation drills.

Chapter 3

Extending and validating our model to predict the effectiveness of building evacuations

To predict the effectiveness of building evacuations is a very difficult task in the general case. In the previous chapter, the historical results of 47 evacuation drills in 15 different university buildings, both academic and residential, involving more than 19 000 persons, was analyzed, and a method based on dimensional analysis and statistical regression was proposed to give an estimation of the exit time in case of evacuation. Comparing this estimated exit time with the real values obtained in evacuation drills, more informed decisions on whether to invest in more training and/or preventive culture of the occupants or to invest in structural improvements of the buildings can be taken.

In this chapter, we both propose a refinement of the method to calculate expected exit times, that leads to an even better adjustment between predictions and real-world results, and we use this refined model to predict the results of evacuations of a new building, whose use and characteristics are different from those previously studied, and whose data was provided by other authors in the bibliography. We show that there exists a correlation between the published results and the predictions generated by our model, both from a quantitative and qualitative point of view.

3.1 Introduction

It is very difficult to predict how well a particular building can be evacuated in the case of an emergency. Building evacuation depends on multiple factors and it is very hard to reach a holistic view of the problem. For this reason, as [Liu et al., 2020] pointed out, partial approaches are not rare in the literature. Many efforts in the study of evacuation drills are more focused on observing particular aspects that influence evacuations, such as the nature of pedestrian movement, evacuation decisions, route choice, or social influence, among other factors [Ronchi et al., 2019], than on collecting data from the entire building seen as a whole. As another example, [Peacock et al., 2012] studied fire drill evacuation data in eight office building occupancies, ranging from 6 to 62 storeys in height, but they focused on what happened in stairwells.

The rationale behind the use of partial, non-holistic approaches in the bibliography is that, in many cases, emergencies in buildings have been studied with the help of computational models, that only take into account certain aspects of the problem. There is a wide range of computational models available for this purpose: [Chunmiao et al., 2012] said that there are more than 22 models that simulate the behavior of buildings with different variants (see also [Kodur et al., 2020]). For example, [Gao et al., 2020] used a computational model to generate the optimal door positions which minimize evacuation distance; while [Arteaga and Park, 2020] developed a particular model to apply to shooter incidents. There are also proposals to use computational models in real time, such as the works published by [Mirahadi and McCabe, 2020] and [Mirahadi and McCabe, 2021]. Interestingly, other authors validate their model proposal with the help of virtual reality tools [Wang et al., 2021a].

To predict the effectiveness of building evacuations from an holistic point of view, in our previous chapter we have analyzed the historical data of 47 evacuation drills in 15 different university buildings, both academic and residential, involving more than 19 000 persons, using a combination of dimensional analysis and statistical regression, in order to give a prediction of the ratio between the exit time and the number of people evacuated. Dimensional analysis [Macagno, 1971, Gibbings, 2011] is a method for reducing complex physical problems to their simplest (most economical) forms prior to quantitative analysis or experimental investigation. It provides a method for calculating sets of dimensionless parameters from the given variables, even if the shape of the equation is still unknown and the choice of dimensionless parameters is not unique [Vaschy, 1892, Buckingham, 1914]. Dimensional analysis has been used in different science areas, from chemistry and mathematics to economics or techno-economics [Andrews and Shabani, 2012]. Besides this, the combination of dimensional analysis and statistical regression had already been used previously (see e.g. [Vignaux and Scott, 1999] or [Shen et al., 2014]). These techniques are particularly suited for the problem studied in the previous chapter, as that work aims to reduce a complex physical problem to a simpler form prior to investigation using statistical data.

In Chapter 2, the historical information collected by the University of Valladolid over the last decade regarding evacuation drills was analyzed. This information includes a total of 47 evacuation drills of 15 university buildings, both academic and residential, invoving 19 198 occupants and 688 external observers. With the help of the structural data of the evacuated buildings, a dimensioless parameter associated to each building, called Characterization of Building Evacuation (CBE) was calculated. Given the CBE for a particular building and the number of people occupying it, we were able to calculate an estimated exit time. The comparison of the estimated exit time for a given building with its measured exit times can be used to guide activities in order to improve the latter. For example, if the estimated time is shorter than the measured time, it would suggest that people behave worse than expected, and that it might be better to invest in improving people's behavior than investing in improving facilities to ease the evacuations. On the contrary, when the estimated time is longer than the measured time, it would suggest that it might be better to invest in the facilities to further ease the evacuation. By using this approach, more informed decisions on how to further improve exit times can be taken.

In this work, we extend that previous study, with the following new contributions:

- We have improved the calculation of the expected evacuation times, redefining the formula of that previous study from a statistical point of view. As a result, we have obtained a better adjustment of those predictions with respect to the data available.

- We have applied this new model to five evacuation drills carried out in a primary school in Spain [Cuesta and Gwynne, 2016]. We have augmented the input data with the building and drills information provided in that work. The results obtained show that the application of our model for that scenario is both consistent with the results obtained in that study from a quantitative point of view, and leads to interesting qualitative observations. This application of our model helps to validate the original proposal, also opening the door to further research.

This work shows that the approach followed in Chapter 2 makes it possible to simplify the study of the simulation results carried out by different authors in different circumstances, helping to find common points that facilitate comparisons. We are aware that it is still necessary to further strengthen the theoretical and empirical knowledge regarding such models, especially considering the enormous variety of conditions produced during an evacuation that depend on the different scenarios. To do so, more data regarding evacuation drills should be included by the research community in their published works. Having access to the data from the evacuation drills that many entities carry out regularly could be very useful for the advancement of investigations in this field. The more data made public in the bibliography, the better our model and other similar proposals will adjust to them.

This Chapter is organized as follows: Section 3.2 describes some related work in this field. Section 3.3 summarizes our previous work, which is used as the baseline for this new contribution. Section 3.4 presents and discusses a model that improves the baseline model. In Sect. 3.5, we add data collected by other authors to the improved model proposed, applying the model and discussing some findings. Finally, Sect. 3.6 presents our conclusions.

3.2 Related Work

Several authors have addressed the problem of taking into account all aspects of building evacuations simultaneously. The review of human behavior during building fire incidents by [Kobes et al., 2010] demonstrated that it is essential to take a holistic approach in modeling building evacuation, incorporating different types of characteristics from different domains of knowledge.

[Kuligowski, 2017] gathered all the available data, studies and research at that moment in the field of human behavior during fires.

Later, [Haghani and Sarvi, 2018] developed an extensive compilation of all empirical studies carried out to date, both with people and animals, concluding that there is a lack of unification to allow studies to be comparable and reproducible.

More recently, [Kinateder et al., 2021] analyzed 116 evacuation drill reports from Canada and realized that reports with more detailed data were needed for a better scientific and practical perspective, because the reports do not collect all the same types of data that would allow comparisons between different buildings and drills, or systematic studies of different aspects linked to the results of the drills.

In order to develop evacuation models, it is important that the real-world information gathered in different drills is made available to the community. Unfortunately, this is rarely the case. For example, even advocating the need of more data available for research, the data presented in [Kinateder et al., 2021] does not include the specific information related to each drill and building, thus preventing its use to feed other evacuation models. On the contrary, [Cuesta and Gwynne, 2016] presented a dataset of five evacuation drills carried out in a primary school in Spain, with the aim that some subsets could be used for model configuration and validation. Later, [Cuesta et al., 2017b] used these data to feed a range of subsequent simulations, conducted by using four computer models and the Society of Fire Protection Engineering's hydraulic model, obtaining interesting conclusions. Although school buildings are not representative of all possible scenarios, it is useful to have this information to augment the available dataset and to assess the applicability of different theoretical models. There are other studies in elementary schools, but they do not study the behavior of people in various drills that completely evacuate the building, as in [Cuesta and Gwynne, 2016]. For example, there are works, such as [Rostami and Alaghmandan, 2021] and [Hamilton et al., 2020], that studied particular aspects involved in evacuations in different real cases in primary schools, but without providing the data regarding the evacuation drills of the entire building.

In the previous chapter, we adhered to this view, gathering information from 47 evacuation drills in 15 different university buildings, while also proposing an analytical method to compare the evacuations of different buildings as a whole. As pointed out by [Lovreglio et al., 2014], the more data there are from different evacuation drills from the same building, the less uncertainty there will be concerning human behavior and the more representative the results. To ensure the representativeness of the information feed to the model, in Chapter 2 we recommend having data from two or more evacuation drills of the same building. As we stated there, having data from more than one evacuation drill helped us to better isolate the particular results of a single drill with differences that can be explained in terms of the human behavior of the occupants of each building.

3.3 The baseline CBE model

In the previous chapter we presented some experimental data regarding 47 evacuation drills in 15 different university buildings, and developed a theoretical model to give a prediction of the ratio between the exit time and the number of people evacuated. As long as this work proposes an improvement to that model,this section briefly summarizes that contribution, in order to put the new findings into perspective.

One of the advantages of the model is that it considers buildings as black boxes, abstracting away non-relevant characteristics. In that work, the data regarding the evacuation drills and the structural characteristics of the buildings being evacuated included the following information:

- The value of the following structural parameters for each building:
  - The total surface of the parts of the building usually occupied (Sf) (in m^2).
  - The number of floors that are usually occupied (F).
  - The number of different staircases that can be used as evacuation paths (St).
  - The number of exits from the building towards the outside (E).
  - The sum of the widths of the exits towards the outside of the building (Me) (in m).
- The elapsed times from when the evacuation alarm sounds until no more people leave the building (Te) for several evacuation drills conducted along the years (in min).
- The number of people leaving the building during that time interval (Np) in each drill.

To facilitate the discussion, Tab. 3.4 shows the data presented in the previous chapter, used to build that theoretical model. Most buildings are academic centers with classrooms or laboratories for students, offices, and other rooms. There are also student residences such as CMSCM, CMSCF and AVIII. AVIII also houses other activities that are governed by different managers. LUCIA is a building with laboratories, spaces and facilities dedicated to research. Their occupants are researchers with experience in evacuation drills. Additional information about the particular characteristics of each building and of their occupants was given in the previous chapter.

In Chapter 2, a dimensionless number, called CBE (*Characterization of Building Evacuation*) was calculated using the structural data of the building. That dimensionless number characterizes the easiness of evacuation of the building. The CBE was defined as follows:

$$CBE = \frac{\sqrt{Sf}}{Me} * \frac{F}{Ea} \tag{3.1}$$

where Ea is the average number of exits per floor, including floor exits towards the staircases and floor exits towards the outside. Ea is obtained as follows:

$$Ea = \frac{St * (F-1) + E}{F} \tag{3.2}$$

Building	Building characterization parameters					Values measured in each evacuation drill		**New expression**
Drill	**Sf** (m2)	**F**	**St**	**E**	**Me** (m)	**Np**	**Te** (min)	**Te/Np*100**
EII-SPC 2013-11	14 683	4	3	3	10	700	9	1.29
EII-SPC 2015-10	14 683	4	3	3	10	700	9	1.29
EII-SPC 2016-11	14 683	4	3	3	10	700	9	1.29
EII-SPC 2017-11	14 683	4	3	3	10	800	7	0.88
EII-SPC 2018-11	14 683	4	3	3	10	500	9	1.80
EII-SFM 2015-05	13 185	6	6	4	6.8	500	5	1.00
EII-SFM 2016-03	13 185	6	6	4	6.8	500	6	1.20
EII-SFM 2017-03	13 185	6	6	4	6.8	800	5	0.63
EII-SFM 2018-05	13 185	6	6	4	6.8	350	4	1.14
FC 2013-04	15 107	4	6	4	8.1	175	9	5.14
FC 2016-11	15 107	4	6	4	8.1	175	8	4.57
FC 2017-11	15 107	4	6	4	8.1	200	6	3.00
FC 2018-11	15 107	4	6	4	8.1	180	5	2.78
AFC 2013-04	11 166	4	7	7	11.23	225	8	3.56
AFC 2016-11	11 166	4	7	7	11.23	600	9	1.50
AFC 2017-11	11 166	4	7	7	11.23	900	5	0.56
AFC 2018-11	11 166	4	7	7	11.23	900	6	0.67
ETIC 2010-03	21 009	3	5	8	14.4	700	6	0.86
ETIC 2011-04	21 009	3	5	8	14.4	700	10	1.43
ETIC 2016-03	21 009	3	5	8	14.4	700	7	1.00
ETIC 2017-03	21 009	3	5	8	14.4	700	6	0.86
ETIC 2018-05	21 009	3	5	8	14.4	500	6	1.20
FFIA 2015-05	21 709	6	6	5	25	1 000	9	0.90
FFIA 2015-11	21 709	6	6	5	25	1 000	12	1.20
FFIA 2017-05	21 709	6	6	5	25	500	6	1.20
FFIA 2018-05	21 709	6	6	5	25	1 000	7	0.7
AVIII 2010	22 726	9	4	10	14	200	8	4.00
AVIII 2015-05	22 726	9	4	10	14	130	7	5.38
AVIII 2015-10	22 726	9	4	10	14	130	10	7.69
AVIII 2017-11	22 726	9	4	10	14	150	12	8.00
AVIII 2018-11	22 726	9	4	10	14	300	8	2.67
CMSCF 2016-05	6 514	8	3	4	3.4	15	8	53.33
CMSCF 2016-11	6 514	8	3	4	3.4	50	6	12.00
CMSCF 2017-11	6 514	8	3	4	3.4	55	4	7.27
CMSCF 2018-11	6 514	8	3	4	3.4	40	5	12.50
BRS 2013-04	2 155	2	1	2	2.01	80	4	5.00
BRS 2014	2 155	2	1	2	2.01	80	4	5.00
ETSA 2016-03	13 605	5	8	4	14.8	350	5	1.43
ETSA 2018-05	13 605	5	8	4	14.8	250	5	2.00
CMSCM 2017-05	4 057	5	2	3	4.1	50	6	12.00
CMSCM 2017-11	4 057	5	2	3	4.1	50	4	8.00
CMSCM 2018-11	4 057	5	2	3	4.1	31	3	9.68
LUCIA 2018-05	5 321	3	2	2	3.4	64	4	6.25
LUCIA 2018-11	5 321	3	2	2	3.4	43	3	6.98

Table 3.1: Building parameters and drill information as presented in Chapter 2. The right column (in grey) contains a new expression based on the data of each evacuation drill. The use of this expression is discussed in Sect. 3.4.

Building	**Avg. values from** [Miñambres et al., 2020a]				**New proposal**	
Drills	**ANp**	**ATe**	**ATe/ANp*100**	**CBE**	**A(Te/Np*100)**	**Var(Te/Np*100)**
EII-SPC	680.00	8.60	1.25	16.16	1.57	0.51
EII-SFM	537.50	5.00	0.93	17.88	0.99	0.07
FCMD	182.50	7.00	3.84	11.04	3.87	1.35
AFC	656.25	7.00	1.07	5.38	1.57	1.93
ETIC	660.00	7.00	1.06	5.03	1.06	0.05
FFia	875.00	8.50	0.97	6.06	0.87	0.13
AVIII	182.00	9.00	4.95	20.77	5.55	5.33
BRS	80.00	4.00	5.00	30.79	5.00	-
CMSCF	40.00	5.75	14.38	60.77	21.28	462.28
CMSCM	50.00	4.33	8.67	35.31	9.89	20.39
ETSA	300.00	5.00	1.67	5.47	1.71	0.16
LUCIA	53.50	3.50	6.54	32.18	6.61	0.26

Table 3.2: Intermediate values used to build our models. The left part (in white) includes the average number of people and exit times, the quotient of these averages, and the CBE for the considered buildings, as described in Chapter 2. The right part (in grey) includes two new expressions: The average of the ratio $Te/Np * 100$ in each building, called $A(Te/Np * 100)$, and the variance of this average, $Var(Te/Np * 100)$. The rationale behind both values is described in Sect. 3.4.

The left part of Table 3.2 (in white) shows a summarized version of the data collected in the evacuations drills, together with the CBE associated with each building, as presented in Chapter 2, where ANp is the average number of people evacuated for each building, and ATe is the average of the corresponding exit times. The fourth column presents the quotient of both values multiplied by 100, and the fifth column shows the CBE for each building. We used these values and statistical regression to obtain a polynomial formula, where CBE is the independent variable and $ATe/ANp*100$ is the dependent variable. The obtained formula is the following:

$$f(x) = 0.0018x^2 + 0.1218x + 0.4289 \tag{3.3}$$

This formula presented a good adjustment to the data available, with $\mathrm{R}^2 = 0.911$. This good adjustment suggested that the behavior pattern could be mathematically modeled by studying the simulations in this way.

We used this formula to get estimations of the exit time needed to evacuate each building, $\hat{Te}$:

$$\hat{Te} = \frac{Np * f(CBE)}{100} \tag{3.4}$$

We believe that $\hat{Te}$ may be a useful indicator to predict the evacuation time of different buildings. Our previous chapter finished analyzing the coherence of the estimations returned by the model, with the average of the real values obtained during the drills, ATe. That analysis led to several interesting observations regarding the behavior of the occupants of each building, followed by a discussion on the applicability of the model to other buildings.

3.4 A new proposal for better evacuation time estimations

As intuition suggests, the value of Te is influenced by the total number of people that should leave the building. It can be expected that the higher the number of persons, Np, the longer it takes to evacuate the building [Chunmiao et al., 2012]. This is because a higher Np means there is a higher possibility that some people will be late in leaving the building for various reasons, such as small incidents or problems in the evacuation, or simply reasons linked to the free will of human behavior.

Our initial study used the quotient of the averages of both values, that is, the ratio $(ATe/ANp) * 100$. After that, we have found that results can still be improved if we take the former observation into account from the beginning. This led us to calculate $(Te/Np) * 100$ and only later obtain their averages. Using the data presented in Table 2.1, the right column of that table (in grey) shows the values for the new expression, while the right part of Table 3.2 (in grey) shows the average

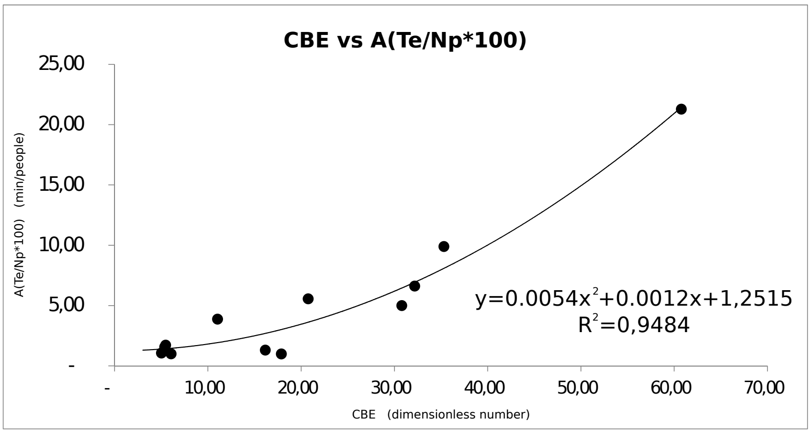

Figure 3.1: New polynomial formula for the CBE, obtained by statistical regression of the available data, using $A(Te/Np * 100)$.

values of $(Te/Np) * 100$ for each evacuation drill of each building, together with their corresponding variances.

Figure 3.1 shows the graphical representation of the CBE versus the new expression, $A(Te/Np * 100)$. As in the previous chapter, we have used these values to obtain a polynomial formula for CBE with statistical regression. The obtained formula, also plotted in the figure, is the following:

$$f(x) = 0.0054x^2 + 0.0012x + 1.2515 \tag{3.5}$$

This new formula presents a much better adjustment to the data, with $R^2 = 0.948$, that is, three points better than our previous proposal. All the qualitative discussion carried out in Chapter 2 regarding the behavior in the evacuation drills of each building with respect to the regression curve of the average behavior in drills is still valid.

Besides providing a better adjustment to the observed data, the new formulation also allows the variance of the ratio $Te/Np * 100$ to be examined, which can be seen as a qualitative vision of the different human behaviors in that building with respect to each drill. A bigger variance means a greater variability in the results obtained in different evacuation drills for the same building. In our case, looking at the data in Table 3.2, it can be seen that the three biggest values for the variance are those of the buildings that have residential activity, that is, buildings whose occupants and resident students responsible for evacuations may vary and, therefore, may not have accumulated experience from different, yearly evacuation drills.

3.5 Inclusion and comparison with data from other published research

As stated in Sect. 3.1, [Cuesta and Gwynne, 2016] presented data collection sets from five different evacuation drills carried out in a school in Spain. The authors expected that these data could be used for the configuration and validation of models. Later, [Cuesta et al., 2017b] used these data to feed a range of four computer-based simulations, conducted using four different evacuation models.

In this section, we use the data provided by [Cuesta and Gwynne, 2016] to augment the data presented in Chapter 2, obtaining a new adjustment formula and comparing its adjustment with the combined dataset. While the model presented in our previous chapter is built using data that belongs exclusively to university buildings, the study presented in this section shows how data collected by different authors from drills conducted in both university and non-university buildings can be used together, thus extending the applicability of this proposal.

To do so, we first describe the characteristics of the Altamira building as presented in their work [Cuesta and Gwynne, 2016]. We then obtain the values for all the parameters needed by the CBE model, and we finally combine all the data in order to obtain a polynomial formula and discuss its accuracy and coherence with the observed results.

[Cuesta and Gwynne, 2016] buildings description

In [Cuesta and Gwynne, 2016], the authors presented the results of different evacuation drills in a school made up of two buildings, a main building and a smaller one. In this study, we incorporate the data from the main building to our model, which we call "AltamiraM". The building is composed of four storeys, P3 to P0. Figure 3.2 shows the layout of the building. As can be seen in this figure, P1 has a grey area, corresponding to a classroom with a direct, independent exit door, and it does not share escape routes with the rest of the building, so it is not considered in this study. Regarding P0, it includes two closed, unused rooms that are also depicted in grey which are not considered either.

As can be seen in the floormap, several evacuation routes converge to the same exit points. This is not an uncommon situation in any building. The model handles this complexity by considering buildings as black boxes, and abstracting away the details of the particular layout of each floor. The addition of more data from different buildings and evacuation drills allows the researchers to further adjust it.

Obtaining building parameters

In order to incorporate this information to model, we should first obtain the building characterization parameters. The first parameter that we calculate is Sf, that is, the total surface of the building, without the areas depicted in grey, for the reasons explained above.

From the dimensions indicated in the figure, the surfaces of each floor can be calculated as follows:

- P3 has $(16.8 + 10.15 + 8)m * 11.5m + 33.20m^2 = 435.12m^2$ [4].
- P2 has $(16.8 + 10.15 + 8)m * (5.7 + 5.7)m + 33.20m^2 = 431.63m^2$.
- P1 has $(16.8 + 10.15 + 8)m * (5.7 + 5.7)m - (10.61 * 5.7)m^2 = 337.95m^2$.
- P0 has the stair 2: $(5.7 + 7.8)m * 1.2m = 16.2m^2$.

Using these values, Sf is equal to $435.12 + 431.63 + 337.95 + 16.2 = 1220.90m^2$.
We now establish the values for the rest of the parameters needed by the model.

- F is the number of floors with usual occupation. In this case, the lowest floor should not be counted since its function is only of transit, so F=3.
- St is the number of staircases. In our case, St=2.
- E is the number of exits. Exit G should not be counted because it is not communicated with any evacuation path of the building, so E=2.
- Me is the sum of the widths of the exits towards the outside of the building. In our case, Me is the sum of Exit D ($1.14m$ wide) plus Exit F ($0.8m$ wide), that is, Me=1.94.
- Regarding the evacuation times in minutes that are taken into consideration (Te), they are those corresponding to the time when all the evacuees left the Main Building, which is the one we study. The same occurs with the number of people evacuated (Np): We only take into consideration the people leaving the Main Building through exits D and F. Consequently, the data to be incorporated into this study are the data provided in Table 12 of [Cuesta and Gwynne, 2016]:

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[4] The floorplan provided by [Cuesta and Gwynne, 2016] does not show the surface of the two rooms surrounding the stairs in P3 and P2. We have estimated their size with respect to the other elements of known sizes as $11.65m \times 2.85m = 33.20m^2$

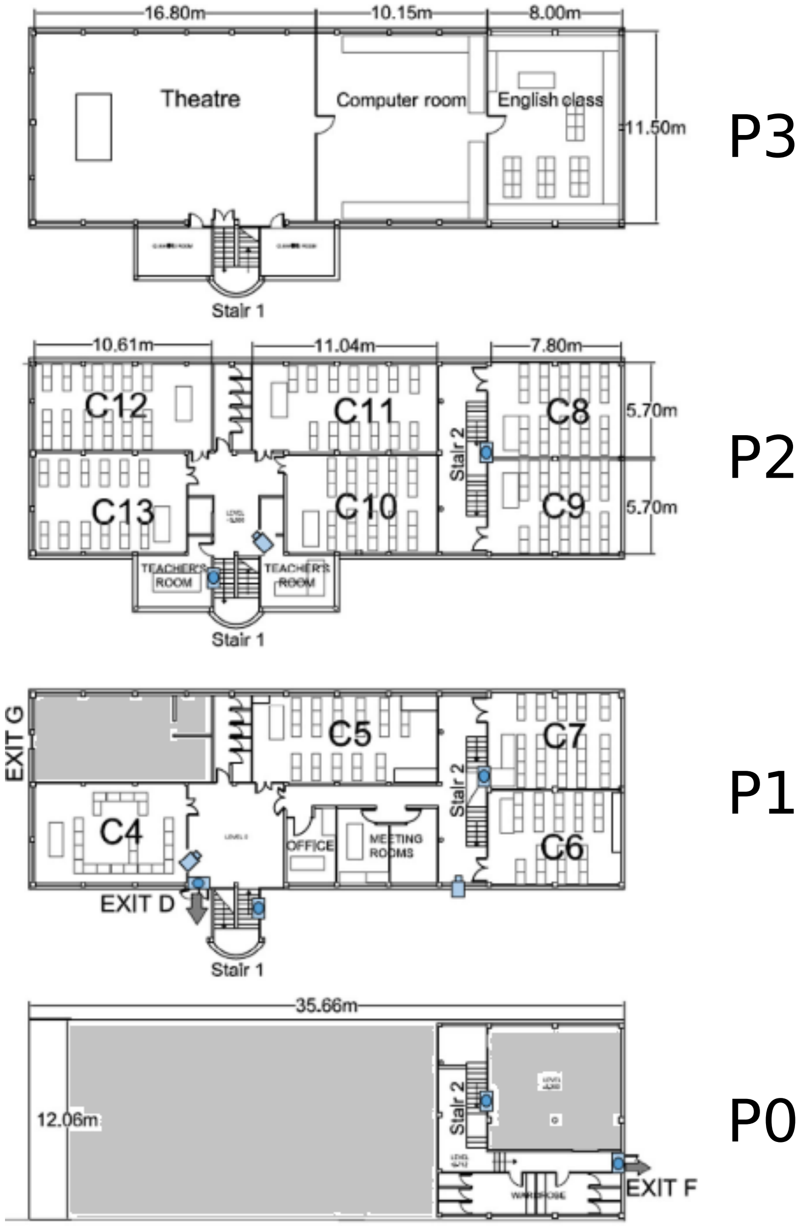

Figure 3.2: Layout of the Main Building as presented by [Cuesta and Gwynne, 2016]. The shadowed areas represent rooms that will not be taken account in this study

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Building	Parameters inherent to the building					Values measured in the evacuation drill		
Drill	**Sf** (m2)	**F**	**St**	**E**	**Me** (m)	**Np**	**Te** (min)	**Te/Np*100**
AltamiraM Drill E1	1 220.90	3	2	2	1.94	263	2.15	0.82
AltamiraM Drill E2	1 220.90	3	2	2	1.94	225	2.05	0.91
AltamiraM Drill E3	1 220.90	3	2	2	1.94	247	3.32	1.34
AltamiraM Drill E4	1 220.90	3	2	2	1.94	244	2.67	1.09
AltamiraM Drill E5	1 220.90	3	2	2	1.94	264	2.37	0.90

Table 3.3: Data of the Altamira Main building extracted from [Cuesta and Gwynne, 2016].

Building	**Avg. values as in [Miñambres et al., 2020a]**				**New proposal**	
Drills	**ANp**	**ATe**	**ATe/ANp*100**	**CBE**	**A(Te/Np*100)**	**Var(Te/Np*100)**
AltamiraM	248.60	2.51	1.01	27.02	1.01	0.04

Table 3.4: New row to be added to Table 3.2.

- Drill E1: Evacuation time is 129s (that is, 2.15min) and Np=263 people.
- Drill E2: Evacuation time is 123s (that is, 2.05min) and Np=225 people.
- Drill E3: Evacuation time is 199s (that is, 3.32min) and Np=247 people.
- Drill E4: Evacuation time is 160s (that is, 2.67min) and Np=244 people.
- Drill E5: Evacuation time is 142s (that is, 2.37min) and Np=264 people.

Table 3.3 summarizes the data that is incorporated into the model.

Data combination and results obtained

Using the building and drill parameters shown in Table 3.3, we can now augment Table 3.2 with an additional row (see Table 3.4).

It is interesting to see the low value of the variance for the Altamira school evacuation times. This means that it has a very stable behavior, not perceiving an evolution of learning in these drills, nor large incidents. The graphical representation of all these data can be made as shown in Fig. 3.3. Again, we used all these values and statistical regression to obtain a polynomial formula, where CBE is the independent variable and $ATe/ANp * 100$ is the dependent variable:

$$f(x) = 0.0065x^2 - 0.0704x + 1.6899 \tag{3.6}$$

The value of R^2, that represents how well this expression adjusts to the experimental data as depicted in Fig. 3.3, is equal to 0.9119. This value is slightly lower than in our previous formula, shown in Sect. 3.4, since this school does not behave in exactly the same way as the average of the university buildings studied. Nonetheless, the value obtained for R^2 is still good, confirming that this approach is robust enough to admit quantitative information from other buildings and evacuation drills. In addition, the analysis from a qualitative perspective is coherent, since in the graph we can see that the Altamira school point ($CBE = 27.02$; $(ATe/ANp)*100 = 1.01$) is below the curve. From a qualitative point of view, this means that, in this evacuation drill, the people of the Altamira school have left the building faster than the prediction returned by the model. As long as the model has been primarily fed with data belonging to evacuation drills of university buildings, our guess is that both the teachers' commitment to the safety and health of their underage students is higher than in a university environment, as well as the students' obedience to their teachers. In this sense, it is relevant to highlight that the evacuation times observed in [Cuesta and Gwynne, 2016] were higher in adolescents than in younger children, suggesting that the former are less likely to follow directions in an evacuation drill than the latter.

3.6 Conclusions and future work

In Chapter 2, a method based on dimensional analysis and statistical regression to predict the effectiveness of building evacuations was presented. This method is based on the use of a dimensionless parameter for each building called CBE (Characterization of Building Evacuations), that

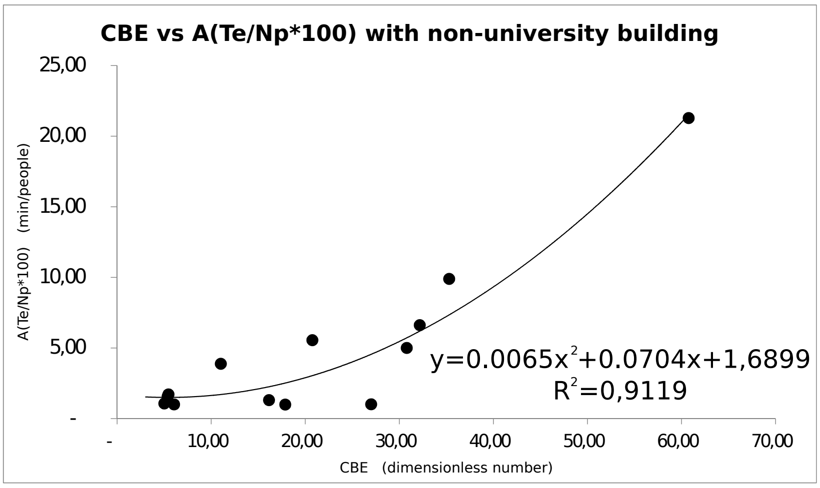

Figure 3.3: Polynomial formula for the CBE obtained by the statistical regression of the available data, using the combined data from Tables 3.2 and 3.4.

depends only on structural parameters of the building. The CBE allows to calculate an expected exit time for that building. By comparing this expected exit time with real exit times measured in evacuation drills, more informed decision can be taken in order to further improve the latter.

In this chapter, the research described in chapter 2 is extended in two ways. First, we show that, using the same input data presented in that work, a better statistical adjustment can be obtained if we use the ratio $A(Te/Np*100)$ for each drill, instead of $(ATe/ANp*100)$. This change improves the R^2 value from 0.911 to 0.948. Second, we augmented the data used to feed the model with data published by other authors which represents an evacuation drill of a non-university building.

Our results show that the inclusion of this data in the model is consistent with the results obtained, both quantitatively and qualitatively. We consider this result promising, because it shows that it is possible to apply this theoretical model to study evacuation drills of buildings outside the university environment. Further research is needed to determine more precisely what kind of buildings can benefit from this approach. We believe that these results are promising and encourages research on this topic.

To further develop this theoretical evacuation model, more data is needed. We would like to encourage researchers in the field to publish data from evacuation drills, including a description of the evacuated buildings and their use. For example, in this paper, we have found that the evacuation drills added to the model were in fact faster than our predictions, probably because of the greater discipline associated with younger occupants. This is an example of an interesting issue related to human behavior that this model may help to analyze. It might be very instructive to have the possibility of comparing these results with other evacuation drills in the same or different contexts. This may lead to different interesting analyses, ranging from the influence of the structural building characteristics in the evacuation time, to the influence of cultural behavior with respect to the evacuation drills in different countries or population groups. We believe that this approach has a very direct, practical application, and we encourage professionals who organize evacuation drills to make public the data they obtain.

Chapter 4

Technological solutions to facilitate automatic gathering of users' locations

Data collection during evacuations is quite a complex task. Evacuation drills offer an opportunity to collect data, but this requires well-organized extra resources. Indoor positioning technologies open up new possibilities for the collection of quantitative data automatically and even in real time. This chapter also aims to provide a solution to take advantage of the possibilities of these technologies, applying the advantages in data collection for the study of evacuation drills.

4.1 Introduction

Outdoor location systems have long been widely known by the general public. GPS is a term incorporated into the vocabulary of daily use. The Global Positioning System (GPS) is a program and tool for satellite-based object navigation. Unfortunately, the GPS system cannot work for navigation inside buildings because the building's rooftop blocks the satellite navigation signal. Therefore, other alternatives are been developed: The navigation system in a building is called Indoor Position System (IPS). IPS do not use satellite signal, they depend on neighboring anchors, a known position of sensors or devices, which either dynamically pinpoint signals or run environmental contexts to let other devices receive the signal [Soewito et al., 2018]. There is currently a range of technologies that allow the development of indoor positioning systems, but for the field of evacuations, it is necessary to combine a small necessary investment for the companies and that its use should be acceptable to the users. In this chapter, we propose a solution that meets these characteristics, and its operation has been checked in a building during an evacuation drill, seeing that we can indeed collect evacuation data, both in real time and storing them for later study.

This chapter is organized as follows: Section 4.2 describes how the distance between a Bluetooth Low Energy (BLE) beacon and a receiving antenna can be estimated, using the strength of the RSSI signal (Received Signal Strength Indicator) emitted by the beacon, and empirically studies the influence of the orientation of the devices for the RSSI signal on the calculation of that distance. Section 4.3 describes a low-cost indoor positioning system which relies on the use of portable, low-cost, Bluetooth Low Energy beacons, and how to concurrently use custom Ultra Wideband devices to enhance precision. Section 4.4 describes the PERIL project, which is a solution to facilitate the positioning of people in the event of an evacuation. Finally, Section 4.5 presents our conclusions concerning the use of this type of technology in the study of evacuation drills.

4.2 On the distance estimation to BLE beacons using Raspberry Pi 3 boards for indoor positioning applications

The Raspberry Pi (RPi) boards family is not only a set of versatile devices suitable for quick prototyping, but robust, low-cost systems that can be used in production. For example, RPi 3B and RPi 3B+ models have integrated WiFi/Bluetooth interfaces, so they can be used to interact with Bluetooth Low Energy (BLE) beacons. In particular, distance among beacons and Raspberries can be inferred using the received signal strength indicator of Bluetooth signals. This feature allows to build low-cost indoor positioning systems, that in turn can be used to track people that works closely for disease prevention.

In this paper we present the results of an empirical study that aims to determine whether RPi 3B and RPi 3B+ models are equally good to be used as receiving stations, and whether their relative orientations with respect to BLE beacons make any difference. Among other findings, in this work we show that the Bluetooth/WiFi antenna design of the RPi 3B+ receives different RSSI values depending on their orientation, thus being a poor choice for this application domain.

4.2.1 Introduction

The Raspberry Pi (RPi) platform [Upton and Halfacree, 2014] is a robust and versatile computer that can be used as a building block of more complex systems. Thanks to its extended connectivity (Ethernet, WiFi and Bluetooth interfaces), its computing capabilities, its low cost and the use of the GNU/Linux operating, the RPi platform is a versatile candidate for Edge Computing applications.

Using RPis as building blocks, our research group has developed XtremeLoc, a low-cost indoor localization system that allows persons and goods to be tracked in situations where GPS is not a cost-effective or feasible solution. The solution consists of the use of Bluetooth Low Energy (BLE) [Gomez et al., 2012] emitters, called beacons, that are carried by the persons or goods that should be tracked. Note that this use of beacons is the opposite of their mainstream use: In our case, beacons are not installed at fixed locations. A set of low-cost, receiving stations based on RPi platform located at fixed places receives the signals emitted by the beacons using their in-board WiFi/Bluetooth antenna. RPi Bluetooth interface not only captures the Bluetooth packet received,

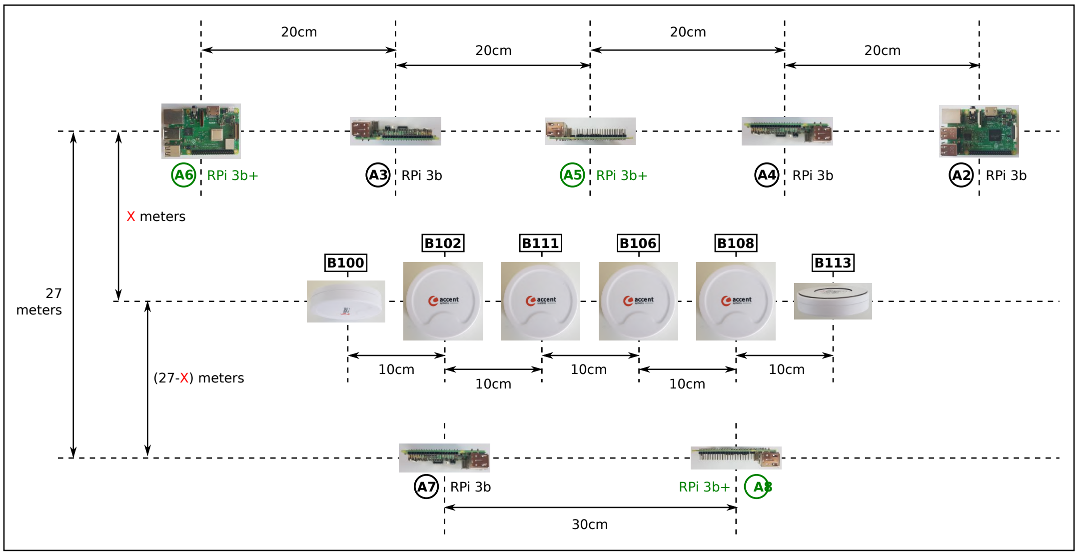

Figure 4.1: Setup of our experiment to estimate beacon distance. Both rows of RPi boards were 27 meters apart. We have moved the bench of beacons between them. The drawing is not at scale.

but also returns their RSSI (Received Signal Strength Indicator) value [Jianyong et al., 2014]. These values are used to calculate the distances to each beacon, and these distances are sent to a cloud-based server. This server uses a trilateration algorithm to determine the position of the elements to be tracked, and draws the position at real time in a web browser.

XtremeLoc is a cost-effective solution for tracking persons and goods. However, it offers a limited precision, of around two to three meters. The reason is that the distance between each beacon and the receiving stations built with RPis is estimated using their RSSI value, that can be affected by different factors, including attenuations due to the presence of obstacles, and the relative orientation of beacons and receiving antennas. By its nature, the first factor is difficult to handle, although it can be mitigated by collecting several, consecutive measures and use a Kalman filter to reduce noise [Welch and Bishop, 1995], thus obtaining a more representative result. The second factor (the influence of the relative orientation of antennas and beacons), can be better study in controlled experiments.

In this section we present the results of an empirical study consisting on the use of two sets of different RPi boards (3B and 3B+) to estimate the distances to a set of Bluetooth beacons located at known distances. Our study aims to answer to different questions: (a) how the relative orientation of RPi 3B boards affects the RSSI value associated to a particular Bluetooth signal; (b) how the relative orientation of RPi 3B+ boards affects the RSSI value associated to a particular Bluetooth signal; (c) how the relative orientation of beacons does affect their RSSI values; and (d) whether the expected propagation model of Bluetooth signals corresponds with the experimental results obtained using both RPi models.

Our experimental results shows an important difference between the behavior of RPi 3B and 3B+ when used for this purpose. We believe that the results of this experimental study would save efforts to the community, and would foster the use of these low-cost technologies for indoor positioning.

4.2.2 Environment setup

We have built an installation composed by two benchs of RPi boards, arranged in two lines 27 meters apart from each other, and a mobile bench of six Bluetooth beacons. The distance among beacons are fixed. In our experiment, we have moved the entire mobile bench of beacons back and forth between both benchs of Raspberries, to different positions. See Fig. 4.1. In this figure, all the equipment is seen from above, in order to appreciate their orientation. RPis A2, A3, A4 and A7 are RPi 3B models, while A5, A6 and A8 are RPi 3B+. All beacons are iBKS-105, manufactured

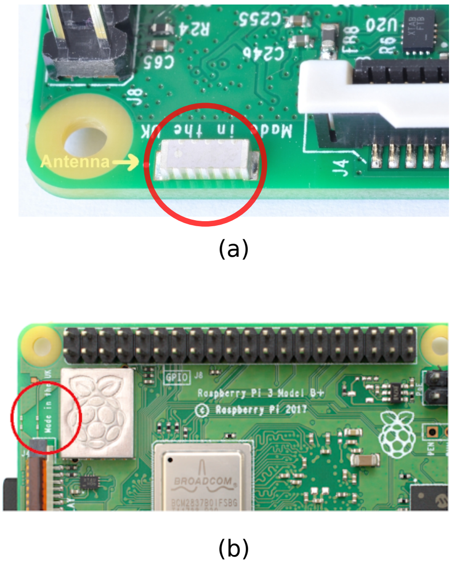

Figure 4.2: RPi boards antennas. (a) RPi 3B antenna (source: `raspberrypi.stackexchange.com`). (b) RPi 3B+ antenna (source: `www.proant.se`).

by Accent Systems, and emitting at +4dB. All three benches are coplanar, 1.5m above the floor. In our experiment, the RPis report the RSSI values obtained to a cloud-based server, using a WiFi connection. We have found that the Bluetooth RSSI values returned by RPi boards are affected by the simultaneous use of the on-board WiFi interface, because both WiFi and Bluetooth interfaces share the same antenna. To avoid these interferences, we have used external WiFi USB sticks attached to each RPi for WiFi communications, disabling the on-board WiFi interface.

We have collected data setting the beacon bench in 22 different positions, all of them parallel to both RPi benchs, and acquiring data during ten-minutes intervals. Each beacon emits one signal per second and was captured by each one of the seven RPis, generating around $(60 \times 10 \times 6 \text{ beacons} \times 7 \text{ RPis}) = 25\,200$ measures per interval distributed into $(6 \text{ beacons} \times 7 \text{ RPis} \times 22 \text{ positions}) = 924$ series of data.

4.2.3 Effects of RPi 3B orientation on the RSSI of Bluetooth signals

Our first study was to determine how the relative orientation of RPi 3B boards affects to the RSSI value of the same Bluetooth signal. To do so, we have compared the series of data collected by three RPi 3B boards (namely, A2, A3, and A4) with respect to the same beacon (labeled 108) at 12.83m. As can be seen in Fig. 4.1, these boards have different orientations with respect to this beacon. Table 4.1 shows the results obtained when analyzed the data collected, while Fig. 4.3 shows the histograms represented the number of signals perceived at different RSSI levels.

As can be seen, all three boards behave approximately in the same way, regardless of their orientation. Average values and median values are similar, the standard deviation with respect to the average is equal to or less than 5%, and the kurtosis (that is, the "tailedness" of the probability distribution)[1], indicates that this distribution produces more values near the media than a normal distribution [Groeneveld and Meeden, 1984] This makes the RPi 3B a good device for capturing Bluetooth signals and estimating distances to beacons using the RSSI values. As we will see in the following section, this is not the case for the other candidate.

4.2.4 Effects of RPi 3B+ orientation on the RSSI of Bluetooth signals

Our second study was to determine how the relative orientation of RPi 3B+ boards affects to the perceived intensity of the same Bluetooth signal. The RPi 3B+ uses a Proant PCB antenna

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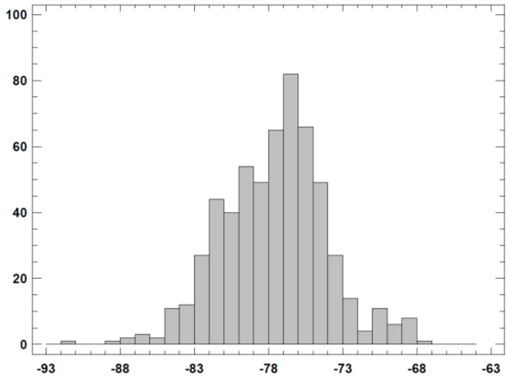
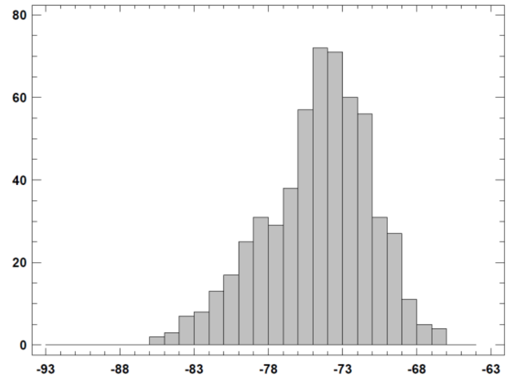
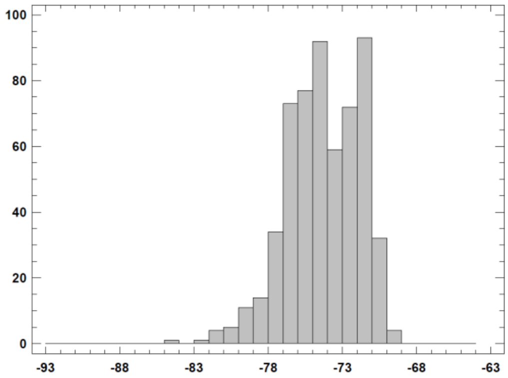
[1] In this paper, we show as kurtosis the calculations of the estimator of the sample excess kurtosis.



A2 board



A3 board



A4 board

Figure 4.3: Histograms that represent the distribution of measures with different RSSI values, received by RPi 3B boards with different orientations.

Beacon 108	**RSSI A2**	**RSSI A3**	**RSSI A4**
Average	-77.09	-74.16	-73.79
Real distance (m)	12.83	12.83	12.83
Median	-77	-74	-74
Mode	-76	-74	-71
Variance	12.53	12.95	6.10
Std Dev.	3.54	3.60	2.47
%Std Dev vs average	5%	5%	3%
Maximum	-67	-66	-69
Minimum	-91	-85	-84
Range (Min-Max)	24	19	15
% Range vs average	31%	26%	20%
kurtosis	0.48	-0.01	0.15

Table 4.1: Data analysis of RSSI values collected by RPis A2, A3, and A4 with respect to beacon 108 at 12.83m.

Beacon 102	**RSSI A5**	**RSSI A6**
Average	-73.86	-63.81
Real distance (m)	12.83	12.83
Median	-74	-63
Mode	-74	-61
Variance	15.71	8.51
Std Dev.	3.96	2.92
%Std Dev vs average	5%	3%
Maximum	-65	-59
Minimum	-92	-75
Range (Min-Max)	27	16
% Range vs average	37%	25%
kurtosis	1.53	0.11

Table 4.2: Data analysis of RSSI values collected by RPis A5 and A6 with respect to beacon 102 at 12.83m.

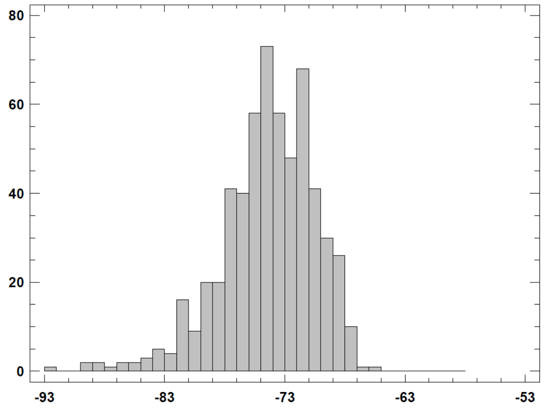
similar to the antenna used in the ZeroW board [rpi,]. The RPi 3B, on the contrary, uses a chip antenna soldered to the board. See Fig. 4.2. We have compared the series of data collected by two RPi 3B+ boards (namely, A5, and A6) with respect to the same beacon (labeled 102) at 12.83m. Recall that these boards have different orientations with respect to that beacon.

Table 4.2 shows the results obtained when analyzed the data collected, while Fig. 4.4 shows the histograms represented the number of signals perceived with different RSSI values.

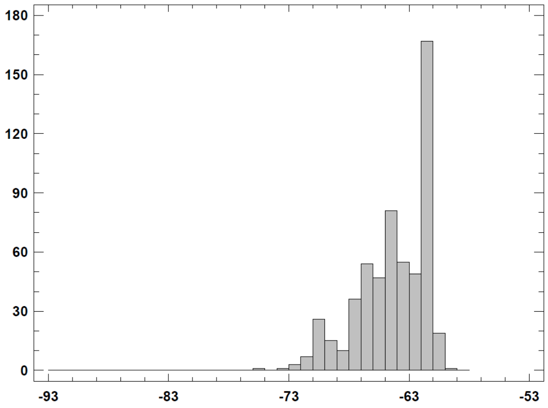
As can be seen in Fig. 4.4 and Table 4.2, results are now quite different. The average RSSI and the corresponding medians are 15% lower for A6 board. The value for the kurtosis show a very sharp curve for A6. Unlike the RPi 3B, the perceived strength of the signals received by RPi 3B+ boards strongly depends on their orientation, making this board not appropriate for estimating the distance to a set of beacons.

4.2.5 Effects of the relative orientation of beacons

Our following question is how the relative orientation of beacons affects to their signals as perceived by the RPis that act as receiving stations. We have calculated the average values for all the diferent distances between the beacon bench and both RPi benchs. The average typical deviation of all Bluetooth signals received with respect to their corresponding mean RSSI values is 5.61% for RPi 3B antennas and 7.01% for RPi 3B+ antennas. This means that the use of RPi 3B+ boards for this purpuse returns a set of measured values that are around 25% more dispersed than using RPi 3B boards, a result that is aligned with the observations carried out in the previous section.



A5 board



A6 board

Figure 4.4: Histograms that represent the distribution of measures with different signal strengths, received by RPi 3B+ boards with different orientations.

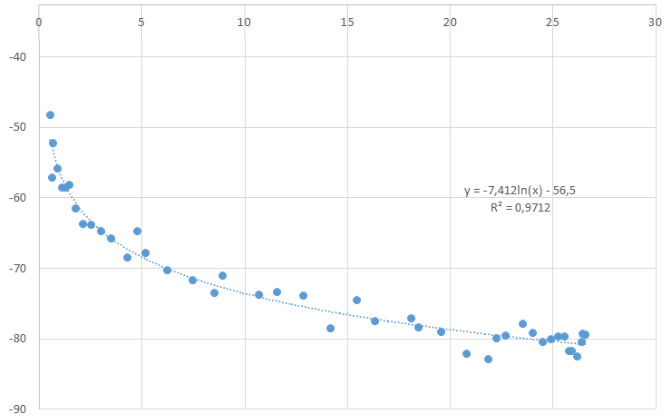
Regarding the orientation of beacons itself, we can conclude that their relative orientation at a given moment is not the main source of uncertaintly for their distance estimation.

4.2.6 On the expected propagation model of Bluetooth signals

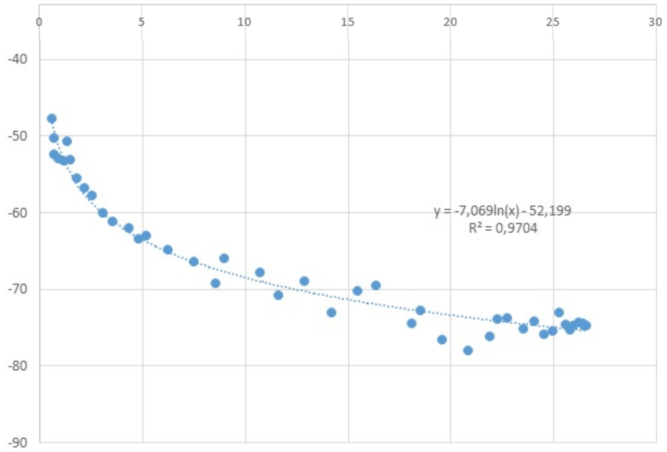
Finally, we aimed to confirm that the propagation model of Bluetooth signals corresponds with the empirical results obtained for both RPi boards. This is indeed the case. Fig. 4.5(a) shows that the logarithmic function $y = -7.412\ln(x) - 56.5$ adjust to the RSSI values returned by the RPi 3B board, for Bluetooth beacons emitting at +4dB. The function has an excellent adjustment with respect to the set of measures, with $R^2 = 0.9712$. Regarding the RPi 3B+ model, the corresponding function for beacons emitting at +4dB is $x = -7.069\ln(x) - 52.199$, with $R^2 = 0.9704$. We have found that both functions, based on experimental data, are better suited for distance estimations than more generic functions found in the manufacturers' datasheets. We encourage the reader to perform a similar experiment with his/her own hardware for improved results.

4.2.7 Summary

The joint use of commodity Bluetooth beacons and RPi boards allows the construction of a low-cost indoor positioning system with an acceptable precision for many practical applications. This study aims to compare the usefulness of two RPi boards, namely 3B and 3B+, for this purpose. We have shown that the antenna included in RPi 3B boards is less sensitive to changes in orientation,



(a) RPI 3B



(b) RPI 3B+

Figure 4.5: Obtained RSSI values with respect to real distance for RPi 3B and RPi 3B+ boards, for beacons transmitting at +4dB.

delivering better results for this purpose in the general case than the one included in RPi 3B+ boards. Regarding beacons orientation, we have shown that their orientation are less critical, allowing the detection of their RSSI values with a typical deviation that is around 5.5% when using RPi 3B boards, and around 7% when using RPi 3B+ boards.

4.3 Xtremeloc: A technically feasible and economically affordable positioning system

In this section we present XtremeLoc, a low-cost indoor positioning system designed to work in situations where GPS is not a valid alternative. XtremeLoc relies on the use of portable, low-cost, Bluetooth Low Energy beacons using the iBeacon protocol. Instead of setting these beacons in fixed positions, they are carried by the persons or goods to be tracked. The beacons broadcast a signal that is received by a set of fixed, low-cost antennas. These antennas estimate the distance to the emitter using the perceived intensity of the signal, and transfer this information to a cloud-based server that calculates the position of the emitter, storing it and displaying it through a web-based interface. The use of this technology allows a precision of around two to three meters. To track elements with a higher precision, XtremeLoc allows the concurrent use of custom Ultra Wideband devices, that allow a precision of around 10 cm while using the same interface. In this paper we describe XtremeLoc architecture and main features, how to use it to find persons and goods and an example of use of this technology to record the behavior of individual persons during evacuation drills.

4.3.1 Introduction to Xtremeloc

In this paper we present XtremeLoc, a low-cost indoor localization system that allows persons and goods to be tracked in situations where GPS is not a cost-effective or feasible solution. The solution consists of the use of Bluetooth Low Energy (BLE) emitters, called beacons, that are carried by the persons or goods that should be tracked. A set of low-cost, fixed receiving antennas collect the signals emitted by the beacons, calculate the distance to each beacon using the perceived intensity of the signal, and send these distances to a cloud-based server. This server uses a trilateration algorithm to determine the exact position of the elements to be tracked, and draws the position in real time in a web browser. Users can either carry a beacon or install a small APP in their smartphones that sends BLE packets, allowing the system to record their movements inside the facility with a precision between two and three meters, in line with the precision reported by other studies using this technology (e.g. [Feldmann et al., 2003], [Forno et al., 2005]).

For applications where a higher precision is needed, XtremeLoc offers the possibility of integrating Ultra Wideband (UWB) technology. Instead of carrying a beacon, the element to be tracked carries a UWB tag. A set of UWB anchors determine the distance to these tags by measuring the time required to the signal to travel between tags and anchors. This technology allows a higher precision, of around 10 cm, that is also in line with results reported by other studies, such as [De Angelis et al., 2009]. All distances collected by UWB anchors are sent to an intermediate server, that injects them to the main XtremeLoc server. XtremeLoc can be used for different purposes, including low-cost tracking of persons or goods using BLE, to flying drones in indoor environments using UWB. One application we are particularly interested is its use to analyze what happens during evacuation drills of large facilities. As long as XtremeLoc allows the individual behavior of the building's occupants to be known, it allows to detect bottlenecks, to know the preferred routes, and to record the position of persons that were not able to evacuate the building, in order to rescue them. This section discusses in detail the related technologies, XtremeLoc architecture, and main features. We also briefly discuss the use of XtremeLoc in the context of evacuation drills as an use case.

4.3.2 Related technologies

Several technologies for Indoor Positioning Systems (IPS) has been proposed so far. However, as [Huang et al., 2019], there is no single indoor positioning technology that is able to balance cost,

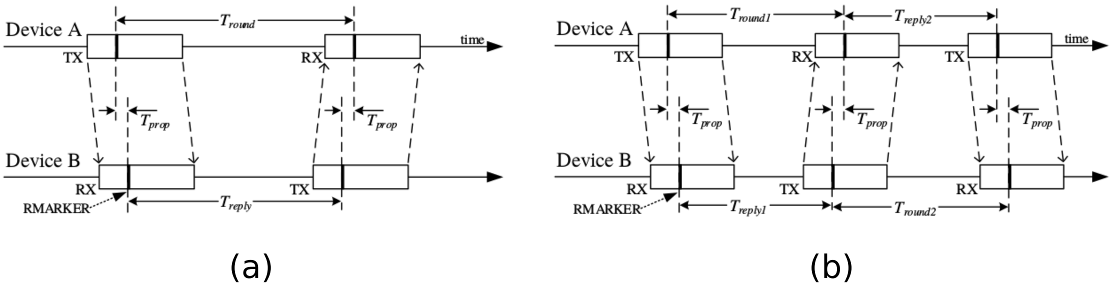


Figure 4.6: TWR protocol: (a) Single-sided; and (b) double-sided using three messages.

accuracy, performance, robustness, complexity, and limitations. Examples for these techniques can be Zigbee, Long Range (LoRa), Radio Frequency Identification (RFID), Ultra-Wide Band (UWB), Wi-Fi, and Bluetooth Low Energy. Each of these techniques has its own characteristics and limitations. We primarly focus on Bluetooth Low Energy (BLE) technology because it has several advantages, including low energy consumption, good positioning accuracy, and BLE devices are easily deployable [Jeon et al., 2018]. The work by [de Blasio et al., 2019] is a good survey about the use of BLE technology for IPS.

The use of BLE technology for IPS is based on the use of the Received Signal Strength Indicator (RSSI), that allows the distance between a BLE emitter and a receiving antenna to be estimated. RSSI indicates the difference between the transmitted and received signal strengths, and distance can be calculated in terms of the perceived attenuation. However, the received signal can also be attenuated by several factors other than distance, including reflection and diffraction around objects, causing multipath and fading effects respectively; transmission loss through walls, floors and other obstacles; channelling of energy, especially in corridors at high frequencies; and motion of persons and objects in the room. In order to mitigate these problems, the RSSI analysis can be enhanced by mapping the radio propagation losses to distance according to a propagation model, and be complemented with the use of a Kalman Filter (KF) in order to improve the accuracy of the calculated position [Cantón Paterna et al., 2017].

The use of BLE technology is a cost-effective way to estimate the position of persons or goods to be tracked, with a precision of around two to three meters. Some applications require a higher precision, such as automatic drone flight inside facilities. For these kind of purposes, XtremeLoc offers the possibility of using Ultra Wideband technology. This technology allows the transmission of information at high speed with a low power consumption, and can coexist with other technologies. Instead of simply measuring the perceived intensity of a given signal, UWB devices rely on the Two-Way Ranging (TWR) protocol. In this protocol, two UWB devices exchange messages, storing the exact times when messages are sent and received, in order to calculate the round trip time. The simplest TWR protocol, called single-sided TWR, includes the exchange of just two messages (see Fig.. 4.6a). Device A starts the data exchange and device B replies to complete it. Both devices store the exact times where transmissions and receptions take place, in order to calculate the flight time using T_{round} and T_{reply}. To enhance precision, a double-sided TWR can be used, where error is reduced by exchanging two pairs of messages and averaging the times recorded. Double-sided TWR can be either implemented using four messages, or reusing the second message to start the second message exchange (see Fig. 4.6b). XtremeLoc Ultra Wideband devices use this three-messages version of the double-sided TWR protocol.

4.3.3 XtremeLoc BLE architecture

XtremeLoc BLE architecture is composed of the following components: Bluetooth Low Energy emitters, receiving antennas, and a cloud-based service that performs the calculations and stores and shows the information in a web-based representation. Figure 4.7 shows the system architecture. We will examine these components in detail.

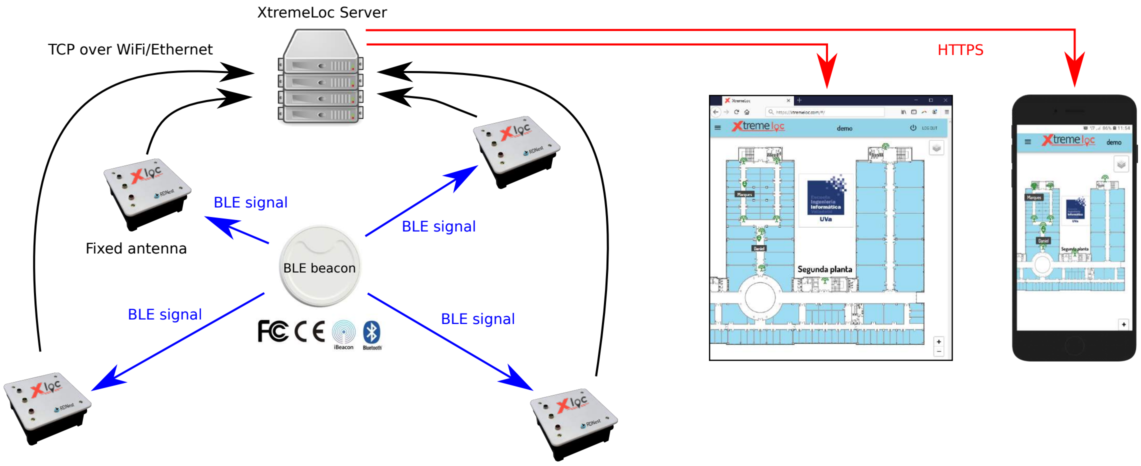


Figure 4.7: Xtremeloc Bluetooth architecture.

Bluetooth emitters

The key characteristic of XtremeLoc is the use of low-cost Bluetooth Low Energy (BLE) emitters as mobile devices. Any BLE emitter capable of broadcasting data packets using the iBeacon protocol can be use for this purpose, such as the iBKS 105 BLE beacon made by Accent Systems[2]. We have found that these emitters represent a good balance between cost (around 15 €) and features. These devices, also called "beacons", are battery-powered devices, with cell batteries that last for a couple of years. The beacons broadcast data packets at configurable, regular intervals, between ten per second to one each five seconds. The broadcasted data packet using the iBeacon protocol includes a unique ID for each beacon, and also an estimation of the remaining battery. This feature allows their batteries to be replaced before they run out of energy.

The broadcast packet also includes information about the power used to broadcast the signal. Comparing the declared intensity of the signal with the perceived intensity, a Bluetooth receiver is able to estimate the distance to the beacon. This is not a precise measurement, however the perceived intensity of Bluetooth signals depends on several factors, including attenuation due to obstacles, position and orientation of both the emitter's and receiver's antennas, etc. Therefore, to use this feature as a way to measure distance, several packets should be received in order to average their perceived intensity. On the one hand, the higher the number of packets emitted per second, the more precise the distance measured, and the more sensitive to sudden changes in such distance, a useful feature when the beacon is traveling fast. On the other hand, the higher the number of packets per second, the higher the power consumption, thus shortening the battery life. The sweet spot depends on the mobility of the target. For example, we have found that emitting three packets per second is a good tradeoff between precision and power consumption to track people carrying this device. Other use cases, for example when tracking a forklift that moves quickly, or an object that is almost always quiet, require a different configuration.

XtremeLoc is based on Bluetooth emissions. These emissions can not only be generated by beacons. Any mobile phone with a Bluetooth interface can do the same task, so a person can be tracked not only by carrying a beacon but also by having a lightweight, background service in his/her mobile phone, that emits XtremeLoc Bluetooth packets regularly. This solution has the advantage of saving costs, using people's phones instead of an external device, although it can be viewed by users as a more intrusive mechanism.

Receiving antennas

The second component of XtremeLoc is a set of receiving stations (called antennas) at fixed, known positions of the infrastructure. These antennas, connected to the Internet using either WiFi or an Ethernet link, scan the Bluetooth signals around, thus detecting packets emitted by the BLE

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[2] https://accent-systems.com/product/ibks-105/.

beacons. Each antenna uses the perceived intensity of the signal to estimate the distance to the beacons in range, and sends this information to a cloud-based server. This information is sent to the server once per second using HTTPS.

To keep the cost of these antennas to a minimum, we use the Raspberry Pi 3b+ platform, an inexpensive system capable of running Linux, using an SD card to store the filesystem. To avoid the degradation of the SD card after intensive use, we have developed a novel solution, with the collaboration of RDNest, a start-up company in the field of IoT in Valladolid, Spain (`www.rdnest.com`). The solution consists of developing a novel operating system, called RDos, based on Linux source code and with a footprint of less than 100 Mb, which includes some software features that allows the life of SD cards to be greatly extended.

In open spaces, receiving antennas should be installed in the vertices of a grid with sides of around 30 to 40 meters. In the presence of walls, more antennas and/or smaller grids may be needed, depending on the materials used in the building. After installation, their position is recorded in the cloud-based service. To avoid the need of physically accessing each antenna for software maintenance, RDos include an automatic software update service. This service periodically connects to the cloud-based server in order to download and install software updates. Both major and minor updates can be launched. Major updates involve replacing the entire filesystem, while minor updates only changes certain files within, basically those related to the Bluetooth listening service and distance estimation. The updating mechanism for major updates is a rather complex process, that implies, among other steps, downloading the new version, verifyig its integrity, an attempt to boot with it, and a rollback mechanism to a previous version (or even to a factory-default version) if something goes wrong. All this process has been designed with robustness in mind.

XtremeLoc cloud-based service

As we said above, all receiving antennas scan their Bluetooth interface, capturing the signals emitted by the beacons. Antennas packet this information and send it regularly (once a second) to the XtremeLoc cloud-based service. This service uses a trilateration algorithm, similar to the one used by GPS receivers, to calculate the position of each beacon inside the infrastructure. To calculate the position unambiguously, this algorithm needs at least the distance to three receiving antennas. All the distances sent by antennas and the calculated position are permanently stored in the service.

The cloud-based service offers a REST API that the system to queue for different purposes, from locating a particular beacon in real time to measuring its battery status or checking the health of the receiving antennas. A web-based frontend uses this information, in conjunction to accesses to a cartography service to picture the position of a particular beacon in real time. The interface works in both laptop and mobile devices (see Fig. 4.8), and not only depicts the position, but also represents graphically the distances as measured by the antennas (Fig. 4.9).

XtremeLoc does not use any proprietary software: all the software stack is open source, as well as the cartography used for building positioning (for this purpose we have used OpenStreetMap [Haklay and Weber, 2008]), and the online generation of the views needed at different scales (using Leaflet [Derrough, 2013]). Therefore, XtremeLoc does not have hidden running costs.

4.3.4 XtremeLoc UWB extension

The use of Bluetooth technology allows XtremeLoc to obtain a precision of around 2-3 meters, enough for many purposes, including the location and tracking of people and goods. Our research group has also built an extension that uses Ultra Wideband [Sahinoglu et al., 2008] technology. With this technology we have obtained an accuracy of around 10 cm, at the cost of more expensive tracking devices. While Bluetooth technology can be used for applications where a 2-3 meters error margin is acceptable, our Ultra Wideband solution offers the precision required, for example, to automatically fly a drone inside a factory or a cathedral.

In BLE, beacons broadcast packets that are received by the antennas within range. UWB devices require a bidirectional communication between each pair of tag and anchors (recall Fig. 4.6). To gain knowledge about this technology, we decided to build UWB devices and their software from scratch. Figure 4.10 shows the UWB devices developed, from the first prototype to a pair of tag

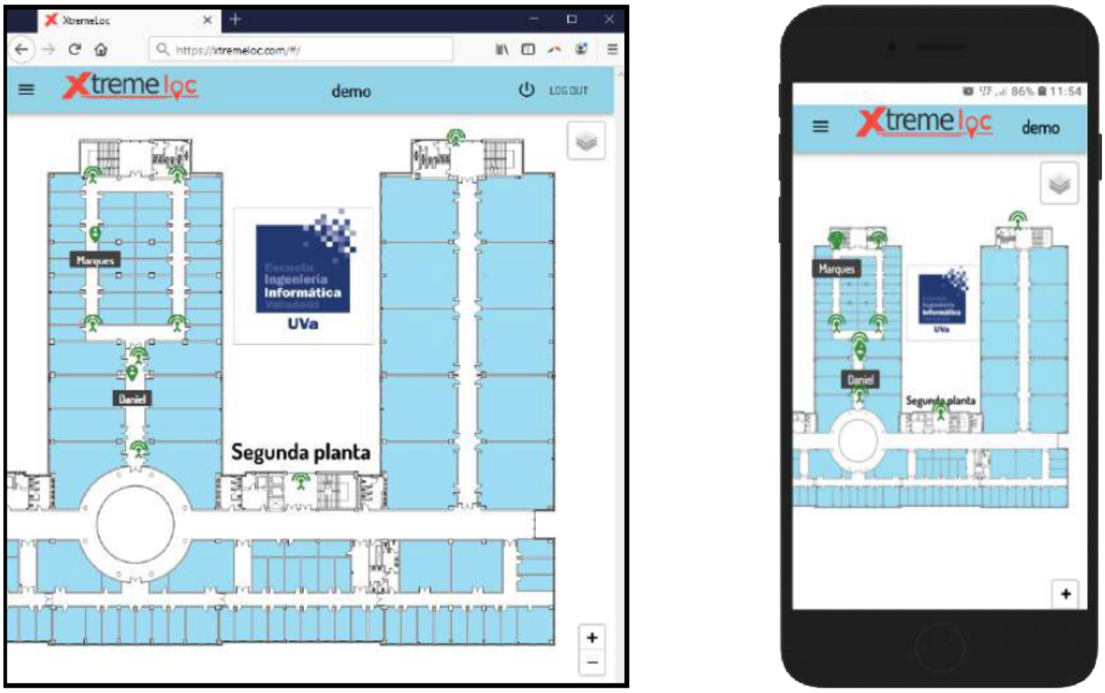

Figure 4.8: Web-based interface for XtremeLoc, depicting positions in real time.

Figure 4.9: Web-based, real-time representation of distances measured to a beacon (Daniel).

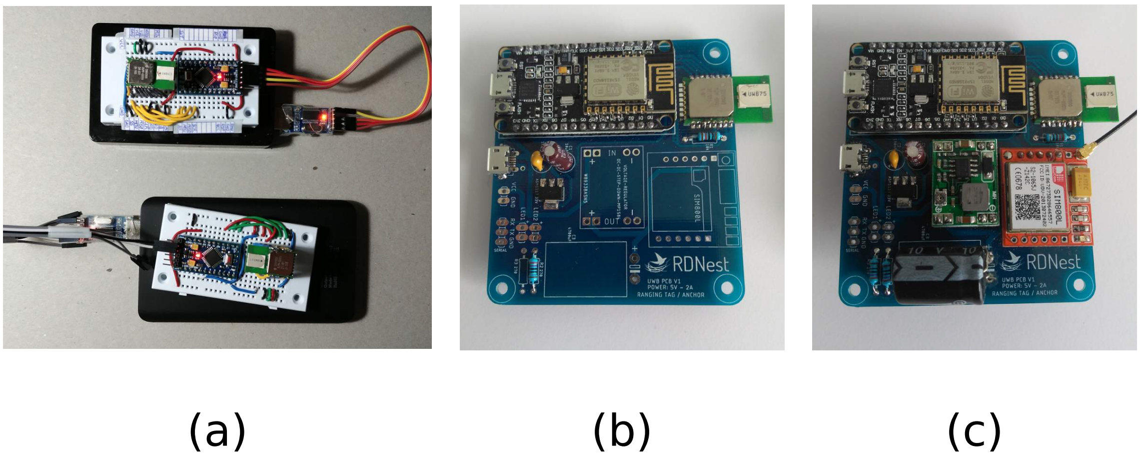

Figure 4.10: UWB devices developed: (a) First prototype; (b) UWB tag Mk1; (c) UWB anchor with GPRS modem, Mk1.

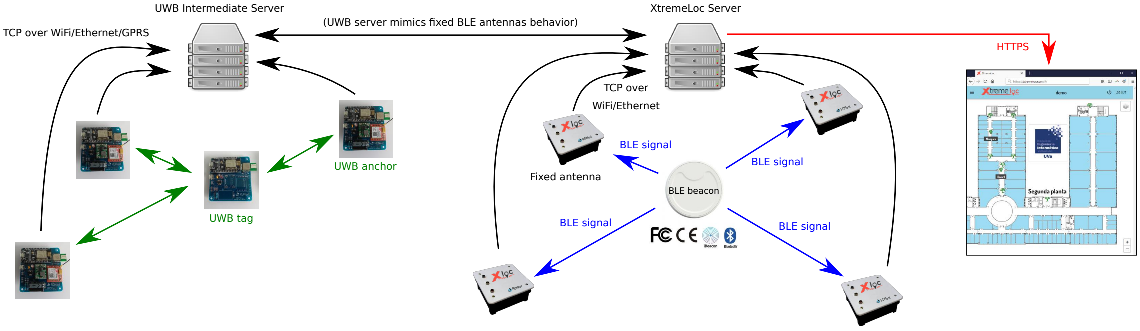

Figure 4.11: Xtremeloc architecture with UWB extension.

and anchor. From the electronic point of view, both tags and anchors are similar, incorporating an UWB chip and a microcontroller to handle communications and calculate in-flight message times. The difference between them is that the anchors should also transmit the distance to each tag in range to a server. Our first prototypes included an Arduino Pro Mini (see Fig. 4.10a). To build Mk1 anchors and tags, we used the NodeMCU DEVKIT 1.0, that includes the esp8266 WiFi module (see Fig. 4.10b and 4.10c). We also added a GPRS modem to our anchors (see Fig. 4.10c) for extended connectivity. To keep costs low, we used the same PCB layout for both tags and anchors. The fabrication cost of these UWB devices is around 120 €, in part due to the high cost of the UWB chip.

From the architecture point of view, we devised the use of UWB technology as an extension of our XtremeLoc system. Figure 4.11 shows how we integrate both technologies. Each UWB tag exchanges separate messages with all UWB anchors within range. This is an important difference with BLE, because in the latter Bluetooth packets are broadcasted, and all antennas receive the same packet. Therefore, if we have B beacons and A antennas, only B packets are required to determine the positions of the beacons. On the contrary, if we have T UWB tags and N UWB anchors, the number of messages exchanged is $T \times N \times 3$, because we use a double-sided TWR protocol with three messages (recall Fig. 4.6b). This behavior imposes a limitation in the number of tags and anchors that can interact within range.

All tags report the calculated distances to a dedicated UWB server using a lightweight TCP protocol. The UWB server stores this information and injects it to XtremeLoc as if it came from a set of regular Bluetooth antennas. In this way, XtremeLoc is not aware of the technology used to measure distances, and we can also use the UWB anchors, tags and server in stand-alone mode for other purposes.

4.3.5 Use case: XtremeLoc and Building Evacuation

A low-cost, low-energy indoor positioning system has a myriad of applications, ranging from tracking for logistic purposes to avoid goods being stolen to tracking patients and workers in all kinds of facilities. When it comes to locating people, it is necessary to have their consent, with the aim of improving procedures or facilitating evacuation in case of disaster. The ability of the cloud-based service to store both the position and the list of distances to each beacon in real time allows this information to be retrieved when needed. This is particularly useful in case of an evacuation due to an accident that affects the entire building. Even if the antennas stop working (due to lack of power, to a failure of the interconnection network, or a fire event), the cloud-based service (if running in an external premise) is still able to indicate the last known position of all the beacons inside the building. This information is very useful for guiding emergency services to rescue a particular person.

Another interesting application of XtremeLoc is to monitor the individual behavior of people with respect to an evacuation drill. This information allows to improve both emergency procedures and pre-event emergency training. The evacuation movement of people inside a particular building is usually studied by recording human behavior at strategic points, either in evacuation drills or in controlled experimental environments, and collecting testimonies of people involved, generally at a later time [Kuligowski and Hoskins, 2011]. By their nature, these records are inexact and incomplete, and only show the aggregated behavior of the participants. As long as XtremeLoc is able to record each individual path, the analysis of the data allows interesting individual behavior patterns to be detected, that remain unnoticed when data is aggregated, such as people that does not find the exit within time; people that follow a sub-optimal path to leave the building, or if there was an unexpected bottleneck not related to the architecture, but to a dangerous situation that was not imagined when the emergency procedures were set up.

4.3.6 Summary

In this section we present XtremeLoc, an indoor positioning system that is both affordable and effective. XtremeLoc uses low-cost, Bluetooth Low Energy devices to broadcast a signal that is received by a set of fixed antennas. This information is sent to a server that uses a trilateration algorithm to locate the emitter with a precision of around 2-3 meters, enough for a myriad of purposes. We have also developed a more precise yet somewhat more expensive solution, that offers a precision of around 10 cm, using Ultra Wideband technology. The XtremeLoc solution has a wide range of applications, from tracking persons, vehicles and goods in any situation where GPS is not a viable solution, to tracking individual behaviors in the context of an evacuation drill.

4.4 PERIL: Prevention of Emergency Risks by Indoor Localization

The PERIL projects[3] start from the collaboration of the MoBiVAP research group and the Health and Safety Service at the University of Valladolid (Spain), and the Castilla y León regional government. The aim of the project is to keep track of persons inside buildings, with the main goal of facilitating localization in case of an emergency. The PERIL project consists of the installation and evaluation of an innovative solution developed by the MoBiVAP research group, with the collaboration of RDNest, a start-up company in the field of IoT. The solution developed consists in the use of Low Energy Bluetooth (LEB) beacons that are carried out by the users of the building, and a grid of static, custom receiving antennas. These antennas collect the emissions from the beacons, and estimate the distance between each beacon and itself. This information is sent to a cloud based service, that uses this information to locate each beacon inside the building, and to draw the position at real time in a web-based browser. The resulting system allows to track the location and movement of people inside the building (where GPS does not work) with a precision

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[3] The PERIL projects (PERIL project, UNIVERSI/17/VA/1, and PERIL II, INVESTUN-18-VA-0001), were supported by the Consejería de Empleo, Castilla y León regional government (Spain) within the Universitas program. This program supports research projects carried out by the public universities of Castilla y León in the field of occupational health and safety.

within two meters and at a very affordable cost. In this work we will describe the use of this solution, called XtremeLoc, in the evacuation drill of the School of Informatics at the University of Valladolid. A grid of more than 30 receiving antennas allowed to individually track the movement of a representative set of more than 50 persons during the drill. This paper will examine the lessons learnt, showing how this technology allows to know the preferred evacuation routes, detect bottlenecks and precisely measure evacuation time.

4.4.1 Introduction to PERIL

Having information about all the people evicted in the process of evacuating a building is a fundamental fact. Currently this is achieved thanks to emergency procedures, emergency communication systems, and pre-event emergency training. The study of human behavior in fires has allowed the development of the aforementioned procedures and it has also been used to model the evacuation movement in computer simulation [Kuligowski, 2015]. The data on which that study has been based on arose from the testimony or interview of the people involved, generally at a later time [Kuligowski and Hoskins, 2011]. This inspection can be electronic, on paper, "face to face", or by phone (e.g [Butler et al., 2017], [Haghani and Sarvi, 2017], using individual questionnaires that ask about the subjective perception of the people evacuated. The other source of data consist on the recording of human behavior in strategics points, either in evacuation drills or in controlled experimental environments: Real space built for the experiment (e.g. [Lian et al., 2017], [Liao et al., 2017]), real space selected for the experiment (e.g. [Zhu and Shi, 2016]), in tunnels ([Capote et al., 2013]), in a real evacuation drill, e.g. in a theater ([Lovreglio et al., 2015], or in a six-storey office building ([Ronchi et al., 2014]). Another source of data is the use of virtual controlled experiment using virtual reality (e.g. [Kinateder et al., 2018], [Lovreglio et al., 2016]).

In this section we propose the use of the technology of indoor (non-GPS) localization systems to build a new tool to collect individual data on human behavior in evacuations drills. (GPS technologies are discarded, because in general they do not work in indoor environments.) The data obtained in this way can both be used to make decisions in real time (such as rescue people) and to perform analysis at a later time. Besides, this opens the possibility of obtaining data on human behavior in the evacuation, including times, routes, decisions, agglomerations, bottlenecks, etc, in a more objective and detailed way than with the use of individual and collective monitoring.

There are already published applications where indoor location is used in emergencies cases. One of them consists on the use of mobile phones with the purpose of employing real-time sensor data as references for evacuation route calculation. For example [Wang et al., 2014] and [Wang et al., 2015] make an attempt to convert sensor systems to sensor graphs and associate these sensor graphs with route graph in order to dynamically generate evacuation adapted to the risk. In their work, [Seo et al., 2017] proposes the use of beacons and Unmanned Aerial Vehicles in emergency response systems for building fire hazard. They present a proof of concept prototype of a monitoring and emergency response method. Finally, [Aedo et al., 2012] use indoor location to adapt information to the context and the profile of each person in order to provide personalized alerts and evacuation routes to all kinds of people during emergency situations in working places.

The use of these technologies in this context is not just a technological matter, but also to find or develop systems that can fulfill their requirements with sufficient quality at an affordable cost.

There are several localization technologies that can be applied to solve different problems, being in many cases complementary systems. Related technologies include the use of WIFI signals (12-meters precision, medium cost), Bluetooth Low-Power (BLE) devices (few-meters precision, low cost), and Ultra Wideband (10-cm precision, high cost). In this work we propose the use BLE technology to instrument the evacuation of a University building, describing the lessons learned, showing how this technology allows to know the preferred evacuation routes, detect bottlenecks and accurately measure evacuation time.

4.4.2 Methodology in PERIL

The study of evacuation drills in large and/or complex buildings requires a large number of observers located at strategic points of the building, to be able to collect data from the evacuation exercise. Human observers represent a significant cost to the organization. The use of cameras instead of human observers is also expensive, and poses additional bureaucratic barriers related to image registration and data protection issues.

Our proposal in the PERIL project is to test the feasibility of using indoor positioning technologies to assist in the localization of people in an emergency drill. To do so, the PERIL project included the development of an indoor positioning system composed by a set of transmitters (beacons), receivers (antennas), and a cloud-based service to offer real-time, on-map positioning and to store historical data.

As transmitters, we use low cost, reduced size (1.5 cm) and low consumption (4 years of autonomy) BLE beacons that can be carried by people to be locatable.

A set of low-cost receiving antennas should be conveniently distributed in the ceilings of the space to be monitored (in our case, the School of Informatics at the University of Valladolid). These antennas collect the emissions from the beacons, and estimate the distance between each beacon and themselves. This information is sent to a cloud-based service, which uses it to locate each beacon inside the building with the help of trilateration algorithms, and to draw the position at real time in a web-based browser.

4.4.3 Results

We have conducted in May 2018 an evacuation drill at the School of Informatics, a building of the University of Valladolid, in Valladolid, Spain. A total of 31 receiving antennas have been placed in the building, mainly in all the exits of the building and accesses to the staircases from the different floors. One antenna was placed in the meeting point, outside of the building.

34 volunteers have carried a beacon during the evacuation drill, allowing the indoor positioning system to record their movements and routes used during the evacuation process. Part of the volunteers were observers of the drill that received the instruction to perform the evacuation integrated with the group, following the instructions of the members of the evacuation team but trying to be the last person to abandon the building. The remaining beacons were carried by normal building users. A total of 500 people evacuated the building.

The system allowed to collect and store the signals emitted by all the beacons, calculating the position of the 34 beacons at real time during the evacuation drill. Each beacon had an unique tag, and it emits their position four times per second. The antennas collect that information and use it to estimate the distance to each beacon.

The data collection is not homogeneous: Each tag has a different number of samples over time. During the data collection process, a software problem generated a signal blackout that affected the reception of all beacon signals during several seconds. However, the system was robust enough to recover on its own, storing the collected signals without additional losses. A total of 19,697 positioning values were stored for further study.

Times are recorded in milliseconds from the Epoch (Jan 1st 1970). The first sample was received at time 1525341014104, associated to beacon 22. The last sample was received at 1525341899151, so the entire monitoring of the evacuation drill lasts for 885 seconds.

The position in space is defined by x, y, z coordinates, where the z indicates the floor (0 for the basement, 1 is the ground floor, 2 is 1st floor, and 3 is 2nd floor). Fluctuations are possible when people move between floors. The values of x and y are between 0 and 1, and are referred to the 2D-projection of the building map, with (0,0) corresponding to one end of the building floor and (1,1) to the diagonally opposite end. Positions outside this range correspond to beacons that left the building towards the meeting point.

The designed system also allows to see at real time, in a website with restricted access, the position and movement of the beacons with their tags in the different floors of the building. The positions are plotted on the plans of each floor of the building, allowing to see simultaneously all the beacons that are on a floor and their movements.

4.4.4 Discussion of results

The evacuation drill experience with the use of the indoor location system developed in the PERIL project has provided 19,697 positions of 34 people during the 885 seconds that delimited the drill, of a total of 500 evacuated people. These positions have been viewed in real time by authorized

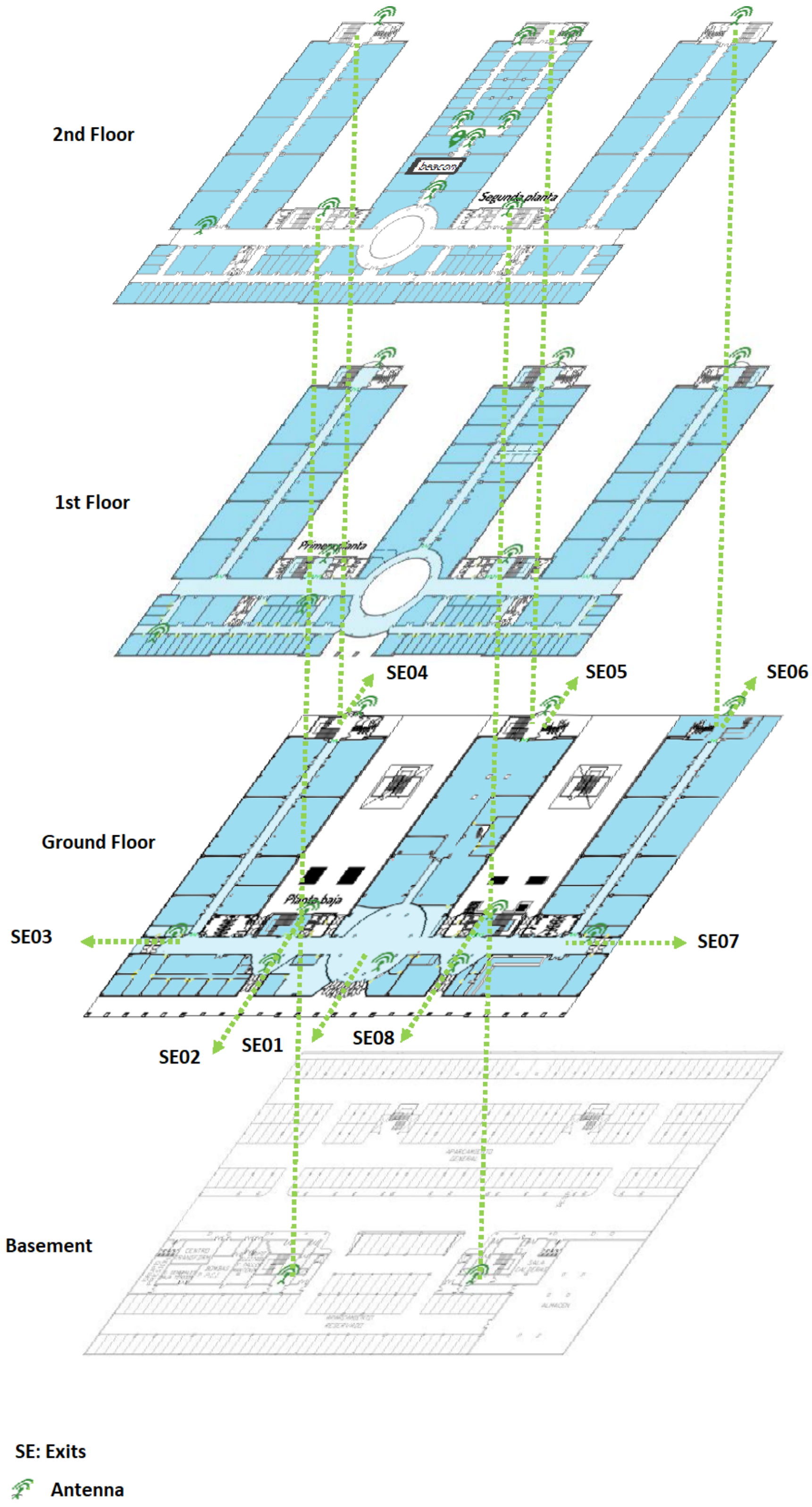

Figure 4.12: Representation of building and antennas.

users connected to the website, so they can see how the evacuation was developing, allowing the detection of anomalous behaviors. Real-time visualization provides the opportunity to have more and better information so that those responsible for the drill can make decisions in the event of difficulties in the evacuation.

The storage of information in a cloud-based service outside the building, in order to both prevent their loss and to allow to further study the individual and collective behaviors, in order to improve protocols and evacuation conditions.

The system has proven its robustness, being able to recover from a software bug (a NaN division) that did not arise in previous tests. This failure gave us the opportunity to improve the system.

It also allows to have objective and quantified data of human behavior during simulated emergencies, allowing its future use in real environments.

The location of all people at real time would be desirable to ensure their safety and abandonment of the building in case of evacuation. However, it is important to find a compromise solution with respect to privacy in places of these characteristics. In other types of enclosures, where access security issues are restricted, for example, nuclear power plants, high-risk laboratories, etc., those responsible can decide to make the use of such a system mandatory.

4.4.5 Summary

As part of the PERIL project, we develop a system that allows the collection and storage of objective data in an evacuation drill. The data is accessible at real time with a web-based interface that allows the persons in charge to visualize where each person is on the building map.

This new approach to the study of evacuations has two main advantages. First, it allows to use the information at real time, which improves the decision-making process for the optimal management of the evacuation. Second, the data is stored in a cloud-based service outside the building, in order to prevent their loss and to allow their use for further study and analysis. This analysis would both allow to look for ways to improve the emergency protocols, and to study human behavior in emergency evacuations, to be able to contrast current mathematical models with real data.

Through the application of the location of the individuals inside the buildings in evacuation drills, and then in emergencies themselves, we are able to evolve the traditional model towards a more dynamic management of evacuations. This will allow obtaining data to study the individual human behavior in the evacuations at an affordable cost. The key to these new opportunities in the field of emergencies is to adapt and customize the tools of indoor location and IoT to the needs of these cases. This is the goal of the PERIL project (Prevention of Emergency Risk by Indoor Localization).

4.5 Conclusions on the use of this type of technology in the study of evacuation drills

In this chapter, we have seen how Indoor localization technologies or indoor positioning systems (IPS) open up a wide field of possibilities for observing and measuring more parameters within evacuation drills.

We have studied the system to achieve the highest quality and reliability, while preserving the lowest possible cost (study of the influence of the RPi- Raspberry Pi board-), always with the aim of feeding the building evacuation models.

We present XtremeLoc, an indoor positioning system that is both affordable and effective. XtremeLoc uses low-cost, Bluetooth Low Energy devices to broadcast a signal that is received by a set of fixed antennas. This information is sent to a server that uses a trilateration algorithm to locate the emitter with a precision of around 2-3 meters, enough for a myriad of purposes, including the location of people in evacuations. We have also developed a more precise yet somewhat more expensive solution, that offers a precision of around 10 cm, using Ultra Wideband technology. This more expensive technology also offers useful applications for evacuations, such as supporting and helping people with disabilities who need more precise directions in an emergency.

We also propose an automated system for collecting quantitative information in the drills, based on IPS, which is economically affordable (PERIL project). We have seen that the proposed system has added advantages such as the possibility of seeing what is happening in real time.

With this chapter, we not only see that IPS can have evacuation data to improve its study, but also offers extensive advantages to improve emergency management in real time. These last advantages are not the object of this Ph.D. thesis, but they still have a high added value to be taken into account by companies when considering the implementation of these systems.

Chapter 5

Conclusions

The approach to the study of evacuations in case of emergency and the evacuation times carried out by researchers over the last 50 years has been through an analytical approach of dividing the problem into pieces, from the perspective of an analysis of the timeline.

My research proposes a holistic approach, as a system as a whole, where each building is a black box characterized by a dimensionless parameter that allows different buildings to be differentiated; with the building being the independent variable of the system, while the relationship between the evacuation time and the evacuated people is the dependent variable, thus allowing the evacuations of different buildings to be compared. In addition, the lack of published data on real evacuations has led me to propose an automatic data collection through the help of indoor location technologies and the cloud, as a solution to facilitating future evacuation studies.

This chapter summarizes the work carried out throughout this Ph.D. thesis, emphasizing the contributions, and the answer to the research question formulated at the beginning of this document. Two different main paths are proposed with different ways for this work, to be continued in the future.

5.1 Summary of the results and contributions

The structure of this research has by achieving objectives 1 and 2, made it possible to answer the first question posed; while, by reaching objective 3, the second question can be answered; then, by reaching objective 4, the third question can be answered.

5.1.1 Innovative approach to evacuation drills that allows the creation of a model to compare evacuations from different buildings.

The first contribution of this Ph.D. thesis has been to obtain an innovative approach to evacuation drills that allows a model to be created to compare evacuations from different buildings.

The first objective of this research has been to collect enough data to be able to propose a new model.

This research work has reviewed all the available data since 2010 on building evacuation drills at the University of Valladolid, and it has been able to collect information from 47 evacuation drills in 15 different buildings, where more than 19,000 people participated in total. To do this, a total of 688 volunteers were needed in the drills, who observed 646 points in the 47 drills. At some observation points there were two observers. Twelve of the 15 buildings also had 2 or more drills. A certain degree of representativeness could be expected from the first buildings, while the other three buildings, from which there was only one drill, have been used as a control group. With the collection of this information, this Ph.D. thesis achieved the first of the milestone objetives and it was possible to start researching the on second objective.

Chapter 1.1 summarizes the approaches in the study of evacuations so far. All have essentially consisted of modeling the development of an evacuation in a timeline analysis, modeling the different portions of a system with a multitude of fractions that interact with each other. This thesis has proposed a more holistic approach, because it has given more emphasis to the certainty that the interaction between the different parts of the system is very difficult to model, and the fact that, until now, it was not possible to compare the evacuations of different buildings. This doctoral thesis proposes an approach from the perspective of general systems theory, considering the system as a black box with a series of inputs and outputs. The inputs are the physical characteristics of the building and the number of people evacuated, while the output is the expected evacuation time for those inputs. The evacuation time is understood as the time from when the evacuation notice is given to the entire building (sirens go off throughout the entire building) until the end of the evacuation, defining this ending as when no more people leave the building. The actions linked to possible or eventual rescues are not taken into account.

In chapter 2, we saw that it is possible to characterize buildings for evacuation with a dimensionless analysis, and this value has been used as an independent variable of the system. The relationship between the evacuation time and the people evacuated is the dependent variable. Both variables have made it possible to carry out a regression analysis of the data collected in the drills. The validity of the regression result was checked in two ways: one concerning the coherence of the results with the qualitative observations of the evacuations, and the other with the results of the evacuations of the group of buildings used as a control group. Thus, we have achieved the second objective.

This work has been published in PLOS ONE, listed as a Q1 level journal in Multidisciplinary Sciences in the JCR 2020 index [Miñambres et al., 2020a].

5.1.2 Improvement of the statistical part of the model. Incorporation of other drills from the bibliography of different authors.

Once the second objective has been overcome, the third objective delimits this part of the research. In this part of the study we propose, on the one hand, to improve the mathematical study with a better statistical adjustment, and on the other, to check if there were published data building simulations of other non-university buildings that could provide the sufficient information to be able to apply the proposed model. Both points have been achieved. Five evacuation drills of a building dedicated to the non-university education of underage children were found. The five drills were introduced into the model with very promising results, helping to validate the proposal, since they fit the model perfectly, both with respect to the statistical adjustment and the explanation of the qualitative analysis of the comparison of the observed results. With this work, the proposed model is consolidated as a comparison tool for simulations of buildings that meet certain characteristics of size and use.

This work has been published in Journal of Building Engineering, listed as a Q1 level journal in Safety, Risk, Reliability and Quality in the JCR 2020-21 index [Miñambres et al., 2022].

5.1.3 Use of Indoor Positioning Systems, Xtremeloc and other technology elements that may facilitate data collection in the future.

The fourth objective was to propose an automated system to collect quantitative information in the drills about what goes on inside buildings, using indoor location technologies that are affordable economically, but at the same time provide sufficient data quality to feed building evacuation models.

With our work, we have set out to build a new tool to collect individual data on human location in evacuation drills. The data obtained in this way could be used both for real-time decision-making by emergency managers (such as rescuing people), and for analysis at a later time. This was done with a project financed by the Regional Government of Castile and Leon, named PERIL (Prevention of Emergency Risk by Indoor Localization). The PERIL project verified that it was feasible to carry out the positioning system, as well as collect and store the information that would allow its later study. In addition, it could be observed in real time.

This work was published in the XIX International Conference on Occupational Risk Prevention (ORP2019), Madrid, 5-7th June 2019 [Miñambres and Llanos, 2019].

In addition, it was necessary to make a proposal for a location system that is technically viable and economically affordable. This implies that the architecture of the system, with its components and software, should offer sufficiently adequate solutions to the problem being dealt with.

XtremeLoc is a low-cost indoor localization system that allows persons and goods to be tracked in situations where GPS is not a cost-effective or feasible solution. This work describes the architecture and main features of XtremeLoc, how to use it for positioning people and goods, and to use them to record the behavior of individual people during evacuation drills.

This work was published in Proceedings of the International Conference on Localization and GNSS (ICL-GNSS 2020), Tampere, Finland, 2-4th June 2020 [Miñambres et al., 2020b].

XtremeLoc is a cost-effective solution for tracking people and things. Nevertheless, it offers a limited accuracy of, around two to three meters. This is because the distance is calculated through the strength of the RSSI signal, which is affected by different factors, such as attenuation due to the presence of obstacles and also the relative orientation of the beacons and receiving antennas.

By its nature, the first factor is difficult to handle, although it can be mitigated by collecting several consecutive measurements and using a Kalman filter to reduce the noise. The second factor (that of the influence of the relative orientation of the antennas and beacons) is best studied through controlled experiments. In this stage, we studied the results of using two sets of different RPi boards (3B and 3B +), through empirical experimentation. The result of our experiment showed an important difference between the models of RPi 3B and 3B+.

The work done in this contribution part was accepted and published in Jornadas Sarteco 2020/2021:[Miñambres et al., 2021].

5.2 Answer to the research question

In the context of evacuation drills, the first question was:

Is it possible to find a model that allows evacuations of different buildings to be compared quantitatively, obtaining a prediction and the possibility of noticing behavior patterns?

With the work of this Ph.D. thesis, we have demonstrated that it is possible to find ways to compare evacuations from different buildings quantitatively, obtaining a prediction and noticing behavior patterns.

> This thesis has shown a way to compare the evacuation times among different buildings, obtaining a prediction for the evacuation time thanks to the historical data set available up to now and the characteristics of the evacuated building. We can see if the time is better or worse than expected given and based on this, in order to make more accurate decisions to prioritize interventions in the building or on raising the awareness of the occupants to improve their behavior in the face of evacuation. It has been proved that the model is consistent both in its theoretical approach, and in the coherence of the data provided by the model, both from a qualitative and quantitative point of view. The latter takes into account the fact that the variability of human behavior is very large; while the simplifications made by the dimensional analysis itself and also by using statistics, mean that 100 per cent accuracy cannot be claimed. It is to be expected that the larger the historical data set, the more robust the model's performance will be. One of the important advantages of the model is that its application is simple and has great practical applications for people who want to compare the results of evacuations from the buildings in which they have an interest with those published in this research. It does not require large investments for its application. However, its simplicity does not detract from the solidity of the approach, which has taken into account different fields of science for its theoretical formulation.

The second question was:

Given a model, is it possible to improve it and introduce a building of a related field, but outside the field where the model has been studied?

With the work of this thesis, it has also been possible to verify that it is possible to improve the initial model by refining the statistical part. It has been verified that the model behaves in a robust way when introducing a building of a related field, but outside the university field, a building whose data have been compiled and published by other authors. It is clear that the model remained valid both when analyzed qualitatively and quantitatively.

It has been proven that the mathematical part of the model can be refined, offering better results in the regression analysis.

It has also been proven that it works both with university buildings, that have different functionalities (academic, research, administrative, library, residential,...), and with another building outside the university environment, but with a similar functionality and characteristics to the university buildings studied. The data of the building and its evacuation drills were gathered and published by other authors. This breaks new ground in finding comparisons between buildings from other fields, that is, if sufficient data is made available to the scientific community from routine evacuation exercises from different buildings in different settings.

The third question was the following:

Is it possible to obtain more quantitative information with indoor positioning / location technologies with sufficient quality and low cost,in order to be able to feed this or other study models of evacuations from different buildings?

The work of this doctoral thesis has made it possible to verify that indoor location technologies can be used to collect and store information in the cloud, which allows its treatment and subsequent study. It has been verified by using these location technologies in real drills. In addition, the use of the components of the location system has been refined in such a way that it allows sufficient reliability, while also maintaining a low cost.

This work has shown that the system deployed in the PERIL project allows the individuals that carry the beacons in evacuations to be located. The PERIL project reveals how evacuation information is stored in the cloud for later analysis, using Xtremeloc (the IPS solution used by PERIL), which has also allowed the locations to be shown in real time. In addition, it has been possible to improve the precision of the location system thanks to a controlled experiment. The experiment studied the degree of robust behavior of its components against orientation changes for equal positions.

5.3 Future Work

This Ph.D. thesis is the first step along two complementary research paths. One is directed towards future developments of various aspects of the model described below; while the other is focused on technological developments for the automatic/intelligent collection of evacuation data.

- The model proposed in this work allows the estimation of the evacuation time of a building and its comparison with other buildings. It has been shown to work for a defined scope. The next natural step is to study, in a disaggregated way, whether the same can be done with buildings of a very different nature, such as sports stadiums, transport stations, etc. The study would have to be started separately for each area. At first, we cannot assume that the evacuation of a train station, for example, will be comparable to that of a school or a university research building. It is necessary to remember that, as explained in the development of the thesis, dimensional analysis does not have a single form. It is perfectly conceivable that, in other types of buildings (with other possible bottlenecks that should be studied), other formulas derived from dimensional analysis may obtain better adjustments for estimating evacuation times. Likewise, buildings whose occupation is by people who are not mostly motor and psychologically independent should be studied separately (for example, hospitals, nursing homes, or homes for people with functional diversity, etc.).

- More evacuation data are needed to facilitate further research. The main barrier to obtaining data is not so much a technical problem, but a cost-benefit problem that companies and society should want to assume. IoT and 4.0 technologies offer the opportunity to create synergies; so that, together with other benefits, the advantage of safety for users in the case of emergencies is achieved, and consequently the necessary evacuation data for further research. In the specific contexts of some companies, beacons or other devices may be used to locate employees and other items of value for multiple purposes, including security and safety in case of emergency; since the interests of the company may be organized to justify this investment. However, in environments with other types of users, other strategies would have to be used. For example, in train stations, airports and places where many people converge and where security is a key element, the IPS could be linked to the passage within an app that manages both. For ticketing issues, more precision would be needed than is offered by beacons, but it could be done with UWB. From the Iphone 11 model onwards, the Iphone has UWB. The incorporation of UWB to IOS and Android devices is a clear opportunity to design mobile apps that are incorporated into IPS in general and Xtremeloc in particular. For other types of environments, such as museums, it could also be associated with other types of advantages, such as audio guides also linked to the ticket. It is necessary to remember that the use of UWB requires many more information exchanges than the use of BLE. This fact, added to the forecast of the massive use of the system by the users of this type of building, makes it necessary to incorporate big data in the future development of the system.

Bibliography

[rpi,] Proant Dual Band Niche antenna licensed to Raspberry Pi. Access: Feb 25th, 2020. http://www.proant.se/en/news/2018/04/03/raspberry-pi-model-b-nbi22.htm.

[Adrion, 1993] Adrion, W. R. (1993). Research methodology in software engineering. In *Summary of the Dagstuhl Workshop on Future Directions in Software Engineering" Ed. Tichy, Habermann, and Prechelt, ACM Software Engineering Notes, SIGSoft* (pp. 36–37).

[Aedo et al., 2012] Aedo, I., Yu, S., Díaz, P., Acuña, P., & Onorati, T. (2012). Personalized alert notifications and evacuation routes in indoor environments. *Sensors*, *12*(6), 7804–7827, https://doi.org/10.3390/s120607804.

[Alvear et al., 2013] Alvear, D., Abreu, O., Cuesta, A., & Alonso, V. (2013). Decision support system for emergency management: Road tunnels. *Tunnelling and Underground Space Technology*, *34*, 13–21, https://doi.org/10.1016/j.tust.2012.10.005.

[Amos et al., 2019] Amos, M., Bénichou, N., Gwynne, S., & Kinateder, M. (2019). *NEED: Networking Activities for Enhanced Evacuation Drills: roadmap for enhanced evacuation drills*. National Research Council of Canada. Construction.

[Andrews and Shabani, 2012] Andrews, J. & Shabani, B. (2012). Dimensionless analysis of the global techno-economic feasibility of solar-hydrogen systems for constant year-round power supply. *International journal of hydrogen energy*, *37*(1), 6–18, https://doi.org/10.1016/j.ijhydene.2011.09.102.

[Arteaga and Park, 2020] Arteaga, C. & Park, J. (2020). Building design and its effect on evacuation efficiency and casualty levels during an indoor active shooter incident. *Safety science*, *127*, 104692, https://doi.org/10.1016/j.ssci.2020.104692.

[Buckingham, 1914] Buckingham, E. (1914). On physically similar systems; illustrations of the use of dimensional equations. *Physical Review*, *4*(4), 345.

[Butler et al., 2017] Butler, K., Kuligowski, E., Furman, S., & Peacock, R. (2017). Perspectives of occupants with mobility impairments on evacuation methods for use during fire emergencies. *Fire Safety Journal*, *91*, 955–963, https://doi.org/10.1016/j.firesaf.2017.04.025.

[Cantón Paterna et al., 2017] Cantón Paterna, V., Calveras Auge, A., Paradells Aspas, J., & Perez Bullones, M. A. (2017). A bluetooth low energy indoor positioning system with channel diversity, weighted trilateration and kalman filtering. *Sensors*, *17*(12), 2927, https://doi.org/10.3390/s17122927.

[Capote et al., 2013] Capote, J., Alvear, D., Abreu, O., Cuesta, A., & Alonso, V. (2013). A real-time stochastic evacuation model for road tunnels. *Safety Science*, *52*, 73–80, https://doi.org/10.1016/j.ssci.2012.02.006.

[Chunmiao et al., 2012] Chunmiao, Y., Chang, L., Gang, L., & Peihong, Z. (2012). Safety evacuation in building engineering design by using buildingexodus. *Systems Engineering Procedia*, *5*, 87–92, https://doi.org/10.1016/j.sepro.2012.04.014.

[Cuesta et al., 2015] Cuesta, A., Abreu, O., & Alvear, D. (2015). *Evacuation modeling trends*. Springer.

[Cuesta et al., 2017a] Cuesta, A., Abreu, O., Balboa, A., & Alvear, D. (2017a). Real-time evacuation route selection methodology for complex buildings. *Fire Safety Journal*, *91*, 947–954, https://doi.org/10.1016/j.firesaf.2017.04.011.

[Cuesta and Gwynne, 2016] Cuesta, A. & Gwynne, S. (2016). The collection and compilation of school evacuation data for model use. *Safety science*, *84*, 24–36, https://doi.org/10.1016/j.ssci.2015.11.003.

[Cuesta et al., 2017b] Cuesta, A., Ronchi, E., Gwynne, S. M., Kinsey, M. J., Hunt, A. L., & Alvear, D. (2017b). School egress data: comparing the configuration and validation of five egress modelling tools. *Fire and Materials*, *41*(5), 535–554, https://doi.org/10.1002/fam.2405.

[De Angelis et al., 2009] De Angelis, A., Dionigi, M., Moschitta, A., Giglietti, R., & Carbone, P. (2009). Characterization and modeling of an experimental uwb pulse-based distance measurement system. *IEEE Transactions on Instrumentation and Measurement*, *58*(5), 1479–1486, https://doi.org/10.1109/TIM.2008.2009204.

[de Blasio et al., 2019] de Blasio, G. S., Rodríguez-Rodríguez, J. C., García, C. R., & Quesada-Arencibia, A. (2019). Beacon-related parameters of bluetooth low energy: development of a semi-automatic system to study their impact on indoor positioning systems. *Sensors*, *19*(14), 3087, https://doi.org/10.3390/s19143087.

[Derrough, 2013] Derrough, J. (2013). *Instant Interactive Map Designs with Leaflet JavaScript Library How-to*. Packt Publishing Ltd.

[Ding et al., 2021] Ding, N., Chen, T., Zhu, Y., & Lu, Y. (2021). State-of-the-art high-rise building emergency evacuation behavior. *Physica A: Statistical Mechanics and Its Applications*, *561*, 125168, https://doi.org/10.1016/j.physa.2020.125168.

[Dong et al., 2019] Dong, H., Zhou, M., Wang, Q., Yang, X., & Wang, F.-Y. (2019). State-of-the-art pedestrian and evacuation dynamics. *IEEE transactions on intelligent transportation systems*, *21*(5), 1849–1866, https://doi.org/10.1109/TITS.2019.2915014.

[Feldmann et al., 2003] Feldmann, S., Kyamakya, K., Zapater, A., & Lue, Z. (2003). An indoor bluetooth-based positioning system: Concept, implementation and experimental evaluation. In *International Conference on Wireless Networks*, volume 272: Citeseer.

[Forno et al., 2005] Forno, F., Malnati, G., & Portelli, G. (2005). Design and implementation of a bluetooth ad hoc network for indoor positioning. *IEE proceedings-Software*, *152*(5), 223–228, https://doi.org/10.1049/ip-sen:20045027.

[Forrest et al., 2018] Forrest, J. Y.-L., Forrest, & Strauss (2018). *General Systems Theory*. Springer.

[Gao et al., 2020] Gao, H., Medjdoub, B., Luo, H., Zhong, H., Zhong, B., & Sheng, D. (2020). Building evacuation time optimization using constraint-based design approach. *Sustainable cities and society*, *52*, 101839, https://doi.org/10.1016/j.scs.2019.101839.

[Gento et al., 2001] Gento, A. M., Minambres, M. D., Redondo, A., & Perez, M. E. (2001). Qfd application in a service environment: a new approach in risk management in an university. *Operational Research*, *1*(2), 115–132, https://doi.org/10.1007/BF02936289.

[Gibbings, 2011] Gibbings, J. C. (2011). *Dimensional analysis*. Springer Science & Business Media.

[Gomez et al., 2012] Gomez, C., Oller, J., & Paradells, J. (2012). Overview and evaluation of bluetooth low energy: An emerging low-power wireless technology. *Sensors*, *12*(9), 11734–11753, https://doi.org/10.3390/s120911734.

[Groeneveld and Meeden, 1984] Groeneveld, R. A. & Meeden, G. (1984). Measuring skewness and kurtosis. *Journal of the Royal Statistical Society: Series D (The Statistician)*, *33*(4), 391–399, https://doi.org/10.2307/2987742.

[Guo et al., 2011] Guo, R.-Y., Huang, H.-J., & Wong, S. (2011). Collection, spillback, and dissipation in pedestrian evacuation: A network-based method. *Transportation Research part B: Methodological*, *45*(3), 490–506, https://doi.org/10.1016/j.trb.2010.09.009.

[Gwynne et al., 2020] Gwynne, S., Amos, M., Kinateder, M., Benichou, N., Boyce, K., van Der Wal, C. N., & Ronchi, E. (2020). The future of evacuation drills: Assessing and enhancing evacuee performance. *Safety science*, *129*, 104767, https://doi.org/10.1016/j.ssci.2020.104767.

[Gwynne and Rosenbaum, 2016] Gwynne, S. & Rosenbaum, E. R. (2016). Employing the hydraulic model in assessing emergency movement. In *SFPE handbook of fire protection engineering* (pp. 2115–2151). Springer.

[Haghani and Sarvi, 2017] Haghani, M. & Sarvi, M. (2017). Stated and revealed exit choices of pedestrian crowd evacuees. *Transportation Research Part B: Methodological*, *95*, 238–259, https://doi.org/10.1016/j.trb.2016.10.019.

[Haghani and Sarvi, 2018] Haghani, M. & Sarvi, M. (2018). Crowd behaviour and motion: Empirical methods. *Transportation Research Part B: Methodological*, *107*, 253–294, https://doi.org/10.1016/j.trb.2017.06.017.

[Haklay and Weber, 2008] Haklay, M. & Weber, P. (2008). Openstreetmap: User-generated street maps. *IEEE Pervasive Computing*, *7*(4), 12–18, https://doi.org/10.1109/MPRV.2008.80.

[Hamilton et al., 2020] Hamilton, G. N., Lennon, P. F., & O'Raw, J. (2020). Toward fire safe schools: analysis of modelling speed and specific flow of children during evacuation drills. *Fire technology*, *56*(2), 605–638, https://doi.org/10.1007/s10694-019-00893-x.

[Huang et al., 2019] Huang, B., Liu, J., Sun, W., & Yang, F. (2019). A robust indoor positioning method based on bluetooth low energy with separate channel information. *Sensors*, *19*(16), 3487, https://doi.org/10.3390/s19163487.

[Hurley et al., 2015] Hurley, M. J., et al. (2015). *SFPE handbook of fire protection engineering*. Springer.

[ISO/TR16738:2009(en), 2009] ISO/TR16738:2009(en) (2009). Fire-safety engineering — technical information on methods for evaluating behaviour and movement of people.

[Jeon et al., 2018] Jeon, K. E., She, J., Soonsawad, P., & Ng, P. C. (2018). Ble beacons for internet of things applications: Survey, challenges, and opportunities. *IEEE Internet of Things Journal*, *5*(2), 811–828, https://doi.org/10.1109/JIOT.2017.2788449.

[Jiang, 2019] Jiang, H. (2019). Mobile fire evacuation system for large public buildings based on artificial intelligence and iot. *IEEE Access*, *7*, 64101–64109, https://doi.org/10.1109/ACCESS.2019.2915241.

[Jianyong et al., 2014] Jianyong, Z., Haiyong, L., Zili, C., & Zhaohui, L. (2014). Rssi based bluetooth low energy indoor positioning. In *2014 International Conference on Indoor Positioning and Indoor Navigation (IPIN)* (pp. 526–533).: IEEE.

[Kinateder et al., 2018] Kinateder, M., Comunale, B., & Warren, W. H. (2018). Exit choice in an emergency evacuation scenario is influenced by exit familiarity and neighbor behavior. *Safety science*, *106*, 170–175, https://doi.org/10.1016/j.ssci.2018.03.015.

[Kinateder et al., 2021] Kinateder, M., Ma, C., Gwynne, S., Amos, M., & Benichou, N. (2021). Where drills differ from evacuations: a case study on canadian buildings. *Safety science*, *135*, 105114, https://doi.org/10.1016/j.ssci.2020.105114.

[Kobes et al., 2010] Kobes, M., Helsloot, I., De Vries, B., & Post, J. G. (2010). Building safety and human behaviour in fire: A literature review. *Fire Safety Journal*, *45*(1), 1–11, https://doi.org/10.1016/j.firesaf.2009.08.005.

[Kodur et al., 2020] Kodur, V., Venkatachari, S., & Naser, M. (2020). Egress parameters influencing emergency evacuation in high-rise buildings. *Fire technology*, (pp. 1–23)., `https://doi.org/10.1007/s10694-020-00965-3`.

[Kuligowski, 2017] Kuligowski, E. (2017). Burning down the silos: integrating new perspectives from the social sciences into human behavior in fire research. *Fire and materials*, *41*(5), 389–411, `https://doi.org/10.1002/fam.2392`.

[Kuligowski and Hoskins, 2011] Kuligowski, E. & Hoskins, B. (2011). Analysis of occupant behavior during a highrise office building fire. In *pedestrian and evacuation dynamics* (pp. 685–697). Springer.

[Kuligowski, 2008] Kuligowski, E. D. (2008). Modeling human behavior during building fires. `https://doi.org/10.6028/nist.tn.1619`.

[Kuligowski, 2009] Kuligowski, E. D. (2009). *The process of human behavior in fires NIST Technical Note 1632*. US Department of Commerce, National Institute of Standards and Technology Gaithersburg.

[Kuligowski, 2015] Kuligowski, E. D. (2015). Burning down the silos: Integrating new perspectives from social science research. In *Proceedings of the 6th International Symposium on Human Behaviour in Fire, Interscience Communications Ltd: London* (pp. 1–12).

[Kuligowski, 2016] Kuligowski, E. D. (2016). Computer evacuation models for buildings. In *SFPE handbook of fire protection engineering* (pp. 2152–2180). Springer.

[Li and Han, 2015] Li, D. & Han, B. (2015). Behavioral effect on pedestrian evacuation simulation using cellular automata. *Safety Science*, *80*, 41–55, `https://doi.org/10.1016/j.ssci.2015.07.003`.

[Li et al., 2017] Li, S., Zhuang, J., & Shen, S. (2017). A three-stage evacuation decision-making and behavior model for the onset of an attack. *Transportation Research Part C: Emerging Technologies*, *79*, 119–135, `https://doi.org/10.1016/j.trc.2017.03.008`.

[Lian et al., 2017] Lian, L., Mai, X., Song, W., Richard, Y. K. K., Rui, Y., & Jin, S. (2017). Pedestrian merging behavior analysis: An experimental study. *Fire Safety Journal*, *91*, 918–925, `https://doi.org/10.1016/j.firesaf.2017.04.015`.

[Liao et al., 2017] Liao, W., Wagoum, A. U. K., & Bode, N. W. (2017). Route choice in pedestrians: Determinants for initial choices and revising decisions. *Journal of The Royal Society Interface*, *14*(127), 20160684, `https://doi.org/10.1098/rsif.2016.0684`.

[Lin, 2006] Lin, Y. (2006). *General systems theory: A mathematical approach*, volume 12. Springer Science & Business Media.

[Liu et al., 2020] Liu, H., Chen, H., Hong, R., Liu, H., & You, W. (2020). Mapping knowledge structure and research trends of emergency evacuation studies. *Safety science*, *121*, 348–361, `https://doi.org/10.1016/j.ssci.2019.09.020`.

[Lovreglio et al., 2016] Lovreglio, R., Fonzone, A., & Dell'Olio, L. (2016). A mixed logit model for predicting exit choice during building evacuations. *Transportation Research Part A: Policy and Practice*, *92*, 59–75, `https://doi.org/10.1016/j.tra.2016.06.018`.

[Lovreglio et al., 2014] Lovreglio, R., Ronchi, E., & Borri, D. (2014). The validation of evacuation simulation models through the analysis of behavioural uncertainty. *Reliability Engineering & System Safety*, *131*, 166–174, `https://doi.org/10.1016/j.ress.2014.07.007`.

[Lovreglio et al., 2015] Lovreglio, R., Ronchi, E., & Nilsson, D. (2015). A model of the decision-making process during pre-evacuation. *Fire Safety Journal*, *78*, 168–179, `https://doi.org/10.1016/j.firesaf.2015.07.001`.

[Macagno, 1971] Macagno, E. O. (1971). Historico-critical review of dimensional analysis. *Journal of the Franklin Institute*, *292*(6), 391–402, `https://doi.org/10.1016/0016-0032(71)90160-8`.

[Miñambres et al., 2004] Miñambres, M. D., Gento, A. M., Redondo, A., & Pérez, M. E. (2004). Prevención de riesgos en un centro universitario mediante el despliegue de la función de calidad (qfd). *Dirección y Organización*, (30), `https://doi.org/10.37610/dyo.v0i30.123`.

[Miñambres and Llanos, 2019] Miñambres, M. D. & Llanos, D. R. (2019). Peril: Prevention of emergency risks by indoor localization. In *Proceeding on the XIX international Conference of Occupational Risk Prevention* (pp. 979–984). `http://www.prevencionintegral.com/en/canal-orp/papers/orp-2019/peril-prevention-emergency-risks-indoor-localization`.

[Miñambres et al., 2020a] Miñambres, M. D., Llanos, D. R., & Gento, A. M. (2020a). Study of historical evacuation drill data combining regression analysis and dimensionless numbers. *PloS One*, *15*(5), e0232203, `https://doi.org/10.1371/journal.pone.0232203`.

[Miñambres et al., 2022] Miñambres, M. D., Llanos, D. R., & Gento, A. M. (2022). Extending and validating a theoretical model to predict the effectiveness of building evacuations. *Journal of Building Engineering*, (pp. 104256)., `https://doi.org/https://doi.org/10.1016/j.jobe.2022.104256` `https://www.sciencedirect.com/science/article/pii/S2352710222002698`.

[Miñambres et al., 2021] Miñambres, M. D., Rojo, V., & Llanos, D. R. (2021). Distance estimation to ble beacons using raspberry pi 3 boards for indoor positioning and social tracking applications. In *Avances en arquitectura y tecnología de computadores. Actas de las Jornadas SARTECO 20/21* (pp. 677–681).: Universidad de Malaga `https://www.infor.uva.es/~diego/docs/empirical-ble.pdf`.

[Miñambres et al., 2020b] Miñambres, M. D., Rojo, V., Román, A., Renero, P., & Llanos, D. R. (2020b). Versatile, low-cost indoor positioning combining bluetooth and ultra wideband technologies. In *ICL-GNSS* `https://www.infor.uva.es/~diego/docs/icl-gnss.pdf`.

[Mirahadi and McCabe, 2020] Mirahadi, F. & McCabe, B. (2020). Evacusafe: building evacuation strategy selection using route risk index. *Journal of Computing in Civil Engineering*, *34*(2), 04019051, `https://doi.org/10.1061/(ASCE)CP.1943-5487.0000867`.

[Mirahadi and McCabe, 2021] Mirahadi, F. & McCabe, B. (2021). Evacusafe: A real-time model for building evacuation based on dijkstra's algorithm. *Journal of Building Engineering*, *34*, 101687, `https://doi.org/10.1016/j.jobe.2020.101687`.

[Mohottige et al., 2020] Mohottige, I. P., Gharakheili, H. H., Vishwanath, A., Kanhere, S. S., & Sivaraman, V. (2020). Evaluating emergency evacuation events using building wifi data. In *IoTDI* (pp. 116–127).

[Moussaïd et al., 2016] Moussaïd, M., Kapadia, M., Thrash, T., Sumner, R. W., Gross, M., Helbing, D., & Hölscher, C. (2016). Crowd behaviour during high-stress evacuations in an immersive virtual environment. *Journal of The Royal Society Interface*, *13*(122), 20160414, `https://doi.org/10.1098/rsif.2016.0414`.

[Ogata, 1980] Ogata, K. (1980). *Ingeniería de control moderna*. Prentice-Hall.

[Ogata, 1995] Ogata, K. (1995). *Discrete-time control systems*. Prentice-Hall, Inc.

[Ogata, 1997] Ogata, K. (1997). *Modern Control Engineering*. Prentice-Hall, Inc.

[Peacock et al., 2012] Peacock, R. D., Hoskins, B. L., & Kuligowski, E. D. (2012). Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories. *Safety Science*, *50*(8), 1655–1664, `https://doi.org/10.1016/j.ssci.2012.01.003`.

[Purser, 2003] Purser, D. (2003). ASET and RSET: Addressing some issues in relation to occupant behaviour and tenability. *Fire Safety Science*, *7*, 91–102, `https://doi.org/10.3801/IAFSS.FSS.7-91`.

[Purser and Bensilum, 2001] Purser, D. A. & Bensilum, M. (2001). Quantification of behaviour for engineering design standards and escape time calculations. *Safety Science*, *38*(2), 157–182, `https://doi.org/10.1016/S0925-7535(00)00066-7`.

[Ronchi et al., 2019] Ronchi, E., et al. (2019). New approaches to evacuation modelling for fire safety engineering applications. *Fire Safety Journal*, *106*, 197–209, `https://doi.org/10.1016/j.firesaf.2019.05.002`.

[Ronchi et al., 2014] Ronchi, E., Kuligowski, E. D., Peacock, R. D., & Reneke, P. A. (2014). A probabilistic approach for the analysis of evacuation movement data. *Fire Safety Journal*, *63*, 69–78, `https://doi.org/10.1016/j.firesaf.2013.11.012`.

[Rostami and Alaghmandan, 2021] Rostami, R. & Alaghmandan, M. (2021). Performance-based design in emergency evacuation: From maneuver to simulation in school design. *Journal of Building Engineering*, *33*, 101598, `https://doi.org/10.1016/j.jobe.2020.101598`.

[Sahinoglu et al., 2008] Sahinoglu, Z., Gezici, S., & Guvenc, I. (2008). Ultra-wideband positioning systems. *Cambridge, New York*, `https://doi.org/10.1017/CBO9780511541056`.

[Seo et al., 2017] Seo, S.-H., Choi, J.-I., & Song, J. (2017). Secure utilization of beacons and uavs in emergency response systems for building fire hazard. *Sensors*, *17*(10), 2200, `https://doi.org/10.3390/s17102200`.

[Serulle and Cirillo, 2017] Serulle, N. U. & Cirillo, C. (2017). The optimal time to evacuate: A behavioral dynamic model on Louisiana resident data. *Transportation Research part B: Methodological*, *106*, 447–463, `https://doi.org/10.1016/j.trb.2017.06.004`.

[Shen et al., 2014] Shen, W., Davis, T., Lin, D. K., & Nachtsheim, C. J. (2014). Dimensional analysis and its applications in statistics. *Journal of Quality Technology*, *46*(3), 185–198, `https://doi.org/10.1080/00224065.2014.11917964`.

[Soewito et al., 2018] Soewito, B., Al Hassyr, F., & Arisandi, T. G. (2018). A systematic literature review of indoor position system accuracy and implementation. In *2018 International Conference on Applied Science and Technology (iCAST)* (pp. 358–362).: IEEE.

[Tavares, 2009] Tavares, R. M. (2009). Evacuation processes versus evacuation models: "Quo vadimus"? *Fire Technology*, *45*(4), 419–430, `https://doi.org/10.1007/s10694-008-0063-7`.

[Tversky and Kahneman, 1974] Tversky, A. & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science*, *185*(4157), 1124–1131.

[Upton and Halfacree, 2014] Upton, E. & Halfacree, G. (2014). *Raspberry Pi user guide*. John Wiley & Sons.

[Vaschy, 1892] Vaschy, A. (1892). Sur les lois de similitude en physique. In *Annales télégraphiques*, volume 19 (pp. 25–28).

[Vignaux and Scott, 1999] Vignaux, V. & Scott, J. (1999). Theory & methods: Simplifying regression models using dimensional analysis. *Australian & New Zealand Journal of Statistics*, *41*(1), 31–41, `https://doi.org/10.1111/1467-842X.00059`.

[Wang et al., 2021a] Wang, D., Yang, Y., Zhou, T., & Yang, F. (2021a). An investigation of fire evacuation performance in irregular underground commercial building affected by multiple parameters. *Journal of Building Engineering*, *37*, 102146, `https://doi.org/10.1016/j.jobe.2021.102146`.

[Wang et al., 2014] Wang, J., Winter, S., Langerenken, D., & Zhao, H. (2014). Integrating sensing and routing for indoor evacuation. In *International Conference on Geographic Information Science* (pp. 268–283).: Springer.

[Wang et al., 2015] Wang, J., Zhao, H., & Winter, S. (2015). Integrating sensing, routing and timing for indoor evacuation. *Fire Safety Journal*, *78*, 111–121, `https://doi.org/10.1016/j.firesaf.2015.08.009`.

[Wang et al., 2021b] Wang, Y., Kyriakidis, M., & Dang, V. N. (2021b). Incorporating human factors in emergency evacuation–an overview of behavioral factors and models. *International Journal of Disaster Risk Reduction*, *60*, 102254, `https://doi.org/10.1016/j.ijdrr.2021.102254`.

[Welch and Bishop, 1995] Welch, G. & Bishop, G. (1995). An introduction to the kalman filter.

[Zhu and Shi, 2016] Zhu, K.-j. & Shi, Q. (2016). Experimental study on choice behavior of pedestrians during building evacuation. *Procedia Engineering*, *135*, 207–216, `https://doi.org/10.1016/j.proeng.2016.01.110`.