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Doctorate in Science and Industrial Technologies

**Modelling and simulation techniques for transport networks
within urban areas applied to logistics and resilience**

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Pamplona, Spain, September 2020

Dedicado a mi familia.

A Hugo y Pau.

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SUMMARY OF THE THESIS

This thesis investigates the use of modelling and simulation techniques in urban areas of smart cities, also exploring how big data can be used to feed these models. These modelling techniques have been applied to two different fields that have been gaining prominence during the last years but where research is still limited: urban logistics and urban resilience. Through this thesis, the author has expanded the research knowledge in these fields by exploring different methods such as meta-heuristics, transport modelling, and agent-based simulation in order to define new methodologies to be applied to urban areas.

Regarding logistics, the author has shown through the use of meta-heuristics that when traffic congestion is considered as a dynamic attribute to optimize delivery routes in urban areas, time can be reduced by 11%, which is crucial for logistics companies in a market that is fiercer every day. This is true not only for urban areas, but this research has also demonstrated that optimizing routes with dynamic congestion attributes is also beneficial at a strategic level for routes between cities. To consider congestion costs in real time, a new approach has been developed in which data from Google is downloaded to feed these meta-heuristic models, although other sources of big data could be also used. In this thesis, a methodology is also presented that has been used to model logistics routes in urban areas considering real-time data and with the flexibility to add different network attributes (gradient, traffic bans, CO₂, etc.) to simulate different scenarios. This can be useful for logistics companies to optimize their deliveries (choosing between van or tricycles, selecting the time of the day to deliver, etc.) but also for public authorities to get guidance on different transport and urban policies (pedestrianization of some streets, traffic bans, etc.).

As for city resilience, the thesis focuses on evacuation planning. A new methodology has been created in which agent-based simulation is used through interconnected sub-models to model a large-scenario evacuation scenario (flooding event as a consequence of a dam collapse). This research defines the data needed to create these models that can be of great help to improve city resilience, and also analyzes how traffic congestion can affect the evacuation procedures.

Through the different research articles that compose this thesis, the author brings light to these fields by developing new methodologies and using real case-studies that can help urban planners, companies, and policy makers to create more efficient, sustainable, and resilient smart cities.

RESUMEN DE LA TESIS

Esta tesis doctoral investiga el uso de técnicas de modelización y simulación en áreas urbanas de ciudades inteligentes, explorando a su vez cómo el big data puede usarse para alimentar estos modelos. Estas técnicas de modelización se han aplicado a dos campos diferentes que han ganado importancia durante los últimos años pero donde la investigación es aún limitada: logística urbana y resiliencia urbana. A través de esta tesis, el autor ha ampliado el conocimiento en estos campos mediante la exploración de diferentes métodos como metaheurísticas, modelización de transporte y simulación basada en agentes de cara a definir nuevas metodologías que se pueden aplicar en áreas urbanas.

En relación al campo de la logística, el autor ha demostrado mediante el uso de metaheurísticas que cuando se considera la congestión del tráfico como un atributo dinámico para optimizar las rutas de reparto en áreas urbanas, el tiempo de reparto puede reducirse en un 11%, lo cual es crucial para las empresas de logística en un mercado que es más feroz cada día. Esto es cierto no solo para áreas urbanas, sino que también se ha demostrado que optimizar rutas considerando la congestión del tráfico también es beneficioso a nivel estratégico para las rutas entre ciudades. Para considerar los costes de congestión en tiempo real, se ha desarrollado un nuevo enfoque en el que se descargan datos de Google para alimentar estos modelos metaheurísticos, aunque también se podrían utilizar otras fuentes de big data. En esta tesis también se presenta una metodología que se ha implementado para modelar rutas logísticas en áreas urbanas considerando datos en tiempo real y con la flexibilidad de agregar diferentes atributos de red (gradiente, direcciones prohibidas, CO2, etc.) de cara a simular diferentes escenarios. Esto puede ser útil para que las empresas de logística optimicen sus entregas (eligiendo entre furgoneta o triciclo, seleccionando la hora del día para entregar, etc.) pero también para servir a las autoridades públicas de guía en materia de políticas urbanas y de transporte (peatonalización de algunas calles, prohibiciones de tráfico, etc.).

En cuanto a la resiliencia urbana, la tesis se centra en la planificación de la evacuación. Se ha creado una nueva metodología en la que se utiliza la simulación basada en agentes a través de submodelos interconectados para modelar un escenario de evacuación a gran escala (evento de inundación como consecuencia del colapso de una presa). Esta investigación define los datos necesarios para crear estos modelos que pueden ser de gran ayuda para mejorar la resiliencia de las ciudades, y también analiza cómo la congestión del tráfico puede afectar los procedimientos de evacuación.

A través de los diferentes artículos de investigación que componen esta tesis, el autor aporta luz a estas cuestiones mediante el desarrollo de nuevas metodologías y el uso de casos de estudio reales con el objetivo de ayudar a planificadores urbanos, empresas y responsables políticos a crear ciudades inteligentes más eficientes, sostenibles y resilientes.

PART I. ABOUT THE THESIS, AUTHORIZATION AND SELECTED ARTICLES.

This thesis is presented as compendium of research articles. This means that the contribution is made by putting together different research papers which have a coherent topic and that have been published (or are ready to be published) in indexed journals or high-impact journals or conferences.

In this thesis, the PhD student has been first author of the majority of the papers except for one where he has been second author. In the ones where he has been first author, he has played a leading role during the whole process, since the proposal of the research up to the publication, including the design of the methodology, data collection exercise, modelling and simulation, and data analysis. In the one where he has been second author, he has developed part of the methodology used.

The presentation of this thesis by compendium of articles has been approved by the thesis advisor and the doctoral committee following the rules of the Public University of Navarra to presenting a thesis in this modality.

AUTORIZACIÓN DEL DIRECTOR DE LA TESIS Y DEL DIRECTOR DEL PROGRAMA DE DOCTORADO A PRESENTAR LA TESIS DOCTORAL *“MODELLING AND SIMULATION TECHNIQUES FOR TRANSPORT NETWORKS WITHIN URBAN AREAS APPLIED TO LOGISTICS AND RESILIENCE”* EN MODALIDAD DE COMPENDIO DE PUBLICACIONES:

Director of the thesis
Fdo.: Dr. Javier Faulin Fajardo

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1. Alvarez P., Lerga I., Serrano A., Faulin J. (2017) Considering Congestion Costs and Driver Behaviour into Route Optimisation Algorithms in Smart Cities. In: Alba E., Chicano F., Luque G. (eds) Smart Cities. Smart-CT 2017. Lecture Notes in Computer Science, vol 10268. Springer, Cham.
SJR (2019): 0.417
2. Alvarez P., Lerga I., Serrano A., Faulin J. (2018) The impact of traffic congestion when optimising delivery routes in real time. A case study in Spain. In: International Journal of Logistics Research and Applications, 21:5, 529-541.
JCR. Impact Factor (2019): 2.152 (Q3); Impact Factor (2018): 2.828 (Q2)
3. Alvarez P., Serrano A., Faulin J., Juan A. (2018) Using modelling techniques to analyse urban freight distribution. A case study in Pamplona. In: Transportation Research Procedia, 33, 67-74.
SJR (2019): 0.476
4. Serrano A., Alvarez, P., Lerga, I., Reyes-Rubiano, L., and Faulin, J. (2017). Pricing and Internalizing Noise Externalities in Road Freight Transportation. In: Transportation Research Procedia, 27: 325-332.
SJR (2019): 0.476
5. Alvarez P., Lerga I., Serrano A., Faulin J. Is time more important than distance to optimize freight delivery routes? An approach using the value of time. Submitted to Transportmetrica B: Transport Dynamics.
JRC. Impact Factor (2019): 2.214 (Q3)
6. Alvarez P., Alonso V. (2018) Using microsimulation software to model large-scale evacuation scenarios. The case of Sangüesa and the Yesa dam collapse. In: Safety Science, 106, 10-27.
JCR. Impact Factor (2019): 4.105 (Q1)
7. Alvarez P., Serrano A., Faulin J., Lerga I. Modelling and simulation of last mile deliveries using the VRP in urban areas. Work in progress (see section 5.2).

PART II. INTRODUCTION

2.1 The importance of transport and logistics

Transport and logistic (T&L) activities are a key sector for worldwide economies, as they contribute to the economic and social progress of modern societies. The transport industry directly employs around 10 million people in the European Union and accounts for about 5% of gross domestic product (GDP). In addition to this, logistics, such as transport and storage, account for 10–15% of the cost of a finished product for European companies (European Commission, 2016). During the last decade, big cities are boosting initiatives and new projects in order to enhance their efficiency, sustainability and resilience. Therefore, T&L activities have an important impact on the development of the so-called smart cities, where big amounts of real-time data (Big Data) are collected through electronic devices and sensors, transmitted through the Internet cloud, and then analyzed using information and expert systems.

By 2050, almost 70% of the world's population is predicted to live in cities that are smart (United Nations, 2015), putting increased strain on urban infrastructure and transport systems. This population growth is leading to an exponential increase in the level of congestion within our metropolis (JRC, 2012), which is producing, on the one hand, several negative externalities within our transport systems such as pollution, noise or accidents. On the other hand, the increased travel times caused by congestion creates transport inefficiencies that also affect urban logistic activities. Adding to that the fact that we live in the one-click Era, where online shopping and on-demand deliveries are changing the way we understand logistics activities within urban areas, it is easy to understand that the way we deliver goods within our urban areas must change too.

In fact, the raise of e-commerce has been especially noted during the 2020 Covid-19 pandemic. During the health crisis, e-commerce in Spain has grown an average of 100% in comparison to the previous year (DCN, 2020). To cope with this increase, the logistic chain, especially the last mile, had to demonstrate resilience and the ability to invent and scale up to a level that was not imagined before, even through the use of robots and autonomous vehicles (see section 2.3.5). However, the conditions in the last mile during the pandemic, without traffic and with people always present at home to receive the parcels, are very different from those from a normal situation in which city centres are congested and where several delivery attempts are needed when people are not at home. With the new normality, people who started buying online during the lockdown will keep doing it (Daimiel, 2020), but with urban areas going back to normal, the situation for last mile carriers will be more complex. If we consider that 40% the logistics companies in Spain have been affected by a temporary lay-off during the pandemic, and that between 25 and 50% of the trips were lost (AECOC, 2020), last mile operators will need to adapt to this new and complex reality.

In this new reality, it is becoming more frequent that the product demand, the driver availability, the mode of transport (truck, bike, tricycle, or electric vehicle, autonomous vehicle or drone in a future scenario), and their position in the map is not known in advance. In these cases, where local conditions are in constant change, the application of traditional approaches –and therefore, the strategic planning process- become unfeasible.

Making use of Big Data collated through on-street sensors, in-vehicle technology and intelligent transport systems is crucial to consider dynamic local conditions (such as congestion, accidents or road closures) in order to optimize delivery routes in a realistic way. Furthermore, with our city centers becoming more sustainable by restricting the access to internal combustion engine vehicles, other modes to deliver goods -electric tricycles, autonomous vehicles or drones- need to be studied to

understand their strengths and limitations. Traffic simulation tools are also in place to help us with this approximation.

In light of the above, it is important to review the evolution of urban logistics during the last decades to understand what the current limitations existing in the field are. Focusing on urban areas, an analysis of the cutting-edge technologies related to logistics, smart cities and urban planning be undertaken to study the role technology needs to play for the future of urban logistics and urban planning.

2.2 Research on smart cities

The concept of smart cities has been a much talked-about topic during the last years, and the interest of the research community on this topic has drastically grown as seen in Figure 1, with almost 5000 papers related to “smart cities” written and indexed in Scopus in 2019.

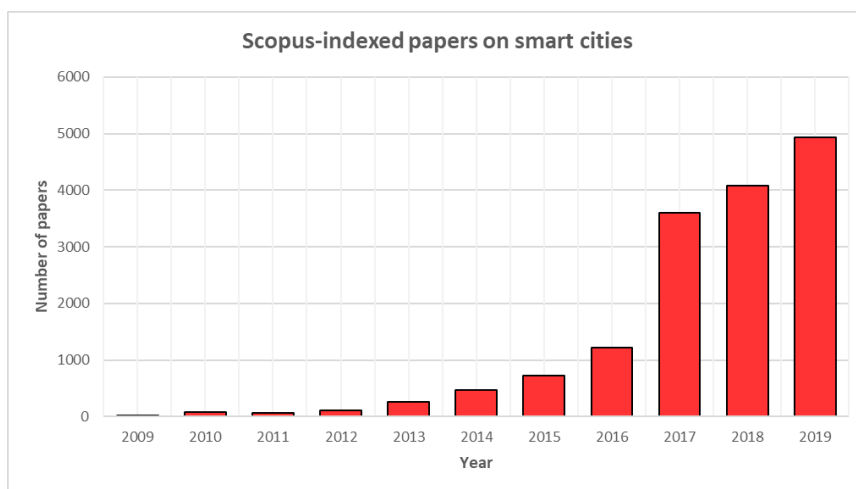


Figure 1. Research interest on “smart cities” in the last years. Papers shown have “smart city” or “smart cities” as a keyword.

However, as already mentioned by Caragliu et al. (2019) in their paper “Smart Cities in Europe”, the concept “smart city” is still quite vague and fuzzy, and the definitions are usually biased towards information and communication technology (ICT) topics, where the Internet is the key identifier of a smart city. According to these authors, a city is smart when

“investments in human and social capital and traditional transport and modern ICT communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance.”

Batty et al. (2012) in an article entitled “Smart cities of the future”, also mentioned that smart cities are often pictured as

“constellations of instruments across many scales that are connected through multiple networks which provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city”.

But the authors also pointed out that cities can only be smart if

“there are intelligence functions that are able to integrate and synthesize this data to some purpose, ways of improving the efficiency, equity, sustainability and quality of life in cities”.

In summary, cities can only be smart if we are smart at using the existing technology (Batty, Axhausen, Giannotti, Pozdnoukhov, & Bazzani, 2012) in order to get advantage of the known information.

In general, the term “transport” or “movement of people” constantly appears in different papers related to smart cities. This goes in parallel with international and national institutions who have invested efforts to create strategies to achieve smart urban growths and resilient planning within our metropolitan areas. Examples of this are the United Smart Cities (USC) program initiated by UNECE which is focused, among other things, on urban mobility (United Nations, 2018), or the European Innovation Partnership on Smart Cities and Communities (EIP-SCC), which is an EU funding instrument that brings together cities, industries and citizens to improve urban live through sustainable integrated solutions and for which sustainable urban mobility and resilience is one of the main research topics (European Commission, 2018).

However, in the existing literature on smart cities, most of the current research does not directly relate to transport, and the studies that focus on urban logistics or urban resilience are almost negligible. For example, if we use Scopus to find all the papers from the last with the keyword “smart city” (or “smart cities”), we find that most of the keywords of those papers are related to Internet of Things (IoT), and Big Data. Figure 2 is a keywords map that has been elaborated using the software VOSviewer.

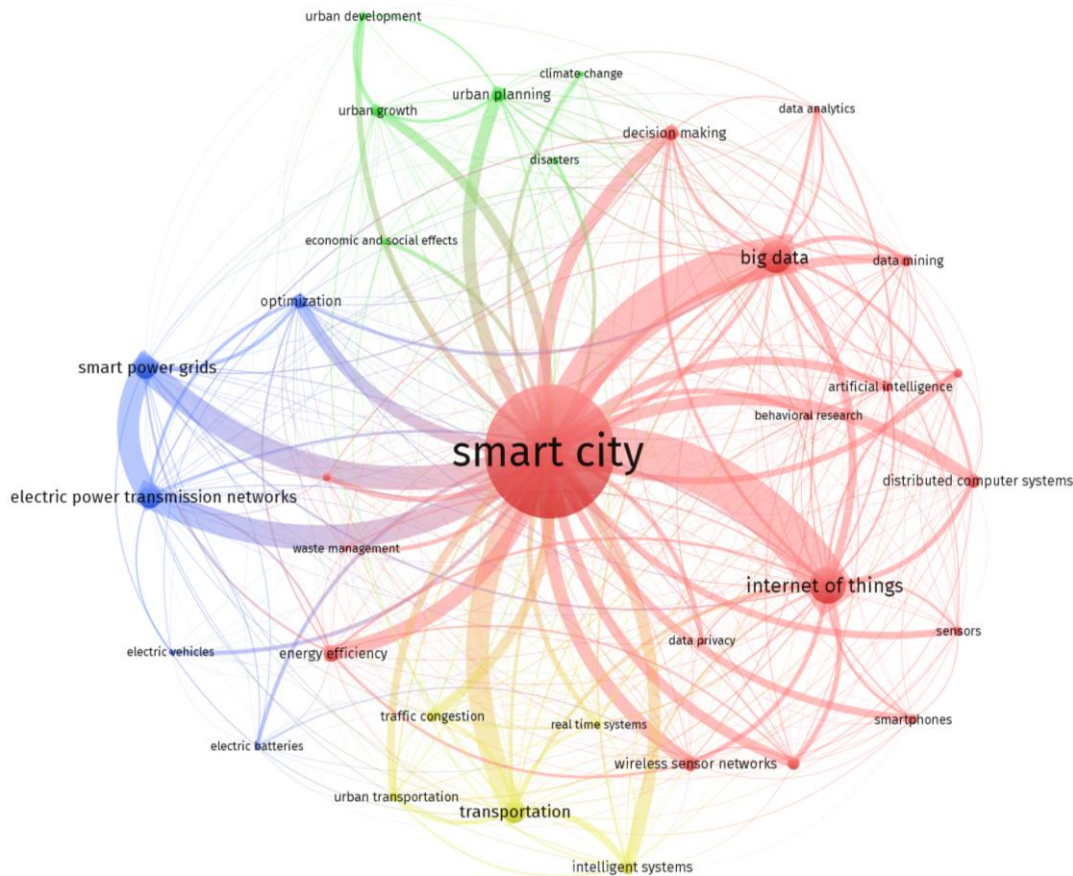


Figure 2. Keywords map created with VOSviewer using bibliographic data from Scopus when looking for the keyword “smart city”.

Figure 2 shows a map where the main keywords for all the papers in which one of the keywords is “smart city”, and the strength of the link indicates how relevant the interconnection between the rest of the keywords are. This keywords map can give us an idea on how relevant those keywords are for papers related to smart cities. For example, the most important keywords are, as mentioned before, “Internet of Things” and “Big Data”, following by “advanced analytics”, and “embedded systems”. We can see how the thickest links are between “smart city” and “Big Data”, and between “smart city” and “Internet of Things”, being the rest of the links much thinner (for example “smart city” and “urban transportation” or “traffic congestion”; or “smart city” and “disasters” or “climate change”). This may indicate that, although there are some papers focusing on smart cities and transport, traffic, and disasters, the current research on smart cities is still focused on the technology behind that (IoT and Big Data).

Looking at Figure 2, four different clusters can be identified. The biggest cluster (in red) is represented by all the topics (keywords) related to Big Data, IoT, sensors, artificial intelligence, cloud computing, analytics, and data mining. This is the most well-known cluster amongst the general population, as it is focused on the technology needed behind our smart cities. The next big cluster (blue) is the one related to smart power grids and energy, and it also includes topics such as waste management, and electric vehicles. The third cluster (yellow) is transport, and the research in this field is mainly focused on urban intelligent transport systems and real-time systems including the study of the traffic congestion within smart cities. However, there are no keywords related to logistics or urban freight distribution. Although research on logistics within smart cities exists, it is limited as it will be shown in the next chapters. Finally, the last cluster (green) deals with urbanism from a more social point of view: urban growth,

planning, economic effects, disasters management, climate change, etc. In fact, this cluster could also fall under the umbrella of “resilience”, a keyword that is not often mentioned (in comparison with the other clusters) in research papers on smart cities.

Of course, it is necessary to note that these four clusters are a simplification of the existing literature, and just the keywords with a high co-occurrence have been selected, i.e. when looking for the keyword “smart city”, just the ones that appear more than twenty times in the Scopus database have been considered. Nevertheless, this draws a good picture of the current state of the art on smart cities, where certain topics such as urban logistics or resilience are much less explored in comparison to others like IoT or Big Data.

2.3 Evolution of urban logistics within smart cities

Following a similar approach as before, Figure 3 shows the research evolution on urban logistics within smart cities, split into different groups: papers related to 1) “urban logistics” or “city logistics”, 2) “smart logistics” (or “smart cities” and “urban logistics”), 3) “electric vehicles” and “urban logistics”, and 4) “drones” and “urban logistics” (or “aerial vehicles” and “urban/city logistics”).

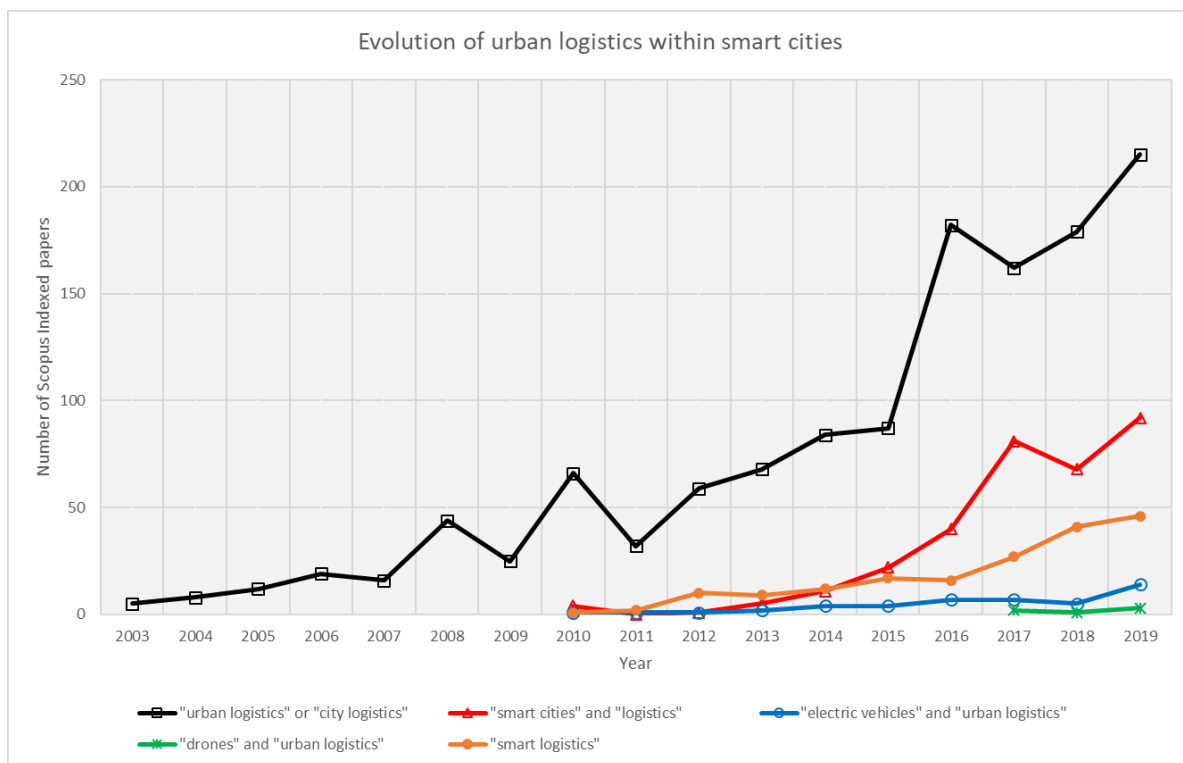


Figure 3. Evolution of research on urban logistics and smart logistics.

With the increased focus put on smart cities and sustainable urbanism, the number of papers related to urban or city logistics is also increasing. However, research on logistics within smart cities (red in Figure 3) only started in 2010, and in 2019 there were only 92 papers published on this topic, in comparison to the 5000 papers related to smart cities that were indexed during the same year (see Figure 1). This means that there was only one publication on logistics and smart cities for every 54 publications on smart cities, which represents less than 2%. However, the fact that a paper focuses on logistics within smart cities does not imply that it is about “smart logistics”. If we check the number of papers directly

related to “smart logistics”, we see that there were only 46 in 2019, therefore less than 1% of the paper on smart cities are related to smart logistics. We can also see how research studies linked to the use of electric vehicles for urban logistics just started a few years ago in 2010, almost in parallel to the research focused on smart logistics, and, since then, the research in this areas has not increased much, although the number of Scopus indexed papers increased to 14 in 2019. Regarding the use of drones or aerial vehicles in urban logistics, there were just 3 papers written in 2019. It is possible that there are more papers related to drones, electric vehicles or urban logistics than the ones captured through this methodology, either because they are not Scopus-indexed papers or for any other reasons. For example, the keywords the authors used did not include the terms we are selecting, or the research was not published. However, the approach taken here provides good insights that allows having a solid point of view on the relevance of urban logistics for the research community.

Moreover, we can now wonder about the characteristics and specificity of urban logistics in smart cities. Thus, if current research in urban logistics is not being focused on electric vehicles, smart cities or drone deliveries (as indicated in Figure 3), what are then the main topics that researchers are currently involved in? In other words, how is the research community taking the challenge of urban logistics? To answer this, we have created another keywords map, in which all the keywords related to papers that contain the keyword “urban logistics” or “city logistics” are represented and interconnected.

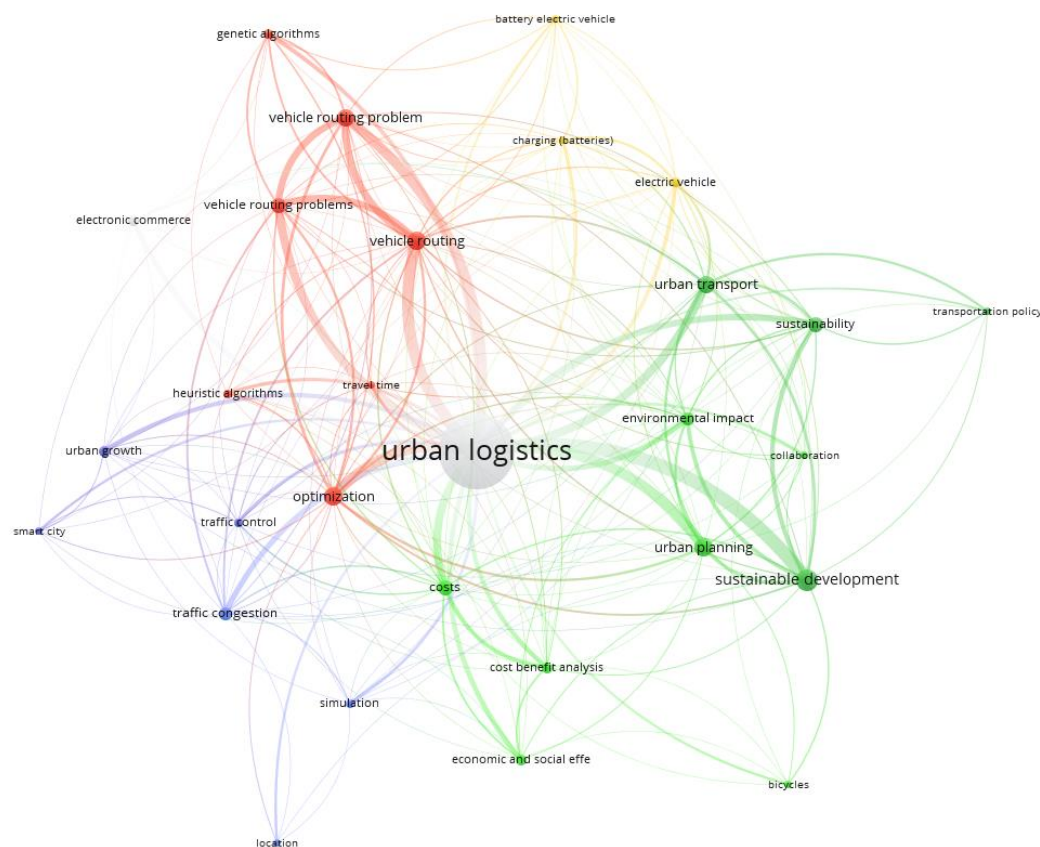


Figure 4. Keywords map created with VOSviewer using bibliographic data from Scopus when looking for the keyword “urban logistics”.

Figure 4 represents the keywords map for the label “urban logistics”. Unlike Figure 2, here the clusters are less defined. This makes sense because at this detailed level (urban logistics), the different fields tend to overlap. However, one can see how the most relevant topic in literature on urban logistics is the vehicle routing problem (VRP), especially the use of algorithms (heuristics and genetic algorithms) to

optimize routes for a vehicle or fleet of vehicles doing deliveries. The other big topic is related to sustainability and urban planning, including environmental impacts and transport policy aspects. As observed in Figure 3, and partially related to sustainability, papers focusing on electric vehicles, batteries and charging stations also appear but in a much smaller scale. We can also see that the number of papers in which traffic congestion is connected to urban logistics activities is very scarce and usually this research only focuses on the congestion effects of logistics without considering a more holistic view (for example connected to the VRP or the environmental impacts). Finally, other keywords such as drones are not present, and other important ones for city logistics, such as location of warehouses or cycle-logistics (bicycles and tricycles), have a limited impact in the research field of urban logistics.

In the next subsections, some important topics of interest related to urban logistics will be explored, focusing on the VRP, electric vehicles, cycle logistics, and drones. The idea is to better understand the current state of the art in these specific fields.

2.3.1 New approaches to optimize delivery routes within urban areas

In logistics, route optimization (also known as the “vehicle routing problem” or VRP) of vehicles (usually trucks and vans) is crucial to minimize transport costs and to be able to compete in a market that is fiercer every day (Faulin et al., 2005). There are tools in place based on heuristics algorithms that allow logistic companies to know which route the vehicle (or fleet of vehicles) should follow to save costs (money, CO₂ emissions, fuel, etc.). The inputs needed for these tools are usually easy to obtain, and basically these are a set of customers (their locations and demands), the capacity of the vehicle, the location of the depot, and the topology of the network (distances and/or times between the different nodes). There may exist other inputs that can be used for more advanced algorithms, such as the time window for each delivery, the different vehicles composing the fleet, the emissions per kilometre travelled, noise, and the driving range, amongst others (Sanchez et al., 2018; Denant-Boèmont et al., 2018). Although it is true that small companies usually optimise routes based on their experience instead of with these tools, this approach is not efficient when the complexity of the problem increases.

However, most of the applications of the vehicle routing problem are still focused at a strategic level (i.e. routes between cities) where most of the approaches aim at minimizing a distance-based cost function without considering other aspects such as congestion effects, transport infrastructure, or driver behavior (Álvarez et al., 2017).

The first Scopus-indexed papers related to VRP were published in the 1970s. In fact, the first one was a piece of research in which the authors developed an approach to optimize public service vehicle routes (Golden, Magnanti, & Nguyen, 1972). During the next twenty years, the knowledge on this field was consolidated, and it was not until the 1990s when the number of publications started to increase exponentially. It was also then when specific papers focused on VRP for logistic activities started to be indexed, although Daganzo published the first one in 1984 (Daganzo, 1984).

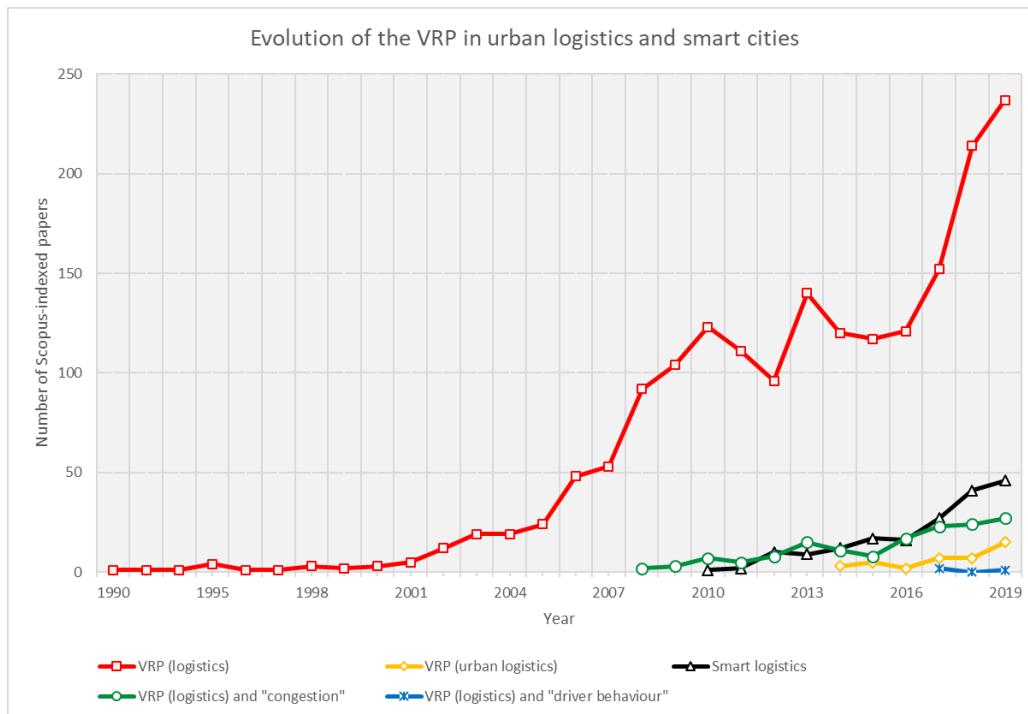


Figure 5. Evolution of papers related to route optimisation (VRP), urban logistics, and smart logistics.

As seen in Figure 5, until 2010, research on VRP was mostly focused on a strategic (macroscopic) level, but the research community commenced to adopt a more micro-level perspective and the study on urban logistics started to be considered, complemented by publications on smart logistics that began to be indexed also in 2010. With urban logistics and smart cities gaining in prominence during the last years, the number of publications per year on smart logistics has increased to around 50 in 2019. However, Figure 5 shows that VRP papers focused on logistics have ignored congestion and driver behaviour effects until recently, when urban logistics and smart cities started to be considered by different authors, and it was not until 2008 when the first indexed paper appeared to study a VRP that includes queues and dynamic travel times (Woensel et al., 2008). Note that there are just a couple of indexed publication in which the driver behaviour aspects are mentioned (Srinivas & Gajanand, 2017) (Abu Al Hla et al., 2019).

Therefore, it is clear that dynamic conditions such as congestion and driver behavior have been excluded from the literature of VRP until now, and even with the current increase in the number of indexed papers published related to urban logistics and smart cities, these aspects are being disregarded. One of the problems of logistic companies within urban areas is that they do not always operate efficiently which leads towards higher-than-optimal vehicle-kilometers due to their inefficient route planning (Jiang & Mahmassani, 2014). Also, in this one-click era, customers often require urgent deliveries that are forcing couriers to adopt a more flexible route planning process (Anbaroglu, 2017). Therefore, one of the main challenges for urban logistics is to investigate how to optimize efficient and robust routes considering the stochasticity of these urban networks, so it is clear that a deeper understanding is needed on how these dynamic conditions can be implemented in our optimization problems.

Amongst the papers in which congestion effects are considered within the optimization problems, the one by Conrad and Figliozzi (2010) is relevant. These authors studied a case study in Portland, Oregon, making use of the Google Maps API to build the origin-destination matrices considering real network attributes, to then adjust the speeds using detailed historical traffic data from the database PORTAL

which collects data from 436 inductive loops. Doing so, the route is optimized taking congestion and bottlenecks into account. However, the use of historical traffic data instead of real-time data limits their applications, especially in the context of the smart cities.

Nha et al (2012) also highlighted the importance of considering dynamic road traffic conditions (congestion, accidents, etc.) when optimizing routes within smart cities. The authors created a scenario with a specific road network in which the Dijkstra algorithm (1959) is applied. Then, the network was simulated using the microsimulation software SUMO (2001). Every time the vehicle reaches a node of the initial planned route, the software checks whether there are changes in any road segment (link blocked by an accident or congestion), and if it is the case, the algorithm is re-applied ignoring those links. To the best of the authors' knowledge, this paper is the first one in which a simulation software is linked to the optimization algorithm to consider congestion effects. The implementation of this approach was in progress by the time the paper was written so there is a lack of details, for example, on how real traffic data is obtained. In addition, this paper is not specifically focused on logistic activities. However, this paper shows that it is possible to intertwine optimization algorithms with simulation approaches leading to an increase in realism of the route planning processes, especially within smart cities.

The last paper presented here is the one by Kim et al. (2016). In this article, the authors propose a dynamic vehicle routing problem model with stochastic travel times under traffic congestion. To this end, Kim et al. (2016) use a real case of a delivery company based in Singapore with a delivery network that consists of a single depot and multiple customers, where customers demand are known, but travel times between customer locations are time-dependent and stochastic due to traffic congestion. The traffic data were collected from the Land Transport Authority (LTA) in Singapore, which provides historical data from street sensors with which averaged vehicle speeds over time for different road segments can be calculated. When a delivery between two nodes takes place, the Google Maps API is used to obtain the road segments that are part of the arch, and each road segment is linked to the historical speed data from the LTA (which is time-dependent). With the speed information available for each road segment, dynamics of the traffic congestion state and probabilities of each segment are estimated and used as inputs to solve the dynamic vehicle routing problem. The comparison made in this paper between the results obtained through this approach and the current practice by the delivery company in Singapore (that ignores traffic congestion) highlights the potential saving from exploiting historical and real-time traffic congestion information, with a 7% improvement in total travel time. However, the paper is somehow similar to the one written by Conrad and Figliozzi (2010), as they also used the Google API, and shares its limitations, as using historical data instead of real-time data (from Intelligent Transport Systems) can limit the applications of this approach.

Summing up, it is clear that traffic congestion is one of the main challenges within urban logistics. This section has reflected how the research community has ignored this topic for decades whilst scholars were mainly focusing on the application of VRP at a strategic level, where minimizing a distance-based cost function was the main objective. However, traffic congestion is dramatically increasing in our cities, and on-demand deliveries are changing the way we understand logistics activities. This has caused that, in parallel with the development of the so-called smart cities, congestion has raised concern amongst the research community in the last years (see Figure 5).

Considering dynamic conditions, such as traffic congestion, accidents, monotonous drives, and fatigue into route optimization algorithms for logistics is something relatively new (Srivatsa & Gajanand,

2016). Future VRP for urban logistics within smart cities will have these variables in real-time, making use of Intelligent Transport Systems and Big Data technologies (Faulin et al., 2019). Agent-based traffic microsimulation or macrosimulation software can be also implemented as part of the optimization approaches to get realistic insights on how traffic conditions may affect routing and to analyze future and what-if scenarios.

2.3.2 *Electric vehicles for urban logistics*

The rapid pace at which our cities are growing is leading to an increase in the movement of good from external areas into the city centers. According to Zavitsas et al. (2010), urban logistics are responsible for 8-15% of total traffic flow in urban areas (Zavitsas, Kaparias, & Bell, 2010), with trucks causing up to 20% of the congestion in some cities like Paris (Dablanc et al., 2011). Also, a report of the European Commission (European Commission, 2013) highlights that city logistics are responsible for about 6% of the total greenhouse gas (GHG) emissions in urban areas. This could suggest logistics should be a central focus for urban policies, but this is not the case, as the movement of goods is often forgotten in many urban plans and transport policies (Hall & Hesse, 2013) (Dablanc, 2009).

In the last years, and due to the increasing concern about air quality within urban areas, electric vehicles are seen as a potential contributor to reduce some of the environmental impacts caused by urban logistics (Corlu et al., 2020). For example, the 2011 White Paper on transport for the EU (European Commission, 2011) stated that one of the challenges for 2030 is to achieve CO₂-free city logistics in major urban centers. Therefore, electric mobility seems essential to achieve this goal.

However, we are still far from this achievement. One of the main reasons is that the cost to buy an electric vehicle is often higher than conventional vehicles with internal combustion engines (Fenga & Figliozzi, 2012) (Egbue & Long, 2012) (Al-Alawi & Bradley, 2013), and this is mainly due to the cost of the battery itself, although the price is likely to be reduced in the coming years. Also, according to these authors, there are uncertainties when it comes to compare the operational competitiveness of electric trucks or vans with traditional vehicles, as the price of electricity may increase if electric mobility (e-mobility) becomes global. Another important aspect to consider is the technical limitations of electric vehicles (range and speed), who is seen as a major hindrance for their implementation in urban logistics (Duin et al., 2013) (Juan et al., 2014). The battery charging time is also a constraint. Depending on the size of the battery and the equipment used, charging times may vary between thirty minutes and several hours (Department of Energy, 2012). In general, for freight transport, batteries are usually charged overnight, or during the driver's lunch break in order to optimize time (Nesterova et al., 2013). Other options are fast charging stations (Hatton et al., 2013), or stations for battery swapping (CALSTART, 2013), where the depleted battery is replaced by a loaded one. However, in all the cases, an infrastructure investment would be needed, which would increase the cost for the logistic company or for the city council (in case of public charging/swapping stations).

Juan et al (2016) also studied the main challenges that arise as a consequence of introducing electric vehicles in the distribution fleet, and highlighted, amongst others, the following ones: the difficulty in developing infrastructure networks for battery recharging/swapping, the added complexity of additional time-window constraints related to short driving ranges, the severe feasibility constraints imposed using heterogeneous fleets of vehicles (traditional ones mixed with electric vehicles) with different driving ranges, and the economic impact of the introduction of electric vehicles over the entire supply chain. However, according to Pelletier (Pelletier et al., 2014), distance range is not a limitation for electric

vehicles within urban areas, as the typical driving distances travelled by urban delivery vehicles are often lower than the range of commercial electric trucks.

Although literature regarding electric vehicles for urban logistics is limited, there are practical examples in which electric vehicles were tested for last-mile deliveries within urban areas. For example, the European Union is funding different projects to show industry, consumers and policy makers how electric freight vehicles can provide a sustainable solution for our cities, offering a plausible alternative to traditional vehicles, especially when these are complemented with cutting-edge logistics applications, innovative logistics management software, and well-designed local policies. In particular, the project FREVUE (Freight Electric Vehicles in Urban Europe) is a €14 million project that is co-funded by the EU Seventh Framework Programme (FP7) in which 32 local and European partners (both public and private) are concentrated in different capitals such as Amsterdam, London, Madrid, or Stockholm to enable the deployment of electric vehicles performing urban logistics services. The results show environmental benefits, as according to the project report we could reduce up to 45% of emissions in our cities using electric vehicles. But this environmental benefit can be also translated into cost savings. For example, if we could electrify 10% of the freight fleet in London by 2021, we could save over €1 billion in reduced health impacts and negative externality costs like pollution (FREVIEW, 2018).

In another case study in Portugal, Duarte et al. (2016) found out that although the purchase cost of an electric vehicle is 46% higher than a traditional internal combustion engine vehicle, there is also a 65% decrease in operational costs due to electric vehicles. Furthermore, they installed an onboard device to monitor both conventional and electric vehicles. Through this device, they obtained data on driving dynamics such as speed, acceleration, road topography, as well as engine parameters. The results indicated that, for urban logistics, electric vehicles drive similar distances than traditional vehicles (therefore the driving range is not always a constraint), and that average speeds are also similar. Furthermore, the electric vehicles presented an efficiency improvement of 76% on energy per kilometer driven. Based on this, they concluded that electric vehicles are adequate for urban logistics, and that long-term policies are needed to facilitate the purchase of these vehicles, and the deployment of charging stations.

Giordano et al. (2017) also think that governments should provide incentives equal to at least the amount of benefits that electric vehicles bring to the society. They recommend that this could be linked to the replacement of older vans, and they put London and Oslo as examples of cities where current government incentives are even higher than the quantified environmental and health benefits, making electric vans more attractive than traditional ones. On the other hand, Quak et al (2016) consider that although financial incentives are currently the most powerful tool to support the market uptake of electric vehicles, a more integrated city management approach will be needed in the long term.

As we can see, according to the literature, there are pros and cons for using electric vehicles for urban logistics. As a summary, Table 1 shows a SWOT matrix in which the strengths, weaknesses, opportunities, and threats of implementing electric vehicles for urban logistics are shown. Some of the items of the matrix have been taken from Quak et al. (2016), and others have been written by the author considering the existing literature already mentioned.

Table 1. SWOT matrix of electric vehicles compared to internal combustion engines vehicles (using inputs from Quak et al, 2015).

<p>Strengths</p> <ul style="list-style-type: none"> - Low fuel costs - Efficiency of operation in case of government support - Good environmental performance - No noise from the vehicle - Positive acceptance by the public - Access to city centres are sometimes less restricted for electric vehicles. 	<p>Weaknesses</p> <ul style="list-style-type: none"> - High purchase costs - Limited loading capacity - Smaller driving range - No better revenue (limited number of customers paying more for deliveries using electric vehicles) - Lack of appropriate infrastructure (battery charging/swapping stations) - Optimization complexity with large or mixed fleets - Limited availability of vehicles - People and companies are still awaiting as technology keeps improving
<p>Opportunities</p> <ul style="list-style-type: none"> - New vehicles have a higher distance range - There is market within specific niches - Availability of public charging points in some cities - Improvements in battery life - Innovative vehicle/battery leasing schemes - Decrease in battery price - Incentives from public organisms - Transport policies support e-mobility 	<p>Threats</p> <ul style="list-style-type: none"> - Unclear regulation regarding certification - Competition on environmental performance from vehicles running on alternative fuels (biogas or natural gas) - Low fuel prices and increasing energy prices. - Other modes of transports (cycle-logistics) may be preferable for last-mile deliveries - Electric vehicles do not solve the problem of urban congestion - Electric vehicles are nowadays dependent on public incentives

Amongst the different strengths of electric vehicles for their use within smart logistics, we could say that the low fuel costs and the good environmental performance (including less noise) are the main ones. On the contrary, the high purchase costs, the driving range, and the lack of appropriate infrastructure are important limitations. However, there exist opportunities that can make electric vehicles to overtake traditional trucks and vans in the coming years, as transport policies are going towards e-mobility and public organisms are creating incentives for the use of these vehicles. However, it is important to note that these public incentives may not work in the long term, and that there also exist other modes of transport (for example cycle-logistics) that can compete with electric vans and trucks, as these do not really solve traffic congestion problems within urban areas.

2.3.3 *Cycling the last mile*

As seen in the previous section, electric vans and trucks are seen appropriate to fight with the increased pollution existing in our cities. However, the massive use of these electric vehicles will not solve other problems that urban logistics is facing in our current cities: traffic congestion, accidents, limited access to our city centers and lack parking spaces (Boussier et al., 2011). Although sustainable urban mobility plans are defending the shift from the internal combustion engines vehicles to electric ones in the mid-term, they are also trying to enhance the livability of our city centers by limiting the access to motor vehicles. Therefore, cycle-logistics, i.e. the use of bikes and tricycles to deliver goods can be a solution, especially for last mile deliveries. Usually these cycles and tricycles are electrically assisted, with payloads between 150 and 300 kilograms, and volume capacities typically around 1500 liters (Tipagornwong & Figliozzi, 2014).

According to the European project *Cyclelogistics* (Cyclelogistics, 2018), on average 51% of all motorized trips in European cities involving the transport of goods could be shifted to bicycles, cargo bikes, or tricycles. This would generate large benefits for the whole society such as less energy

consumption and CO₂ emissions, reduced congestion, noise levels and pollution, and increase in space for citizens.

The research on cycle-logistics is very scarce, it is mainly focused on the European context, and it is usually related to case studies of specific cities and companies trying to implement cycle-logistics (Schliwa et al., 2015). As an example, in the last decade, just about a dozen of papers linked to cycle-logistics were indexed in Scopus. One of the most relevant is a study by Brown et al (2011), in which they focus on the role that urban consolidation centres (UCCs) play in reducing freight traffic and its environmental impacts in towns and cities. Based on a real case study in London, they use an urban micro-consolidation platform located in the delivery area from which electrically-assisted cargo tricycles do the deliveries, instead of the traditional approach in which vans or trucks travel from their depots to the final customers located in the city centre. Their results indicate that the total distance travelled by parcel delivered decreased by 20%, and the CO₂eq emissions by 54%. This result is in line with a study in Portland, Oregon, where it was found that using electric tricycles for urban deliveries can reduce the annual CO₂ emissions by 50% (Saenz-Esteruelas et al., 2016).

Lenz and Riehle (2013) state that the motivation behind the use of bikes or tricycles by companies (usually small companies) is not just the result of conviction and awareness. The advantages of cycle-logistics in urban areas in comparison with trucks and vans also play an important role. According to the author of this thesis, the main factors that influence a company to start shifting to cycle-logistics are cost factors (bikes and tricycles are cheaper than vans), the higher speed of cycles within city centres in comparison to other vehicles, the advertising impact of cycle freight, and more important the increasing bans on motor vehicles and the restricted vehicle access to the historical/central areas of the cities. During this doctoral thesis, the author has also interviewed two cycle-logistics companies in Spain (*Txita* in San Sebastian, and *Oraintxe* in Pamplona), and both agree on the point that the restricted access (pedestrianized zones, one-way streets, narrow streets, etc.) is the main cause for them to use bikes and tricycles instead of vans, and not the environmental awareness as some people might think.

The Transport for London (TfL) report “*Cycle freight in London: A scoping study*” (TfL, 2009) lists the practical advantages and disadvantages of cycle-logistics, which are listed in Table 2.

Table 2. *Advantages and disadvantages of cycle-logistics (TfL, 2009).*

<p>Advantages</p> <ul style="list-style-type: none"> - <u>Purchase cost</u>: cycles are cheaper than vans. - <u>Operating cost</u>: tax, insurance, storage and depreciation are also lower for cycles than for vans. - <u>Parking costs and congestion-charges</u>: cycles can be parked almost everywhere and congestion-charge schemes do not apply to cycles. - <u>Speed in congestion</u>: journey times are much less affected by traffic conditions. - <u>Driver training requirement</u>: drivers do not require a driving license. - <u>Low environmental impact</u>: although the “green” benefit, as already mentioned, is not the main factor for the existing small companies, larger companies that want to enter the cycle-logistics market can consider it as a relevant factor. 	<p>Disadvantages</p> <ul style="list-style-type: none"> - <u>Security</u>: security concerns is a relevant variable for companies that are not already using cycles, although these fears may be exaggerated, as there are almost no instances of theft of cycles or payload reported. - <u>Limited range</u>: range is an issue when the distribution hubs are far away from the city centres. With secondary hubs located closer to the centre, or with the use of the van itself as a mobile hub range should not be a problem. - <u>Limited payload</u>: this is also an issue when the hubs are far from the delivery points. Also, some companies underestimate the payload of currently available cycles. - <u>Driver fatigue</u>: this can be a problem for a company when existing drivers do not want to switch to using a bike or a tricycle, but this can improve through the use of electrically assisted cycles or tricycles.
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Apart from these practical pros and cons, the report suggests that there also exist practical and human factors regarding the use (or lack of use) of bikes and tricycles for freight transport within urban areas. With regards to the human factors, it is indicated that social perceptions towards cycle-logistics is probably the single largest factor inhibiting the use of cycles in this way. However, among transport and logistics professionals, the issue is related to a lack of information on the vehicles now available, rather than attitudes that are hardened against them. This view is also shared by Schliwa et al (2015), for whom the acceptance of cargo cycles by businesses and customers as a suitable mode of transport is one of the major obstacles identified.

As a parallel research, in 2017, this thesis' author has also studied the social perceptions of different groups towards cycle-logistics in the Old Town of Pamplona (Spain). Results are shown in Table 3, being 0 totally opposite to the use of cycles and tricycles for urban deliveries, with 4 being completely in favour. As it can be seen, the general population has a good opinion of promoting cycle-logistics, probably because its link to sustainability. Logistics companies have also a positive view of these new modes, and this may be caused because they think that, in the specific case of Pamplona, they are needed to improve the efficiency of freight distribution. However, businesses from the Old Town (mostly restaurants, bars and shops) are more negative about this idea, probably because they think that this will affect their businesses, mostly due to the limited capacity of the tricycles and their inability to transport certain goods such as pallets, beer barrels, or fresh products.

Table 3. *Opinion on the promotion of cycle-logistics in the Old Town of Pamplona.*

	Opinion on the promotion of cycle-logistics
Businesses (n=50)	1.82
Logistic companies (n=10)	2.5
General population (n=400)	2.99

Therefore, the literature review has shown that using bikes and tricycles for urban deliveries is feasible (Faulin et al. 2016), especially for last mile deliveries and when the distribution hubs (or urban consolidation centres) are within the delivery area. In comparison to electric vans, electrically assisted cycles have a better accessibility to the city centres, as they can park almost anywhere, and they can sometimes use pedestrianized zones that are restricted to general traffic. However, the limited capacity is one of the biggest disadvantages, although this constraint can be avoided through the creation of urban consolidation centres or logistics micro-platforms close to (or within) the city centres. With cities trying to become more sustainable, new policies are being created to reduce speed limits, narrow traffic lanes, restrict access (or parking) to motor vehicles, or to extend cycling infrastructure in our city centers, which will for sure result in the improvement of the competitiveness of cycle-logistics.

2.3.4 *Is drone delivery a reality?*

If we have pointed before that the research on smart logistics, and especially the one related to electric vehicles and cycle-logistics is limited, the literature on drone deliveries, also known as UAVs (unmanned aerial vehicles) has been inexistent until a couple of years ago. In Scopus, for example, there are only 20 papers (from 2014 and 2019) that contains the keyword “drone delivery”, and most of them focus on theoretical approaches (including the VRP) or case uses not directly related to last-mile deliveries.

Although the media coverage with respect to drones and drone delivery is increasing, this new mode to deliver goods is seen by some experts as a utopic and futuristic technology, as a security and privacy threat by part of the general population, and frightening and improbable by others. Some authors (Jenkins & Vasigh, 2013) think that the proliferation of drones will have a positive impact in the market, for example with about 103,776 new jobs created in the US by 2025 leading to an economic impact that will total \$82.5 billion. However, most of the applications in which drones have already shown a direct applicability are related to photogrammetry, agriculture and environmental monitoring, entertainment, and engineering surveillance. Also, in emergency and rescue management, drone delivery has been found practical to deliver medications and first-aid equipment in devastated areas (Chowdhury et al., 2017) (Fikar et al., 2016).

As for urban logistics, the future of drone delivery is still unclear. It is true that using drones instead of vans would reduce traffic congestion in the city, but the problem might be passed to the sky. According to Anbaroglu (2017), there are many challenges to utilize drones for freight distribution in urban environments. On the one hand, we have the social challenges that are related to physical safety (the parcel or the drone could fall), privacy (sensors and cameras will be installed in the drones), and general perception and acceptance of this new mode of delivery. Secondly, there exist barriers that need to be addressed by the public authorities, such as the tracking of all the drones doing deliveries, or the identification of non-authorized drones. Finally, technological challenges are also important, for example the limited battery life of the drones or their ability to detect humans to maintain minimum separation distances. Kunze (2016) states that one of the key assets for using drones for deliveries in urban areas is the dispensability of drivers, although drone operators might be needed. Also, he mentions other problems for the implementation of drone deliveries such as the noise emission, security (sabotage), safety (harm to humans or to helicopters), local ecological impacts (birdlife), lack of adequate air traffic regulations, and energy efficiency.

Regarding energy efficiency, Figliozzi (2017, 2020) has shown that drones are about 47 times more efficient than typical diesel delivery vehicles in terms of energy consumption, and about 1000 times more in terms of emissions. However, in terms of energy consumption and emissions per unit distance and per kilogram of payload delivered, conventional vans are more efficient, as they can deliver 380 times more cargo than the drone. Furthermore, if electric vans are used, then the drone is not more efficient in case there are more than 10 customers per route, which is usually the case in the last-mile. Also, Figliozzi (2017) states that in dense urban areas tricycles perform also better than drones in terms of both energy consumption and lifecycle CO_{2e} emissions (Figliozzi, 2017).

From this PhD student's point of view, there is a key point that is often forgotten. Transport and logistic infrastructure is also a very important challenge that needs to be addressed before drone deliveries in urban areas become feasible. Even with improved technology that allows to have hundreds of drones above the streets, and even with new legislation and increased social acceptance, we must not forget that the key point of drone delivery is to effectively deliver a parcel. Nowadays, our cities are not prepared to receive drones. We do not have the adequate infrastructure in our houses or blocks of flats. Not everybody has a garden or a balcony where a drone could land. One idea would be to build *droneports* above our buildings or in some tactical places. Another one could be to place lockers in public places that are adapted to receive parcels from drones. Or we could use electric or autonomous vans that park outside the city, and that can send drones guiding them towards an urban consolidation center where tricycles will receive the parcel to then complete the last mile.

There is yet a lot to think about, and a lot to do. In the next years, it will be possible to see drone deliveries in some rural areas in which the constraints of a dense city do not apply. But, if we want to see hundreds of drones flying around our sky, we will need to wait, as we are not there yet.

2.3.5 *Using robots to deliver parcels*

During the Covid-19 pandemic, autonomous robots have become a crucial element for urban deliveries, as the lack of a driver and human contact reduces the possibility of getting infected during a delivery. In the US, robots were already used at airports, universities, or large corporate campuses. For example, the robot delivery service company Starship Technologies, founded in 2014, has completed 100,000 autonomous deliveries and travelled more than 500,000 miles to date (Forbes, 2020). However, during the health crisis, the interest in autonomous vehicles to deliver goods has increased in different countries, and autonomous vehicles have become a sign of resilience in urban logistics.

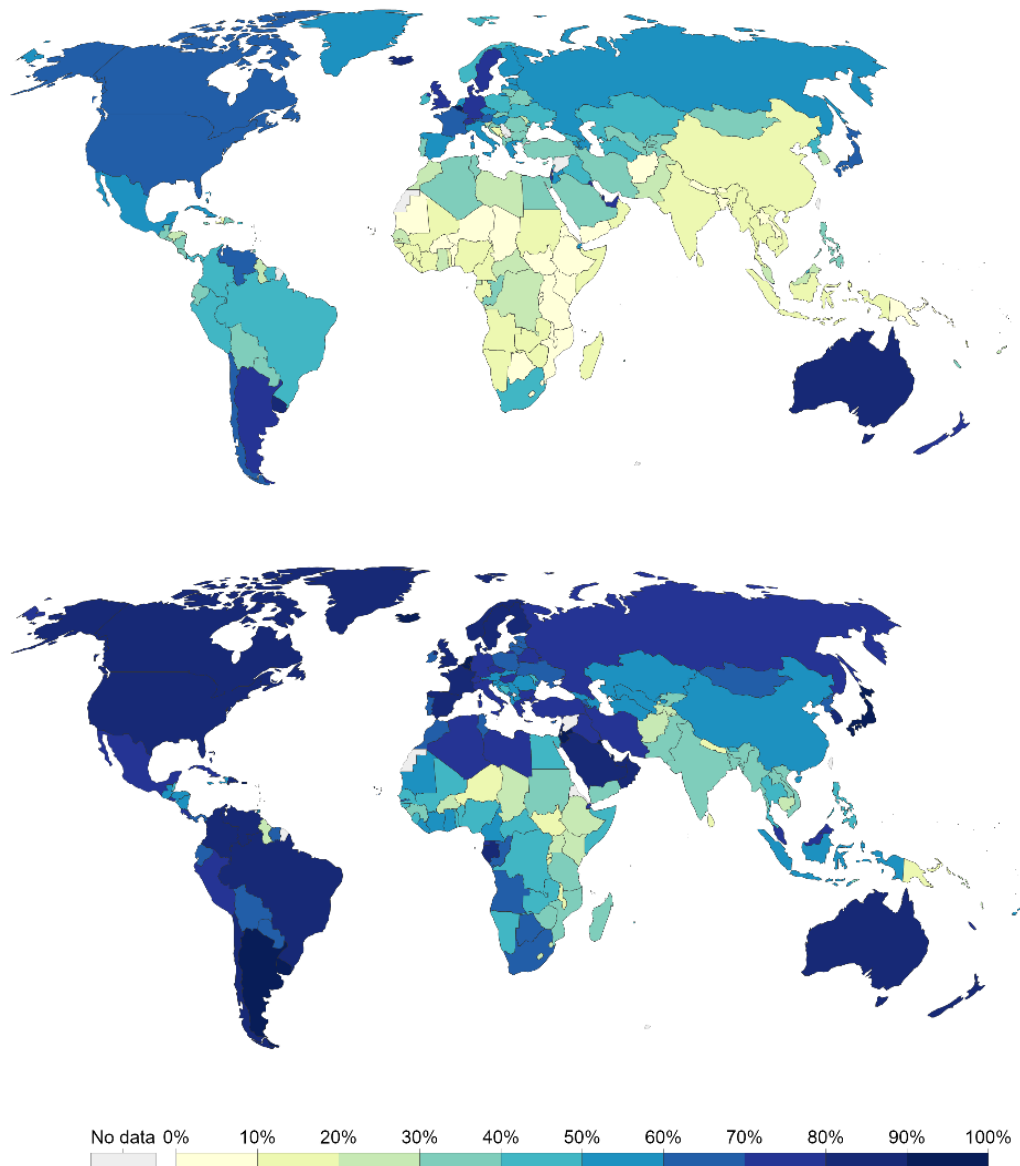
For example, in China, 16 communities in the city of Zibo received daily fresh products using autonomous vans that use cameras and deep-learning algorithms to drive. With a capacity to load 1 ton, this alternative helped to reduce the risk of infection (Guizzo, 2020). In Milton Keynes (UK), robots were also used to deliver food to its 200,000 residents during the lockdown, thanks to agreements with different chains like Tesco or Co-op (The Guardian, 2020).

As we enter the “new normal” period, these autonomous vehicles will stay to become part of the urban logistics scenario. According to Jennings and Figliozzi (2019), although autonomous delivery robots used together with mothership vans could be a viable alternative to standard delivery vehicles, the scalability of this industry will depend on the regulations set by local authorities and governments. In general, according to Jennings and Figliozzi (2019), using robots in certain scenarios could lead to a reduction in delivery times, distance travelled, and cost, although this will also depend on the number of customers, distance, type of parcel, and time each customer spends to pick up the parcel. Furthermore, although it may look that using robots could have associated benefits in terms of traffic congestion, Jennings and Figliozzi (2020) mention that, in fact, there could be an indirect increase in the number of vehicle-miles related to package delivery caused by the lack of restrictions in terms of driver fatigue or working hours, which could impact traffic congestion in urban areas. Apart from this, these robots will add new externalities and issues, mainly related to pedestrian safety (more congested sidewalks) and parking space (mothership vans will require longer parking stay).

Therefore, although the research is still very limited, it is true that in certain scenarios autonomous robots could be a cost-effective alternative. It is likely that during the next years delivery companies will start implementing this alternative in order to cope with the growing on-line demand.

2.4 Resilient cities

Whilst we have seen in the previous sections that transport and logistics activities are key for our economies, cities also have an important role to play in our societies. They are the centre of economic, social and cultural activities. However, over the last decades, cities are rapidly changing. According to the United Nations, by 2050 68% of the global population will live in cities (United Nations, 2019). In 2100, this ratio will increase to 85% (OECD, 2015). If we compare it to the figures from 1960, when only 34% of the population lived in cities (World Bank, 2020), it is understandable that this urban phenomenon is affecting how the cities are evolving (see Figure 7).



Source: UN World Urbanization Prospects (2018)

OurWorldInData.org/urbanization • CC BY

Note: Urban populations are defined based on the definition of urban areas by national statistical offices.

Figure 6. Percentage of urban population. 1960 (above) vs. 2017 (below)

This unprecedented era of increasing urbanization is posing several challenges related to housing, employment, environment, climate change, transport infrastructure, education, and safety, amongst

others. It is known that the effects of some of the main problems our society is facing are also more acutely observed in urban areas (JRC, 2019). Examples of these problems are climate change, heatwaves and flooding, pollution, congestion, crime, a lack of affordable housing, shortages of clean water and electricity, and health; for example, over 90% of Covid-19 cases occur in urban areas according to the United Nations (United Nations, 2020). These challenges could lead to great opportunities to achieve a sustainable development if a correct approach is followed. In fact, the Urban Agenda for the EU (European Commission, 2019) and the global New Urban Agenda (United Nations, 2017) recognise the importance of cities in achieving a sustainable way of living. However, this means we will have to change the way cities are planned, designed, developed and governed. In other words, the battle for achieving the sustainable development goals will be won or lost in our cities.

2.4.1 The concept of urban resilience

The general definition of resilience relates to the ability of a system, a person or a thing to recover quickly or to return to its original state after being disturbed (Oxford University Press, 2020). The word resilience is commonly used in fields such as psychology or sociology, and we could say that the history of city resilience started with the resilience of their populations. Campanella and Godschalkt (2011) show through different historical examples (the 1755 Lisbon earthquake, the Great Galveston hurricane of 1900 in Texas, or the WWII) that no major city has been permanently ruined in the last 300 years and that even in the ancient world cities were rarely abandoned as a consequence of a catastrophic event (Campanella & Godschalk, 2011) As the authors mention, *“just as a city is more than the sum of its buildings, it may also be only as resilient as its citizens. Resilient citizens have enabled urban resilience throughout history.”*

Apart from the socio-political aspects of resilience studied by Campanella and Godschalkt, it is true that during the last years the concept of resilience has also moved to the field of sustainable development and urban planning. This has been partially caused in response to some of the biggest challenges our societies are facing: climate change, declining oil supplies, terror attacks, global pandemics, and other threats. In fact, one of the Sustainable Development Goals stated by the United Nations aims at *“making cities and human settlements inclusive, safe, resilient, and sustainable.”*

The New Urban Agenda (United Nations, 2017), for example, mentions that

“readdressing the way cities and human settlements are planned, designed, financed, developed, governed and managed [...] will help to end poverty and hunger in all its forms and dimensions; reduce inequalities; promote sustained, inclusive and sustainable economic growth; achieve gender equality and the empowerment of all women and girls in order to fully harness their vital contribution to sustainable development; improve human health and wellbeing; foster resilience; and protect the environment.”

With a more practical focus, the UN-HABITAT’s “City Resilience Profiling Programme” provides governments (national and locals) with tools for measuring and increasing resilience to multiple hazards, including those associated with climate change, especially flooding events (United Nations, 2018). There are also private organisms that aim at increasing the resilience in our cities. As an example, the Rockefeller Foundation established in 2013 in the wake of Hurricane Katrina and Superstorm Sandy “The 100 Resilient Cities programme” to help cities to develop new resilience strategies, providing principles, indicators, and practises. However, this program ended in 2019 after internal discussions, a

change in leadership, and the intention of the Foundation to address resilience and climate from different and new perspectives (Bliss, 2019).

In the EU, regional policies have also started to highlight the importance of developing resilient cities. For example, the Urban Agenda for the EU clearly mentions that *“European citizens are facing pressing challenges in all places – environmental degradation and climate change, demographic transition, migration and social inequalities – and cities are on the frontline to deliver solutions. To ensure the sustainable and resilient development of Europe, we need to follow the principle of multi-level governance”*. Furthermore, the document *“The Future of Cities”* by the Joint Research Centre of the European Commission (JRC, 2019) mentions that city communities will play a substantial role in reshaping their own futures, and that *“strengthening local administrations and empowering citizens will contribute to building urban resilience to new challenges and better protecting human, economic and natural assets in cities and their surroundings.”*

However, what does urban resilience exactly mean? Meerow et al. (2010) state that the meaning of urban resilience is malleable, allowing researchers and practitioners to use a common term without requiring them to necessarily agree on its exact definition, which sometimes creates inconsistencies (Meerow, Newell, & Stults, 2016). The authors reviewed the academic literature on urban resilience, identifying the most influential studies, and developed a refined definition that addresses conceptual tensions and that includes different perspectives. According to them *“urban resilience refers to the ability of an urban system -and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales- to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.”*

Although this definition is, of course, correct from a conceptual point of view, in practice it is usually simplified so that its understanding and application becomes easier. For example, according to the European Commission (JRC, 2019), a resilient city is the one which *“assesses, plans, and acts to prepare for and respond to all hazards – sudden and slow onset, expected and unexpected.”* In other words, a resilient city is a city that *“face shocks and persistent structural changes in such a way that it keeps on delivering societal well-being without compromising that of future generations”* (Manca et al., 2019).

As we can see, urban resilience is a broad topic that covers from earthquakes to flooding events, rapid migration, cyber-attacks, terrorism, and pandemics (Covid-19) amongst others. However, during the last years almost all the urban resilience projects and strategies, especially in Europe, have been focused on climate change impacts (although right after the 11-S terrorist attacks the focus was on terrorism). The reason behind this is that Europe is a region prone to increased risks of floods, heat events, and wildfires, and there is a huge potential to reduce these risks with the adoption of novel strategies (European Commission, 2014). According to UN-HABITAT over the last decade natural disasters have affected more than 220 million people and causing an economic damage of USD100 billion per year. By 2030, natural disasters will cost cities three times more than today, and climate change may push millions of urban residents into poverty (UN-HABITAT, 2015). To fight this, between 2014 and 2020 the EU has allocated €180 to finance climate change actions and projects. This represented 20% of the total EU budget. For the next EU long-term budget 2021-2027, the Commission has proposed that at 25% of EU expenditure will contribute to climate action (European Commission, 2020) which shows the importance the EU places on tackling climate change.

As part of the mentioned budget, the EU is financing some projects in order to address local entities to take proactive, preventive and corrective measures to mitigate climate change impacts. Some of the

main projects are RESCCUE, BRIGAD, RESIN and EU-CIRCLE (BRIGAD, 2019), in which there are also Spanish organisms involved. The objective of these projects is to create and test risk models, adaption framework, strategies, and multi-scale methodologies.

However, although these projects have brought to light some of the needed innovations that can help cities, city administrators and governments will need to act quickly to adapt these tools if they want to help their own cities to be prepared and be resilient. Although history has taught us that our cities will survive, the question is how well they will survive and, in the current context where cities are becoming smart, urban resilience should become an important part of the strategy.

2.4.2 Current research on resilience in smart cities

Before focusing on how urban resilience is adopted in the smart city context, it is necessary to understand how urban resilience has evolved during the last decades. Although papers focused on resilience started to be indexed in 1874, they were only focused on materials science. It was in 1948 when the first paper focused on psychology, “*The amazing resilience of children*”, appeared (Audric, 1948). After the 1960s, the term resilience started to be also applied to other fields such as ecology and sociology. However, until the 1990s, there were only a couple of papers per year on resilience, and most of them were still related to materials science and engineering. In the 1990s, the topic started to revolve around psychology, sociology, and demography, and by the year 2000 the topic of resilience and environment, more focused on the climate change, started to gain in prominence together with some research around resilience and urban areas. Since then, the research community has increased the interest around resilience, and the number of publications has grown linearly with 4131 papers indexed in 2019 as shown in Figure 7.

Figure 7 shows the number of Scopus-indexed papers during the last decades that include in the title the words “resilience”, “urban resilience”, “urban” + “resilience”, “resilience” + “environment/climate”, and “resilience” + “smart city”. As mentioned before, it was after the year 2000 when the term resilience started to be applied to fields related to environment, sustainability, and urbanism. Since then, the growth of the published papers focusing on resilience, environment, and urban areas has increased reaching a total of 427 papers published in 2019, which represents 11% of all the research published on resilience, in comparison to the 2% in 2005. This indicates, as commented in the previous section, the importance of this topic for the research community and the governments during the last years.

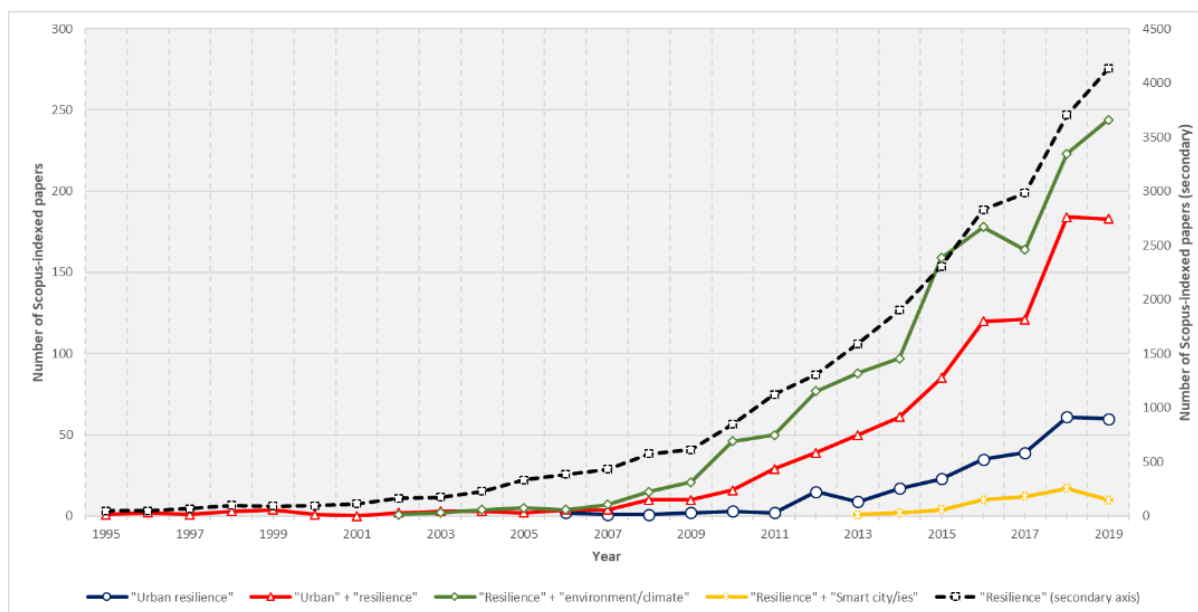


Figure 7. Evolution of the research related to resilience.

Most of the papers whose titles include “resilience” and “environment” focused on the sea level rise, wildfires and other negative effects of the climate change. As for the articles on “urban” and “resilience”, until 2007 the main topic was education and other socio-cultural and demographic aspects. However, after 2007 the trend shifted towards disaster management, especially flooding events. This “new” research interest was mainly influenced by recent events such as the Indian Ocean tsunami in 2004, and the Katrina hurricane in 2005.

However, Figure 7 also shows how the term “urban resilience” only started to be developed after 2013. Although then the research still focused on disasters (flooding, hurricanes, terrorism) and climate change, this field starts a new phase and evolves; not only does it show what resilience is or why our cities need to be resilient, but it also provides frameworks, methodologies, and indicators to include resilience into the urban planning process. We could therefore say that “urban resilience” as a unique field of study was born in 2013 when institutions and public organisms (as indicated in the previous section) put it as a critical objective for the future of our cities and our future generations.

Finally, we can see in Figure 7 that the publications focused on smart cities and resilience are very scarce and only started in 2013, a few years after the first pieces of research on smart cities were published (see Figure 2). In 2018, there were only 17 indexed papers, and in 2019 the number decreased to 9, which indicates that this is a new field of research (resilience within smart cities) which is currently being developed.

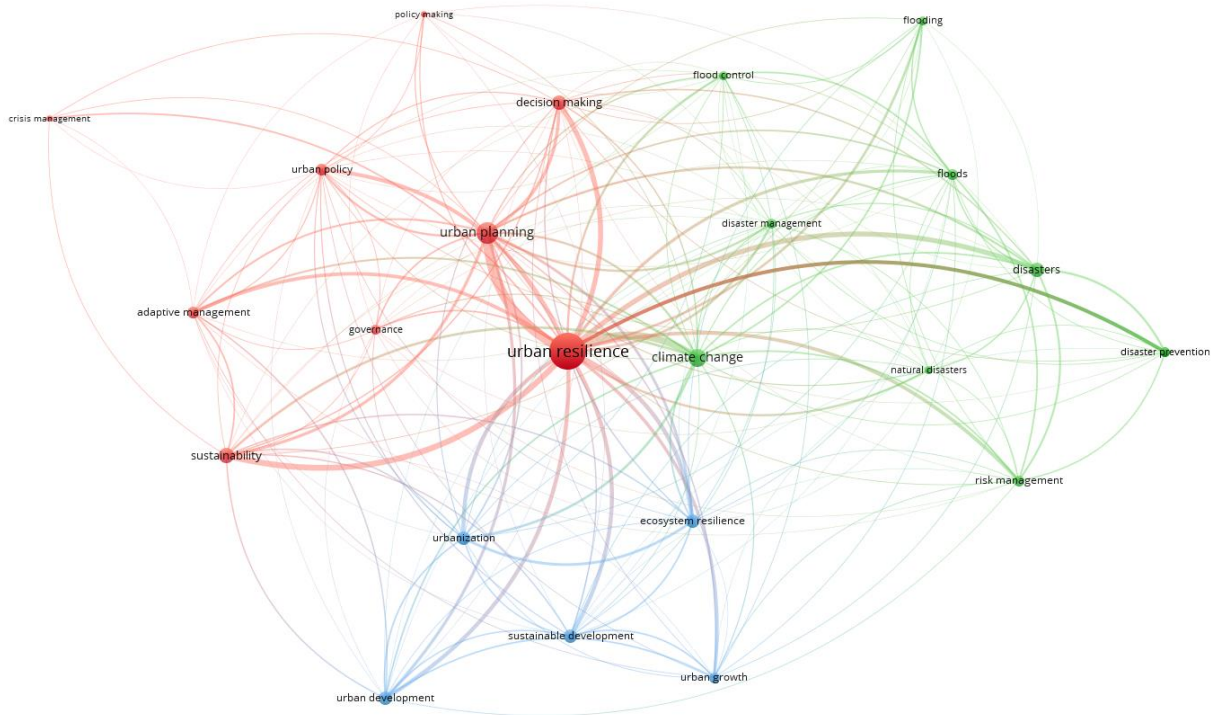


Figure 8. Keywords map created with VOSviewer using bibliographic data from Scopus when looking for the keyword “urban resilience”.

Similar to previous keywords maps shown in preceding sections, Figure 8 allows us to understand to which terms the papers written on urban resilience are connected. The figure shows that most of the papers related to urban resilience talk about urban planning, climate change, sustainability, and decision-making. We see there are three main clusters. The biggest cluster (in red) is related to those papers more focused on urban planning, policy and government, i.e. how to prepare our cities to become resilient from a planning and policy perspective. The second cluster (in green) focuses on climate change and disaster management, giving special attention to flooding events. Finally, the last cluster (in blue) is about urbanization, urban growth, and sustainable urban development. Of course, this methodology based on keywords maps is a simplification, and although there exist a couple of papers that also analyse other aspects such as terrorism, big data, or modelling techniques, the impact of those is much smaller.

It is important to highlight that Figure 8 does not show “smart city” as a keyword present in the papers focusing on urban resilience, which means that the research on smart cities and resilience is scarce. We could also see this in Figure 2, where it was shown that “urban resilience” or “resilience” were not a relevant keyword in the indexed papers related to smart cities. Although urban resilience (with the meaning we are using in this paper) might be a new term, this is not the case for the concepts behind it (disasters, climate change adaption) and their connection to smart cities. For example, in Figure 2 we saw that although the keyword “resilience” did not appear, there were others such as climate change, disasters, and decision-making that are directly related to urban resilience.

One question that may arise is, why is urban resilience disconnected from the concept of smart city? According to Van den Bosch (Van den Bosch, 2017) the concepts smart and resilient city have different roots. Whilst the concept of smart cities was boosted a decade ago (2008-2012 during the economic crisis) by companies like IBM, Siemens, or Philips as part of their strategy to find new markets, the concept of resilient city is promoted by international organizations and association of cities in order to

improve their capabilities to deal with hazards, especially those related to climate change. Consequently, some researchers consider resilience as a characteristic of smart cities as there are some elements in the concept of smart city that are also contained in the concept of resilience (Papa et al., 2015). However, for others, the concept of smart cities is still abstract and unclear, and they think that the problems smart cities attempt to solve are not in reality relevant existing problems (Arafath et al., 2018). Indeed, Viitanen and Kingston (2014) criticized the influence of international technology firms in the smart city revolution. Thus, according to Viitanen and Kingston (2014), using the perspective of green growth, and through public-private partnerships, these big players are using the lucrative framework of smart cities for the expansion of digital consumerism, which paradoxically does not lead to a sustainable growth. Instead, this technological growth tend to disadvantage those with less purchasing power, reducing digital inclusion and making the city less resilient in facing future social and climate risks (Viitanen & Kingston, 2014).

Under the PhD student's point of view, a city will only become smart if it is resilient, and to get there we will need to use the technology in a smart way, and not only for the sole purpose of using it (or having it). Without a proper long-term strategy that answers the question "Why do we need smart cities?", we will just be adding tools and modules to our cities as if they were the extended version of a traditional city. We can have a smart city where everybody (and everything) is interconnected, where the streets are full of sensors, with our fridges able to forecast how many eggs we will need to buy, and where all the cars will be shared, electric and autonomous. However, if this city is not able to cope with a pandemic, with a flooding event, or with a terrorist attack, it will not be resilient. The smart city is not the goal, but the mean to reach resilience, sustainability, and equity.

2.4.3 Modelling techniques applied to urban resilience

We have previously seen (section 2.3.1 and in Figure 4) that modelling and simulation techniques are currently being used to improve and optimize urban logistics within urban areas. However, with respect to urban resilience, the research on simulation or modelling techniques is very limited. Between 2016 and 2019, for example, less than 3% of the Scopus-indexed papers on urban resilience were related to modelling and/or simulation techniques (most of them focused on disasters, especially flooding events). This is an indication that the area of urban modelling applied to urban resilience is relatively new.

In the past years, most of the studies have aimed at developing frameworks, qualitative analyses, and conceptual structures around urban resilience. These approaches are usually based on assumptions that are difficult to put into practice, as they are mainly theoretical and especially because they do not fully contemplate the particularities of each city, or of a city over time (Ribeiro & Gonçalves, 2019). Although conceptual frameworks are important to set a common scenario that makes it possible to understand what we are trying to analyse, it is also important to know how we are going to analyse it. That is why other researchers (Tyler et al., 2016) developed semi-quantitative indices to be used for urban planning and monitoring of climate adaptation interventions at the urban level. An example of this is the City Resilience Index developed by the Rockefeller Foundation (ARUP, 2020). However, these indices are static, and they cannot give us information on, for example, how a disaster will evolve, nor the flexibility to know what the best solution is at a very specific moment. This is partially solved with the latest quantitative approaches developed, especially the ones that use dynamic modelling (Datola et al., 2019). These dynamic models can provide more insights considering the city as a complex system defined by the interaction of different agents (residents, workers, government, etc.) with various subsystems (housing, transportation, etc.) in space-time dimensions.

Indeed, Brundermar et al. (2016) indicated that these dynamic techniques, especially agent-based modelling (ABM), can be a powerful tool for urban resilience, although most of the research on modelling applied to urban resilience use statistical modelling or other type of approaches, and only in a couple of cases agent-based simulation was used (Felsenstein & Mas, 2018). Through ABM it is possible to identify problems that need to be addressed by planners and policy makers in order to transform cities in resilient communities. One of the main benefits of ABM is the possibility to consider dynamic and collective behaviours when real-world tests are costly or impossible, although building very detailed models of urban areas is time-consuming and often these models need to be simplified. However, Brundermar et al. (2016) states that although ABM have been commonly used to model smaller scenarios such as music festivals or events, similar approaches can be used for resilience modelling at a larger scale.

ABM in urban planning is not something new. There has been research in which ABM has been used to model flooding events (Dawson et al., 2011), earthquakes (Crooks & Wise, 2013), or terrorism (Park et al., 2012). However, this research has been mostly theoretical, presenting frameworks without a direct application or, when the study cases have been real, the models contained numerous simplifications and the area of study was very limited.

But things have changed in the last years, and this topic has become more relevant for the research community. Recent events such as hurricanes Harvey and Irma in 2017 (more than 200 fatalities, and tens of thousands of evacuees), the wildfires in Fort McMurray in Canada in 2016 (90,000 evacuees), the Ecuador earthquake in 2016 (650 fatalities), or the Oroville dam in California (200.000 evacuees) remind us that natural, technological and/or human-made disasters have a high cost in terms of lives and material losses, and have put the research community on a mission to create more resilient cities.

With urban and transport planners currently developing new strategies to increase the resilience capacities of our cities, and with the new big data technologies being in place to build smart cities that allow capturing data in real time, large scale evacuation will be an important part of urban and transport planning in the coming years with the aim of building resilient and safer cities

2.5 Summary of the articles selected.

The previous sections have shown that the smart city research field is booming. However, the research community has been focusing on some specific areas such as Big Data, Internet of Things, or smart power grids, when others have been overlooked. This thesis brings light to some of the areas mentioned in the previous sections where research has been more limited but where there has been an increased interest in recent years:

- 1) Optimization and modelling of delivery routes in urban areas making use of metaheuristics, modelling and simulation techniques, and Big Data, and
- 2) Modelling of evacuation processes in urban areas making use of agent-based simulation.

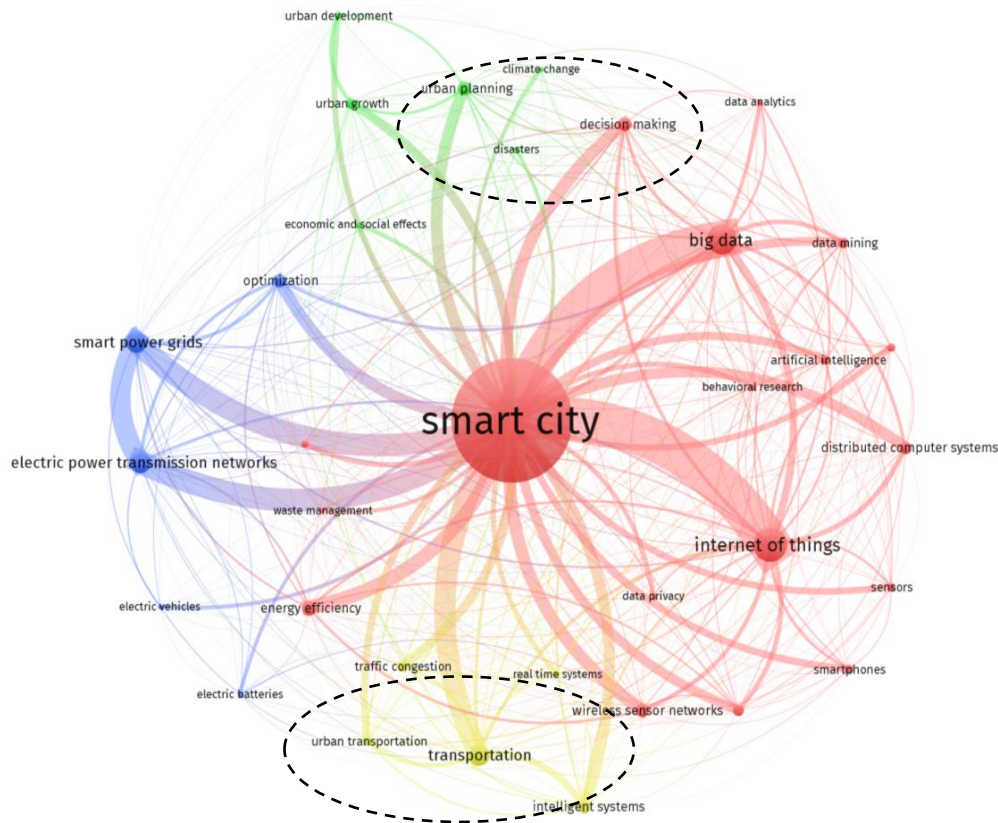


Figure 9. Focus areas of this doctoral thesis circled in black, showing their connection with other fields related to smart cities.

A summary of the articles listed in Part 3 of this thesis is shown below.

- **Article 1: Alvarez P., Lerga I., Serrano A., Faulin J. (2017) *Considering Congestion Costs and Driver Behaviour into Route Optimisation Algorithms in Smart Cities*. In: Alba E., Chicano F., Luque G. (eds) *Smart Cities. Smart-CT 2017. Lecture Notes in Computer Science, vol 10268*. Springer, Cham.**

Congestion costs have been excluded from the study of traditional vehicle routing problems until very recently. However, with our urban areas experiencing higher levels of traffic congestion, with the increase in on-demand deliveries, and with the growth of intelligent transport systems and smart cities, researchers are raising awareness on the impact that traffic congestion and driver behaviour has for urban logistics. This paper studies the evolution of the vehicle routing problem, focusing on how traffic congestion costs and driver behaviour effects have been considered so far, and analysing how the research community has to deal with this challenge.

- **Article 2: Alvarez P., Lerga I., Serrano A., Faulin J. (2018) *The impact of traffic congestion when optimising delivery routes in real time. A case study in Spain*. In: *International Journal of Logistics Research and Applications*, 21:5, 529-541.**

This paper studies the importance of considering congestion costs when optimising delivery routes. Through the analysis of two study areas (the region of Catalonia and the city of Barcelona, in Spain), four different scenarios have been implemented and compared in which different objective functions are minimised: Euclidean distance, real distance, real time with static congestion, and real time with dynamic congestion. The data have been collected from Google Maps, which allows us to obtain information on traffic conditions in real time. The results indicate that minimising real time considering

congestion as a dynamic attribute which varies throughout the day is the most efficient method to optimise delivery routes, especially within urban areas. For the two study areas, and using this dynamic approach in which real-time congestion costs are reflected into the vehicle routing problem, savings in time up to 11% have been obtained.

- **Article 3: Alvarez P., Serrano A., Faulin J., Juan A. (2018) Using modelling techniques to analyse urban freight distribution. A case study in Pamplona. In: Transportation Research Procedia, 33, 67-74.**

The city of Pamplona, in Spain, is currently experiencing several changes regarding sustainable mobility such as pedestrianization of some streets in the city centre, and access control to the Old Town for motor vehicles through the use of automatic number-plate recognition. However, some groups including local neighbours and businesses are raising complaints as they are being affected by these measures. This is also the case for couriers and logistics companies which have now to comply with new regulations regarding delivery routes throughout the Old Town. This paper will present a comprehensive study of the situation that is being carried out, and in which social perceptions and freight traffic patterns in the Old Town of Pamplona are analysed to understand how urban freight distribution could be improved in the area. For this purpose, we make use of a survey-based research to the stakeholders, i.e. pedestrians, logistics companies, retailers, and authorities of Pamplona. Results highlight pollution derived from transportation, lack of parking spaces as well as invasion of public spaces in the city centre are the key issues for improving freight transportation in the Old Town. Finally, placing a distribution centre in the nearby and the promotion of the cycle logistics are seen as the future of the urban distribution in Pamplona.

- **Article 4: Serrano A., Alvarez, P., Lerga, I., Reye, L., and Faulin, J. (2017). Pricing and Internalizing Noise Externalities in Road Freight Transportation. In: Transportation Research Procedia, 27: 325-332.**

People living close to main roads may suffer from the nuisance of traffic and noise pollution. This paper assesses the effect of full routing cost in vehicle routing decisions by internalizing the external cost of noise. On a first step, noise externalities are economically assessed through a contingent valuation procedure. Secondly, a novel methodology is proposed to allocate the external costs to the road network links. Results show significant differences in routing planning depending on the approach: minimization of traditional internal cost versus minimization of full cost. These results encourage further research in pricing and methodologies to internalize externalities.

- **Article 5: Alvarez P., Serrano A., Faulin J. Is time more important than distance to optimize freight delivery routes? An approach using the value of time. Submitted to Transportmetrica B: Transport Dynamics.**

Traditional approaches to optimize freight delivery routes are based on minimizing a distance-based cost function. New approaches use also time as the objective function to minimize. However, the trade-off between time and distance is sometimes unclear. This paper presents a new approach to optimize delivery routes in which both time and distance are used together to optimize delivery routes. For this purpose, the operating cost of a vehicle and the value of time have been used to convert time and distance into monetary units. Through the study of three different networks in Spain with different level of detail (the region of Catalonia, the city of Barcelona, and the old part of Pamplona), the results have indicated that minimizing both time and distance provides better results than the traditional approach, especially at a local level where congestion effects are more relevant.

- **Article 6: Alvarez P., Alonso V. Using microsimulation software to model large-scale evacuation scenarios. The case of Sangüesa and the Yesa dam collapse. In: Safety Science, 106, 10-27.**

The use of computer models to analyse evacuation scenarios and human behaviours in emergencies has greatly increased due to their capabilities to simulate these processes. These models have been commonly applied to different types of infrastructures in isolation, and little is known about their use for large-scale evacuation. This paper explores the capabilities of micro-simulation tools for modelling large-scale evacuation, and also presents the development and application of a computer based large-scale modelling tool. A novel methodology is proposed here in which different sub-models are connected to represent the different levels of the evacuation scenario. The methodology has been applied to a real case study: a small town in Spain, Sangüesa, which is in risk of flooding as a consequence of a potential collapse of the Yesa dam. The inputs used were taken from survey data, census data, plans of the town, data obtained from the emergency plan, data from other research studies (flooding models and acoustic models), and a literature review process on human behaviour in emergencies. The study was focused on the evacuation scenario at night (2:00 AM assuming the majority of residents are sleeping) as one worst-case scenarios. Four scenarios were developed in order to analyse the impact of (1) two preevacuation time distributions identified for residential evacuation at night and (2) group behaviours (with and without) during the evacuation process. Results showed that the time needed to evacuate the whole town (between 33 and 44 min) is not sufficient, as in case of a dam collapse the water could reach Sangüesa in about 23 min.

Apart from the above articles selected, **in the Appendix (section 5.2) a work in progress article (Article 7) is included whose title is “Modelling and simulation of last mile deliveries using the VRP in urban areas”**. This article, currently under review, presents a new approach in which the vehicle routing problem is intertwined with modelling and simulation techniques in order to analyse different urban scenarios. The methodology presented in this paper will provide a new tool that can be used by different stakeholders; by logistics companies to optimize delivery routes in real time considering existing conditions in the network, and also by transport planners and policy makers to understand how transport and urban policies (pedestrianization, traffic bans, incentives for cyclelogistics, etc.) will affect freight distribution in our city centres. This approach is flexible and adaptive (for different use cases in different cities), scalable (improved and more complex algorithms can be installed), and ready to be used in the smart city context, where sensors can provide real-time information to feed the models.

Figure 10 shows a diagram with the recommended order in which the articles should be read. We can see the connections between the different articles and the main topics (transportation, logistics, urban planning, resilience, and big data).

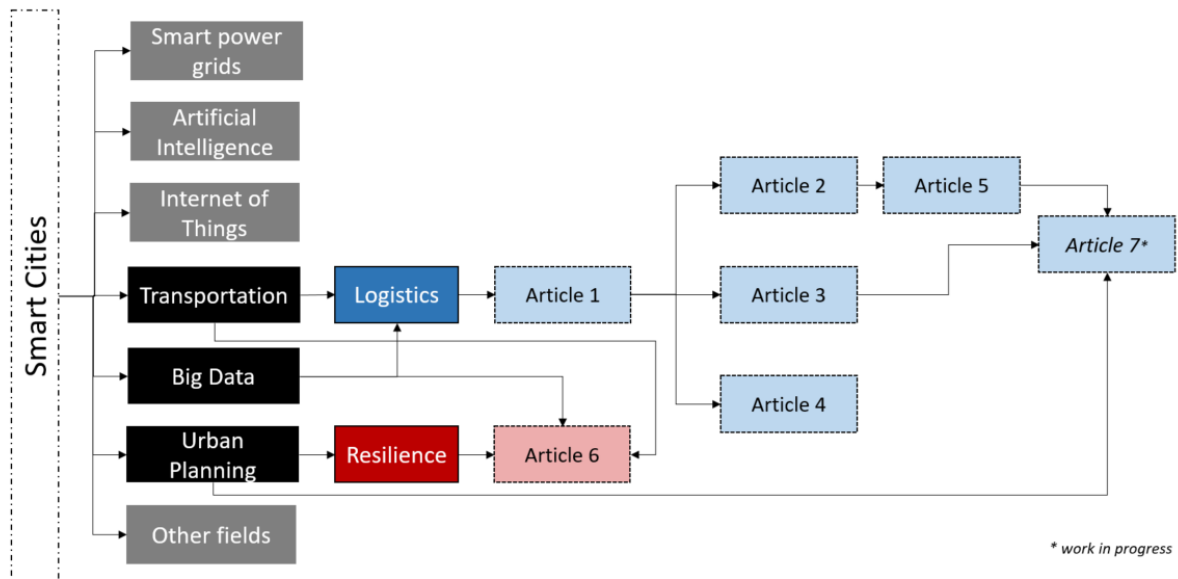


Figure 10. Recommended order in which the articles should be read.

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PART III. ARTICLES SELECTED

3.1 Article 1: Alvarez P., Lerga I., Serrano A., Faulin J. (2017) Considering Congestion Costs and Driver Behaviour into Route Optimisation Algorithms in Smart Cities. In: Alba E., Chicano F., Luque G. (eds) Smart Cities. Smart-CT 2017. Lecture Notes in Computer Science, vol 10268. Springer, Cham.

Considering Congestion Costs and Driver Behaviour into Route Optimisation Algorithms in Smart Cities

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Abstract. Congestion costs have been excluded from the study of traditional vehicle routing problems until very recently. However, with our urban areas experiencing higher levels of traffic congestion, with the increase in on-demand deliveries, and with the growth of intelligent transport systems and smart cities, researchers are raising awareness on the impact that traffic congestion and driver behaviour has for urban logistics. This paper studies the evolution of the vehicle routing problem, focusing on how traffic congestion costs and driver behaviour effects have been considered so far, and analysing how the research community has to deal with this challenge.

Keywords: Vehicle routing problem · Congestion · Driver behaviour · Smart cities · Big Data

1 Introduction

The Vehicle Routing Problem (VRP) is one of the recurring topics existing in the literature on transport and logistics activities [1]. In 1954, Dantzig, Fulkerson, and Johnson wrote a seminal paper [2] to solve a large-scale traveling salesman problem (TSP). However, it was in 1959 when Dantzig and Ramser [3] developed the first algorithmic approach applied to optimise delivery routes between petrol stations. This was the first record related to a VRP, as we know it today, although it was later improved (in 1964) by Clarke and Wright [4] to solve a problem in which a fleet of trucks of different capacities had to be used for delivery from a central depot to several delivery points. A few years later, different versions of VRP emerged and were applied to different fields such as fleet routing [5], bus routing [6], or waste collection [7]. However, it was not until 1972 when the words “*vehicle routing*” appeared together in the title of a research work by Golden, Magnanti and Nguyen [8], in which they used heuristic programming to develop a multi-depot routing algorithm. In that period, researchers tried to solve the problems in a more realistic way, using more constraints such as vehicle capacity, time windows, or different fleet configurations.

The possibilities to study more realistic variations of VRP were limited due to the computational complexity required, and it was not until the 1990s when research on

VRP accelerated mainly due to microcomputer capability and availability, which allowed the introduction of meta-heuristics into the study of VRP applications.

The VRP field has greatly evolved since those first studies written decades ago, and hundreds of new papers on more complex variants of the VRP are being released every year. These new approaches take into account new constraints such as the stochastic effects of real-life problems by using simheuristics [9], the range limitations when delivering with electric vehicles and even drones, or the changing conditions existing in the market by considering real-time information to enhance dynamic vehicle routing problems.

Nevertheless, the scale at which VRP are being used has not change much in more than 55 years, as the majority of applications are still focused at a strategic level (i.e. routes between cities) where most of the approaches aim to minimise a distance-based cost function without considering other aspects such as congestion effects, transport infrastructure, or driver behaviour.

By 2050, 70% of the world's population is predicted to live in cities [10], putting increased strain on urban infrastructure and transport systems. Adding to that the fact that we live in the one-click Era, where online shopping and on-demand deliveries are changing the way we understand logistics activities within urban areas, it is easy to understand that the way we optimise urban logistics routes must change too. Making use of Big Data technologies, traffic simulation software, and considering dynamic local conditions such as congestion effects or driver behaviours is necessary to get realistic solutions to our optimisation problems.

Therefore, this paper aims to study how current VRP approaches are suitable for their use in urban logistics, specifically focusing on how congestion effects and driver behaviours are being considered. To do this, the latest published papers on city logistics, which include congestion and driver behaviour effects, have been analysed. The advantages and the disadvantages of the different approaches have been also described to understand how convenient they are for their use in real urban scenarios. Finally, the authors draw some conclusions on how future research on this topic should addressed.

2 Methodology

The following methodology has been applied in order to analyse how appropriate current approaches are when considering congestion effects and driver behaviours into VRP.

2.1 Number of Indexed Publications per Year

Using Scopus, a search has been performed to check the number of indexed publications per year related to (1) "Vehicle Routing Problem", (2) "Vehicle Routing Problem" AND "logistics", (3) "Vehicle Routing Problem" AND "logistics" AND "congestion", (4) "Vehicle Routing Problem" AND "logistics" AND "driver behaviour", (5) "Urban logistics", and (6) "Logistics" AND "smart cities".

Through this, it is possible to get a broad picture of how VRP and logistics have evolved, and how relevant aspects such as congestion costs and driver behaviour have been for researchers.

2.2 Literature Overview

A comprehensive analysis of all the papers related to VRP (focused on logistics) in which congestion and driver behavioural aspects are considered has been performed. A table has been created in which the following attributes are scored.

- **Title**
- **Author**
- **Year**
- **Relevance (R)** of congestion effects or driver behaviour within the whole paper. From 0 (no relevant at all) to 5 (extremely relevant).
- **Originality (O)**. How original is the approach used to consider congestion/driver behaviour effects within the VRP field? From 0 (no original at all) to 5 (extremely original).
- **Practicality (P)**. How practical/realistic is the approach used to consider congestion or driver behaviour within the VRP field? From 0 (no practical at all) to 5 (the approach is completely realistic and practical).
- **Age (A)**. How new is the paper? The more up-to-date a paper is, the more likely it is that it includes aspects related to cutting-edge technologies or approaches. The value is 5 (2017 or 2016), 4 (2015 or 2014), 3 (2013 or 2012), 2 (2011 or 2010), 1 (2009 or 2008) or 0 (before 2008). If $R = 0$, then $A = 0$.
- **Continuity (C)**. Does the paper lay the foundation for future research? The value goes from 0 (the paper has no continuity) to 5 (it is very likely that more papers are written based on this one).
- **ROPAC value**. It is the sum of the paper's relevance (R), originality (O), practicality (P), age (A), and continuity (C). The maximum value is 25, and the minimum is 0. The higher the value is, the more important the paper is for the field.

2.3 Analysis of the Five Papers with the Highest ROPAC Value

The five papers with the highest ROPAC values will be described, focusing on how congestion costs or driver behaviour effects have been taken into account.

3 Analysis of Results

As commented in Sect. 2, the analysis has been split into three main parts: number of indexed publications per year (evolution), general literature overview, and analysis of the five papers with the highest ROPAC value.

3.1 Number of Indexed Publications per Year

Figure 1 shows the evolution of the research done in the field of vehicle routing problems in the last decades. Note that just Scopus-indexed papers are considered.

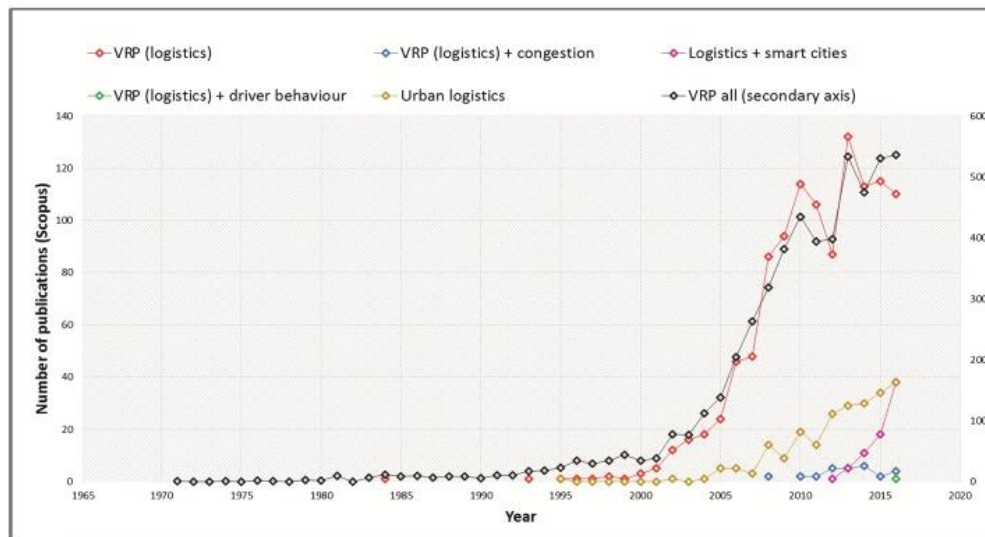


Fig. 1. Evolution of VRP, and urban logistics within smart cities.

The first indexed papers related to VRP were published in the 1970s. In fact, the first one was a piece of research [11] in which the authors developed an approach to optimise public service vehicle routes. During the next twenty years, the knowledge on this field was consolidated, and it was not until the 1990s when the number of publications started to increase exponentially. It was also then when specific papers focused on VRP for logistic activities started to be indexed (although Daganzo published the first one [12] in 1984).

Until 1995, research on VRP was mostly focused on a strategic (macroscopic) level, but the research community commenced to adopt a more micro-level perspective and the study on urban logistics started to be considered. Since then, research on this field has greatly increased, and it has been complemented by publications on logistics and smart cities that began to be indexed in 2012. Nowadays, the number of indexed publications related to VRP reaches more than 500 papers per year. For VRP focusing on logistics, the approximate figure drops to 110 per year, following the same tendency as general VRP publications. With urban logistics and smart cities gaining in prominence during the last years, the number of publications has increased to 40 indexed papers by year.

However, it is shown in the figure that VRP papers focused on logistics have ignored congestion and driver behaviour effects until recently, when urban logistics and smart cities started to be considered by different authors, and it was not until 2008 when the first indexed paper appeared [13] to study a VRP that includes queues and dynamic travel

times. Note that there is just one indexed publication (a survey from 2016) in which the driver behaviour aspects are mentioned [14].

Therefore, it is clear that congestion and driver behaviour effects within VRP have been excluded from the literature until now, and even with the current increase in the number of indexed papers published related to urban logistics and smart cities, these aspects are being disregarded.

3.2 General Literature Overview

All the papers indexed in Scopus related to vehicle routing problem for logistics activities in which congestion and/or driver behavioural effects are mentioned have been analysed according to the methodology stated in Sect. 2. Table 1 shows the scores for each paper, which have been agreed by all the authors.

Table 1. Scores of each paper.

Paper	Year	R	O	P	A	C	ROPAC
[15]	2016	5	3	4	5	4	21
[17]	2017	4	4	4	5	4	21
[19]	2014	4	4	3	4	4	19
[21]	2012	4	4	4	3	4	19
[23]	2010	5	4	4	2	4	19
[25]	2012	3	4	4	3	4	18
[27]	2014	3	3	3	4	3	16
[29]	2012	4	3	3	3	3	16
[13]	2008	4	3	4	1	4	16
[32]	2017	3	2	2	5	3	15
[34]	2015	3	3	3	4	2	15
[36]	2016	2	3	2	5	2	14
[14]	2016	5	1	1	5	2	14
[39]	2013	2	3	3	3	3	14
[41]	2011	3	2	2	2	4	13
[16]	2013	2	3	2	3	2	12
[18]	2012	2	3	2	3	2	12
[20]	2014	2	2	2	4	1	11
[22]	2015	1	2	1	4	1	9
[24]	2013	2	1	1	3	1	8
[26]	2013	2	1	1	3	1	8
[28]	2008	3	1	2	1	1	8
[30]	2011	2	1	1	2	1	7
[31]	2012	2	1	0	3	0	6
[33]	2014	0	0	0	0	0	0
[35]	2014	0	0	0	0	0	0
[37]	2014	0	0	0	0	0	0
[38]	2010	0	0	0	0	0	0
[40]	2016	-	-	-	-	-	-

The maximum ROPAC score (21) is for the paper written by Kim et al. in 2016 [15] which is called “Solving the dynamic vehicle routing problem under traffic congestion”, and for the one [17] by Huang et al. “Time-dependent vehicle routing problem with path flexibility” from 2017. On the other hand, there are four articles scoring zero, being the oldest one the paper [38] written by Danielis in 2010 on “Urban freight policies and distribution channels”. One of the indexed papers [40] was not accessible to the authors, therefore it was not analysed. The average ROPAC values is 11.41, and the median is 13.

3.3 Analysis of the Five Papers with the Highest ROPAC Value

The five papers with the highest ROPAC value are described. Although more papers with high ROPAC values could be analysed to give a wider vision, it has been checked that no decisive aspects have been missed when excluding the rest of the papers from this analysis.

3.3.1 Algorithms to Quantify Impact of Congestion on Time-Dependent Real-World Urban Freight Distribution Networks [23]

Through a real case study in Portland, Oregon, the authors make use of two main data sources. On the one hand, they use the Google Maps API for implementation of the time-dependant vehicle routing problem (TDVRP), and on the other hand, they obtain historical travel time data from the Portland Transportation Achieved Listing (PORTAL).

Conrad and Fligiozzi used the Google Maps API (open-source) to obtain the optimised route taking into account high-quality network data, which incorporates road hierarchy and restrictions. By selecting the customer distribution and the depot on the screen, the interface calculates the shortest paths between customers and builds the distance and travel time OD matrices. Free-flow speeds are obtained using these travel times and distances from the Google Maps API. Using detailed traffic data from PORTAL (obtained from 436 inductive loop detectors), the speeds are later adjusted to take into account congestion effects, which will be applied at the bottleneck locations that can be added into the algorithm.

The proposed methodology developed by the authors to integrate real network data into the TDVRP was a significant improvement for representing the congestion effects in congested urban areas. However, the use of historical traffic data instead of real-time data limits their applications, especially in the context of the smart cities.

3.3.2 A Comparative Study of Vehicles' Routing Algorithms for Route Planning in Smart Cities [21]

Nha, Djahel and Murphy highlight the importance of considering dynamic road traffic conditions (congestion, incidents, etc.) when optimising routes within smart cities. The authors present a classification of different dynamic route planning algorithms and then compare their performance when they are applied in real networks.

To this end, first, the best route is calculated using the chosen algorithm (Dijkstra, Genetic Algorithm, etc.). Then, when a vehicle reaches a junction, the traffic conditions are checked and the route is re-calculated taking into account the updated traffic conditions. Finally, the algorithm stops when the final destination is reached.

To analyse the performance of this framework, the authors use the open-source traffic microsimulation software SUMO, together with the TRACI interface, which allows manipulating the simulation as it runs. As an example, they create a scenario with a specific road network in which the Dijkstra algorithm is applied. Then, the network is converted to SUMO format to simulate the initial route given by Dijkstra, and the simulation begins. Every time a vehicle reaches a node, the program checks whether there

are changes in any road segment (link blocked by an accident or congestion), and if it is the case, the algorithm is re-applied ignoring those links.

To the best of the authors' knowledge, this paper is the first one in which a simulation software is linked to the optimisation algorithm to consider congestion effects. The implementation of this approach was in progress by the time the paper was written so there is a lack of details, for example, on how real traffic data is obtained, and how it is connected to the simulation software. In addition, this paper is not specifically focused on logistic activities. However, we think that this paper shows that it is possible to intertwine optimisation algorithms with simulation approaches leading to an increase in realism of the route planning processes, especially within smart cities.

3.3.3 Cyber-Physical Logistics System-Based Vehicle Routing Optimization [19]

The authors introduce the concept of cyber-physical logistics system (CPLS) which is a logistics system which incorporates sensors, heterogeneous communication network, and dynamic network interfacing as well as distributed computation technology to process the logistics information in real-time. Using real-time collection, transmission, and processing of the customers demand, vehicle status, and traffic information, the authors propose a routing adjustment model to minimise the total distribution cost. The decision-making centre collects all the information from customers (demands), road network (using traffic sensors) and delivery vehicles and optimise the routes.

Although the paper pays important attention to the communication network (TCP/IP, communication delays, data loss), the authors also focus on how road congestion is taking into account to optimise the delivery routes. They use a probabilistic model to calculate the congestion probability in the network. When a vehicle is travelling, the congestion probability should be lower than the setpoint. The decision-making process constantly update the congestion status and re-optimize the route if necessary. Therefore, the optimisation model (solved by a learnable evolution genetic algorithm) minimises the total distribution cost, constrained not only by customer time-window, vehicle maximum travelling distance, or vehicle capacity, but also by congestion.

To verify the proposed approach, the authors explain a case study in which they simulate a distribution system with 10 customer nodes, 1 distribution centre and 5 vehicles, and the results show the effectiveness of this method to reduce the total cost by re-adjusting the delivery routes taking into account congestion.

This paper is a good example on how new technologies and Intelligent Transport Systems can be applied to improve route optimisation algorithms. We think that this paper provides a good approach that could be useful in smart cities, and we strongly believe that future methodologies to develop VRP will be based on something similar to what is shown in this paper.

3.3.4 Solving the Dynamic Vehicle Routing Problem Under Traffic Congestion [15]

In this paper, the authors propose a dynamic vehicle routing problem (DVRP) model with nonstationary stochastic travel times under traffic congestion. To this end, Kim et al. use a real case of a delivery company based in Singapore with a delivery network

that consists of a single depot and multiple customers, where customers demand are known, but travel times between customer locations are time-dependent and stochastic due to traffic congestion. Real traffic information is also used.

Before estimating traffic congestion and travel time distribution, the authors highlight that the Euclidian distance (commonly used in other approaches) is inappropriate, and therefore they make use of the real road segments between two nodes. The traffic data were collected from the Land Transport Authority (LTA) in Singapore, which provides historical data from street sensors with which averaged vehicle speeds over time for different road segments can be calculated. When a delivery has to be made between two nodes, the Google Maps API is used to get the road segments that are part of the arch, and each road segment is linked to the historical speed data from the LTA (which is time-dependent). With the speed information available for each road segment, dynamics of the traffic congestion states and probabilities of each segment are estimated (see paper for details) and used as inputs to solve the dynamic vehicle routing problem through a rollout algorithm.

The comparison made in this paper between the results obtained through this approach and the current practice by the delivery company in Singapore (that ignores traffic congestion) highlights the potential saving from exploiting historical and real-time traffic congestion information, with a 7% improvement in total travel time. However, the paper is somehow similar to the one written by Conrad and Figliozzi, as they also used the Google API, and shares its limitations, as using historical data instead of real-time data (from Intelligent Transport Systems) can limit the applications of this approach.

3.3.5 Time-Dependent Vehicle Routing Problem with Path Flexibility [17]

In this paper, the authors have introduced the “Path Flexibility” concept, which consists on considering path selection in the road network as an integrated decision (according to the traffic congestion) in the time-dependent vehicle routing problem, minimising the total cost. The authors have applied this approach (TDVRP-PF) and compared it to the traditional one in the urban area of Beijing, using the speed patterns data of the road network from October 14th to 18th (2013). The roads have been classified depending on their average speed.

The results evidence that the TDVRP-PF may not only change the path between two customer nodes within the same route, but there can be structural changes in routes or even vehicle-customer assignments. Apart from this, two variants are included: TDVRP-PF-a (the assignments are fixed as in the TDVRP solution) and TDVRP-PF-r (the routes are fixed as in the TDVRP solution).

The proposed VRP modification developed by the authors to introduce path flexibility into the TDVRP allows minimising the total cost compared to the traditional VRP, making use of the congestion data to recalculate the routes using different paths. However, the use of traffic data from 4 days in 2013 introduces a sampling error in the data that could be fixed by using historical or real-time data.

3.3.6 Summary

Table 2 shows a summary of the papers studied. Some papers [15, 23] make use of the Google Maps API as the interface, and they use traffic data from official sources (databases) to analyse congestion effects. However, they use historical data rather than real-time data, which may limit their applicability. Others [19] develop a theoretical approach to be used within smart cities, in which traffic sensors, and in-vehicle technology can collect real-time information to gain insight on congestion costs that will be used in the route optimisation process, but the paper does not show any real case study or application. There is one paper [17] in which an approach is developed to take into account how congestion affects re-routing within urban areas, but the data used is poor. And Nha et al. [21] propose the use of microsimulation software (using traffic congestion as an input) together with optimisation, but there is a lack of details on the overall methodology. It is also important to note that in most of the papers, congestion costs are considered through a probabilistic approach or based on averaged speeds, rather than estimating the real delay existing in each link of the network. Therefore, it can be seen that although each paper has its own advantages, there is a need to intertwine and improve the different approaches to further develop a more comprehensive and strong methodology.

Table 2. Summary of the main characteristics of the papers analysed.

	Type	Routing interface	Traffic data source	Traffic data type	Congestion calculation
Conrad and Figliozzi [23]	TDVRP	Google Maps API	Database. Inductive loops	Historical	Speed function
Nha et al. [21]	–	Microsim software	–	–	–
Lai et al. [19]	–	–	Sensors	Real-time	Probabilistic
Kim et al. [15]	DVRP	Google Maps API	Database. Inductive loops	Historical	Probabilistic
Huang et al. [17]	TDVRP-PF	–	Other	Weekly	–

4 Conclusions and Future Research

Traffic congestion is one of the main challenges within urban logistics. This paper has reflected how the research community has ignored this topic for decades whilst scholars were mainly focusing on the application of VRP at a strategic level, where minimising a distance-based cost function was the main objective. However, traffic congestion is dramatically increasing in our cities, and on-demand deliveries are changing the way we understand logistics activities. This has caused that, in parallel with the development of the so-called smart cities, congestion has raised concern amongst the research community in the last years.

However, there are only 30 Scopus-indexed papers in which the terms “*vehicle routing problem*”, “*logistics*”, and “*congestion*” have been considered together. In this paper, those articles have been analysed and rated taking into account the impact they are likely to have for other researchers. Then, the five papers with the highest scores have been described in order to understand how different authors account for congestion costs or driver behaviour within the VRP field.

The results show that there are two main approaches. The first one (more related to traffic engineering) makes use of traffic microsimulation software and intelligent transport systems (Big Data, sensors, communications technologies) to improve the realism of traditional approaches to consider real-time traffic congestion effects. However, these frameworks are very theoretical and may lack from direct applicability. On the contrary, there are some authors (more related to the operations research field) that have focused on the improvement of traditional approaches by considering traffic congestion as another input, using historical data and without considering the real congestion but an estimate given by a speed or probability function.

Considering congestion costs into route optimisation algorithms for logistics is something relatively new. Future VRP for urban logistics will have to consider congestion, driver behaviour effects and road conditions (accidents, road closures...) in real-time, making use of Intelligent Transport Systems and Big Data technologies. Agent-based traffic microsimulation or macrosimulation software can be also implemented as part of the optimisation approaches, to get realistic insights on how traffic conditions may affect routing and to analyse future and what-if scenarios.

To this end, the VRP needs to be addressed from a more comprehensive perspective. Urban logistics needs a multidimensional approach, and researchers from different fields (operations research, traffic engineering, smart cities...) need to play together if we want to improve how goods are delivered in the smart cities of tomorrow.

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Using Modelling Techniques to Analyze Urban Freight Distribution. A Case Study in Pamplona (Spain)

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Abstract

The city of Pamplona, in Spain, is currently experiencing several changes regarding sustainable mobility such as pedestrianization of some streets in the city center, and access control to the Old Town for motor vehicles through the use of automatic number-plate recognition. However, some groups including local neighbors and businesses are raising complaints as they are being affected by these measures. This is also the case for couriers and logistics companies which have now to comply with new regulations regarding delivery routes throughout the Old Town. This paper will present a comprehensive study of the situation that is being carried out, and in which social perceptions and freight traffic patterns in the Old Town of Pamplona are analyzed to understand how urban freight distribution could be improved in the area. For this purpose, we make use of a survey-based research to the stakeholders, i.e. pedestrians, logistics companies, retailers, and authorities of Pamplona. Results highlight pollution derived from transportation, lack of parking spaces as well as invasion of public spaces in the city center as the key issues for improving freight transportation in the Old Town. Finally, placing a distribution center in the Old Town and the promotion of the cycle-logistics are considered as the future of the urban distribution in Pamplona.

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1. Introduction

Old cities were not made for cars. Morphology of most of European city centers is based on an irregular matter that corresponded to an unplanned urban development. That irregularity as well as the abuse of the private vehicle as a means of transport has generated several mobility problems within the city (traffic jams, lack of parking spaces, noise and air pollution, lack of space for the pedestrian...) that makes life in cities increasingly unsustainable.

Many cities around the world have decided to improve the mobility of their citizens with the so-called 'sustainable urban mobility plans' (Fenton, 2017; Boisjoly and Yengoh, 2017), that are tools to improve the internal flows of the city (motorized or not) and which seek to cover the needs of citizens proposing alternative means of transport and/or infrastructures. However, this would mean a change in the actual status in the city center that not always reach total approbation due to several conflict of interest for the stakeholders such as users, retailers and logistics companies.

It is not only a mobility problem but also a health problem as emissions from vehicles have seriously increased air pollution in the cities. According to air quality indicator (EEA, 2017) carbon monoxide, lead, nitrogen dioxide, particulate matter, and sulfur dioxide values have skyrocketed from 1980.

Examples of this phenomenon can be easily found in big cities such as Paris or Madrid (Slovic and Ribeiro, 2018; Prieto et al. 2017). In the former, there is a running plan to restrict and pedestrianize the city center in order to halve the number of private cars on the roads. While, in the latter, it is becoming increasingly often traffic restriction to park in the city center. And it is not only a problem affecting to the big cities, but also to the small and medium ones because in these the percentage of use of the private vehicle against the public transport is greater.

Freight distribution is one of the biggest actors playing in the city center that aggravate the saturated traffic situation. The increasing relevance of urban transportation is consequence of both, an increase of the population living in cities and an increase of e-commerce. Moreover, as freight urban transportation is mainly about distribution of goods to the last consumer, most deliveries are rather small, with many stops and attempts to meet the customer, which results in a noticeable increase of presence in the roads.

Application of sustainable urban mobility plans are not usually in line with interests of logistic companies. Higher restriction to access to the city center or to park to load or unload may compromise profitability of logistic companies that as their current delivery policies are not feasible anymore.

Literature about coexistence among the stakeholders in city centers is really scarce and it is mainly devoted to sustainability issues such as the case developed by Atakara and Akyay (2017). In their research, a survey is conducted for investigating the environmental, economic, and ecological problems because of the increasing importance of city centers. Similarly, Gedik and Yildis (2016) assessed the users' role in transforming the city center in an environmentally friendlier area. They found users' opinions have a big impact on authority's decision-making. Nevertheless, literature presents a gap in the role which transportation plays in urban distribution and its coexistence with pedestrians, retailers, and authorities. This article shows a picture on how urban transportation is working in the city center of Pamplona (Spain) by conducting a survey-based research to the stakeholders (pedestrians, logistics companies, retailers, and authorities). The surveys were administrated in a face-to-face and online ways, as well as formal interviews to the authorities of Pamplona. In total, we achieved a database of 540 surveys. Therefore, it can be showed how Pamplona is facing this city logistics problem and how it is possible to understand social perceptions from stakeholders towards new ways of delivering goods within the Old Town of Pamplona.

2. The case of Pamplona

Pamplona is a medium size city in Northern Spain having more than 190,000 inhabitants. The Old Town is known as one of the biggest in Spain, with more than 1 km² and 10,000 inhabitants. It is also a very dynamic area where monuments, government offices, shops, bars and restaurants coexist. Moreover, the irregular morphology of their narrow streets make problematic the coexistence of pedestrians and vehicles.

Mobility of Pamplona is summarized in the Table 1 with data from Pamplona (Pamplona Municipal Council, 2017) with a comparison with Madrid (Madrid Municipal Council, 2014). As can be seen, trends have followed

inverse direction. While in Madrid transportation moving towards more sustainable modes such as walking (or cycling) and public transportation in detriment to the private car, Pamplona was doing the inverse path.

Table 1. Mobility distribution in Pamplona and Madrid

	Pamplona		Madrid	
	1996	2013	2004	2012
Waking + cycling	50%	47%	26%	29%
Public Transport	13%	12%	43%	42%
Cars	32%	36%	31%	29%
Others	5%	5%	-	-

In summer 2017, the sustainably urban mobility plan of Pamplona was adopted leading to many changes in the city center and in the surrounding areas. The details of the plan are described in numerous regulations that are accessible through the webpage <http://www.plandeamabilizacion.com>, in Spanish. The goal of the plan is to reduce the use of private vehicles, prioritize sustainable means of transport such as walking and cycling, and give more relevance to the public transportation by bringing closer stops to the city center. In order to do this, the access to the city center has been restricted to non-authorized vehicles. For getting the authorization, vehicles must accomplish some requirements such as having a residence in the city center for the residents or providing a service in the city center for firms. In early October 2017, there were about 7,000 solicitors to gain access, of those, only 5,800 permits were granted, 2,200 of them were residents and 3,600 belong to companies.

The urban plan also consisted on the pedestrianization of many streets as well as the restriction of many others to public transports such as buses and taxis. Furthermore, more than 700 car parking spots have either disappeared or turned into only-residents ones, making the access to the city center by car pretty difficult.

With regard to the freight transportation, hard time windows have been applied: deliveries are only allowed between 8:00h and 11:00h, as well as from 14:00h to 16:30h. Additionally, the Old Town has been divided into 4 different areas that vehicles must follow in the sense if one enters through one, one ought to exit through the same one. The existence of the zoning system, designed by the authorities of Pamplona, is motivated by five arguments: (i) to guarantee the safe movement of pedestrians and cyclists within the Old Town; (ii) to allow an organized and peaceful access for all the citizens to the shops, households, cultural buildings, schools, public organisms and monumental areas; (iii) to stimulate the economy and the urban development of the area; (iv) to reduce the number of motor vehicles passing through the Old Town; and (v) to get a better urban quality in the area, reducing the visual impact and the emissions caused by motor vehicles. The Figure 1 shows the actual zoning system in the Old Town of Pamplona.



Figure 1. Zoning system in the Old Town of Pamplona

3. Methodology

The details of the methodology are going to be summarized in the following sentences. First of all, the data collection consisted on surveys and interviews carried out in November 2017. The Table 2 shows the number of data collected depending on the methodology, i.e. online surveys, face-to face survey, and personal interviews for the stakeholders. The online surveys was sent by Internet the 1st November 2017 using several distribution lists available in Pamplona such as the university and city associations. Those surveys included extra questions for identifying fake respondents. The survey was also directly sent to shops, restaurants, and bars (retailers), and logistic companies that operate in the city center through their webpages. Personal surveys were carried out to pedestrians that were walking in the Old Town in the second week of November (6th to 12th November 2017) in two shifts: from 11:00h to 12:00h and from 18:00h to 19:00h. There were also some face-to-face surveys to selected retailers and logistic companies that asked so in their mails. To those logistics companies that were extremely involved in the Old Town sustainability plan, an interview was asked instead.

Table 2. Data source for surveys and interviews

Stakeholder	Online survey	Personal survey	Interview	Total
Pedestrians	450	50	-	500
Retailers	15	5	-	20
Logistic Companies	10	-	5	15
Authorities	-	-	5	5
Total	485	55	10	540

The questionnaires included a number of questions related to general data as well as questions related to the mobility in the city and the freight distribution in the city center. Particularly, the survey consists of 25 questions, which last for about 10 minutes and it was divided into 3 parts. Firstly, identifying data in order to differentiate the users of the sample based on different groups (gender, age, socioeconomic status, and so on). Subsequently, general data is collected to gradually focus on the issue of the freight distribution in the Old Town. For this reason, surveyed people are first asked about issues such as sustainability or pedestrianization in general, to later move to a more specific topics such as the freight distribution in the Old Town or the cycle-logistics as a way of distributing goods. Secondly, a list of questions related to frequency of going to the Old Town, the mode of transport and the frequency used to travel through the city. Thirdly, questions related to sustainability have the objective of knowing how sustainable the respondent thinks mobility is. Moreover, additional data are obtained related to the importance that users give to different problems that may exist in the Old Town (pedestrianization, pollution, access control...). Finally, other data about the freight distribution in the Old Town are collected related to the importance that users give to the freight distribution, its sustainability, how this distribution should be carried out or the inconvenience caused by the traditional delivery vehicles. The questionnaire ends with an open question about urban freight distribution. Details on survey structure is given in the Table 3.

Table 3. Structure of the surveys

Number of questions	Time	Topic
7	1'	General information
4	2'	Mobility habits
3	3'	Perceptions on the Old Town
11	4'	Perceptions on the urban freight distribution

The results here presented consist on three groups of questions. Firstly, identifying the importance of several transportation problems (pollution, noise, lack of parking spaces, lack of cycling lines, lack of accessibility, lack of public transport, excessive access control, excessive traffic, excessive freight traffic, and lack of pedestrianization) from pedestrians, retailers, and logistics companies viewpoints. Secondly, the opinion of the pedestrians regarding allowing motorized vehicles in the Old Town. Thirdly, identifying the importance of freight transportation problems (excessive number of trucks, visual impact, accidents, urban space invasion, and excessive speed) again from pedestrians, retailers, and logistic companies' viewpoints. For instance, for the evaluation of the importance of pollution as a transportation problem it was asked: *'how much importance do you give to the pollution emitted from*

vehicles in the Old Town of Pamplona?’ and the answers consisted on marking in a 4-point scale ranging from “No importance” to “Very important”. The remaining questions followed a similar pattern.

With respect to the interviews, authorities from local and regional government and logistic operators were chosen for a formal interview. In these interviews the experts were asked about various topics such as what they considered to be the main problem, the challenges they face and possible improvements and solutions. Finally, they were asked about their opinion about the cycle-logistics and how they see the promotion of these vehicles in the freight distribution in the Old Town of Pamplona.

4. Results

The sample consisted of 58% of women and 42% of men having an average age of 46 years old. Those distributions are in line with the population of Pamplona so the sample is representative.

The problem identification from the pedestrians, retailers and logistic companies are showed in the Figure 2. Air and noise pollution is the most important problem for the pedestrians whereas excessive freight traffic and the lack of pedestrianization remains as a marginal problem. Nevertheless, one consequence of the sustainable mobility planning is the Old Town saturation in the time windows so air and noise pollution will be noticeable higher in those moments and much lower the rest of the day. At the same time, pedestrianization does not seem to be a priority for the pedestrians but essential for the authorities. It is remarkable retailers consider that lack of accessibility is the biggest problem. Actually, they have publish internal surveys highlighting a noticeable loss of sales due to the urban mobility plan.

Regarding the controversial issue of not allowing to enter motorized vehicles with exceptions, it seems that pedestrians are mainly agree, however, it is remarkable the 27% of those that prefer to remove the exceptions as can be seen in the Figure 3.

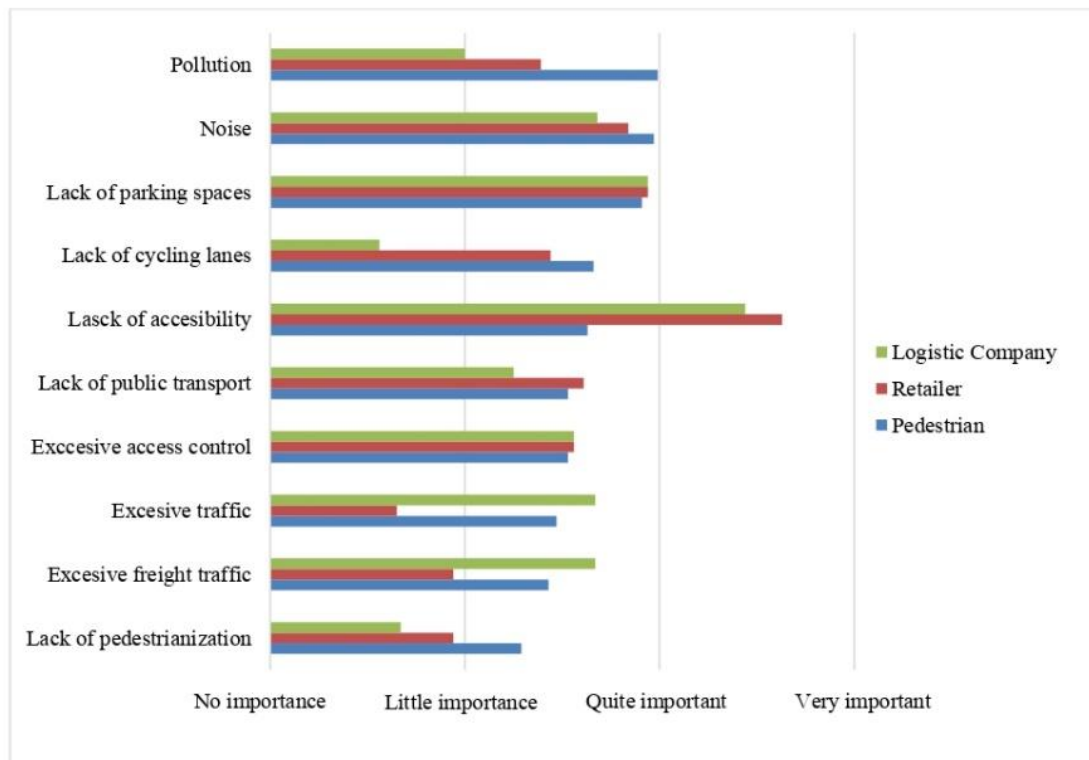


Figure 2. Transportation problem identifications by stakeholders

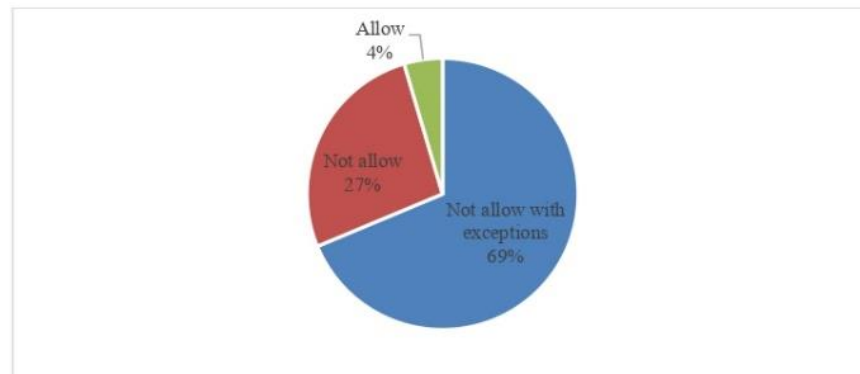


Figure 3. Allowing to access to the Old Town with motorized vehicles. Data from pedestrians.

Focusing on the freight distribution, space invasion of trucks is the biggest problem for the pedestrians, whereas visual impacts is for the retailers. Accidents is a major issue for the logistics operators. The entire information is showed in the Figure 4.

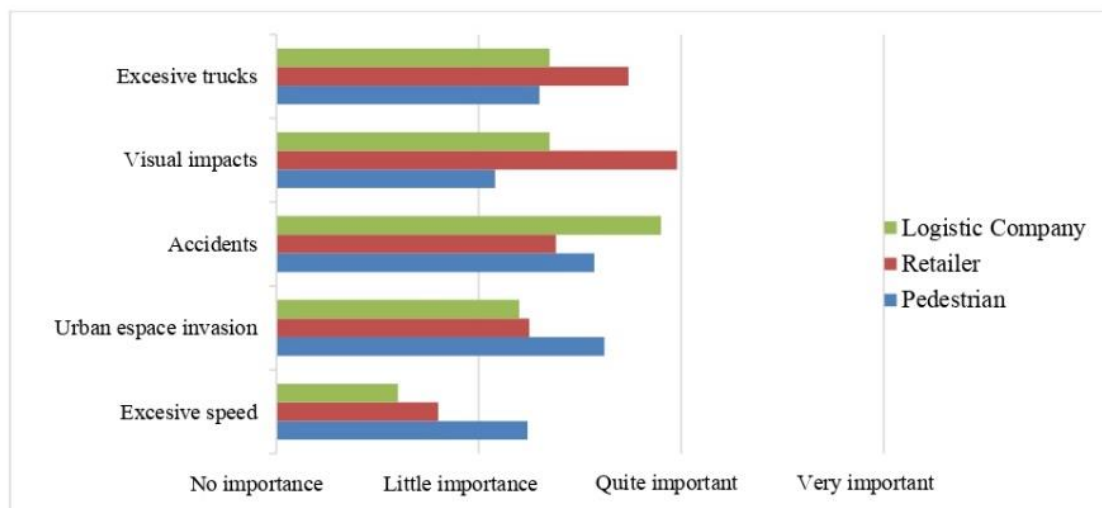


Figure 4. Freight transportation problem identifications by stakeholders

The experts and authorities list some ways of improving the freight transportation in the Old Town. Those suggestions include an increase of non-polluting vehicles, such as electric vehicles and cargo-bikes. Additionally, the creation of a consolidation center in the city center is seen as an efficient way of reducing the vehicles.

5. Conclusions

The city of Pamplona is experiencing a lot of changes related to sustainable mobility as an urban sustainable mobility plan has recently been applied, mainly affecting freight distribution in the Old Town. Shops, restaurants, pedestrians, and people living in that area are complaining as the excessive access control to the Old Town is disturbing the livability of the Old Town, and also a decrease in sales has been perceived. For that reason, this study aims to understand what the social perceptions of the people of Pamplona are regarding freight distribution in the Old Town.

Results suggest freight transportation is of great importance for the stakeholders. In addition, freight transportation generate a number of drawbacks to users such as pollution, limited parking slots, invasion of public space, and accidents. Firstly, the new concern regarding the environment is placing its focus on environmentally friendlier modes of transportation and it is reflected in the results of our survey, being the pollution the largest problem in the city center of Pamplona. Controversially, difficulties for finding parking slots are also of highest importance. This situation is due to the fact that Pamplona is a medium size city having necessity of improving its public transportation network. Thirdly, as the Old Town of Pamplona is one the most dynamic points in the city where plenty of activities meet every day at every time, the invasion of their streets by vehicles is also considered as a huge problem. Finally, the accidents, as a consequence of the previous lines, are a barrier for more important social development in the city center. For all this, pedestrians, logistic companies, retailers and experts in the field believe that measures should be taken in the future. A distribution center nearby the city center as well as the use of cargo-bikes is seen as a good alternative to mitigate both environmental and social effects of the saturated city center.

Finally, promising additional research can be made on this direction. Firstly, a comparison of social perception can be performed between different cities in order to obtain key indicators. Secondly, a quantitative model is planned to be developed using the automatic number plate recognition system, similarly to the work developed by Zheng et al. (2017). This would allow to measure the phenomenon with real-time data. Finally, current research trends are in line with the optimization of the logistics operations. For instance, solving the vehicle routing problems with environmental criteria (Lin et al. 2014), or the environmentally friendlier facility location problem (Harris et al., 2014). To this respect, availability and quality of the data obtained would be of utmost interest.

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3.4 Article 4: Serrano A., Alvarez, P., Lerga, I., Reye, L., and Faulin, J. (2017). Pricing and Internalizing Noise Externalities in Road Freight Transportation. In: Transportation Research Procedia, 27: 325-332.



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Pricing and Internalizing Noise Externalities in Road Freight Transportation

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Abstract

People living close to main roads may suffer from the nuisance of traffic and noise pollution. This paper assesses the effect of full routing cost in vehicle routing decisions by internalizing the external cost of noise. On a first step, noise externalities are economically assessed through a contingent valuation procedure. Secondly, a novel methodology is proposed to allocate the external costs to the road network links. Results show significant differences in routing planning depending on the approach: minimization of traditional internal cost versus minimization of full cost. These results encourage further research in pricing and methodologies to internalize externalities.

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Keywords: Externality; Contingent Valuation Methodology; Noise; Internalization; Pricing; Vehicle Routing Problem

1. Introduction

According to the **European Commission (2016)**, half of all goods in Europe are moved using road transportation, being the responsible of 5% of the European GDP and employing about 3 million people. Furthermore, road freight transportation accounts for 24% of all greenhouse gases emitted in the European Union which contributed to global warming and it is also source of stress, sleep disturbance and other noise-related issues. Therefore, research on road transportation economic, social, and environmental impacts is of utmost interest.

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Transport planning has long been focused on its economic aspects. Traditionally, researchers have paid great attention to route optimization in order to get the cheapest way to fulfill a transport activity without considering environmental impacts. However, negative externalities of road freight transportation related to air pollution and excessive noise levels are particularly perceptible. In this context, different green transportation concepts aiming to reduce these impacts have recently been presented (Kadziński et al. 2017; Muñoz-Villamizar et al. 2017; Toro et al. 2017). Most optimization models consider emission estimations which are based on routing characteristics such as distance, load levels, vehicle type, or road gradient, and which ultimately depends on fuel consumption. These estimations are then included in the objective function in order to minimize the relevant variable.

By either focusing on monetary or environmental goals, different factors are considered as decision variables. Thus, in order to efficiently account for internal and external routing costs, new pricing models are necessary to incorporate external costs on corporate decision-making processes (Demir et al. 2015). One possibility to evaluate non-market goods, i.e. air pollution, noise, etc., is through the contingent valuation method (CVM) (Istaiti et al. 2014). The CVM is based on stated preference surveys in which a population sample is asked for their willingness-to-pay (WTP) to achieve a hypothetical scenario with a greater level of utility. That is, through the CVM a hypothetical market is created for a commodity that could be bought by customers. The obtained value refers to the difference in the welfare of the individual by passing from the current scenario to the new one. Concerning the case-study area we have chosen the Spanish region of Catalonia due its role as connection point between Spain and France crossing the Pyrenees.

The literature presents a wide range of different emission models which typically replace 'traditional' optimization objectives related to costs reduction. In this work, we want to go one step beyond these approaches by internalizing negative externalities. Firstly, external cost from noise pollution is estimated through stated preference surveys. Secondly, a methodology based on source-receptor relationship is proposed to allocate the external costs to the links. Finally, several instances were generated within the case-study region allowing us to identify transport management insights.

2. Related Literature

An externality refers to a situation in which the costs or benefits of production and/or consumption of goods and services are not reflected in its market price (Pigou, 1920). In other words, externalities are those activities that affect others without paying for them or being compensated. According to Ranaiefar and Regan (2011), negative routing externalities can be classified into four different impact areas: the (i) economy, which includes congestion, road damage and longer travel times; (ii) society, comprising accidents, intrusion and noise pollution; (iii) ecology, encompassing biodiversity destruction and climate change; and (iv) the environment, including waste, air, and water pollution. Many research works have tried to physically measure such externalities. To this respect, Demir et al. (2015) gave an extensive review on externalities modeling in which they accounted for several different methodologies to deal with noise and air pollution, congestion and accidents. Similarly, Demir et al. (2015) also includes a pricing section, concluding that further research should be made in that direction.

In order to internalize such externalities in delivery route planning, monetary values have to be considered to price these factors. Therefore, a large-scale survey, applying the CVM, was conducted in the case-study area, (Catalonia, Spain). This methodology was adopted by authors such as Lera-López et al. (2014) or Lera-López et al. (2012) in a Spanish region to study air and noise pollution obtaining WTP values around €8 per externality, household, and year. In extremely polluted areas, such as Shanghai in China, the value rises to nearly €65 in the similar hypothetical scenario of air quality improvement (Wang et al. 2015).

Physical measure of noise pollution (mainly in decibels) is complex as it takes into account many factors such as surface, tire typology, or meteorology (Kephelopoulou et al., 2012). The consideration of non-traditional factors is more frequent in the case of air pollution, where the Green Vehicle Routing Problem (GVRP) has become a recurrent topic. Since emissions and fuel consumption are related, most of the GVRP research has focused on the minimization of fuel consumption through optimizing a relevant variable (i.e. load, speed, road gradient...) as discussed by Demir et al. (2014) and Lin et al. (2014). An approximation is given by Bektaş and Laporte (2011) where the pollution routing problem is defined. The authors concluded that the minimization of emissions does not result in the minimization of costs, whereas emission costs are quite insignificant in comparison to fuel and driver costs. It is remarkable that those emissions costs are simply computed by a cost figure provided by DEFRA (2007) who estimated the value of a ton of

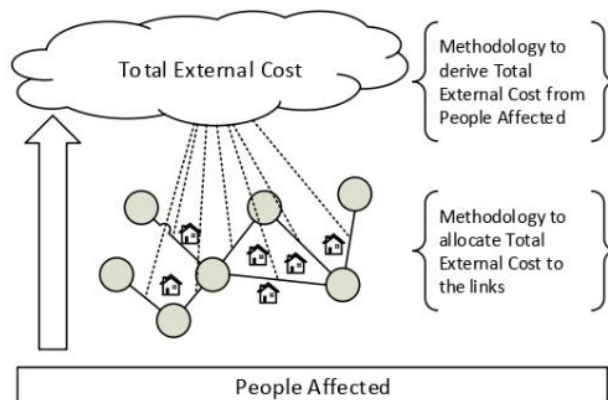
CO₂ in GBP 27 (2002). Fuel consumption is then translated into CO₂ emissions at a rate of 2.32 kg of CO₂ per liter as suggested by Coe (2005). In this last paper there is no evidence of internalization. Zhang et al. (2015) later discussed a similar problem in which internalization of emissions cost was carried out through a similar unit emissions cost value based on fuel consumption. In that case, the cost emission per liter of fuel consumption was set to CNY 0.64, while no information about that figure was provided. Finally, a recent example is presented by Eshtehadi et al. (2017) in which the relationship between fuel consumption and speed is illustrated. According to the authors, there exists inefficiency in the use of fuel at low speeds resulting in higher consumption. Later, a decrease of consumption occur until some point (60-65 km/h) when fuel consumption increases again as a result of aerodynamic drag. Then the fuel consumption may be scaled by the payload.

Certainly, scientific literature has focused on two approaches without mixing. On the one hand, literature about emission measurement, i.e. CO₂, where the physical measure is implemented into optimization problems with the goal of obtaining the least polluting solution. On the other hand, literature focused on the economic quantification of some range of externalities but without further implication in logistics activities. Therefore, there is a gap where very few papers have tried to bring some light because either a simplistic vision or an incomplete implementation.

3. Methodology

In this way, the methodology we are going to use consists of two steps as described in Figure 1: (i) deriving the total external cost and (ii) allocating this cost to the edges which usually lodge different kinds of population. Afterwards, when the vehicle passes through the edges these external costs can be added to the internal ones forming the full cost. Finally, the full cost is considered in the route planning process.

Figure 1. Methodology overview



3.1. Total External Cost

The total external cost is the economic valuation of the externality under consideration within a reasonable time period in a given region. To this respect, it is assumed that WTP values given by the population are a good approximation of the economic value of the externality since it takes into account the socioeconomic characteristics and their real externalities affliction (economic quantification of the welfare loss). Thus, the total external cost can be computed as the summation of all WTP obtained values. Once the total external cost is estimated, an approach to allocate it is necessary as next subsection describes.

3.2. Cost Allocation Model

The cost allocation model is partially inspired by the Impact Pathway Approach (European Commission, 2003) in which transport externalities are mainly generated by heavy commercial vehicles (the source) and assumed by the affected people (the recipients) according to the aforementioned methodology. Thus, allocation is made to edges depending on the number of households affected and the intensity of heavy traffic. Therefore, the external cost associated to the edge i is computed according to Equation 1:

$$\epsilon_i = \frac{T_i \cdot H_i}{\sum_i T_i \cdot H_i} \cdot E \quad (\text{Eq. 1})$$

Where T_i is the average flow of heavy vehicles passing through edge i , H_i are the households affected in that specific link, and E is the total external cost, with $\sum \epsilon_i = E$.

4. Case Study

A case study has been developed to test the proposed methodology in the Spanish region of Catalonia. This region is particularly important in road freight transportation as it is one of the two major connections of the Iberian Peninsula to the rest of Europe. Actually, according to the Spanish-French Observatory of Road Transport at the Pyrenees (2016) more than 30,000 vehicles use the Mediterranean route daily, being 10,000 of them heavy ones.

4.1. Total external cost and parameter setting.

A contingent valuation survey was conducted in the case study region. To estimate the WTP for reducing traffic-related noise externalities, the population was chosen among inhabitants of Catalonia in Northeast Spain. The region has a population of 7.5 million people where a total of 800 households were surveyed through phone interviews. The questionnaire, which was carried out in December 2013, consisted of 3 sections, as suggested by Mitchell and Carson (1989): (i) *introduction*, where the problem is described; (ii) *contingent valuation* that contains open-ended questions used to obtain WTP; and (iii) *classifying questions* aiming to obtaining further information from respondents (age, gender, income, and environmental concerns). The survey results state that an average household is willing to pay €8.52 in order to reduce its noise nuisance. Moreover, a total of 223,280 households are sited within 200 meters along major roads. That results in a total external cost for noise of €1,902,347.

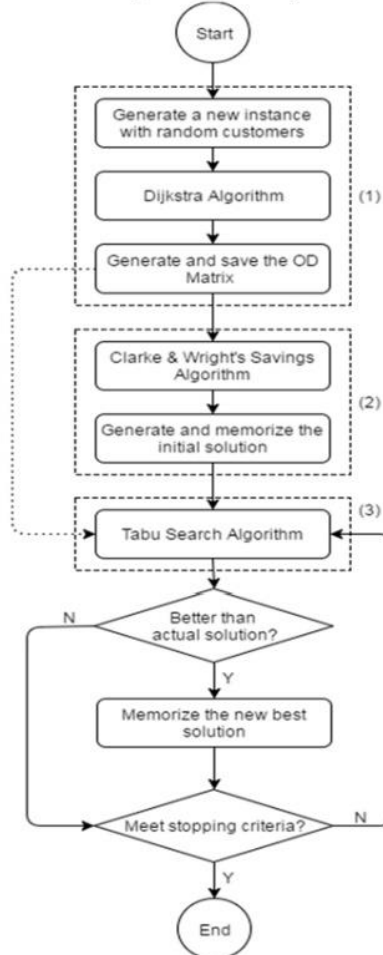
4.2. Solution procedure

The proposed method has been implemented as a Java application, mainly because it allows a rapid, platform-independent development of algorithms that can be used to test our approach.

Our procedure consists of three phases as shown in Figure 2:

- *First phase (1)*. The process starts with the generation of a new random instance of customers within the road network of Catalonia. Then, the Dijkstra Algorithm generates the OD matrix (minimum distances) between the depot and all the customers and saves it into an external file.
- *Second phase (2)*: Making use of the file generated, the best solution that CWS heuristic is able to achieve is saved in order to be implemented as an initial solution in the Tabu Search.
- *Third phase (3)*: Improvement of the solution through a Tabu Search. That metaheuristic guides the local search heuristic algorithm to explore the space of solutions beyond local optima. To do so, a flexible memory is implemented based on Taillard et al. (2016), where some previous movements are saved to avoid them during a number of iterations. Its operating core is the following:
 1. Selection of an initial solution (in our case the CWS solution).
 2. Choice of the environment and generation of a new solution.
 3. Evaluation of the objective function.
 4. Update of the best solution.
 5. Stopping Criteria.

Figure 2. Solution procedure



5. Results

A real road network in Catalonia, Spain, was used to test the proposed methodology. It consists of more than 330 edges and 310 nodes. Different cases of minimizing Internal Cost (IC), External Cost (EC) and Full Cost (FC) were set as the objective function for the Vehicle Routing Problem (VRP). Note that the IC corresponds to the traditional distance-based VRP in which a cost parameter of 1.12 €/km has been applied. This value is appropriate for an average articulated truck operating in Spain (Spanish Ministry of Transportation, 2015). The EC refers to the cost assigned to edges through Equation 1 whereas FC is the summation of IC and EC.

A total of 10 customers and one depot were randomly assigned to the nodes and 5 instances were created in which the initial proposed WTP value varied from €8.52 to 3 times higher. A Visual Basic program was developed to create 30 runs per instance in order to take stochasticity effects into account. Results indicate that similar results are obtained when increasing the number of customers, although these are not reported due to space limitations. Moreover, truck capacities were set to 50 and customer demands were randomly assigned in the interval [1, 12.5]. Before each run, customers are randomly reassigned to the nodes, then our solution procedure is applied with the three proposed objectives, i.e. min IC, min EC and min FC. Preliminary results are shown in Table 1, where values correspond to the average for the 30 runs.

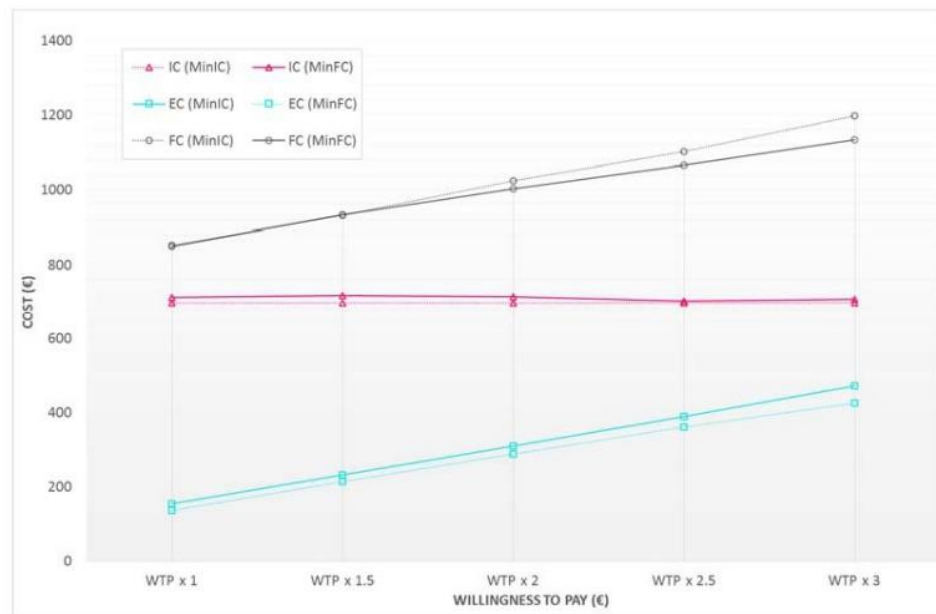
Table 1 Numerical results corresponding to Min IC, EC and FC

	Min IC			Min EC			Min FC		
	IC	EC	FC	IC	EC	FC	IC	EC	FC
WTP x 1.0	699	154	854	1035	124	1160	713	137	850
WTP x 1.5	699	232	931	1050	187	1237	718	214	933
WTP x 2.0	699	311	1025	1070	240	1311	715	288	1003
WTP x 2.5	699	389	1103	1090	301	1391	704	361	1065
WTP x 3.0	699	472	1198	1084	358	1443	709	425	1134

According to Table 1, internalization of external costs would increase total costs by 21%-22% (FC/IC), having further implication in the routing design. Focusing on the base scenario (WTPx1.0), Min IC and Min EC show extreme solutions, being Min FC the intermediate one. When minimizing full cost (Min FC) instead of internal costs (Min IC), the IC raises by 2% whilst the EC drops by 11%. This leads to a more profitable FC (difference with Min IC is -0.5%) which highly improves (-5%) in a hypothetical scenario of WTPx3.0. The ratio EC/FC is also improved when full cost is minimized instead of internal cost (16% and 18% respectively), although the best ratio is obtained when we minimize the external cost (10%). The values obtained are in line with those from the literature (Márquez and Cantillo, 2013). The results show that even in the WTPx1.0 scenario, our approach of optimizing the full cost leads to more efficient solutions.

The effect of increasing the value of the externality (WTP) is better described in Figure 3. On one hand, FC and EC show an increasing tendency as the WTP values go up. On the other hand, the greater the WTP values are, the higher the difference is between the FC when FC is minimized and the same cost when IC is minimized.

Figure 3. Results comparison varying initial WTP up to 3 times higher



In this case-study, the internalization of the external cost caused by noise would lead to a significant change in the routing planning. An illustrative outcome is described in Figure 4. Numbers in circles represent the order in which the customers are being visited. In this scenario, trucks have to return to the depot only once. Routes vary depending on the variable being minimized: internal cost (left) or full cost (right). Note that routes obtained when the full cost is minimized (i.e. when the externalities are being considered) avoid passing through high-density areas such as

Barcelona downtown or other littoral areas. As seen in Table 1, the avoidance of certain edges needed to take noise into account increases the internal cost, although the full cost is minimized.

Figure 4. Changes in routing planning minimizing IC (left) and minimizing FC (right)



6. Conclusions and further research

Profit and loss accounts of transportation firms contemplate costs related to operational activities such as purchases of raw materials, salaries of employees, or assets depreciation, among others. Nevertheless, costs in environmental/social terms are not included in their conventional balance reports and, therefore, they are beyond their control. By definition, externalities are outside the market mechanisms, i.e. they are not reflected in prices. Thus, externalities are not always considered by transport companies which leads to inefficiencies in the market and to the environment and social detriment. Significant externalities arise from road transportation that should be added to the traditional internal cost in order to achieve a full fair cost. By internalizing external costs, transport companies will consider such effects in their decision making processes and so they would be measured, controlled and optimized.

Moreover, research on transportation externalities is of highest interest as cities and regions are becoming more sustainable. From a social point of view, noise pollution emitted from traffic may increase the risk of heart disease, hearing loss, stress, or sleep disturbances. This work addresses the topic of internalizing the external cost of noise. For this purpose, a contingent valuation survey was conducted in Catalonia, Spain, to derive the external cost of noise. A novel methodology is later implemented to allocate the total external cost caused by noise to every link in the road network.

Results suggest that transport decisions (for example, routing planning) would significantly change if internalization were performed. First, accounting for external costs leads to an increase in costs of about 20%; secondly, a new optimization dimension is presented in which full cost replaces the traditional internal cost optimization.

Future research directions involve the internalization of a wider range of externalities such as air pollution, congestion or accidents. Moreover, a more sophisticated methodology would be required to quantify these externalities, as well as for estimating the total external costs. Finally, an effective and realistic tool for internalization would be necessary, for example through taxes or tolls.

Acknowledgments

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3.5 Article 5: Alvarez P., Serrano A., Faulin J. *Is time more important than distance to optimize freight delivery routes? An approach using the value of time. Submitted to Transportmetrica B: Transport Dynamics.*

Alvarez, Lerga, Serrano-Hernandez, and Faulin

IS TIME MORE IMPORTANT THAN DISTANCE TO OPTIMISE FREIGHT DELIVERY ROUTES? AN APPROACH USING THE VALUE OF TIME.

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ABSTRACT

Traditional approaches to optimize freight delivery routes are based on minimizing a distance-based cost function. New approaches use also time as the objective function to minimize. However, the trade-off between time and distance is sometimes unclear. This paper presents a new approach to optimize delivery routes in which both time and distance are used together to optimize delivery routes. For this purpose, the operating cost of a vehicle and the value of time have been used to convert time and distance into monetary units. Through the study of three different networks in Spain with different level of detail (the region of Catalonia, the city of Barcelona, and the old part of Pamplona), the results have indicated that minimizing both time and distance provides better results than the traditional approach, especially at a local level where congestion effects are more relevant.

Keywords: Vehicle Routing Problem, Urban Logistics, Time, Distance, Congestion, Last-mile Distribution, Value of Time

Alvarez, Lerga, Serrano-Hernandez, and Faulin

INTRODUCTION

Transport and logistics are essential activities for worldwide economies, due to their contribution to the economic and social progress. The transport industry directly employs around 10 million people in the European Union and accounts for about 5% of gross domestic product (GDP). In addition to this, logistics, such as transport and storage, account for 10–15% of the cost of a finished product for European companies (European Commission, 2016). In the literature, the optimization of vehicle routing problems (VRP) is one of the most common topics related to these activities, whose approaches have been evolved from the traditional VRP problems that consider fleets with different configurations (Baldacci et al., 2008) (Toth & Vigo, 2014) to ones with more complexity that consider time windows (Baldacci et al., 2012), different distribution levels (Perboli et al., 2011), or that use simulation-optimization approaches (Juan et al., 2015). Furthermore, more original problems have been also solved, such as routing problems using electric or hybrid vehicles for which the driving range is the main constraint (Conrad & Figliozzi, 2011) (Mancini, 2017) (Paz et al., 2018), or using drones for which energy use and emissions are some of the existing challenges (Dorling et al., 2017) (Figliozzi, 2017). However, these solutions have been developed optimizing logistic routes by minimizing a distance-based objective function in most cases, and therefore without considering the importance of time.

During the last decades, traffic congestion has exponentially increased (JRC, 2012), mainly because of the population growth in urban cities and also due to the changes in products demand, where on-demand deliveries and online shopping are changing the way people buy goods and products. Congestion itself may cause several negative externalities within the transport system and the society (European Commission, 2014). Apart from an increase in air and noise pollution, stress levels, or fuel costs, road congestion also leads to higher and more unreliable travel times which result in negative economic effects because of an inefficient delivery of goods, services and resources. In this sense, congestion costs can be evaluated as the loss of welfare derived from an infrastructure inefficient use, and an adequate conversion of time into monetary units would make it possible to analyze the whole picture from an economic perspective. However, traffic congestion is not the only variable that affects travel time, but there are other factors such as network topology, speed limits, roadworks, or accidents that also need to be taken into consideration. Therefore, it is clear that travel time should be also contemplated when optimizing delivery routes.

Nowadays, the VRP approach based on time consideration is starting to be studied (Alvarez et al., 2017), and results show that, although a decrease in travel time could be obtained, this may lead to an increase in distance travelled. Therefore, the question about the best approach for a company arises: is saving time less or more expensive than saving distance? And, what is the trade-off between these two costs? There is a lack of further investigations in minimizing not only distance (the traditional approach) or time (a more up-to-date approach), but distance and time together in order to understand which approach fits better to companies' operations.

Let us consider as an example the scenario A shown in Figure 1. If a company bases their optimization approach on minimizing distance, they would choose link 2 (7 Km) to go from A to B. However, the link is a rural road, and although there is no congestion (green color) the speed limit is set to 50 Km/h and the road passes through a small town, so the driver would need 8.4 minutes to travel between the two locations. Therefore, the company may decide to travel using link 1 because, although having a longer distance (12 Km), the speed limit is set to 90 Km/h, so the travel time is reduced to 8 minutes. It is clear then that the approach in which travel distance

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is minimized leads to different results than the one in which travel time is the variable to minimize.

In the example explained in the scenario B, there are some road sections in link 1 with increased congestion (in red). This may be caused by roadworks taking place in the highway, because of the high traffic demand existing during the peak hour, or due to an accident. This situation has caused a decrease in the speed that leads to an increase in the travel time (from 8 minutes to 9 minutes), so the company now can decide that the truck should be using link 2 as the travel time is now lower.

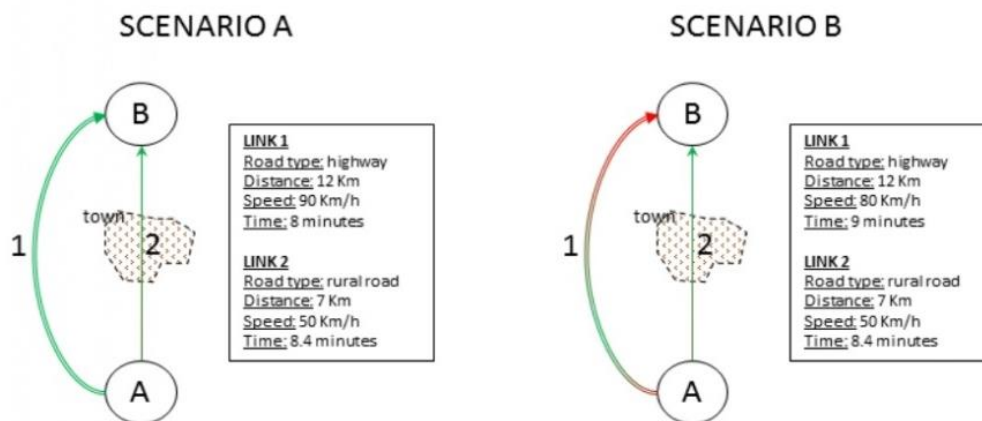


Figure 1. Examples of two scenarios in which both time and distance affects routing decisions.

It is evident that using the functions of distance or time by themselves does not always produce realistic nor optimal results. When congestion effects are not present, there exists a perfect correlation between distance and time, therefore the route obtained when minimizing distance must be the same as the one obtained when minimizing time, and also the same as the one in which the sum of distance and time has been minimized. However, if congestion or other dynamic network conditions such as changes in demand, accidents or roadworks happen, the results between these approaches will be different.

Therefore, both time and distance are important objective functions to consider when optimizing delivery routes, with time being a dynamic attribute which can vary throughout the day. Having said that, it is important to note that there exist other factors that influence how companies optimize delivery routes which are not related to time or distance. These are, among others, familiarity of the driver with the route (which improve driver's efficiency), road type (which is related to road safety), or increase in CO₂ emissions caused by congestion (stop-and-go traffic). However, the main approaches used to optimize delivery routes focus on time or distance.

In light of the aforementioned ideas, this paper studies the potential benefits of considering time and distance together into the vehicle routing problem. Similarly to the methodologies commonly used to derive the economic cost of congestion, travel time can also be translated into monetary units. According to the welfare theory, individuals may prefer to spend more time traveling at a cheaper price than faster trips at a higher cost. These decisions are made based on the cost of the time, also known as Value of Time (VoT). In parallel, the distance travelled can also be converted

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into a monetary cost by using the operating cost of a vehicle which directly depends on distance. Therefore, this paper implements a new methodology in which a full cost function, which depends on both distance and time, is minimized in order to optimize delivery routes. For this purpose, three different scenarios have been built to represent real road networks in Spain: the region of Catalonia (regional level), the city of Barcelona (city level) and the Pamplona Old Town (local level).

LITERATURE REVIEW

The Vehicle Routing Problem (VRP) is a generalization of the Traveling Salesman Problem, whose purpose is finding the optimal set of routes in cost or distance for a fleet of vehicles delivering goods or services to various locations. It was not until 1959 when Dantzig (Dantzig & Ramser, 1959) developed a linear programming formulation to obtain an exact solution to optimize delivery routes between petrol stations. A few years later, Clarke and Wright (Clarke & Wright, 1964) proposed a heuristic method through which a near-optimal solution can be obtained for real delivery problems. Over the last 40 years, some variants have been introduced in order to add complexity and more realism to the problem, such as the capacitated VRP (CVRP), the VRP with time windows (VRPTW) (Chiang et al., 2014), the split delivery VRP (SDVRP) (Wang et al., 2013), the heterogeneous fleet (HFVRP) (Prins, 2009), the periodic VRP (PVRP) (Yao et al., 2013), or the Pickup and Delivery VRP (PVRP) (Nagy & Salhi, 2013). Moreover, new approaches have been developed lately that consider actual concerns such as CO₂ minimization (Bektas & Laporte, 2011), congestion effects (Kok et al., 2012), consumption and range limitations when delivering with electric vehicles and drones (Catay & Keskin, 2017) (Figliozzi, 2017), or even the stochastic effects of real-life problems by using simheuristics (Juan et al., 2015).

Although the scale at which VRP are being used has changed in the previous 60 years, the majority of applications are still focused at a strategic level (i.e. routes between cities) where most of the approaches aim to minimize a distance-based cost function without considering other aspects such as time, congestion effects, or driver behavior (Srinivas & Gajanand, 2017). Over the last years, some researches have introduced their interest in the field, minimizing time instead of distance (Alvarez et al., 2017). Examples of those problems are given by Conrad and Figliozzi (2010), who integrated historical traffic data from the Portland Oregon Regional Transportation Archive Listing (PORTAL) with the Google Maps API for the implementation in a VRP; Kim et al. (2016) who made use of real time data from the Land Transport Authority to solve a real case in Singapore employing the Google Maps API; and Huang et al. (2017) who demonstrated the importance of considering real time data instead of historical one.

It is important to note that, as far as we know, the optimization of logistic routes considering both time and distance has not been profoundly studied because these variables are usually correlated within the scope they have been applied to strategic routing, for which congestion effects are not as relevant as for urban areas (Crainic et al., 2004) (Colak et al., 2016). However, with traffic congestion growing at a phenomenal rate, particularly within urban areas (United Nations, 2015), the correlation between time and distance becomes weaker. Therefore, the importance of considering time and distance together takes a fundamental place into the optimization of logistics routes (De Jong, 2016) (De Jong et al., 2016). In this paper, an approach has been developed which is based on introducing both variables within the same objective function. For this purpose, time and distance have been converted into monetary units. As explained in the introduction section,

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the distance travelled can be transformed into monetary units by using the operating cost of a vehicle, and the same can be done with time by using the Value of Time (VoT).

In literature, transport economists consider the VoT as the opportunity cost of the time that a traveler spends on the journey (Becker, 1965). In other words, it is the amount of money that a traveler would be willing to pay in order to save time -or the quantity of money they would accept by losing time- (Mouter & Chorus, 2016). Among the last decades, the concept Value of Time has been progressively taken into account in order to design transport infrastructure projects and transport policy measures (Gwilliam, 1997) (De Jong, 2014), becoming a crucial aspect in the context of the cost-benefit analysis (De Jong, 2016). It has been applied, for example, to analyze whether improving the bus frequency will entice car users to switch to public transport (Wardman, 2004) (Transport for London, 2016), or to design cordon charging schemes (Eliasson, 2009) or toll roads to penalize car users (Brownstone & Small, 2005) (Nie & Liu, 2010). However, the use of the VoT for optimization of logistics routes has been inexistent to the best of the authors' knowledge.

Since the development of choice models and stated choice data collection methods in 1960s, a great amount of studies has taken place in order to relate travel time and travel costs (Abrantes & Wardman, 2011). The studies show that there is a huge variation in the Value of Time not only from person to person, but also caused by other factors. For example, Johnson (1966) incorporated work time and leisure time into the studies as separate arguments of the traveler's utility function, showing that the value of working time differs from the value of non-working time. This conclusion was also obtained by other authors (Li et al., 2010). In 1971, DeSerpa went a step forward in the integration of time in standard microeconomic demand theory and distinguished the travel time spent by necessity and the time spent by choice (De Serpa, 1971). Moreover, with the aim of considering the travel time variability, Gaver and Knight were among the first to take into account the impact of the roads congestion in the Value of Time (Gaver Jr, 1968) (Knight, 1974). Therefore, this heterogeneity in the value of time is caused by the working conditions, the day of the week (Hossan et al., 2016), and the time of the day, but also depends on the age, the gender, the household income (Lam & Small, 2003), and other characteristics of the trip, such as the trip purpose, frequency, urgency (Patil et al., 2011), or mean of transport (car, bicycle, truck, van, etc.) (Borjesson & Eliasson, 2012).

Although the Value of Time is widely used by transport planners, there exists potential for the VoT to be also used when optimizing logistic routes, although it is true that research related to the VoT and logistics is more limited. Given the above findings from the literature, this paper shows a methodology to consider distance and time together by using the value of time and the operating cost of a vehicle. Due to the lack of similar studies, this works analyses whether optimizing delivery routes by considering the joint effect of time and distance gives better results than the existing approaches in which these variables are used in isolation.

METHODOLOGY

The methodology used in this paper has the aim of understanding which approach is better for logistics companies to optimize delivery routes: minimizing distance, minimizing time, or minimizing the sum of both variables. With the purpose of adding both variables together, they have been converted into monetary units (€), using the operational cost per kilometer (€/Km) and the value of time (€/hour). Note that distance and time are perfectly correlated only when

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congestion is not present. In other cases where local dynamic conditions change, this correlation becomes weaker, and the results from the different approaches may differ.

Models

Three different models have been set to analyze the effect of each of these approaches.

- Model 1 (M1): minimizing the internal cost (IC)

This model is the traditional one in which distance is minimized, so the optimized route from this model would be the same as the one from a model in which travel distance were minimized. However, as stated before, distance (D) has been converted into monetary units to allow a comparison between the different models. To do so, the direct cost of a vehicle operation (value of operation, VoO) has been considered which is the cost of the amortization of the vehicle, the financing cost, the cost of the vehicle insurance, the fiscal costs, the cost of the petrol and the tires, and the maintenance and reparation costs. The units are €/km. Therefore, the internal cost (IC), is given by the equation 1 below:

$$IC (\text{€}) = VoO (\text{€/Km}) \times D (\text{Km}) \quad (\text{Equation 1})$$

- Model 2 (M2): minimizing the cost of time (CoT)

This model is similar to the one in which time is minimized so the optimized route from this model would be the same as the one from a model in which travel time were minimized. However, the variable to minimize is not the time but the cost of time, which depends on the value of time (VoT) and on the total travel time (T), and is given in the equation 2 below:

$$CoT (\text{€}) = VoT (\text{€/hour}) \times T (\text{hour}) \quad (\text{Equation 2})$$

- Model 3 (M3): minimizing the full cost (FC)

This model takes into account the joint effect of time and distance through the minimization of the sum of both variables after converting them, as seeing before, into monetary units. Therefore, in this model the full cost (sum of IC and CoT as seen in equation 3) is the variable which is being minimized.

$$FC (\text{€}) = IC (\text{€}) + CoT (\text{€}) \quad (\text{Equation 3})$$

For each link i within a network with a total of n links, the variables IC, CoT and FC are obtained in all of the models, but the FC will be output that will be used to make comparisons between them.

The objective functions below (equation 4 to equation 6) summarize the differences between the three models.

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Model 1

$$FC = \text{Min} \left(\sum_{i=1}^n (VoO_m \times d_i) \right) + \sum_{i=1}^n (VoT_m^h \times t_i) \quad (\text{Equation 4})$$

Model 2

$$FC = \sum_{i=1}^n (VoO_m \times d_i) + \text{Min} \left(\sum_{i=1}^n (VoT_m^h \times t_i) \right) \quad (\text{Equation 5})$$

Model 3

$$FC = \text{Min} \left(\sum_{i=1}^n (VoO_m \times d_i) + \sum_{i=1}^n (VoT_m^h \times t_i) \right) \quad (\text{Equation 6})$$

where

FC is the full cost of the route, in €.

i represents each link of the network.

n indicates the number of links within the network.

VoO is the operating value of the vehicle, in €/Km.

m indicates the mode of transport (HGV or LGV)

d indicates the distance travelled.

VoT is the value of time, in €/h.

h indicates the day of the week (weekday or weekend)

t represents the travel time.

The constraints applied to these VRP models have been taken from the CVRP depicted by Toth and Vigo in their book “*Vehicle routing: problems, methods, and applications.*” (Toth & Vigo, 2014).

Inputs

To calculate the full cost for each link and for the routes in each model, the costs per kilometer of vehicles operation (VoO) as well as the values of time (VoT) are needed. For the IC, the value of operation (VoO) has been taken from the official Spanish guidelines (Ministerio de Fomento, 2017). This cost is directly related to distance, and the units are in €/Km. Data for HGV corresponds to an articulated truck of general cargo (the average cost between truck loaded and unloaded has been taken), and LGV corresponds to an average van.

As for the CoT, due to the lack of studies regarding the VoT in Spain, they have been taken from the WebTag guidance from the UK (Department for Transport, 2013), as they are thought to be valid for the scope of this paper or at least, they are an upper bound of the real costs, helping us to make decision with an appropriate consideration of time in transportation. Data for HGV

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corresponds to OGV1 and OGV2 (working) for an average weekday, and data for LGV corresponds to LGV (work, freight) also for an average weekday. In order to consider the possible variability in the VoT between Spain and the UK, different sensitivity factors (α) will be applied to the original values. All the values are indicated in Table 1.

Table 1. Operational costs and values of time (Ministerio de Fomento, 2017; Department for Transport, 2013)

Vehicle	Operational cost	VoT
HGV (trucks)	1.147 €/km	14.35 €/hour
LGV (van)	0.9857 €/km	14.62 €/hour

Process

In order to put into practice the models developed, three different scenarios/networks in Spain have been modelled: the region of Catalonia (regional level), the city of Barcelona (city level) and the old town of Pamplona (local level). These road networks have been modelled based on the real road topology of the studied areas therefore all the important junctions and links have been considered. More details will be shown in the next section. Distances and travel times (for all hours of the day) of each individual link have been obtained from the Google Maps API to then calculate the cost in monetary units for each link using the value of time and the operating cost of the vehicle. Once all the inputs needed have been calculated, the optimization process takes place.

The following algorithm has been designed to solve the previous models (1), (2) and (3). It has been developed in Java and Visual Basic, and it consists of five different steps:

1. Generation of a new instance of depot/customers randomly assigned within the road network using a Visual Basic programme. Different parameters can be set (truck capacity, number of clients, starting time, etc.) in order to take stochasticity effects into account.
2. Then, the origin-destination (OD) matrix is generated and used by the Dijkstra algorithm (Dijkstra, 1959) to obtain the costs (IC, OC or FC) between the depot and all the customers for each of the three scenarios.
3. Now, the Clarke and Wright Savings algorithm (CWS) (Clarke and Wright, 1964) is implemented in order to obtain the best preliminary solution that CWS heuristic is able to achieve, again for each scenario.
4. This solution is the initial solution for the Tabu Search (TS) algorithm (Toth & Vigo, 2014), which is run to improve the preliminary solution. This metaheuristic guides the local search heuristic algorithm to explore the space of solutions beyond local optima. To do so, a flexible memory is implemented based on Taillard's method (Taillard, 2016), where some previous movements are saved to avoid them during a number of iterations.
5. The final solution is obtained and the route is saved together with its internal cost (IC), the cost of time (CoT), full cost (FC), as well as links used, and step 1 is repeated in order to create another run with a new set of customers. This will allow to obtain a sample size of solutions that is big enough to perform the statistical analysis and to

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obtain realistic results taken randomness into consideration. The computational time for each run is about 1 to 2 minutes.

The whole process is shown in the diagram of Figure 2.

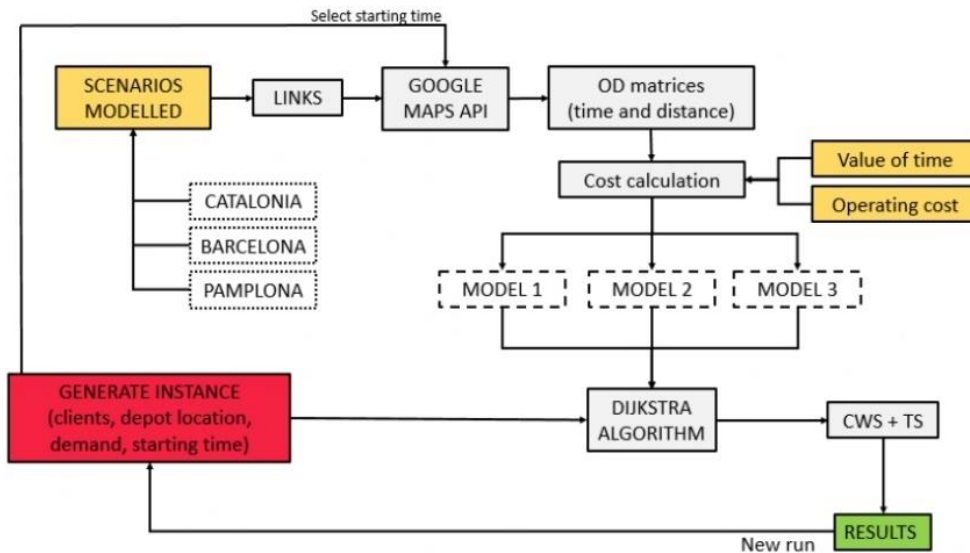


Figure 2. Diagram showing the methodology used.

CASE STUDIES

The commented methodology has been applied to three real scenarios in Spain. The first scenario (S1, regional level) is focused on the region of Catalonia (in Spain) due to its highlighted place for the Spanish logistic activities, mainly because of the freight transportation from/to France (over 60% of the exported freight is transported by road (CIMALSA, 2017)). The second scenario (S2, city level) is represented by the city of Barcelona, with a population of 1.6 million. Its logistic activity is important due to the huge amount of businesses, with more than 56,000 in an extension of about 102 km² (Barcelona City Council, 2015), and also because of the tourism demand. Finally, the third scenario (S3, local level) corresponds to the old town of Pamplona (Navarra, Spain). The reason to model this area of Pamplona is its saturated zone of shops and bars, with about 1,500 in 1.4 km² (ANET, 2015). Furthermore, the city council is currently investigating the pedestrianization of some streets and studying how to change the way freight is distributed, therefore this scenario is a perfect example to be included in this work. The previous scenarios range from the regional level to the local level which can give an insight into how important minimizing time or distance is depending on the context.

All the road networks have been modelled in QGIS (QGIS Development Team, 2017). The road network of Catalonia (S1) has a length of 12,000 Km, and it has been modelled considering all the national roads and highways within the region. In total, 92 nodes and 342 links have been modelled. As for the city of Barcelona (S2), the network modelled is composed by 43 nodes and 197 links, and the main freight routes within the city as well as the real restrictions and bans existing in the main urban roads have been considered. Finally, the modelled network of Pamplona (S3) consists

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of 115 nodes and 374 links, drawing a realistic map of the city center as all the roads including real restrictions and bans are also considered.

Figure 3 includes plots of the three scenarios in which the level of detail for each scenario can be observed. On the one hand, the region of Catalonia (S1) has been modelled just using national roads and highways. This is a more strategic level, for example representing deliveries between cities. On the other hand, the scenario for Barcelona (S2) includes all the main roads of the city but local streets are excluded. This would represent deliveries between different parts of the city. Finally, the scenario for the Old Town of Pamplona (S3) includes all the streets, and this would be valid for a realistic representation of, for example, on-demand deliveries and last mile deliveries. Apart from the reasons given above, the old part of Pamplona has been modelled in detail instead of a local area of Barcelona because its simplicity, and also because this scenario might be useful for the city council of Pamplona to test real transport and logistic policies in the city.

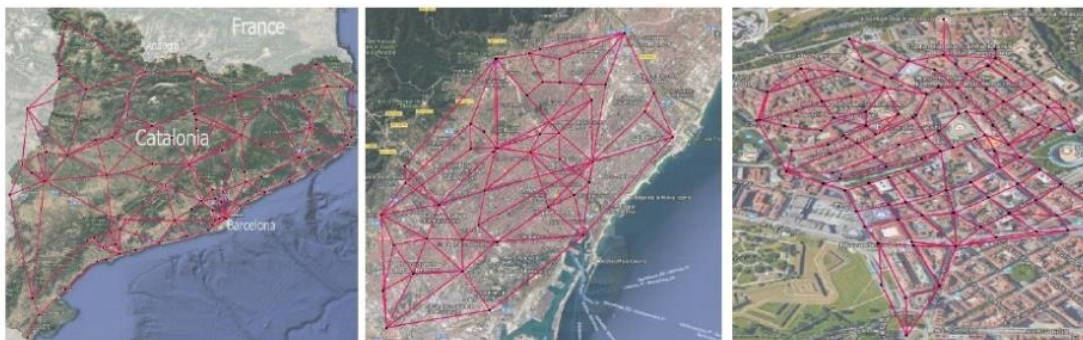


Figure 3. Networks modelled showing the cases of Catalonia (S1, left), Barcelona (S2, middle) and Pamplona (S3, right).

ANALYSIS OF THE RESULTS

To obtain reliable results, a total of 100 instances have been run for every model (M1, M2 and M3), every network (S1-Catalonia, S2-Barcelona and S3-Pamplona), and every vehicle type (truck and van). In each run, 10 clients and 1 depot are randomly assigned within the road network using a uniform distribution $U[0,1]$, and the client demand is also randomly generated ($U[0,1]$). For this paper, the truck capacity has been set to 50 units and the starting time of the route has been set to 8 AM. The inputs used from Google Maps correspond to an average Monday from October 2017.

As the values of the VoT have been taken from the UK guidance, a sensitivity analysis has been performed factoring the VoT by a sensitivity factor $\alpha = 0.7, 1, 1.2, 1.5, \text{ and } 1.8$. By doing this, it is ensured that the possible variation in the value of time between Spain and the UK has been considered. Therefore, a total of 9,000 runs (100 instances x 3 models x 3 scenarios x 2 vehicle types x 5 sensitivity factors) have been automatically generated.

Table 2 to Table 6 shows the modelling results for the different sensitivity factors (α) used. The full cost (in euros) is presented for the three studied models. Also, the %CoT indicates the importance of the cost of time within the full cost (CoT/FC). Two more columns have been added which present the savings in full cost obtained when minimizing one scenario instead of the other (M3 vs M1, and M2 vs M1).

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On the one hand, when the approach in M3 is used instead of the approach in M1 (M3 vs M1), it can be seen that savings in full costs are the highest when this is applied to the network of Pamplona (local level), and the potential savings decrease when applied to the network of Catalonia (regional level). This indicates that minimizing full cost (IC + CoT) produces higher savings when the network modelled is a local network, as the network is modelled in more detail and congestion effects are more relevant. Although with M3 higher savings are obtained in all the networks, these are small when the networks are modelled in less detail and from a more strategic point of view (the cases of region of Catalonia and the city of Barcelona). The reason for this is, as seen in Table 2 to Table 6, that the %CoT in local networks is much higher than in the other networks, i.e. time (or the cost of time) is more relevant than distance (or the internal cost). No relevant differences are obtained between HGV and LGV. Furthermore, through the sensitivity tests, it can be observed that when the value of time is increased (and so is the %CoT), higher savings are obtained when the approach from M3 is applied.

Table 2. Modeling results for a VoT with $\alpha=0.7$

VoT x 0.7		FULL COST (IC + CoT), €				M3 vs M1	M2 vs M1
		M1	M2	M3	% CoT	% Saving	% Saving
CAT	HGV	1356	1381	1355	13%	0.05%	-1.81%
	LGV	1238	1262	1237	13%	0.09%	-1.94%
BAR	HGV	105	109	105	32%	0.45%	-3.21%
	LGV	95	98	95	36%	0.52%	-3.20%
PAM	HGV	19.8	18.8	18.2	62%	7.85%	5.03%
	LGV	18.3	17.2	16.8	64%	8.24%	6.07%

Table 3. Modeling results for a VoT with $\alpha=1$

VoT x 1		FULL COST (IC + CoT), €				M3 vs M1	M2 vs M1
		M1	M2	M3	% CoT	% Saving	% Saving
CAT	HGV	1479	1510	1477	18%	0.13%	-2.10%
	LGV	1387	1406	1385	19%	0.17%	-1.32%
BAR	HGV	124	126	123	38%	0.87%	-2.15%
	LGV	111	113	110	41%	0.87%	-1.64%
PAM	HGV	23.5	21.5	21.2	65%	9.85%	8.57%
	LGV	22.9	21.3	20.8	68%	9.09%	7.34%

Table 4. Modeling results for a VoT with $\alpha=1.2$

VoT x 1.2		FULL COST (IC + CoT), €				M3 vs M1	M2 vs M1
		M1	M2	M3	% CoT	% Saving	% Saving
CAT	HGV	1583	1609	1581	20%	0.14%	-1.59%
	LGV	1383	1407	1380	23%	0.21%	-1.77%
BAR	HGV	137	138	135	43%	1.02%	-0.93%
	LGV	118	119	116	46%	1.22%	-0.82%
PAM	HGV	26.5	23.9	23.5	69%	11.34%	9.62%
	LGV	25.9	23.4	23.0	70%	11.15%	9.46%

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Table 5. Modeling results for a VoT with $\alpha=1.5$

VoT x 1.5		FULL COST (IC + CoT), €				M3 vs M1	M2 vs M1
		M1	M2	M3	% CoT	% Saving	% Saving
CAT	HGV	1644	1667	1641	24%	0.20%	-1.41%
	LGV	1445	1462	1441	28%	0.28%	-1.20%
BAR	HGV	148	149	146	49%	1.26%	-0.77%
	LGV	130	130	129	50%	1.37%	0.09%
PAM	HGV	31.1	27.1	26.9	72%	13.34%	12.72%
	LGV	31.4	26.5	26.4	75%	16.01%	15.65%

Table 6. Modeling results for a VoT with $\alpha=1.8$

VoT x 1.8		FULL COST (IC + CoT), €				M3 vs M1	M2 vs M1
		M1	M2	M3	% CoT	% Saving	% Saving
CAT	HGV	1661	1674	1657	27%	0.24%	-0.76%
	LGV	1534	1546	1529	31%	0.37%	-0.76%
BAR	HGV	165	165	162	53%	1.87%	0.03%
	LGV	145	144	142	54%	2.10%	0.66%
PAM	HGV	35.6	29.6	30.2	75%	15.08%	16.82%
	LGV	35.1	28.9	28.6	77%	18.46%	17.75%

Figure 4 shows the relationship between %CoT and the potential savings obtained when the approach from M3 is used instead of the one from M1, taking into account all the results from Tables 2 to 6. As commented before, it can be seen that the potential savings are higher for the local network of Pamplona, and these decrease in the case of Barcelona (city level), being almost negligible for the network of Catalonia (regional level).

Furthermore, it can be seen that, for the three networks analyzed in this paper, the relationship between %CoT and potential savings is not linear but exponential, following the curve given by equation 7. The software Minitab (Minitab Inc., 2017) has been used to calculate the Standard Error of the Regression, $S=0.0093708$, and the coefficient of determination, $R^2=0.99$, indicating that the exponential model properly fits the observed data.

The ratio between both axes in Figure 4 can be seen as the elasticity between %CoT and the potential saving (savings ratio). It is shown that the savings ratio in the regional network of Catalonia is almost inelastic, as changes in the %CoT do not affect the obtained savings much. On the other hand, the savings ratio in network of Barcelona (city level) is more elastic, being the savings ratio of network of Pamplona (local level) the most elastic one, as through small changes in the %CoT greater savings can be reached.

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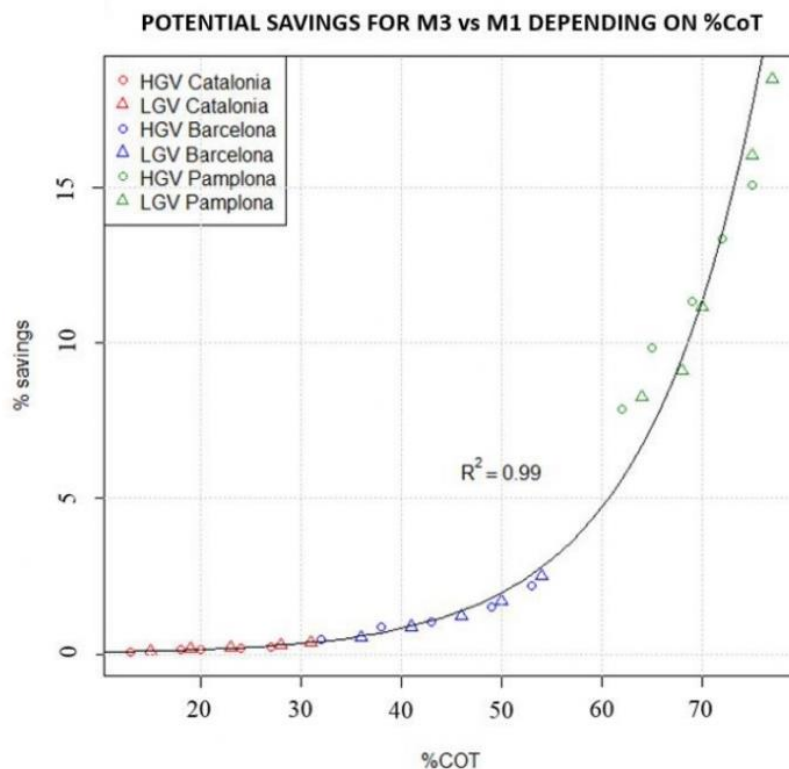


Figure 4. Relationship between %CoT and potential saving between M3 and M1.

Equation 7 shows the correlation between potential saving (%S) and the %CoT.

$$\%S = 0.0241 \times e^{8.789 \cdot \%CoT} = 0.0241 \times e^{8.789 \cdot \left(\frac{CoT}{IC+CoT}\right)} \quad (\text{Equation 7})$$

Although the parameters of this equation may vary for other scenarios, it is considered to be valid to demonstrate that there exists an exponential correlation between %CoT and potential savings. This could be useful to understand whether a company in which distance (M1) is the only parameter considered to optimize routes could obtain higher savings if time were also considered (M3).

Let put as an example two companies (Table 7) that are at present using only distance to optimize their routes. The first company (1) has an average internal cost of 1,300 euros, and an average cost of time of 2,500 euros. Applying the formula from equation 7, the potential saving this company could get if the approach from M3 were applied (minimizing both time and distance) instead of the approach from M1 would be of 8%. Therefore, this company may decide to start taking time into consideration when optimizing routes. However, another company (2) has an average internal cost of 1,520 euros, and an average cost of time of 1,300 euros. This company could get a saving of 0.6% if they changed the approach they use for route optimization, therefore this company may make the decision to continue with their current approach in which just distance is minimized.

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Table 7. Examples of potential savings using the approach from S3.

Company	IC (€, distance*VoO)	CoT (€, time*VoT)	Savings (S)
1	1300	2500	8%
2	1520	1300	0.60%

Through the above, it has been seen that minimizing time and distance together (M3) gives better results than when only distance is minimized (M1), and the more detailed the network is, the greater the obtained savings are.

Results in Tables 2 to 6 also show the difference between minimizing time and minimizing distance (M2 vs M1). It can be observed that minimizing time gives better results when the %CoT is higher, i.e. when the network is more local and when the value of time is higher. It must be also noted that when %CoT is very high, M3 is more similar to M2 as the FC almost consists of CoT only. On the other side, when %CoT is low, M3 is more similar to M1, as the distance (IC) is the most important component of the FC.

Figure 5 shows that the relationship between the ratio CoT/IC and the potential savings follow a linear correlation with $R^2=0.95$. The red area indicates the non-saving domain in which minimizing distance is better than minimizing time. It is observed that minimizing time starts to be a better solution (savings are obtained) when the ratio CoT/IC is close to 1.

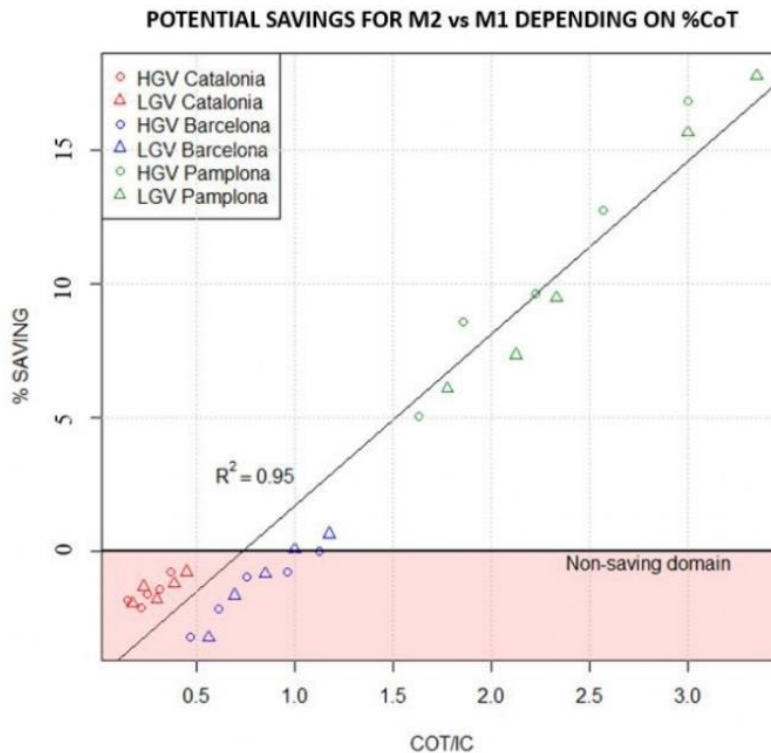


Figure 5. Relationship between CoT/IC and potential saving between M2 and M1.

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Following with the example from Table 7, it could be said that company 1 would get greater savings when minimizing time instead of distance, whilst company 2 would not get better results as the ratio CoT/IC is lower than 1, so it is better for them to keep minimizing distance, or time and distance together.

In summary, it has been shown that for local networks in which the cost of time is relevant, the approach M3 in which the sum of time and distance is minimized produces higher savings. Also, it has been shown that when the cost of the time is equal to or higher than the internal cost, minimizing time, M2, is a better option than minimizing distance, M1.

DISCUSSION AND CONCLUSIONS

Traditional approaches to optimize freight delivery routes have been focused on a strategic point of view where distance is usually the variable to minimize. As seen in the literature review section, current approaches also start making use of time minimization. Although those approaches give similar results when congestion effects are not important as time and distance are highly correlated, the increased congestion existing in our cities and the expansion of on-demand deliveries are forcing researchers and companies to better understand the trade-off between time and distance. Is minimizing time better than minimizing distance when optimizing logistic routes?

This is trying to answer this question by developing three models in which time, distance, and the sum of time and distance have been used to optimize delivery routes. For this purpose, the operating cost of a vehicle as well as the value of time have been applied to convert distance and time into monetary units. Through the modelling of three different networks, from a regional perspective (less detailed network) to a local perspective (more detailed), results have shown that minimizing both time and distance together always give better results, these being especially significant at a local level, for example when optimizing last-mile deliveries in our city centers. Furthermore, results have indicated that the approximate limit from which minimizing time is better than minimizing distance is set when the cost of time approaches the internal cost.

The conclusions reached in this paper could be useful for logistics companies, in particular for the ones doing last-mile deliveries, as it has been demonstrated that considering time could lead to important saving for logistics operators. Also, the presented methodology could be beneficial to analyze the operation of companies with fleets consisting of vans, trucks and tricycle or bikes. Should the company do certain deliveries using vans, or is it better to use tricycles? With the current approaches, the distance minimization approach would not be useful, as although the distance travelled might be the same for all the vehicles, not as regards the speeds and travel times. Using only time as an objective function to optimize the route would not be valid either, as the operating cost also differs between the different types of vehicles, and it should be also taken into consideration. Therefore, the approach given in this paper in which both the operating/internal cost and the cost of time are considered together could give more realistic results.

Finally, it is important to note that the use of the value of time within the objective function to optimize delivery routes is something new, so data on this field, especially for vehicles such as tricycles and delivery bikes, are very scarce. Therefore, the research community should continue

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working in order to study the value of time more in depth, also considering other modes of transport such as the ones used in cyclelogistics.

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3.6 Article 6: Alvarez P., Alonso V. Using microsimulation software to model large-scale evacuation scenarios. The case of Sangüesa and the Yesa dam collapse. *Safety Science*, 106, 10-27.

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Using microsimulation software to model large-scale evacuation scenarios. The case of Sangüesa and the Yesa dam collapse

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A B S T R A C T

The use of computer models to analyse evacuation scenarios and human behaviours in emergencies has greatly increased due to their capabilities to simulate these processes. These models have been commonly applied to different types of infrastructures in isolation, and little is known about their use for large-scale evacuation. This paper explores the capabilities of micro-simulation tools for modelling large-scale evacuation, and also presents the development and application of a computer based large-scale modelling tool. A novel methodology is proposed here in which different sub-models are connected to represent the different levels of the evacuation scenario. The methodology has been applied to a real case study: a small town in Spain, Sangüesa, which is in risk of flooding as a consequence of a potential collapse of the Yesa dam. The inputs used were taken from survey data, census data, plans of the town, data obtained from the emergency plan, data from other research studies (flooding models and acoustic models), and a literature review process on human behaviour in emergencies. The study was focused on the evacuation scenario at night (2:00 AM assuming the majority of residents are sleeping) as one worst-case scenarios. Four scenarios were developed in order to analyse the impact of (1) two pre-evacuation time distributions identified for residential evacuation at night and (2) group behaviours (with and without) during the evacuation process. Results showed that the time needed to evacuate the whole town (between 33 and 44 min) is not sufficient, as in case of a dam collapse the water could reach Sangüesa in about 23 min.

1. Introduction

Recent events such as hurricanes Harvey and Irma who caused widespread and catastrophic damage in the Caribbean, Texas, and Florida (El País, 2017) (September 2017, more than 200 fatalities, and tens of thousands of evacuees), wildfires in Haifa, Israel (Carey and Smith-Spark, 2016) (November 2016, with 60,000 evacuees) and Fort McMurray, Canada (Fieldstadt, 2016) (May 2016, two fatalities and nearly 90,000 evacuees), Ecuador earthquake (Wyss, 2016) (April 2016, about 650 fatalities), Oroville dam in California (Associated Press, 2017) (February 2016, 200,000 evacuees) and Bento Rodrigues dam disaster in Brazil (BBC News, 2015) (November 2015, 17 fatalities), remind us that natural, technological and/or human-made disasters have a high cost in terms of lives and material losses.

Emergency management normally relies on fixed protocols aimed at reducing the effects and consequences of these disasters (when these are imminent or actually happening). The evacuation of populated areas is a common strategy in severe emergencies. Evacuation protocols

normally define actions such as the person responsible for the evacuation, resources to be activated to support the evacuation, when and how the area needs to be evacuated and where evacuees need to go.

With urban and transport planners currently developing new strategies to increase the resilience capacities of our cities, there is also a need to develop a broader point of view on evacuation planning which includes the evacuation of a large area of the city.

For decades, the analysis of evacuation has been focused on different types of infrastructures in isolation such as office, residential and recreational buildings, sport stadia and transport interchanges (Stahl, 1982; Ronchi, 2013; Capote et al., 2012). In fact, the evacuation process has been studied with an emphasis on how the people behave and move during a fire evacuation from those infrastructures (Kuligowski, 2016).

The use of computer models to analyze and plan emergency evacuations has greatly increased recently due to their capability to study these processes as dynamic events as they change over the time instead of static events (Kuligowski et al., 2010; Gwynne et al., 1999). Large scale evacuation modelling is mostly approached from a vehicular

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evacuation point of view. For this reason, most of the current models are focused on analyzing whether the current transport infrastructures enable the evacuees to leave the populated area in non-congested situations or to define the resources to be activated (e.g. buses, patrols, or ambulances).

These models usually have a macroscopic approach and disregard the pedestrian evacuation, as well as the impact of how the evacuees react or behave during an emergency. In macroscopic simulation (macrosimulation) models, evacuees are not represented individually, instead they are considered as a continuous flow. However, as is well known, evacuation is a highly stochastic process due to the complexity of human actions and decisions (Averill, 2012; Alvear et al., 2014), and therefore considering individual and group behaviors is crucial (Drury and Cocking, 2007).

The field of fire safety engineering on the other hand, has been highlighting the impact of human behavior in fire situations for decades. As a result of this concern, many research works have been carried out in order to understand, study and quantify the evacuee's actions and decisions (Kuligowski, 2016; Proulx, 2002; Shields and Boyce, 2000; Kobes et al., 2010; Gwynne and Boyce, 2015), and most of the current evacuation models use a microscopic approach.

The quantification of these actions and decisions relies on the identification and definition of parameters which can predict human behaviors and movements in fire such as pre-movement times, emergency route choice, exit choice, group behaviors and walking speeds (Kuligowski, 2016; Proulx, 2002; Shields and Boyce, 2000; Kobes et al., 2010; Gwynne and Boyce, 2015). In addition, data collection on human actions and decisions from experiments and drills, interviews, and real fire events, has allowed for the creation of an important database of these behavioral and movement parameters, especially for building environments (e.g. pre-evacuation times in residential and office building, walking speeds in stairs or wayfinding) (Gwynne, 2009).

The use of computer models to understand evacuation processes has greatly increased recently due to their capacity to simulate these factors (i.e. pre-movement times, walking speeds and route choice) in more detail than ever before. Additionally, the use of random variables to represent these stochastic parameters, enable the modeler to represent the uncertainty of an evacuation. Whilst most of these studies have been focused on fire evacuation, other fields such as crowd modelling take advantages of microsimulation tools to ensure a level of comfort and safety of people by representing pedestrian movements within different infrastructures. Although there are various studies (Ronchi et al., 2015; Lämmel et al., 2008; Veeraswamy et al., 2015; Lämmel et al., 2010; Durst et al., 2012; Bernardina et al., 2014) that highlight the possibilities of current micro simulation software for modelling large scale, the application of microsimulation software for real scenarios is still limited.

Based on the advantages of micro simulation models for representing evacuation processes and human actions and decisions, this paper explores micro simulation models' capabilities to study large scale pedestrian evacuation. Based on a proposed methodology composed by interconnected sub-models, this work analyses the evacuation of a small town in Spain, Sangüesa (5000 inhabitants) in case of a collapse of the Yesa dam. Modelling software (Legion, see Section 2.6) was used to simulate the evacuation process at night, as a worse-case scenario when the majority of residents are asleep.

2. Methodology

2.1. Model build overview

The analysis of evacuation using microsimulation software has been commonly focused on different types of infrastructures in isolation such as office buildings, sports stadia, and transport interchanges (Alvarez et al., 2016). However, modelling a large-scale evacuation scenario for an urban area is complex, as it is necessary to consider all the different

locations in which the evacuation processes take place, such as the households, the buildings, and the streets. Developing a very detailed model in which every household and building is included altogether is possible, but at this scale this is not practical as it is very time-consuming and simulation run times can become very large. Therefore, a new methodology which simplifies the whole procedure was developed. This consists of the use of interconnected sub-models that represent different parts of the evacuation process.

First, the evacuation taking place inside the house was analyzed through an extensive literature review in order to obtain data about pre-evacuation times and actions people perform before leaving their household. Secondly, the evacuation of the building was simulated using the software *Legion Spaceworks* (Section 2.6), considering the different types of residential buildings existing in the town (see Section 2.3).

The last step was the modelling and simulation of all the streets, including slopes and hills, through which the evacuees aim to reach the safe assembly areas.

This methodology based on interconnected sub-models allows for a simplification of such a complex scenario, but maintaining the connectivity between all the parts of the evacuation process so that the validity of the simulation results is maintained. The outputs of each sub-model are the inputs for the subsequent sub-model.

Fig. 1 shows the methodology used with the three interconnected sub-models, which will be explained in detail in the next sections.

2.2. In-house sub-model

This sub-model does not make use of any computer microsimulation, as the time taken by the evacuees to leave the household, which includes the recognition time and the response time, is already included within the pre-evacuation time given by other authors and guidance (Brennan, 2000; British Standards, 2004; Proulx et al., 2006; Proulx and Fahy, 1997; Proulx, 2001). Therefore, a detailed microsimulation model of how evacuees move inside the house is not needed. Section 3.6 includes all the data used to estimate the pre-evacuation time distribution, i.e. the time taken for people to evacuate the household, which is the output of this sub-model.

2.3. In-building sub-model

This sub-model only applies when there are blocks of flats. For terraced houses this sub-model is ignored, so in these cases the in-house model would directly feed into the on-street model. The in-building sub-model starts once the evacuees have left the household, and making use of microsimulation it represents the evacuation process taking place inside the building (or block of flats) before reaching the street. To accurately represent the existing buildings, on-site visits and measurements were carried out to then create five standard buildings that represent the main building typologies in the town:

- Building type 1: typical building from the old part of the town, characterized by buildings with two or three floors, a single household per floor, and narrow stairs.
- Building type 2: block of flats with two floors and two households per floor.
- Building type 3: block of flats with three floors and two households per floor.
- Building type 4: block of flats with four floors and two households per floor.
- Building type 5: block of flats with four floors and four households per floor.

In this sub-model, the evacuees from each household leave the house following the time distribution (input) given by the in-house sub-model. Three evacuees per household has been taken as a standard,



Fig. 1. Methodology. Interconnected sub-models.

Table 1
In-building evacuation time for each building typology and pre-evacuation time.

	Brennan		British standards	
	Mean	Stand. Dev.	Mean	Stand. Dev.
TYPE 1	0:11:44	0:02:59	0:15:19	0:01:36
TYPE 2	0:12:02	0:03:27	0:15:32	0:01:46
TYPE 3	0:12:12	0:03:10	0:15:37	0:01:44
TYPE 4	0:12:18	0:03:07	0:15:48	0:01:39
TYPE 5	0:12:12	0:03:07	0:15:46	0:01:45

considering the average household size given by national and regional statistics (INE, 2016; NASTAT, 2016). The output of the in-building sub-model is a distribution of the time at which evacuees reach the street (building evacuation time), and it is affected by the different building typology. Therefore, as Table 1 shows, there is a specific time distribution for each building typology.

Section 3 indicates all the inputs needed for this sub-model: building dimensions (3.7), group effects (3.8), and horizontal (3.9) and vertical (3.10) speeds.

2.4. On-street sub-model

This sub-model represents the evacuation process taking place through the streets, from the moment the evacuees leave the building until they reach a safe assembly area. In order to develop this sub-model, street plans, altimetry data, census data, flooding models (Section 3.4), data on evacuation speed from the literature (Section 3.9), and data from questionnaires (Section 3.2) have been used.

Firstly, using census data by street provided by the Sangüesa City Council (Ayuntamiento de Sangüesa, 2015), and through site-visits and pictures from Google Street View, a specific household/building demand has been assigned to each model entrance which represents a house, a block of flats, or a section of the street (where less level of

detail is required). With this, a realistic representation of the town is obtained, in which the total demand for each street is consistent with the census data, and where the demand for each building has been estimated by using pictures from Google Street View to analyze the number of floors, with households per block estimated according to the number of households shown on the intercom systems (automatic entry-phones) located at each door. In total, this sub-model has 587 model entrances, each of these with a specific demand.

Secondly, a standard building typology has been assigned to each of the buildings. In order to guarantee the continuity between the sub-models, a building evacuation time distribution (input) has been assigned to each building (or pre-movement time distribution to each terraced house) according to its typology.

Fig. 2 shows the on-street sub-model, with green rectangles indicating the 587 model entrances.

Finally, the safe assembly areas have been set (model exits) according to the flooding models (Alonso et al., 2017; Alvarez et al., 2015; Confederación Hidrográfica del Ebro, 2013), and evacuation routes have been created and assigned to each of the buildings. Evacuees make use of these routes to reach the safe areas, and their speed (Proulx, 2008) will be affected by parameters such as group cohesion (Drury and Cocking, 2007) or street gradient (Lämmel et al., 2010), giving a great level of detail to the model.

The outputs of this sub-model are the model results, and consist of a total evacuation time distribution to reach a safe area, i.e. required safe egress time or RSET (British Standards Institution, 2004; Babrauskas et al., 2010; Averill et al., 2008), flows in the main evacuation routes, and density maps.

2.5. Model scope

Section 3 shows the data collection exercise and the model calibration. However, regarding the scope of this model, it is important to note that this model represents the case in which everybody follows the evacuation plan (Ayuntamiento de Sangüesa, 2014; Ayuntamiento de



Fig. 2. On-street sub-model with different spatial objects used to model movements.

Sangüesa, 2017). Therefore, there are survey data (use of the car, helping behaviors, etc.) that although have not been directly considered to calibrate the model as they do not correspond to what is mentioned in the evacuation plan, they are needed to draw conclusions and to compare the ideal situation in which the evacuation plan is followed (future situation when people have been informed and the plan is properly implemented), with the current situation in which some people are not aware of how they should evacuate (current situation without the implementation of the plan).

Furthermore, due to the limitations of the software used (Section 2.6) to model assisted evacuation, and considering the limited data existing in this field (Gwynne and Boyce, 2015), the assisted evacuation of the nursing home has been excluded from the model.

2.6. Capabilities and limitations of the software Legion

As already mentioned, the microsimulation software *Legion Spaceworks* has been used to build this evacuation model. This software has been calibrated and validated with empirical data (Berrou et al., 2007; Still, 2000), and it is broadly used by public organisms such as governments or city councils (Kuligowski and Peacock, 2005; London Underground, 2009; Rail, 2011; Transport for London, 2010; Directorate of Road Network, Transport for London, 2008) to model evacuation scenarios. Furthermore, Legion views the occupants as intelligent individuals and social, physical, and behavioral attributes are assigned probabilistically from empirically established profiles derived from video footage of actual pedestrians. The agents include memory,

willingness to adapt, and preferences for walking speeds, personal space, and acceleration. The software also simulates the attempt of evacuees to lower their levels of inconvenience, frustration, and discomfort during an evacuation (Kuligowski and Peacock, 2005).

For this study, one of the main limitations of the software was the complexity to take stochasticity effects into account, as the time distributions had to be entered manually, as there are no options to consider more complex time distributions for the agents to enter the model (such as truncated normal or lognormal). Also, there is not a straightforward approach to model groups (for example, families), nor assisted evacuation within the model.

3. Data collection and model calibration

3.1. Overview

Model calibration is crucial to create accurate models and to obtain valid results. A model in which the results are based on incorrect assumptions or inaccurate data may lead to misleading results, as it does not represent the reality. Therefore, data collection and calibration is one of the most important parts when creating simulation models, especially for evacuation scenarios in which the role of evacuees and their actions and decisions embed great complexity.

The inputs used in this model can be separated into three major groups. First, we have inputs based on real data, such as census data, street plans, altimetry information, or building measurements. Secondly, there are data that cannot be practically obtained in our application scenario through direct observations so that they need to be taken from other research studies developed for similar scenarios through a literature review process. This is the case with data related to pre-evacuation times during an emergency, the horizontal and vertical evacuation speeds, change in speed with respect to gradient, ASET,¹ or location of the safe areas (streets not reached by the water) in the case of a Yesa dam collapse. The third group of inputs contains the ones related to human actions during this particular emergency scenario, such as routes evacuees would choose or % of people using the car to evacuate. These inputs were estimated through a stated preference survey based on questionnaires in which the sample was statistically representative of the whole population.

The next sections will examine the inputs used in more detail.

3.2. Survey

A survey was distributed amongst the population from Sangüesa in order to obtain data about how inhabitants would react in the event of a Yesa dam collapse. The sample was representative of the population, stratified by age group and gender according to the census data from June 2015 (Ayuntamiento de Sangüesa, 2015). The final sample size was formed by 465 persons, resulting in a confidence level above 95% with an error lower than 5%. The statistical analysis was performed using the software SPSS.

In the next sections some of the data obtained from the survey will be commented on, but, as a summary, the following is a list of the main questions that were asked.

- Age and gender.
- Disability or impediments to use stairs.
- Knowledge of the evacuation plan (location of the safe assembly areas, ASET, etc.).
- If they heard the alarms at 02:00 AM, which actions they would take

¹ Available Safe Egress Time (ASET), this term is commonly used in Fire Engineering to define the available time until the situation is untenable for the evacuees (due to the smoke or fire). For the purpose of this paper, this term will be applied and used to define the available time until the flood wave reaches Sangüesa (see Section 3.4).

- at home before evacuating (using the phone, getting dressed, meeting the family...)
- Location of their house, and route they would use during an evacuation.
- Whether they would go to different parts of the town to help others before evacuating.
- Whether they would use the car to evacuate (knowing that they have about 23 min).
- Whether they think the information provided by the authorities is enough.

3.3. Preparedness for evacuation

The survey results show that 66% of the inhabitants know nothing about the evacuation plan, 34% of them do not know where to go during an evacuation scenario, and 70% do not know how much time they have to evacuate the town. These discouraging results indicate the lack of awareness amongst the population, probably caused by a lack of official information on this topic. In the survey, 85% of the population said the information given by public organism was scarce. As the preparation of the population could easily increase through information and presentations, for this model it has been assumed that everyone knows how to proceed during an emergency situation (see Section 2.5).

3.4. Flooding models: ASET and safe assembly areas

The ASET or Available Safe Egress Time has been taken from the Sangüesa flooding models developed by Revuelto (Alonso et al., 2017; Alvarez et al., 2015). By applying the software Modelo Iber v2.3 (Bladé et al., 2014), a bidimensional mathematical model used to simulate water flows in rivers, and based on a Digital Elevation Model from the *Instituto Geográfico Nacional*, his model concludes that in case of a collapse in the Yesa dam, the water would reach Sangüesa in less than 30 min. Revuelto also mentions that, depending on how the dam collapses, the water could only need 23 min to reach the town. This result is also consistent with other official documents (*Confederación Hidrográfica del Ebro*, 2013; *Ayuntamiento de Sangüesa*, 2014) that state that the water would reach Sangüesa in less than 30 min, therefore evacuees would need to evacuate (considering safety factors) in about 20 min. For the purpose of this paper, and to remain on the conservative side, the ASET time has been set to 20 min.

Fig. 3 shows the level of water in the town at minute 23 from the dam collapse, which has been used to set the safe areas, which are the zones not affected by the flooding (zones without coloring). In the on-street sub-model, and according to the emergency plan of the town (*Ayuntamiento de Sangüesa*, 2014), the evacuees first have to reach a safe area to then head towards the assembly area (circled in red²).

3.5. Audibility of the sirens

In order to evacuate the town, and according to the Yesa Dam Emergency Plan (*Ayuntamiento de Sangüesa*, 2014), it is necessary to have a proper alarm system which consists of arrays of sirens located in strategic places so that an acoustic level of 75 dB can be reached in the streets. In a real scenario, the evacuation would take place just in those locations where the population knew that an emergency is happening, which expected to be largely dependent on hearing the sirens; anyone unable to hear the sirens may be unaware and so may not initiate evacuation until too late, or at all.

An audibility study of the sirens was also carried out and it concluded that the sirens audibility in the streets is not high enough for people to realize that they need to evacuate (Alvarez et al., 2015). Fig. 4

shows an audibility map of the streets, showing that since at present there is just one array of sirens in the town, and that its current location (red cross) is not appropriate, most of the people within the flooding area (indicated in blue) would not perceive the 75 dB stated in the Yesa Dam Emergency Plan.

However, as this is something that could be improved through the relocation or addition of sirens, which is out of the scope of this paper, this model will assume that the whole population can perceive the sirens (see Section 2.5).

3.6. Pre-evacuation times

Information on evacuation times in households when people are sleeping is very scarce (Gwynne and Boyce, 2015). Fig. 5 shows the different pre-evacuation time distributions that have been used in this model (in-house sub-model): pre-evacuation time given by Brennan (2000) (2–21 min), and pre-evacuation time given by the British Standards (2004) (10–20 min). Since in those research studies the distribution type is not defined (just the values), a truncated normal distribution was used with $\mu = (Max + Min)/2$ and $\sigma = (Max - \mu)/3$ (with given values assumed as mean values). These times (average evacuation times) are consistent with other reputed authors and studies such as the ones by Proulx and Fahy (1997) and Proulx (2001) or the guidelines from the Canada National Research Council (Proulx et al., 2006). Furthermore, to consider the variability between both distributions, a different scenario will be created for each of the distributions (see Section 4 for details).

3.7. Building dimensions

Measurements on building dimensions (distance from each floor to the street, stair width, location of household doors, etc.) from eleven residential buildings of different building typology (see Section 2.3) were registered. These measurements were used to create the in-building sub-model for each building type so that they are an accurate representation of the existing buildings in the town.

Although each household has the same pre-evacuation time distribution (Section 3.6), the total in-building evacuation time (pre-evacuation time plus building evacuation time) will vary according to the building typology, as seen in Table 1.

3.8. Groupality

Although a few studies have shown the importance of *groupality* in non-large-scale evacuation scenarios, in most of the microsimulation models evacuees are treated as individual agents that aim to escape without considering others. Research studies have shown that people do not usually leave companions behind, and that family groups tend to escape or die together in this kind of emergency situations (Drury and Cocking, 2007). This is consistent with the survey results (see Section 3.16) that show that families would evacuate the house together in the event of a Yesa dam collapse.

Although considering group behavior is essential to create realistic models, not all the microsimulation software have the capabilities to model groups. In this study, family groups account for a high proportion of the total population, and therefore it was necessary to take this into account when calibrating the model.

Therefore, the term *groupality* was implemented, which is defined as a binary variable. In a scenario with groupality 0 the group behavior is not considered, and all the evacuees leave by themselves without forming part of a group. In contrast, in a scenario with groupality 1 all families in the population evacuate as a group, and all the people above 80 years old also live with the family. None of the previous situations are 100% realistic, as there are families but also single or older people living by themselves, so although it is not practical to model the exact real solution, it would be something in between.

² For interpretation of color in Figs. 3–5, 9–13 and 16, the reader is referred to the web version of this article.

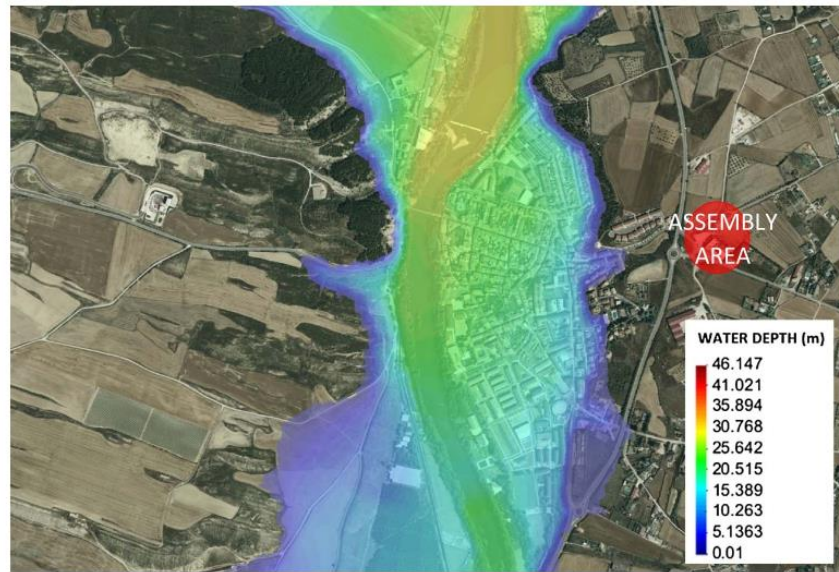


Fig. 3. Flooding area given by the flooding models by Revuelto (2017).

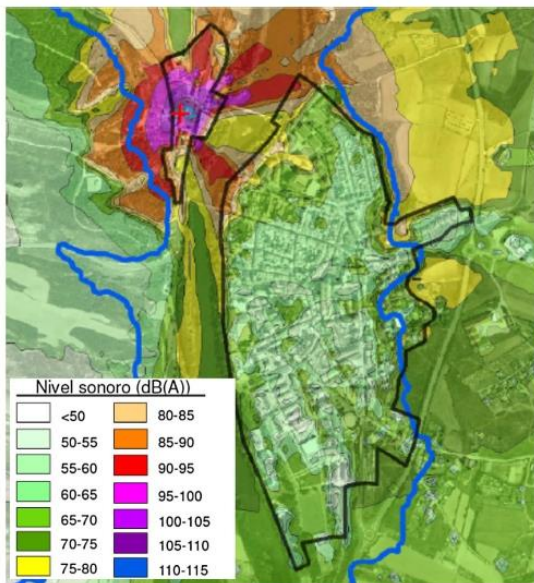


Fig. 4. Audibility map of the sirens in the town (CECOR S.L.)

The term “groupality” has been introduced here as it will be used in the next sections.

3.9. Horizontal evacuation speed

For horizontal surfaces, speeds given by Proulx (2008) have been applied, as shown in Table 2. These speeds have also been used and recommended in other studies and documents (Gwynne and Boyce, 2015; Capote et al., 2013), so they are considered appropriate for their use in this paper. However, it is important to note that these speeds are individual speeds, i.e. related to a scenario with groupality 0 in which group behavior has not been considered.

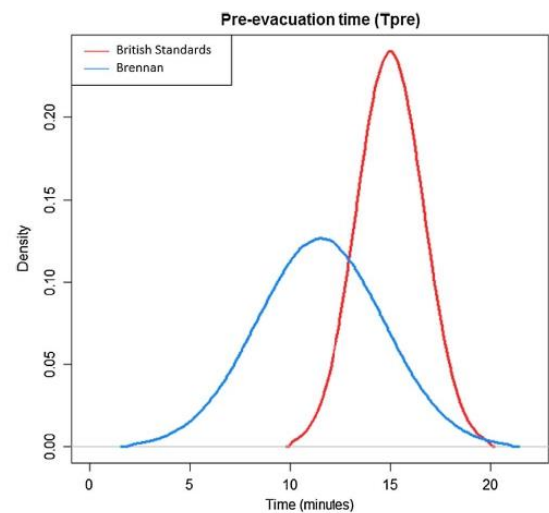


Fig. 5. Pre-evacuation time distributions used in the in-house sub-model.

Table 2
Horizontal speeds for a scenario with groupality 0.

Age range	Mean (m/s)	SD (m/s)
< 61 (no mobility impairments)	1.25	0.32
61–80	0.95	0.32
> 80 (walking stick)	0.81	0.38

It is necessary to have group speeds for a scenario with groupality 1. Although there are no conclusive studies on evacuation speed for groups, it is known that the speed of a group is the speed of the slowest member of the group (Jakling et al., 2015). With this in mind, and assuming a normal distribution for the speed, we have performed a Montecarlo simulation using the software R to estimate the average speeds for groups.

To estimate the speed of a group formed by K persons, we have generated 30.000 (n) random groups, i.e. 30.000 sets of speeds (s_1, \dots, s_K), with s_1 to s_K being the speeds of each member of the group, where each of them could belong to a different speed distribution.

We know that the group speed of each group will be the speed of the slowest member of a group, so $S_K = \text{Min}(s_1, \dots, s_K)$.

Therefore, Eqs. (1) and (2) give the group average speed and its standard deviation:

$$S_K = \frac{\sum_{i=1}^n \min(s_1, \dots, s_K)}{n} \tag{1}$$

$$\sigma_K = \sqrt{\frac{\sum_{i=1}^n (\min(s_1, \dots, s_K) - S_K)^2}{n}} \tag{2}$$

We can use the formulae above to calculate the group speeds of different group formations, with K number of members, and in which each member of the group could have a different individual speed, even from a different speed distribution.

A specific case would be a group formed by the same type of people, i.e. all the members follow the same speed distribution. Using Montecarlo, we have estimated S_K and σ_K for different K values, and for a specific group formed by people below 61 years old in which each member has an individual speed $s \sim N(1.25, 0.32)$ as indicated in Table 2.

Fig. 6 indicates a strong relationship between the number of persons forming a group, the individual speed of the members of the group (when they belong to the same speed distribution), and the average speed of the group. Note that when $K = 1$, the group speed S_K equals the individual speed.

We have performed these estimations for different group typologies (but all following the same speed distribution), always obtaining the same results.

Therefore, the following formulae the average group speed (S_{group}) and its standard deviation (σ_{group}) can be estimated for a group formed of K members in which every person has an individual speed that follows the same normal distribution in which the average individual speed and the standard deviation are $S_{individual}$ and $\sigma_{individual}$, and under the assumption that the group speed is the speed of the slowest member of the group.

Table 3
Horizontal speeds for a scenario with groupality 1.

Group typology	Attributes	Mean (m/s)	SD (m/s)
1	3 people aged < 61	0.98	0.24
2	2 people aged 61–80	0.74	0.25
3	3 aged < 61 + 1 aged > 80	0.63	0.31

$$S_{group} = S_{individual} \times K^{-0.218} \tag{3}$$

$$\sigma_{group} = \sigma_{individual} \times K^{-0.218} \tag{4}$$

In the scenario with groupality 1, the assumption is that everyone forms part of a group. The three groups that have been considered after analyzing census data (Ayuntamiento de Sangüesa, 2015) are: (1) group formed just by three people below 61 years old, (2) group formed by two people aged 61–80, and (3) a group formed by a person aged above 80 and three people aged below 61. For the first two groups, as all the members follow the same speed distribution, equations 3 and 4 have been applied. For the last one, a Montecarlo simulation has been implemented to then apply equations 1 and 2.

Finally, the group speeds for a scenario with groupality 1 are shown in Table 3.

3.10. Evacuation speed on stairs

It has been considered that for speed when descending stairs, groupality has a little effect, as the speed is constrained to the stairs capacity and the speed of each individual (depending on age) rather to a group cohesion attitude (Kuligowski et al., 2015).

Data from Proulx (2008) for people descending stairs during an emergency have been used, and are indicated in Table 4.

3.11. Age stratification

Human behavior in emergencies depends on different variables. Survey results (see Section 3.15) have indicated that human actions during an emergency situation vary by gender and age; for example, younger men show a more helpful attitude and take more risks than older women. However, for the purpose of this model, age is the most

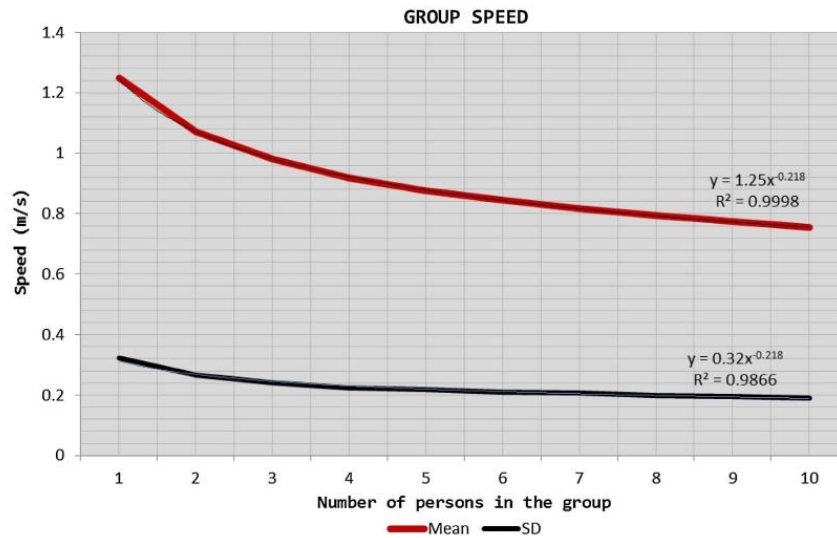


Fig. 6. Estimation of the group speed depending on the number of persons forming the group, after using a Montecarlo simulation.

Table 4
Evacuation speed on stairs.

Age range	Mean (m/s)	SD (m/s)
< 61 (no mobility impairments)	0.7	0.26
61–80	0.36	0.14
> 80 (walking stick)	0.28	0.17

Table 5
Age stratification used in a scenario with groupality 0.

Age range	< 61	61–80	> 80
%	73%	19%	8%
Population	3619	942	397

important sociodemographic variable, as it is directly related to the evacuation speed.

As commented in the previous sections, the model has been calibrated using different speeds for different age ranges (groupality 0) and different group typologies (groupality 1). However, it was necessary to know the age stratification of the modelled population to apply these speeds to the model agents, i.e. to know which percentage of evacuees will use each individual speed (groupality 0) or group speed (groupality 1).

Using census data from June 2015 (Ayuntamiento de Sangüesa, 2015), the age stratification has been calculated, and it is shown in Table 5. This stratification has been applied to a scenario with groupality 0, in which there are no groups. This means that, for example, just people above 80 years old (8% of the total) will use the individual speed corresponding to that age range.

However, in a scenario with groupality 1, the% of the population falling into each group typology is needed.

Group Typology 3: families with a person above 80. If we consider that all the people aged above 80 years old (397 people) live with a family group formed by other three people aged below 61, the number of people falling in the group typology 3 would be $397 + (397 \times 3) = 1588$ people.

Group Typology 2: family group of two adults aged 61–80. We consider that these people live together, in groups of two people, therefore the number of people falling into group typology 2 remains 942 people.

Group Typology 1: families without a person aged above 80. The number of people falling in this group typology would be $3619 - (397 \times 3) = 2428$ people.

Based on this, Table 6 indicates the% of people that falls into each of the group typologies.

As commented before, the real situation would be something in between of groupality 0 and groupality 1. Therefore, rather than calculating an exact solution, this study will estimate a range of possible solutions.

3.12. Persons with reduced mobility (PRMs)

The survey results have indicated that about 8% of the population have a type of disability makes the use of stairs difficult for them. Most of them are above 60 years old, so the speed reduction for this age group already includes this kind of impediments. Also, it is thought that these effects due to disabilities have already been included within the

Table 6
Group typology used in a scenario with groupality 1.

Group typology	1	2	3
%	49%	19%	32%
Population	2428	942	1588

range of results given by using different scenarios (see Section 4).

It is important to note that this study also ignores the nursing home or other kind of evacuees that would need an assisted evacuation, and it is out of the scope of this paper (Section 2.5).

3.13. Speed reduction coefficients for slopes

In water-related emergencies (like flooding or tsunamis) the evacuees move upward to reach the safe areas. Due to the importance of the gradient for the evacuation in this scenario, slopes and hills have been considered when building the on-street sub-model, using data from altimetry plans. It was then necessary to apply a speed reduction coefficient for the zones where the gradient was significant. Although few studies have been conducted to understand how slopes affect evacuation speed, data from a research study (Lee and Hong, 2015) have been used to develop a formula that correlates evacuation speed and gradient.

The formula is shown in Eq. (5), where SR is the speed reduction coefficient to be applied to the horizontal speed, and Q° is the degrees of the slope.

$$SR = 0.019 \times Q \tag{5}$$

As an example, in the model, the steepest evacuation path has a slope of 16%, which is equivalent to 9.1 degrees. Applying the formula, a speed reduction coefficient of $SR = 0.173$ (or 17.3%) should be applied, which means that for an adult aged below 61 years old, their speed on the slope would be $S_{slope} = (1 - 0.173) \times 1.25 = 1.03$ m/s.

3.14. Evacuation routes

Fig. 7 shows the different areas into which the town has been split, and the possible evacuation routes people could use. These pictures were shown in the survey, but no information was given about the best route to choose.

The results from the survey were analyzed and some corrections were applied. For example, evacuation route 1 Fig. 7 was removed as official documents (CHE, 2013) say that the river should not be crossed during an evacuation, and we are assuming that everybody has a good knowledge of the evacuation plan (Section 2.5). Therefore, these evacuees were assumed to choose the next nearest route according to their household location. Furthermore, in the survey nearly 50% of the people from area 3 stated that they would use a different route which is the forest between evacuation route 2 and 3. The same happened with area 14, where about 10% of the population of that area mentioned that they would use a narrow path to reach the safe area. These new routes were included in the model.

Although most of the respondents chose the nearest route, there exist areas (8 and 9) for which the distance to different routes (route 3 and route 4 in Fig. 8) is similar. In these cases, respondents chose indistinctly maybe based on their personal preferences (more familiar route, minimum gradient, wider streets, fewer turns, etc.). These preferences have been also considered in the model to make it more realistic, so evacuees from the same building can choose different routes if the distances are alike. Therefore, although the software Legion automatically assigns routes through the streets based on the lowest cost (distance, congestion...), the evacuation routes and the final destinations are predefined based on the real choices evacuees would make.

Fig. 8 and Table 7 show the actual evacuation routes and route utilization used in the model, after taking all the previous corrections into consideration.

3.15. Use of the car

The survey results also showed that just 23% of the population would use the car to evacuate the town during an urgent evacuation scenario. We believe that the car should not be used unless it is essential

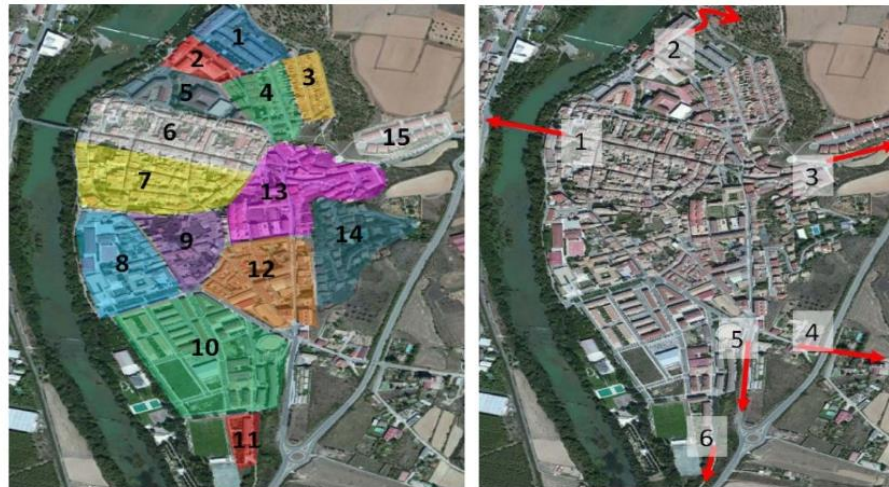


Fig. 7. Areas in which the town has been split, and possible evacuation routes.

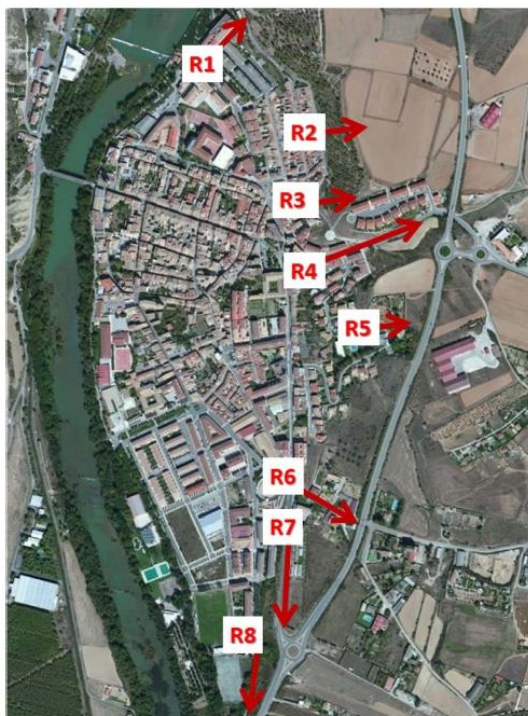


Fig. 8. Evacuation routes using in the model.

(for example, for an assisted evacuation), as due to the proximity of the evacuation routes it is more efficient to escape on foot. This is also stated in some reports from the Sangüesa City Council (Ayuntamiento de Sangüesa, 2017) and in the evacuation plan (Ayuntamiento de Sangüesa, 2014). The reason for some people to mention that they would use the car could be that (1) they have not read the evacuation plan and they ignore the ASET so they think they have more time to evacuate, (2) they need to help with in an assisted evacuation, or (3)

Table 7
Actual route utilization in the model.

	Evacuation route selected							
	1	2	3	4	5	6	7	8
House location 1	86%			14%				
2	63%			38%				
3		25%	25%	50%				
4	29%		25%	46%				
5	57%			43%				
6				100%				
7				85%		15%		
8				11%		79%	11%	
9				23%		50%	27%	
10						47%	31%	21%
11								100%
12				26%		60%	14%	
13				92%		8%		
14				57%	10%	33%		
15						100%		

they ignore the problems traffic congestion could create during an evacuation of this type in Sangüesa.

Therefore, in this specific model (02:00 AM), vehicular traffic has been excluded from the simulation as the evacuation plan suggest it should not be used. Also, to include vehicular traffic a different software which could mix pedestrian and vehicular modelling would be required.

Nevertheless, in one of the scenarios (see Section 4) a situation in which a few cars are blocking the main evacuation route has been modelled, to show how cars could certainly worsen the evacuation process.

3.16. Helping behaviors outside the family groups

In the survey, people were asked whether they would go to different parts of the town to help others before evacuating knowing that they just have 23 min to evacuate. 87% answered that they would evacuate directly together with their family, without going to other parts of the street or the town. 9% indicated that they would go to help others but just in the same street, and just 4% said that they would go to even different parts of the town before evacuating. Results also show that

Table 8
Summary of model calibration parameters.

Parameter	Assumed?	Source	Observations
Building dimensions	Yes	On-site measurements	On-site measurements were registered from different buildings
Preparation for evacuation	Yes	Survey	Although the survey indicates people are not prepared, this could improve through training
ASET time	Yes	Alonso et al. (2017), Alvarez et al. (2015), Confederación Hidrográfica del Ebro (2013), Ayuntamiento de Sangüesa (2014)	Although the ASET time given by different studies say the water would reach the town in less than 30 min, an ASET of 25 min has been considered considering safety factors.
Safe areas	Yes	Alonso et al. (2017), Alvarez et al. (2015), Confederación Hidrográfica del Ebro (2013), Ayuntamiento de Sangüesa (2014)	The safe areas are defined by those not affected by the flooding
Audibility of the sirens	Yes	Alvarez et al. (2015)	Although the study by CECOR shows that sirens would not be heard in the current situation, it is assumed that this could improve through the relocation or addition of sirens
Pre-movement times	Yes	Breman (2000) and British Standards (2004)	This is consistent with other sources: Proulx, Canada National Research Council
Groupality	Yes	Drury and Cocking (2007) and developed by the authors	An ad-hoc methodology has been applied in which group behavior is simplified by using group speed
Horizontal evacuation speed	Yes	Proulx (2008), Jakling et al. (2015) and developed by the authors	For the group evacuation speeds, a Montecarlo simulation was performed to derive formulas that estimate group speeds
Evacuation speed on stairs	Yes	Proulx (2008)	It has been considered that groupality has little effect, as the in-building evacuation time does not influence the total evacuation time much
Age stratification	Yes	Ayuntamiento de Sangüesa (2015)	Data from census were used
Persons with Reduced Mobility	Yes	Survey	Most of the PRM are elderly whose speeds are already influenced by mobility impediments
Speed reduction coefficient for slopes	Yes	Lee and Hong (2015)	A speed reduction coefficient has been estimated for the main slopes
Evacuation routes	Yes	Survey	Personal preferences taken from the survey have been considered
Use of the car	No	Survey and Ayuntamiento de Sangüesa (2017)	Just 23% of the people would use the car, but better training and awareness could easily reduce this percentage much further, considering that people should not use the car in the studied scenario
Helping behaviors	No	Survey	Improving the training of the population would increase the percentage of people that would evacuate straightaway

young men would be the ones taking more risky attitudes when helping others.

Based on these survey results, and as the modelling of the helping behaviors in which some evacuees would go to a different location before their final evacuation is complex, the model also ignores it. We would need very specific data about where people go and what people do, which is impractical and time-consuming. In addition, improving the training of the population would increase the percentage of people that would evacuate straightaway, and official documents (Ayuntamiento de Sangüesa, 2014; CHE, 2013) state that people should evacuate straightaway.

3.17. Model calibration summary

Table 8 is a summary of the model calibration parameters and data sources used.

4. Scenarios

In Section 3 it has been commented all the inputs and variables that have been considered to build the model. Some of the inputs present a high variability showing the uncertainty existing when modelling this scenario. This is the case for the pre-movement times and for the groupality (group typology and speed) of the evacuees.

The high variability of these inputs is related to the complexity to model human behaviors in emergencies. Therefore, it was necessary to build different scenarios for the same model taking into account the different variable combinations. This means that the results will not indicate an exact figure, but a range (like a confidence interval) in which the results could fall.

Although the variability of possible evacuation scenarios is unlimited, the authors have considered the evacuation at night (2:00 AM assuming the majority of residents are asleep) as one of the worst-case scenarios and the focus of this study. The different variables previously defined (pre-evacuation times and groupality) are considered to define the evacuation scenarios to model with the software Legion. The rest of the parameters will not change between scenarios.

Table 9 shows the matrix of scenarios.

Apart from the scenarios created by combining the variables, another scenario C has been built to take into account possible cars obstructing the main evacuation route. Although this is not a vehicular model, these obstacles represent cars in the main evacuation route parked or waiting for others to evacuate. This scenario was implemented after analyzing the survey results (see Section 3.14), and observing that some people would use the car to evacuate. Scenario C will be useful to understand whether obstacles in evacuation routes such as parked cars, cars used to evacuate, or temporary fences due to roadworks could worsen the evacuation process.

It can be noted that scenario A0 will be the most optimistic scenario, as the average pre-movement time will be the lowest one (based on Brennan), and group behavior will not be considered, so average speed of evacuees will also be faster. On the contrary, scenario B1 or scenario C will be the most pessimistic one.

Although the scenario modelled is one of the worst-case scenarios, it must be noted that it is still optimistic because, as commented in

Table 9
Matrix of scenarios.

Groupality	Pre-mov. Time	
	Brennan (2–20 min)	British Standards (10–20 min)
0 (no group behavior)	A0	B0
1 (with group behavior)	A1	B1/ C ^a

^a In scenario C, some cars acting as obstacles are placed on the main evacuation route.

Section 2.5, it has been considered that the emergency plan (Ayuntamiento de Sangüesa, 2014) is strictly followed: people evacuate on foot, sirens can be heard by the entire population, people evacuate straightaway, etc. This assumption is thought to be valid, as this “perfect” scenario is the one that would exist if the evacuation plan were completely and correctly implemented.

Section 5 will describe the main results obtained.

5. Model results

This section shows the main modelling results, which have been divided in four parts: flows in the main evacuation routes, average density maps, simulation plots to show the effects of cars obstructing the main evacuation route, and total evacuation times and percentiles.

5.1. Flows in the main evacuation routes

The maximum flows during the evacuation occur in scenarios B0 and B1, as the distribution given by the British Standard makes people evacuate in a shorter period of time (between 10 and 20 min since the start of the emergency). There is little difference between scenario B0 and B1 in terms of evacuation flows and densities, so in order to simplify things we will name them just scenario B.

According to the simulation results, evacuation routes R1, R4 and R6 (see Fig. 7) are the main ones, with R4 (Javier street) being the one in which the maximum flows occur as it is located in the town center and it directly leads towards the safety areas. For the mentioned scenarios, the peak minute occurs 19 min after the emergency starts.

As Fig. 9 indicates, the flow in R4 reaches 315 evacuees/minute.

Fig. 10 represents the evacuation flows for the scenario C, in which four stopped cars obstructing the evacuation route R4 have been modelled (see Fig. 15). In this case, the flow in R4 is just 235 evacuees/minute. The difference with the flow in scenario B (315 evacuees/minute) indicates that, if there are cars obstructing the evacuation route, a bottleneck will be formed in which 80 evacuees/minute will not be able to pass. This could cause a critical situation for the evacuees and should be considered in the evacuation plan.

5.2. Average density map during the peak minute

As the maximum flows occur in scenarios B (B0 and B1), average density maps for the peak minute (minute 19) will be shown for these scenarios.

The different colors indicate different level of service (LoS) (Fruin, 1971), as shown in Table 10.

Fig. 11 shows the average density map for the peak minute for the whole town. As mentioned before, the highest densities occur in evacuation routes R1, R4 and R6, where densities reach LoS D or even E. Although R1 shows higher densities, this route is an open path through the forest so, in reality, evacuees could use more space if needed as the route wide is not constrained.

It is also seen that most of the streets have enough capacity to cope with the demand, therefore LoS A and B are not exceeded in the internal areas of the town. The LoS increases (LoS B and C) as people from different areas reach the evacuation routes that act as collector roads merging all the flows from different neighborhoods. However, the streets here are wide enough and no major issues are expected.

Fig. 12 shows a detailed view of the main evacuation route R4. As

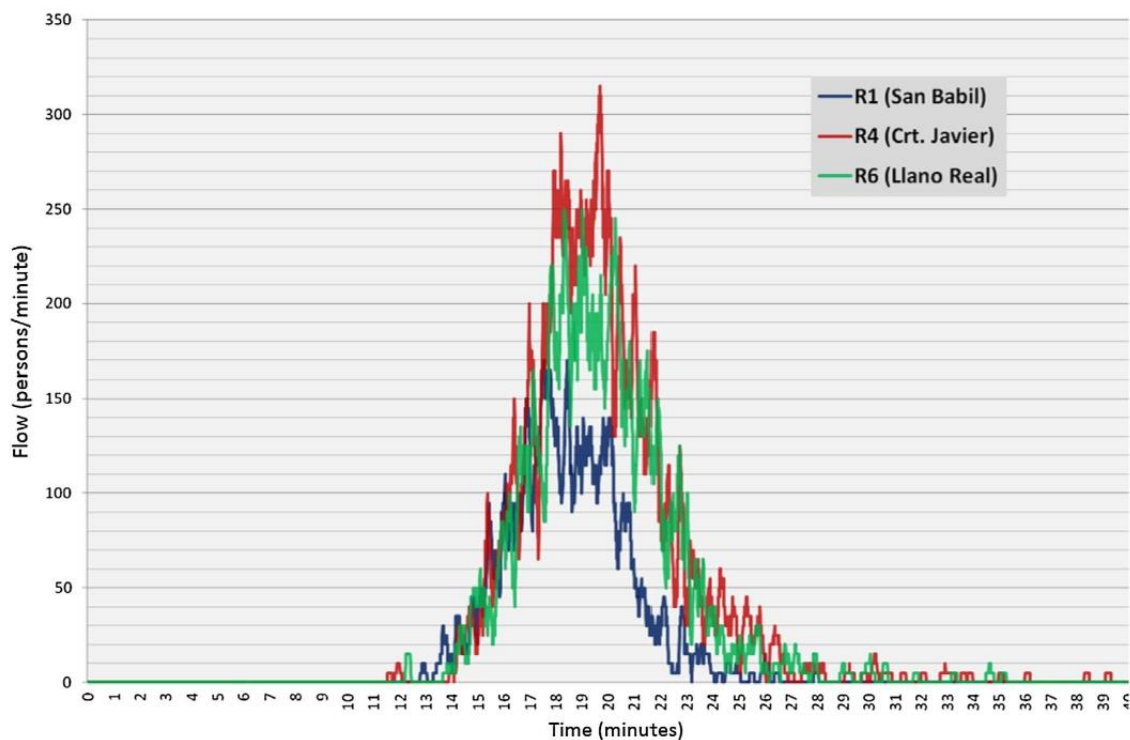


Fig. 9. Flows in the main evacuation routes, during scenario B.

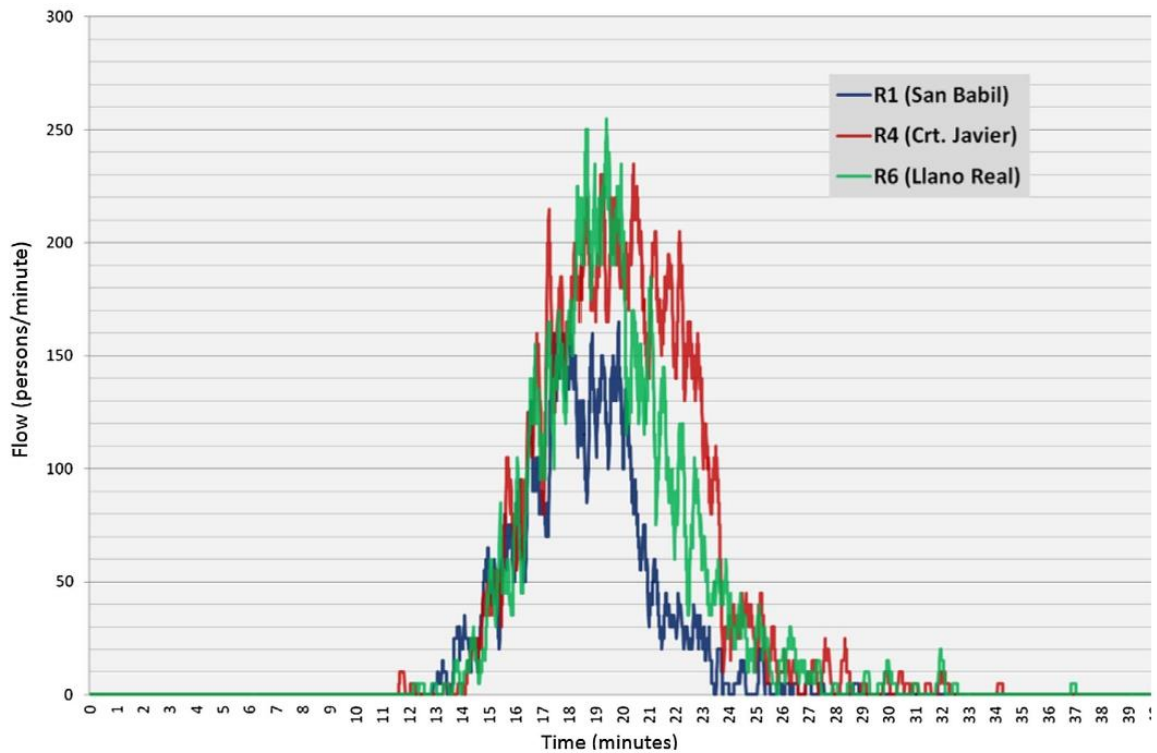


Fig. 10. Flows in the main evacuation routes, during scenario C.

Table 10
Legend for the difference LoS.

Color	LoS	Limit inferior
Dark Blue	LoS A	3,3 m ² /person or higher
Blue	LoS B	2,3 m ² /person
Green	LoS C	1,4 m ² /person
Yellow	LoS D	0,93 m ² /person
Orange	LoS E	0,46 m ² /person
Red	LoS F	Lower than 0,46 m ² /person

commented before, no capacity problems are observed. Although the LoS F is reached in some road sections, this only occurs during the peak minute.

For the scenario C in which some cars are blocking the main evacuation route R4 (see Fig. 13), the average density increases reaching a level of service F that is maintained for more than three minutes. This high density, added to the bottleneck mentioned in Section 5.1 could lead to a critical situation for the evacuees.

The acceptance of a LoS F is very much depending on the environment and state of dynamics. For example, the *Guide to Safety at Sports Grounds (Green Guide)* (Football Licensing Authority, 2008) defines as the maximum permitted density for safety a density of four persons per square meter, which is reached in this scenario (see Fig. 15). However, the concept of a LoS or density limit needs to be also related to flow rate, so a combination of both density and flow is needed

to assess the risk (Still, 2000). For example, regarding spectator facilities, the *British Standards* (BSI Group, 2012) mentions that on a level surface the maximum flows must be 82 persons per meter width per minute. Considering that for the situation in which cars are blocking the route Fig. 15 the available width is about two meters, this would mean that the maximum flow is 164 persons/minute. However, the actual flow is 315 persons/minute Fig. 9, therefore this situation is not acceptable.

It is also interesting to know how long this high density can be sustained to be considered critical. For this purpose, the approach used by Still (2000) in his PhD thesis has been used, in which the time limit to be exposed to high densities is given by the total number of people waiting to pass divided by the flow. In our scenario, counting the number of people in Fig. 15 (140 persons) and knowing that the flow (from Fig. 10) is 235 persons/minute, we obtain a time limit of less than 40 s, which means that evacuees should not be exposed to high densities (four persons per square meter) for more than 40 s. Therefore, as in this scenario the high densities (LoS F) they experience last more than three minutes, the situation can be defined as critical.

It must be noted that Fig. 13 indicates the average density during the peak minute, therefore higher densities at certain instants should be expected. Furthermore, scenario C has just four cars blocking the route, so the situation could be much worse if more cars were acting as obstacles (reducing the available width), which is likely to happen if people were using the car to evacuate.

5.3. Effects of cars obstructing the evacuation route

Fig. 14 is a screenshot of the microsimulation model showing the maximum flows in the evacuation route R4 during scenario B, and Fig. 15 shows the same but for scenario C, when some cars are blocking

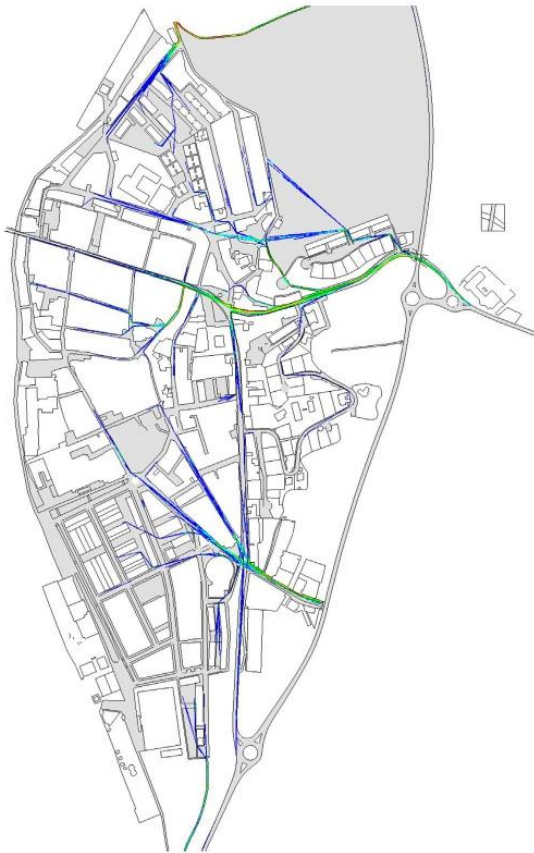


Fig. 11. Average density map for the whole town in minute 19. Scenario B.

the street. As mentioned before, if people used the car to evacuate (scenario C) a critical situation could occur in which evacuees would have problems to evacuate due to the bottleneck formed.

5.4. Total evacuation time and percentiles

Fig. 16 shows the cumulative histogram for the evacuation time, for each of the scenarios that have been analyzed. The white area represents the ASET in the case of a Yesa dam collapse. As it can be observed, scenario A0 is the most optimistic one, i.e. the one in which the RSET time is lower. However, the authors think that a scenario like this in which group behavior is not considered is not likely to happen. On the contrary, scenario B1 is the most pessimistic one.

Small differences between scenario C and scenario B1 have been found, which means that even with only four cars blocking the main evacuation route, the evacuation time distribution is affected.

Table 11 indicates the number of people that reach the safe areas before the flooding of the town, i.e. the number of people for which their RSET is lower than the ASET. It can be noted that, for the most optimistic scenario (A0), 69% of the town population would get to evacuate. This figure would be just 26% in the worst scenario.³

The figures in Table 12 indicate that, according to the different

³ Although according to flooding models by Revuelto [35], the water could reach the town in 23 min, data in Table 11 are results for the ASET (20 min), considering safety factors.

scenarios analyzed, the time needed to evacuate the town to the safe areas (percentile 99) would be between 33 and 44 min (RSET time).

A difference of 30 s exists for the percentile 80 between scenarios B1 and C, which indicates how cars blocking the main route can affect the evacuation time. In this case, this effect is limited, and temporary, because just four cars were modelled.

5.5. Summary of the results

The simulation results have shown that the evacuation routes have enough capacity to cope with the demand during an evacuation scenario if everyone evacuated on foot. Although flows would reach 315 evacuees/minute in the main evacuation route, high densities would not be maintained over time and critical situations would not be likely to happen. However, if there were cars blocking the main evacuation routes, caused for example by some people evacuating by car, a bottleneck could be formed in which high densities could lead to a dangerous situation for the evacuees, reaching the LoS F during a few minutes.

Regarding evacuation times, the results indicate that the time needed to evacuate the whole town to a safe area (RSET) would be between 33 and 44 min. Considering that, according to the flooding models explained in Section 3.4, the ASET is 20 min, this means that the total evacuation of the town would not be possible. Furthermore, we need to understand that the model results reflect a perfect situation in which the evacuation plan has been properly implemented and the population is well informed on how to evacuate (see Section 2.5). However, survey results have shown that the current situation is far from perfect, as most of the people are not correctly informed on how to proceed during an emergency (see Section 3.3), the sirens may not be heard in the town (Section 3.5), and some of the evacuees would use incorrect routes (Section 3.14) or would make use of the car (Section 3.15), which will increase evacuation times. Therefore, in reality, without the evacuation plan properly implemented, the situation would be much worse meaning that people would require much more time to evacuate the town, or which is worse, that the evacuation would never start as the sirens cannot be perceived.

Taking the previous results into account, it is clear that actions should be in place (1) to eliminate the risk of flooding or (2) to reduce it. According to some experts (Arrojo, 2004; Gracia et al., 2015), one of the options to eliminate the risk would be to lower the level of water in the Yesa dam (which, on top of this, is being controversially expanded at the moment) so that the flooding could not reach the town of Sangüesa. As for reducing the risk, it is crucial that the evacuation plan is efficiently implemented. However, this paper has shown that even if the population were perfectly informed and prepared for an evacuation, and even if the sirens were audible along the whole town, the total evacuation could not be possible. Therefore, the evacuation plan of the town should also state other alternatives, for example staying at the higher floors of the building and await rescue.

6. Discussion

This study provides an overview on how microsimulation models can be applied for large-scale pedestrian evacuation for towns and cities, which is traditionally approached from a vehicular and macroscopic point of view.

Computer evacuation models have been commonly focused on infrastructures in isolation such as office buildings, sports stadia, music festivals and transport interchanges. However, the applicability of these models to large-scale evacuation scenarios for towns or cities has been limited. One of the reasons behind this is the complexity of modelling such scenarios as it is necessary to consider different locations at different levels: houses, buildings, and streets. Another reason is the need for an in-depth data collection programme which consists not only of plans of the area or census data, but also in specific information related



Fig. 12. Average density map for evacuation route R4 in minute 19. Scenario B.



Fig. 13. Average density map for evacuation route R4 in minute 19. Scenario C.



Fig. 14. Screenshot from the microsimulation. Maximum flow in evacuation route R4. Scenario B.

to the emergency being analyzed (evacuation routes, ASET, or location of the safe areas), and different aspects of human behavior during the emergency (use of the car, group behavior, pre-evacuation times...).

A novel methodology based on inter-connected sub-models has been proposed that allows simplifying the whole evacuation procedure whilst maintaining the connectivity between all the parts of the evacuation process and guarantying the results. In this study, the model has been split into three sub-models (in-house, in-building, on-street), but due to the flexibility of the methodology, different sub-models could be added to study different scenarios or to add more realism to the whole evacuation process. For example, “in-school” and “in-shop” sub-models could be used to study the evacuation of the town in the morning instead of at 02:00 AM. Also, an “in-nursing home” sub-model could be added to accurately consider assisted evacuation. Therefore, this methodology is flexible and it could be extrapolated to other emergency and evacuation scenarios.

The application study, the evacuation of Sangüesa in event of the Yesa dam collapse, demonstrates that the proposed methodology can be correctly applied to model a large-scale evacuation scenario. The case study also shows the specific type of data required to model this kind of scenario. Apart from using census data, plans of the town, data obtained from the emergency plan, or other kind of data that can be extrapolated from other papers, this study shows the importance of understanding the human behavior and the actions and decisions evacuees would take during an emergency of this type. As the data related to similar emergency scenarios is very scarce, a survey was needed to comprehend the likely local human behavior in this specific scenario. The survey highlights some key behaviors inherent to the case study. This kind of surveys are needed for large-scale evacuation as the human actions and decisions depend on a vast number of parameters such as social or cultural factors, characteristics of the town, type of emergency, perception of the risk or personal circumstances.



Fig. 15. Screenshot from the microsimulation. Maximum flow in evacuation route R4. Scenario C.

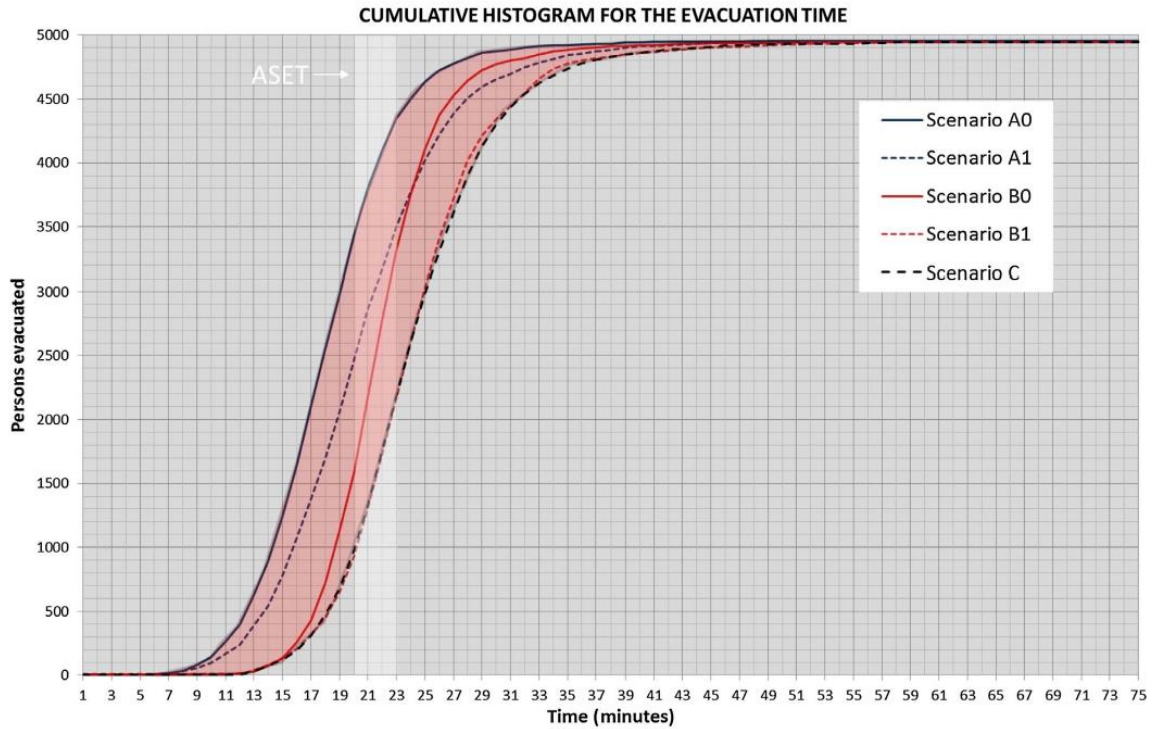


Fig. 16. Cumulative histogram for the evacuation time.

In the case study, the survey results indicate that a low percentage (23%) of the population would use the car to evacuate. This might be mainly due to the topology of the town, the length, and characteristics of the evacuation routes, but also because it may take more time to go to the garage to take the car rather than evacuating on foot. The survey also provides an overview on the evacuation route choice based on the location of the house. As the evacuees are highly familiar with the town, this choice is in many cases based on the shortest perceived path, and includes routes through the woods and through hills. This means

that, even living in the same building, some families would use a road whilst other would prefer going through the forest. The survey also demonstrates that, as expected, this kind of evacuation includes a high level of groupality, as families would stay together in case of emergency evacuation. In addition, the case-study suggests that the majority of the residents would directly evacuate together with their families, rather than going to other parts of the town to help others. This is because the time they have to evacuate (23 min) is very limited and not enough to go to other places.

Table 11
People evacuated in each scenario.

Scenario	Persons evacuated	%
A0	3437	69%
A1	2468	50%
B0	2171	44%
B1	1301	26%
C	1319	26%

Even with the number of possible evacuation scenarios being unlimited, the application case is focused on one of the worst-case scenarios, the evacuation while most of the residents are asleep at home (2:00 AM). Regarding the whole evacuation process, the population would not be able to evacuate on time in case of dam collapse for any of the analyzed scenarios.

Table 12
Percentiles for the evacuation time.

People evacuated	A0	A1	B0	B1	C
50%	0:17:52	0:20:01	0:21:29	0:23:42	0:23:40
80%	0:21:32	0:24:44	0:24:29	0:27:45	0:28:13
90%	0:23:43	0:27:31	0:26:19	0:31:03	0:31:07
99%	0:32:35	0:39:06	0:35:07	0:43:39	0:43:40

As Table 11 shows, even in the most optimistic scenario (scenario A0) less than 70% of the population would evacuate in 23 min. In the most pessimistic scenario (scenario B1), only 26% of residents would evacuate before the water reaches Sangüesa. Considering that groupality mainly affects walking speeds (the group would adapt their speed to the slowest member of the group), results on evacuation times show the impact of groupality during a large-scale evacuation; a decrease of 19 percentage points in people evacuated is reached when groupality is considered. This shows the importance of considering groups in these kinds of scenarios.

In addition, pre-evacuation times are a determinant factor in large-scale evacuation as shown in the results. As Table 11 indicates, there is an increase of 25 percentage points for the number of people evacuated when Brennan is used (scenario A0 and A1) instead of British Standard (scenarios B0 and B1). More research would be needed on pre-evacuation times in this kind of emergency to develop models that are more accurate.

It was also demonstrated that cars blocking the main evacuation routes (scenario C) could affect the evacuation times, although a more detailed analysis (using vehicular microsimulation) would be needed to quantify it. Moreover, a critical situation with high densities and a bottleneck could occur if there are cars blocking the evacuation route.

In general, results obtained by large-scale modelling could be useful to improve the evacuation procedures and the emergency management. Outcomes could highlight problems or deficiencies in a populated area, which can endanger the residents of a town in case of emergencies. The case-study presented here has analyzed a number of possible evacuation scenarios showing that microsimulation tools and the proposed methodology has the potential to easily analyze this kind of emergencies.

7. Model limitations

It has been widely discussed that validation is a challenging process constrained by the data available (Kuligowski, 2016), and that sometimes the validation exercise is not possible due to the lack of experimental data-set, especially on behavioral patterns (Ronchi et al., 2013). In this model, the main limitation is that the validation exercise is not possible, as this would imply to have a flooding event caused by a dam collapse which would lead to thousands of fatalities. Furthermore, there are no available data of similar flooding events (dam collapses with a very urgent evacuation). Therefore, this model is not validated. In the future, if an evacuation drill were held, it would be possible to get some data, although this is not thought to be sufficient for a validation exercise, mainly because (1) the drill had to be at night when people are sleeping, which is not likely to occur, and (2) the main objective of a drill is to train people on how to evacuate, and their behaviors and actions during the drill may not be the same as the ones they would have during a real emergency. Having said this, it must be noted that the software Legion is itself a validated model broadly used in different kind of evacuation scenarios as explained in Section 2.6.

8. Future lines of research

The more complex scenarios and models are, the more we know about the lack of knowledge we have in this field. As the level of accuracy to which microsimulation modelling is applied increases, so too must the accuracy of inputs used. However, the lack of data, especially related to human actions and decisions (i.e. pre-evacuation times, walking speeds, group behaviors and speed), highlights the need for future research to collect behavioral data not only in fire situations but also in other kind of emergencies (terrorist attacks, tsunamis, earthquakes...) and for other types of environment (i.e. schools, hospitals, nursing homes, etc.). The data collection in this field could rely on similar techniques employed in fire safety engineering such as data collected from real scenarios, drills, large and small-scale experiments, and surveys. The collected data would allow researchers and modelers to validate large-scale models in the future, which is the major limitation of this study as already mentioned in Section 7.

Vehicle evacuation is also a key aspect. Although, as the survey confirms, the use of vehicles in the particular scenario of Sangüesa might not be a relevant parameter to consider in case of an emergency (as most people would not use the car), the combination of pedestrian and vehicular evacuation using microsimulation modelling should be studied.

Current microsimulation software were not developed to simulate large-scale evacuation. Therefore, future works should focus, on the one hand, on improving this type of tool to optimize the modelling of large-scale evacuation scenarios by decreasing the computational cost. Secondly, there is a need of adding additional input variables (for example groupality, fatigue, fear, or knowledge of the evacuation procedure) and output variables (optimal routes, resources needed such as buses or ambulances, etc.). Finally, new software should provide interconnectivity with other applications such as Google Maps, software

to model floods, or acoustic models, among others, in order to represent the evacuation procedure in a more realistic way. For example, some routes will become impassable as the flood progresses or, depending on the alarm system, the sirens will not be heard by everyone.

Future research should also embrace new technologies to enhance the input information of the evacuation models. For example, smart cities use communication technologies facilitating the information exchange in real time (i.e. traffic information, parking availability, occupancy levels in public areas). This type of information could provide a very realistic picture of the model inputs, but could be used also during the emergency to optimize the evacuation process by an appropriate emergency management.

9. Conclusions

This paper presents a methodology to model large-scale evacuation scenarios by using micro-simulation tools. Current microsimulation software has sufficient flexibility to represent the evacuation process of a populated area (town, village, or cities) including the behavioral factors of residents. The use of interconnected models allows the modeler to simplify such a complex procedure without losing the required accuracy to represent the scenario. Based on specific data collection (site-visits, surveys, census data, mapping and behavioral data collected from literature), the proposed methodology can be applied to large scale scenarios, and results can be used to highlight possible problematic aspects or deficiencies in local areas to be improved in order to ensure the safety of residents.

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PART IV. RESEARCH OBJECTIVES, METHODOLOGY, CONCLUSIONS, FUTURE LINES OF RESEARCH AND CONTRIBUTIONS.

4.1 Research objectives

Considering the state of the art described in Part II and the current limitations in the field of smart cities, urban logistics, and urban resilience, the research objectives of this thesis are the following:

- To analyse the existing bibliography to date regarding smart cities, focusing on the main problems the research community is facing with respect to urban logistics and urban resilience.
- Regarding urban logistics:
 - o To review the bibliography on how traffic congestion affects the distribution of goods, especially in urban areas.
 - o To develop a VRP (Vehicle Routing Problem) model to understand how traffic externalities (especially time lost due to congestion) affect the optimization of logistics routes, both at regional and urban level.
 - o To intertwine the use of the VRP, simulation and modelling techniques and big data applied to urban logistics to help city planners and authorities to make decisions on transport policies (CO₂ emissions, cyclelogistics, pedestrianisation of city centers, etc.).
 - o To study, through surveys, different opinions from inhabitants, businesses, distribution companies and authorities regarding the use of cyclelogistics or electric vehicles for last-mile distribution.
- Regarding urban resilience:
 - o To review the bibliography on how urban resilience is considered within the smart cities field, to understand the areas that are not fully developed.
 - o Focusing on disasters, to use agent-based simulation techniques to create a new methodology to model evacuation scenarios in urban areas so that public authorities have more tools to drive urban policies and to plan for more resilient cities.

4.2 Methodology

In order to achieve the objectives presented in section 4.1, this section presents the methodology the author has followed. It is important to note that each paper has a different/specific methodology, although in general terms they all follow the same approach that is summarized here.

4.2.1 Literature review

The first phase of the research involved an exhaustive review of the literature on smart cities, covering the two main study areas of this doctoral thesis: urban logistics, and urban resilience. In order to have a broad view of the main research interests of the research community, the areas in which the research is still limited, and the key limitations researchers are facing, keywords maps were created through the software VOSviewer using bibliographic data from Scopus. After the analysis of the areas that are gaining in prominence during the last years, the author could see that within urban logistics and urban resilience there are some that could be further developed, especially with respect to the use modelling and simulation techniques to consider traffic congestion. For the specific case of urban logistics and VRP approaches, an index (ROPAC) was defined which was applied to each paper analyzed in order to focus on the most relevant ones considering its relevance, originality, practicality, age, and continuity. After having reviewed the most relevant articles regarding route optimization in urban areas

considering congestion (for urban logistics), and evacuation modelling (for urban resilience), it was possible to set the next steps needed to further improve these models.

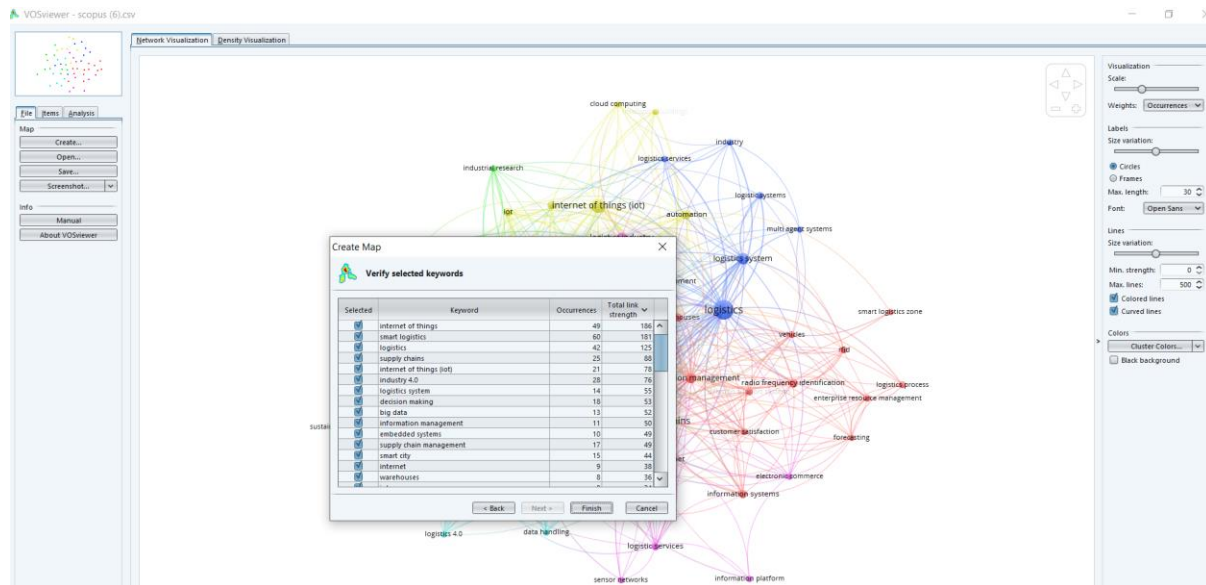


Figure 11. Screenshot showing the software VOSviewer, used during the literature review process

4.2.2 Model design

The second phase of the research was the model design. The starting point to design the models was to look at the current models and algorithms already used by other researchers as already mentioned in Part II. After understanding how those models work, improvements were added in order to get insights that allowed us to reach the objectives. However, every paper or research task required specific models adapted to each circumstance and scenario. More details on the specific methodologies for each paper can be seen in Part III. Here, only a brief summary will be given, differentiating between the field of urban logistics, and the area of urban resilience.

1.1 Urban logistics

To analyse how different variables (congestion, CO₂, etc.) affects route optimization within urban areas, the following approach was used. Each model consists of four main components (see Figure 12), although as already mentioned depending on the specific characteristics of each scenario the model may vary.

The first component is the instance generator, which was done through a Visual Basic program (created ad-hoc for this research). Through the instance generator, different simulation runs could be performed selecting different depot locations, client location, demand, starting time of the route, etc.

The second component is the network model, which was done through QGIS. In this network model, the topology of the network is defined: links, nodes, distances, speeds, etc. This network model is not only used for visualization purposes, but the tables from QGIS contain all the information on the network topology needed to run the model.

The third component, built in JAVA, downloads the data from the Google Maps API, although connection with other big data sources could be created. These data are used in each link of the network model.

Finally, the fourth part, also programmed in JAVA, integrates the previous components, generating instances and running the VPR algorithms in the selected networks. In this thesis, as already seen in Part III, the Dijkstra, Clarke and Wright, and Tabu search algorithms were used.

These four components are connected through a Visual Basic program also run from the instance generator.

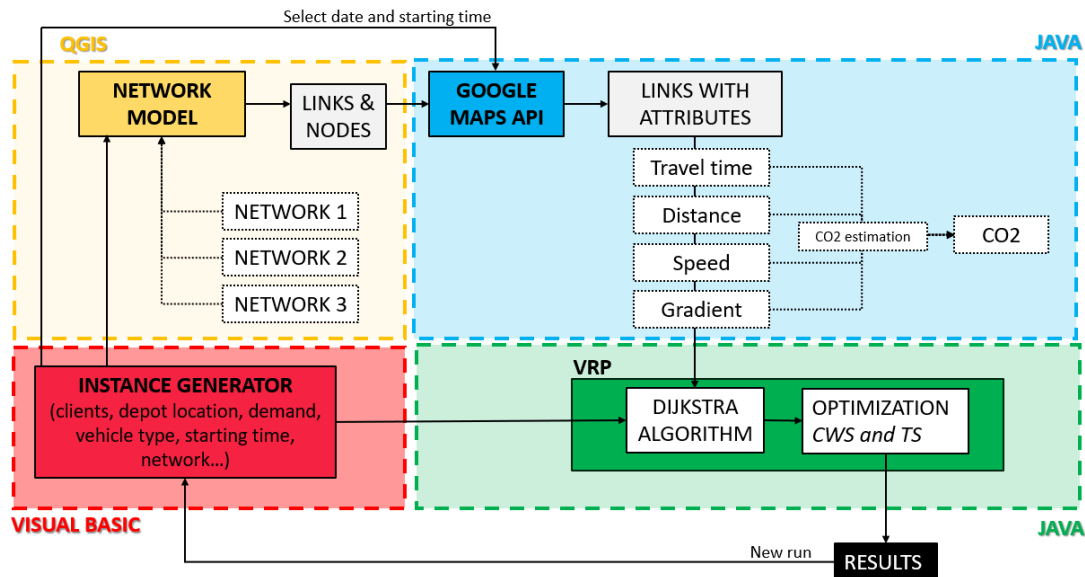


Figure 12. This figure shows an algorithm of a typical model used in this thesis to analyze urban logistics.

1.2 Urban resilience

For the specific case of evacuation modelling, an agent-based model was used. After getting all the inputs needed for the models (both from the literature and from different data collection exercises), three different sub-models were created (see Figure 13) and connected to model a large-scale evacuation scenario. This methodology has been completely new in this research field. More information and details on this methodology can be found in the article embedded in Part III.



Figure 13. New methodology created for large-scale evacuation modelling using interconnected submodels.

4.2.3 Scenario design

With the models defined and prepared to be fed, it was time to design the scenarios that were going to be modelled and analyzed. Again, here, for each paper, the scenarios modelled were different, but, in all the cases we needed to answer the following questions: What are we trying to solve here? Where? At what level (urban or regional)? Which variables are involved? How can we model it without losing information?

In each research task, the answers to these questions were different. It is not the same to analyze whether congestion affects more at urban level or at regional level (for which different networks at a different zoom are needed; Figure 14), to analyze how cyclelogistics affects urban deliveries in the Old Town of Pamplona (for which a more detailed model is needed), or to model a large-scale evacuation scenario in the city of Sangüesa (for which the details need to be at the level of microsimulation models; Figure 15).

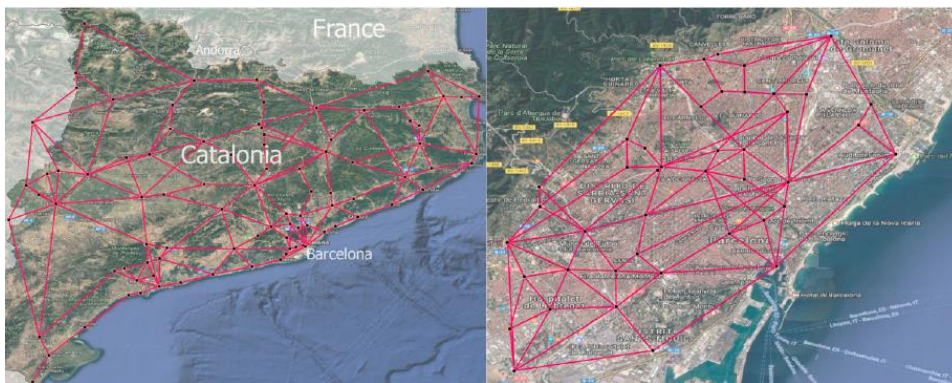


Figure 14. Different scenarios modelled to understand whether congestion affects more at urban level in the route optimization processes.



Figure 15. Scenario to be applied to an agent-based microsimulation to analyze large-scale evacuation scenarios.

4.2.4 Data collection

Data collection is one of the key aspects of the models as the network is defined by different variables (time, distance, speed, etc.) that need to be inserted. Although for some models random data points were used, in other cases the inputs used were real. The different methods for data collection that have been used in this thesis are:

- **Google Maps API to get data in real-time (times, distances, etc.).** This was used to consider dynamic congestion effects in some VRP papers. This task was integrated in the model, as through a Java program the data could be downloaded from the servers.
- **Traffic counts.** For the specific model of the Old Town of Pamplona, manual traffic counts were performed to know the number of vehicles entering the Old Town.
- **Speed measurements.** Related to the above, speed of vehicles were taken to be able to calibrate the models.
- **Route tracking.** For the same purposes, we tracked real vans and trucks doing the deliveries to be able to calibrate the model, also checking how much time it took.
- **Surveys to know the perception of businesses, neighbors, and logistics companies** regarding cyclelogistics, electric vehicles, and other aspects related to urban logistics.
- **Surveys to understand the perceptions and attitudes people** would have during an evacuation scenario in Sangüesa. This was needed to feed and calibrate the microsimulation model.
- **Measurements of buildings to be able to model them with an agent-based microsimulation software.**
- **Interviews in two different companies (Txita and Oraintxe) to their managers** to understand the perception of cyclelogistics companies in relation to urban logistics.
- As mentioned, in other cases, model runs were performed using **random demands, clients, and depot locations.**

Due to the complexity and the importance that some of the inputs had for the mode (for example, the ones related to the speed of the vehicles, or the data on how people would react during an evacuation, etc.), some of them had to be analysed through statistical methods before their application into the model. For this purpose, the software Minitab and R were used.

4.2.5 Simulation

With all the scenarios created, it was possible to run the model. Depending on the objective, the model was run in diverse ways. For the VRP research, the model created has a functionality to generate different random runs automatically in order to consider stochasticity effects, for example, changing the depot location, the number of clients, the starting times of the routes, etc. For the model of the Old Town of Pamplona, we simulated different what-if scenarios. Apart from generating different instances, we could use different networks (Old Town pedestrianized, some streets closed to traffic, etc.) and simulate them automatically. Finally, regarding evacuation modelling, a microsimulation software (Legion) was used to run the scenarios. See the different articles in Part III for more information about the model runs,

4.2.6 Calibration and validation

Although the calibration and validation exercises are not necessarily needed when the model is used to compare, for example, two theoretical approaches in which the scenario is not real, the situation is different when these models are used to model real scenarios. In these cases, we need to make sure the

model is reliable to represent the reality. For this purpose, it is important to calibrate and validate the model. The calibration and validation was used, for example, to model the Old Town of Pamplona, where we were able to track vans and trucks doing deliveries and we recorded how much time the whole delivery route took in reality. Before creating what-if scenarios, the model was calibrated using the base scenario to check that the modelled time was close to the real time recorded. In addition, we checked that routes given by the model were similar to real routes. With this calibration in place, we could assure that the model worked before applying it to what-if scenarios.

4.2.7 Analyses

Finally, the results are analysed. Each model run generates a .txt file (a *log* file) that flags possible errors during each model run; for example, if there is no possible route to reach a client because it is located in an inaccessible link. Therefore, we can control that all the results are reliable. Once this is confirmed, the results are imported into Excel for their analysis. The analysis usually consists in the comparison of the study variables between the different scenarios modelled.

4.3 Final conclusions (English)

This thesis explores different aspects of urban logistics and urban resilience that are especially relevant today due to the development of so-called smart cities.

In Part II, we have seen how research on smart cities, although it is growing year after year, is generally limited to specific fields such as Big Data technologies, Internet of things or smart energy grids. There were almost 5,000 articles indexed in Scopus in 2019 related to smart cities, but only a minority of those articles addressed transportation and urban planning problem from a more social scale. Over the last decade, research has focused more on the tools needed to build smart cities (how we can build smart cities) rather than why we need to live in cities that are smart. It sometimes looks that we are not using technology in the right direction, or maybe we are using it in a selfish way just to meet our needs as individuals, but not as a society. In fact, although Part II has shown that there are many international and national organizations that are trying to promote more sustainable and resilient cities, the current industry is still focused on the technologies necessary for this purpose, so, in this sense we can say that we are still far from achieving smart cities that truly serve to create smart societies. This, for example, would explain why we have sensors in our buildings and houses to adapt the lights or the temperature, or in our streets to know where there are more parking spaces available, but it is still difficult to use this technology to create, for example, more resilient cities, or to optimize the distribution of goods within urban areas. Therefore, this thesis covers two main topics in the field of smart cities that, although relevant, are still little explored: urban logistics and urban resilience.

First of all, we can start with urban logistics. As seen in the introduction, the transport sector employs 10 million people in Europe, generates 5% of its GDP, and is responsible for 15% of the final cost of a product (European Commission, 2016). Taking into account the rapid population growth and the migratory movements from rural to urban areas, it seems clear that transport and logistics should be a fundamental part of the development of the smart cities, giving name to what is known as smart urban transport and logistics. However, as seen in Part II, in 2019 there were only 50 Scopus-indexed articles focused on smart logistics.

The true is that the approaches used to optimize delivery routes within urban areas have not changed much in recent decades. For example, logistics companies continue to optimize routes considering either experience or intuition, or algorithms that only consider distance or travel time. The problem is that with the increasing level of urbanization our cities are experiencing, congestion is becoming a major problem for logistics companies in charge of last-mile deliveries. In addition, the momentum of online shopping highlights the change in the route planning process: from the traditional methodology in which routes were planned in advance to the current trend in which the route must be established in real time and adapts taking into account actual traffic conditions, such as congestion, accidents or road closures. In fact, we have Big Data technologies available, but some logistics companies are not yet adapted to this new era where advance planning is becoming obsolete. And this lack of real-time planning associated with high dynamism has had its maximum exponent during the Covid-19 crisis, when areas, neighborhoods, cities, and countries have been closed overnight. And it is in this context of great competition when companies have had to demonstrate their supply and distribution capacity because, although the price war may be online, the final battle to satisfy the customer is won in the last mile. And, to win, we need tools more adapted to the changing and dynamic scenarios that are experienced every day.

In this thesis, therefore, some of the current VRP optimization methods to optimize routes in urban areas have been analyzed. After understanding their weaknesses and possible opportunities, a new methodology is presented in which a dynamic and time-dependent VRP has been used so that delivery routes can be optimized considering real-time traffic congestion data collected, for example and in this case, from Google Maps. In this way, it has been seen that optimizing routes considering dynamic conditions in real time (congestion, accidents, etc.) allows reducing the route time by up to 11%, which implies significant savings for transport and logistics companies, which in the current context of fierce competition can be crucial. In addition, following the idea of using a dynamic VRP fed by real-time data, this thesis has also brought a new methodology that serves to analyze transport policies in relation to the distribution of urban goods that may be of great interest for the application within smart cities. In general, transport models and urban transport plans ignore the distribution of goods and focus more on public transport or private vehicles. In fact, there are many simulation tools to understand how traffic flows behave in different scenarios, and they are widely used to decide policies on urban planning and transport. However, the analysis of goods flows in the urban context is usually done using more qualitative techniques that, to a large extent, are based on intuition and past experiences. But, in this thesis, it has been seen that it is possible to create simplified models that intertwine optimization techniques (VRP) with modeling and simulation techniques to understand how different urban policies could affect the distribution of goods in our cities. Thus, analyzing a practical case in the city of Pamplona, we have demonstrated how public authorities can benefit from this new approach to adapt today's logistics activities to the future of smart cities, but also logistics companies can benefit, since with these new forms of optimization they will be able to compete in an increasingly complex and fierce market. And, in a world in which our cities are becoming smart, the tools we use to plan delivery routes have to be too.

Apart from urban logistics, in part II it was also seen that most articles focused on smart cities are not focused on issues such as urban planning and urban resilience. While it is true that urban resilience is a relatively new field (compared, for example, with logistics), during the last decade there has been a great push by national and international organizations, which are sending a clear message that urges our metropolises to be designed in a way that they can adapt and recover from natural disasters, especially climate change. Therefore, it is somewhat worrying that most research on the topic of urban resilience

focuses on theoretical frameworks and methodologies that do not always have easy practical application.

This thesis analyzes the evolution of the concept of urban resilience and focuses on a specific aspect: catastrophes and evacuation of population. Although there are many models and software to analyze how large groups of people can be evacuated, these models are usually used in certain infrastructures in isolation. For example, in train stations to model how people evacuate in case of fire, or in football stadiums to see if there will be capacity problems that could pose a risk to people, such as human avalanches.

However, until now, these models had not been applied to urban areas as a whole, due, among other things, to the difficulty of designing these scenarios, modeling these behaviors, and collecting the data necessary to feed the models. Therefore, this thesis tried to shed some light on this topic and presents a new methodology that serves to model large-scale evacuation scenarios through the use of microsimulation tools and interconnected sub-models. This allows to represent the evacuation process of a populated area using all the power of these simulation tools, but in a simplified way by connecting different sub-models. The proposed methodology can be applied to large-scale scenarios (villages, neighborhoods, towns, cities) and the results can be used to highlight possible problematic aspects or deficiencies in urban centers that should be corrected to guarantee the safety of residents in case of evacuation. In this research, an agent-based simulation has been applied to a practical case in the city of Sangüesa (Navarra, Spain), where the evacuation of residents as a consequence of a collapse in the Yesa dam has been modeled. The results show that, in the event of a collapse, and in the best scenario (people know how to evacuate) only 69% of the population could evacuate in time. These results are very useful for public bodies, so that they can improve action plans and take the necessary actions to minimize risk.

But, in addition, in a smart city, this evacuation model could be fed by real-time data: flows of people, occupation of buildings, rain, water levels in rivers or seas, probability of earthquakes, traffic, etc. In this way, at any time, simulations could be run to understand how prepared the city is for an eventual evacuation. With this, it could be known, for example, which are the most vulnerable areas that would suffer the most damage so that emergency services can be prepared if necessary, and plan evacuation processes in advance so that thousands of lives are saved. A smart city will only be so when it is also resilient.

In summary, this thesis has investigated two important areas for our society, such as urban logistics and urban resilience, but which, until now, have not been widely studied from the point of view of smart cities. In this thesis, an analysis of the current situation in each of these fields has been performed, understanding what the current limitations are, and new modelling tools have been presented that can be used today to build the smart cities of tomorrow.

4.4 Conclusiones finales (español)

Esta tesis explora diferentes aspectos sobre logística urbana y resiliencia urbana que son especialmente relevantes hoy en día debido al desarrollo de las llamadas ciudades inteligentes.

En la parte II se ha visto cómo la investigación sobre ciudades inteligentes, aunque está creciendo año tras año, generalmente se limita a campos específicos como las tecnologías de Big Data, Internet de las

cosas o redes de energía inteligentes. De los casi 5000 artículos indexados en Scopus en 2019, hay sólo una minoría de artículos que tratan de forma específica problema de transporte y urbanismo desde una escala más social. Durante la última década, la investigación se ha centrado más en las herramientas necesarias para construir ciudades inteligentes (en el cómo podemos construir ciudades inteligentes) en lugar de en el porqué de la necesidad de vivir en ciudades que son inteligentes. Esto hace que, a veces, pueda parecer que no estamos usando la tecnología en la dirección correcta, o tal vez la estamos usando de manera desordenada solo para satisfacer nuestras necesidades como individuos, pero no como sociedad. De hecho, aunque se ha visto en la parte II que son muchas las organizaciones internacionales y nacionales que están tratando de impulsar ciudades más sostenibles y resilientes, la industria actual aún está centrada en las tecnologías necesarias para tal fin, por lo que, en este sentido podemos decir que aún estamos lejos de lograr ciudades inteligentes que, de verdad, sirvan para crear sociedades inteligentes. Esto, por ejemplo, explicaría por qué tenemos sensores en nuestros edificios y casas para adaptar las luces o la temperatura, o en nuestras calles para saber dónde hay más espacios de estacionamiento disponibles, pero aún es difícil usar esta tecnología para crear, por ejemplo, ciudades más resilientes, o para optimizar la distribución de mercancías dentro de las áreas urbanas. Por lo tanto, esta tesis abarca dos temas principales del ámbito de las ciudades inteligentes que, aunque relevantes, aún están poco explorados: logística urbana y resiliencia urbana.

En primer lugar, se trata el tema de la logística urbana. Como se ha visto en la introducción, el sector del transporte emplea a 10 millones de personas en Europa, genera el 5% de su PIB, y es responsable del 15% del coste final de un producto (European Commission, 2016). Teniendo en cuenta el rápido crecimiento poblacional y los movimientos de zonas rurales hacia zonas urbanas, parece claro que el transporte y la logística debe ser parte fundamental del desarrollo de las smart cities, dando lugar a lo que se conoce como transporte y logística urbana inteligente. Sin embargo, según se ha visto en la parte II, en 2019 apenas había 50 artículos indexados en Scopus centrados en logística inteligente.

Y es que, los enfoques utilizados para optimizar las rutas de entrega dentro de las áreas urbanas no han cambiado mucho durante las últimas décadas. Por ejemplo, las empresas de logística siguen optimizando rutas considerando o bien la experiencia y la intuición, o bien algoritmos que solamente consideran, en su mayor parte, la distancia o el tiempo de viaje. El problema es que con el creciente nivel de urbanización que están experimentando nuestras ciudades, la congestión se está convirtiendo en un problema importante para las empresas de logística que necesitan hacer la entrega de última milla. Además, el impulso de las compras en línea pone de manifiesto el cambio existente en el proceso de planificación de rutas: desde la metodología tradicional en la que las rutas se planificaban por adelantado hasta la tendencia actual en la que la ruta debe establecerse en tiempo real y se adapta teniendo en cuenta las condiciones reales del tráfico, como la congestión, los accidentes o el cierre de carreteras. De hecho, tenemos tecnologías de Big Data disponibles, pero algunas empresas de logística aún no están adaptadas a esta nueva era en la que la planificación anticipada se está volviendo obsoleta. Y esta falta de planificación en tiempo real asociada a un alto dinamismo ha tenido su máximo exponente durante la crisis del Covid-19, cuando de un día para otro se han cerrado zonas, barrios, ciudades, y países. Y es en este contexto de gran competencia cuando las empresas han tenido que demostrar su capacidad de suministro y distribución porque, aunque la guerra de precios pueda ser online, la batalla final para satisfacer al cliente se gana en la última milla. Y, para vencer, se necesitan herramientas más adaptadas a los escenarios cambiantes y dinámicos que se experimentan día a día.

En esta tesis, por lo tanto, se han analizado los métodos de optimización VRP existentes para optimizar rutas en áreas urbanas y, tras entender sus debilidades y posibles oportunidades, se presenta una nueva metodología en la que se ha utilizado un VRP dinámico y dependiente del tiempo, de forma que se puedan optimizar las rutas de entrega considerando la congestión del tráfico utilizando datos de

congestión del tráfico en tiempo real recopilados, por ejemplo y en este caso, de Google Maps. De esta forma, se ha visto que optimizar rutas considerando las condiciones dinámicas en tiempo real (congestión, accidentes, etc.) permite reducir el tiempo de ruta de hasta un 11%, lo que supone importantes ahorros a las empresas de transporte y logística, lo que en el actual contexto de competencia feroz puede ser crucial. Además, siguiendo la idea de usar un VRP dinámico alimentado por datos en tiempo real, esta tesis también ha traído una nueva metodología que sirve para analizar las políticas de transporte en relación a la distribución de mercancías urbana que puede ser de gran interés en la aplicación en ciudades inteligentes. Por lo general, los modelos de transporte y los planes de transporte urbanos ignoran la distribución de mercancías y se centran más en el transporte público o los vehículos privados. De hecho, hay muchas herramientas de simulación para entender cómo se comportan los flujos de tráfico en diferentes escenarios, y son ampliamente utilizadas para decidir políticas en materia de urbanismo y transporte. Sin embargo, los análisis de flujos de mercancías en el contexto urbano se suelen hacer mediante técnicas más cualitativas que, en gran parte, están basadas en la intuición y en experiencias pasadas. Pero, en esta tesis, se ha visto que es posible crear modelos simplificados que entrelazan técnicas de optimización (VRP) con técnicas de modelado y simulación para comprender cómo las diferentes políticas urbanas podrían afectar la distribución de mercancías en nuestras ciudades. Así pues, analizando un caso práctico en la ciudad de Pamplona, se ha visto cómo los organismos públicos se pueden beneficiar de este nuevo enfoque para adaptar las actividades logísticas de hoy al futuro de las smart cities, pero también las empresas logísticas, ya que haciendo usos de nuevas formas de optimización serán capaces de competir en un mercado cada vez más complejo y feroz. Y es que, en un mundo en el que nuestras ciudades se están volviendo inteligentes, las herramientas que utilizamos para planificar rutas de entrega también tienen que serlo.

Dejando de lado la parte de logística urbana, en la parte II también se vio que la mayor parte de artículos centrados en smart cities no están centrados en temas como urbanismo y resiliencia urbana. Si bien es cierto que la resiliencia urbana es un campo relativamente nuevo (en comparación, por ejemplo, con la logística), durante la última década ha habido un gran impulso por parte de organismos nacionales e internacionales, los cuales están enviando un mensaje claro y conciso que apremia a que nuestras metrópolis se diseñen de forma que puedan adaptarse y recuperarse de catástrofes naturales, especialmente del cambio climático. Por lo tanto, es algo preocupante que la mayor parte de investigaciones sobre el tema de la resiliencia urbana se centren en marcos teóricos y metodologías que no siempre tienen una fácil aplicación práctica.

Esta tesis analiza la evolución del concepto de resiliencia urbana y se centra en un aspecto concreto: catástrofes y evacuaciones de núcleos de población. Se ha visto que, si bien existen muchos modelos y software para analizar cómo se pueden evacuar grandes grupos de personas, normalmente estos modelos se utilizan en infraestructuras concretas. Por ejemplo, en estaciones de tren para modelizar cómo evacua la gente en caso de incendio, o en estadios de fútbol para ver si habrá problemas de capacidad que puedan suponer riesgo para las personas, como avalanchas humanas.

Sin embargo, hasta ahora, estos modelos no se habían aplicado a áreas urbanas en su conjunto, debido, entre otras cosas, a la dificultad que entraña diseñar estos escenarios, modelizar estos comportamientos, y recoger los datos necesarios para alimentar los modelos. Por lo tanto, esta tesis ha querido arrojar un poco de luz sobre este tema y presenta una metodología nueva que sirve para modelizar escenarios de evacuación a gran escala mediante el uso de herramientas de microsimulación y submodelos interconectados. Esto permite representar el proceso de evacuación de un área poblada utilizando toda la potencia de estas herramientas de simulación, pero de forma simplificada mediante la conexión de diferentes submodelos. La metodología propuesta se puede aplicar a escenarios a gran escala (aldeas, barrios, pueblos, ciudades) y los resultados se pueden utilizar para resaltar posibles aspectos

problemáticos o deficiencias en los núcleos urbanos que deberían subsanarse para garantizar la seguridad de los residentes en caso de evacuación. En esta investigación, la metodología de simulación basada en agentes se ha aplicado a un caso práctico en la ciudad de Sangüesa (Navarra, España), donde se ha modelizado la evacuación de los residentes como consecuencia de una rotura en la presa de Yesa. Los resultados muestran que, en caso de rotura, y en el mejor de los escenarios (la gente sabe cómo evacuar) sólo el 69% de la población podría evacuar a tiempo. Estos resultados son de gran utilidad para organismos públicos, de forma que puedan mejorar los planes de actuación y realizar las acciones necesarias para minimizar el riesgo.

Pero, además, en una smart city, este modelo de evacuación podría estar alimentado por datos en tiempo real: flujos de persona, ocupación de edificios, lluvia, niveles del agua en ríos o mares, probabilidad de terremotos, tráfico, etc. De esta forma, en cualquier momento, se podrían hacer simulaciones para entender cómo de preparada está la ciudad ante una eventual evacuación. Con esto, se podría saber, por ejemplo, cuáles son las áreas más vulnerables que sufrirían mayor daño de forma que se puedan preparar los servicios de emergencia si fuese necesario, y planificar los procesos de evacuación con antelación de forma que se salvaran miles de vidas. Porque una ciudad inteligente sólo lo será cuando sea también resiliente.

En resumen, esta tesis ha investigado sobre dos áreas importantes para nuestra sociedad como lo son la logística urbana y la resiliencia urbana, pero que, hasta ahora, no han sido muy estudiadas desde el punto de vista de las smart cities. En esta tesis se ha hecho un análisis de la situación actual en cada uno de estos campos, comprendiendo cuáles son las actuales limitaciones, y se han presentado nuevas herramientas de modelado que pueden usarse hoy para construir las ciudades inteligentes del mañana.

4.5 Future lines of research

A number of research lines remains open after the conclusion of this research.

- a) Regarding urban logistics and the VRP, it could be possible to adapt the methodology used in this thesis (heuristics) together with micro- or macro-traffic simulation software in which different variables such as distance, time, pollution, or noise can be analysed together (simheuristics). Also, these software can also have connection to real-time data.
- b) The model created for the VRP (article in progress shown in Appendix 5.2) could become a small software to be used by city councils and/or public organisms to drive transport and urban policies with respect to urban logistics, because usually transport modelling software does not consider freight (at least not with the level of detail given by a VRP).
- c) The model of the Old Town of Pamplona could be improved by adding real-time data from number plate recognition cameras which could give real-time insights about routes taken by vehicles, speeds, and route time amongst others. This could be used for the calibration of the base scenario.
- d) The survey implemented in Pamplona regarding urban logistics could be replicated in other cities in order to compare social perceptions towards, for example, cyclelogistics or electric vehicles. These data could be powerful for public authorities when driving new policies.

- e) Regarding urban resilience, the evacuation model for Sangüesa is not validated because, as commented in the article, it is not possible (it would require a flooding event). Therefore, the city council of Sangüesa could organize drills to prepare the population, and these drills would be used to validate the model and get better insights for a better calibration process.
- f) The evacuation model for Sangüesa could be connected to other models and tools including a landslide model of the dam and a flooding model of the river. All the existing sensors in the dam could estimate the probability of the dam collapse and the existing level of water, and the sensors in the river could feed the evacuation model to know for example the areas of the city that would be affected.
- g) In addition, the evacuation model for Sangüesa could be fed by real-time data using on-street sensors to know where the population is or the occupancy levels in different parts of the city so that the authorities could know at any time how people would evacuate during an evacuation scenario. This would be a crucial support for emergency services, for example to know which roads to close, which areas will be the most affected, or where to send resources (ambulances, police, etc.)

4.6 Contributions

The research undertaken in this thesis has helped the research community to broaden the knowledge with respect to urban logistics and urban resilience. However, it is important to note the relevance this thesis has for the society as can be seen through the following contributions.

With respect to urban logistics

- The research undertaken in the Old Town of Pamplona was presented in 2017 to the councillor responsible for Mobility, and several meetings were held to advise on how these models could be applied to improve freight distribution in the city of Pamplona. Unfortunately, due to a change in government, the priorities of the city council changed, and it was not possible to continue with the model application in real life.
- Nevertheless, the models created through this thesis can be useful for the city council of Pamplona (and other city councils or public authorities), as well as for last mile operators to guide business decisions and future transport and urban policies.

With respect to resilience and evacuation planning

- The city council of Sangüesa, after having access to the results of the evacuation model, commissioned this author the preparation of a document called “*Hoja de Ruta hacia el Plan de Evacuación de Sangüesa / Zangoza (PES)*”. The objective of this document was to set the necessary steps to prepare an evacuation plan for the city of Sangüesa. The document was sent to the city council and to the Government of Navarra in October 2017.
- On June 2018 the City Council of Sangüesa, as recommended by the document created by the author, created the working group on the evacuation plan in order to start working on the evacuation plan.

- The Ley Foral 20/2018, of December 24, on the General Budgets of Navarra for the year 2019, includes the item 050007 02500 4609 134103 which is called “Agreement with the City Council of Sangüesa / Zangoza for the financing of the Evacuation Plan” which was endowed with 145,000 euros (Figure 16).

Source:

https://gobiernoabierto.navarra.es/sites/default/files/03-anexo_gastos.presupuestos_2019.pdf

<http://www.navarra.es/NR/rdonlyres/3FE24EB9-8CE3-4BE3-9C4A-5EE05B896AE7/442583/5Partidas1.pdf>

- With this budget, the City Council of Sangüesa commissioned a project to understand where the alarms should be placed. During 2020, the city council will commission the project to install the alarms in the urban area.

Gobierno de Navarra y Ayuntamiento de Sangüesa firman un Protocolo General de Actuación sobre evacuaciones ante el riesgo de inundaciones
viernes, 16 de noviembre de 2018

Concreta las actuaciones necesarias para evacuar a la población, en particular a la que permanece en edificios vulnerables como centros educativos o residencias de ancianos

La consejera de Presidencia, Función Pública, Interior y Justicia del Gobierno de Navarra, María José Beaumont, y el alcalde de Sangüesa / Zangoza, Ángel Navallas, han suscrito este viernes un protocolo general de actuación para coordinar, desde el punto de vista técnico, las actuaciones necesarias que permitan, en caso de inundaciones, la evacuación de la población en general y, en particular, de aquella que permanece en edificios vulnerables, como es el caso de centros educativos o residencias de ancianos.



Figure 16. Official communication announcing the agreement between the Government of Navarra and the City Council of Sangüesa.

(Source: https://www.navarra.es/home_es/Actualidad/Sala+de+prensa/Noticias/2018/11/16/Protocolo+inundaciones.htm)

PART V. APPENDICES

5.1 Articles selected, quartiles, and impact factors.

Here the articles selected for this thesis, including quartile and impact factor, are presented. When the PhD student was first author, he coordinated the research, developed the methodology, led the data collection and analyses, wrote the paper, and managed the submission and presentations in international conferences and seminars. In the one where he was second author (Article 4), he developed part of the methodology.

JCR, as first author:

Article 2: Alvarez P., Lerga I., Serrano A., Faulin J. (2018) The impact of traffic congestion when optimising delivery routes in real time. A case study in Spain. In: International Journal of Logistics Research and Applications, 21:5, 529-541. <https://doi.org/10.1080/13675567.2018.1457634>
Impact Factor (2019): 2.152 (Q3); Impact Factor (2018): 2.828 (Q2)

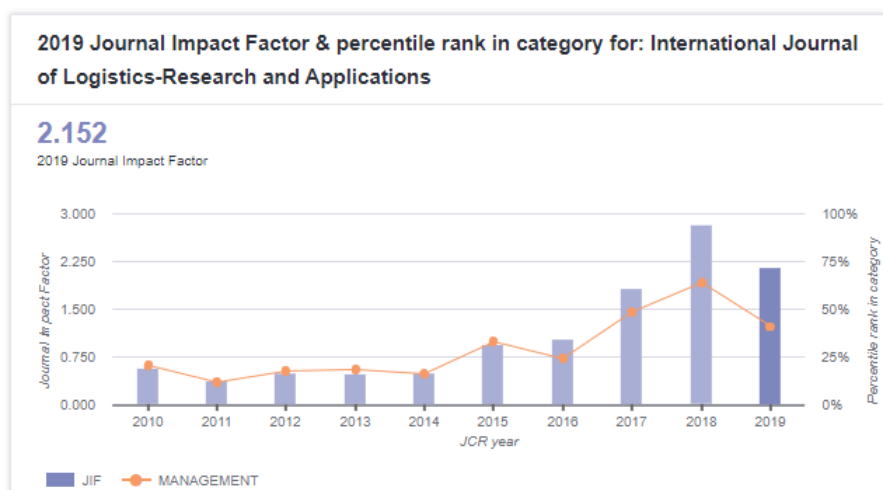


Figure 17. Impact Factor for International Journal of Logistics - Research and Applications (Clarivate Analytics)

Article 6: Alvarez P., Alonso V. Using microsimulation software to model large-scale evacuation scenarios. The case of Sangüesa and the Yesa dam collapse. In: Safety Science, 106, 10-27. <https://doi.org/10.1016/j.ssci.2018.02.021>.
Impact Factor (2019): 4.105 (Q1)

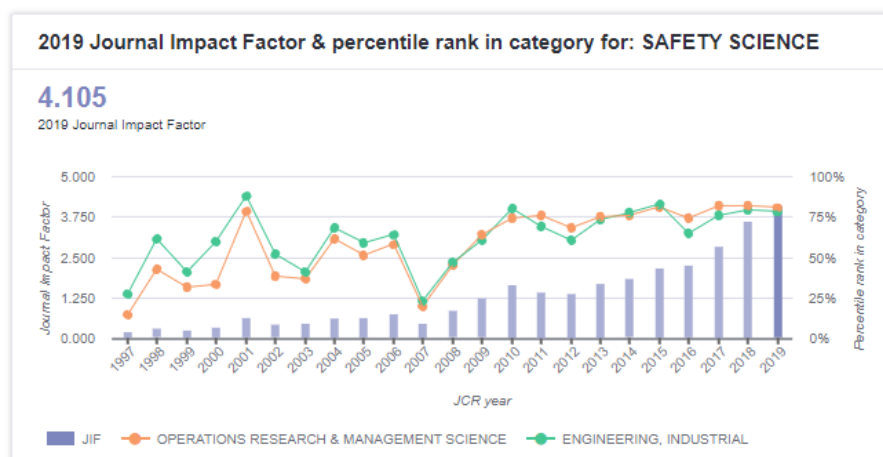


Figure 18. Impact Factor for Safety Science (Clarivate Analytics)

Non-JCR, as first author:

Article 1: Alvarez P., Lerga I., Serrano A., Faulin J. (2017) Considering Congestion Costs and Driver Behaviour into Route Optimisation Algorithms in Smart Cities. In: Alba E., Chicano F., Luque G. (eds) Smart Cities. Smart-CT 2017. Lecture Notes in Computer Science, vol 10268. Springer, Cham. https://doi.org/10.1007/978-3-319-59513-9_5. SJR (2019): 0.417



Figure 19. Scimago statistics for Lecture Notes in Computer Science (Scimago)

Article 3: Alvarez P., Serrano A., Faulin J., Juan A. (2018) Using modelling techniques to analyse urban freight distribution. A case study in Pamplona. In: Transportation Research Procedia, 33, 67-74. <https://doi.org/10.1016/j.trpro.2018.10.077>. SJR (2019): 0.476

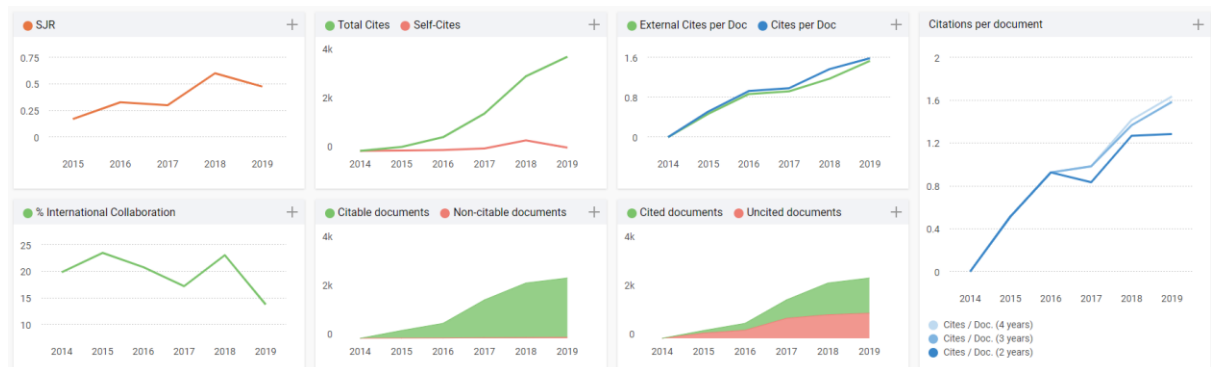


Figure 20. Scimago statistics for Transportation Research Procedia (Scimago)

As second author. The author of this thesis developed part of the methodology.

Article 4: Serrano A., Alvarez, P., Lerga, I., Reye, L., and Faulin, J. (2017). Pricing and Internalizing Noise Externalities in Road Freight Transportation. In: Transportation Research Procedia, 27: 325-332. <https://doi.org/10.1016/j.trpro.2017.12.059>. SJR (2019): 0.476

Sent for publication as first author:

Article 5: Alvarez P., Serrano A., Faulin J. Is time more important than distance to optimize freight delivery routes? An approach using the value of time. Submitted to *Transportmetrica B: Transport Dynamics*. Impact Factor (2019): 2.214 (Q3)

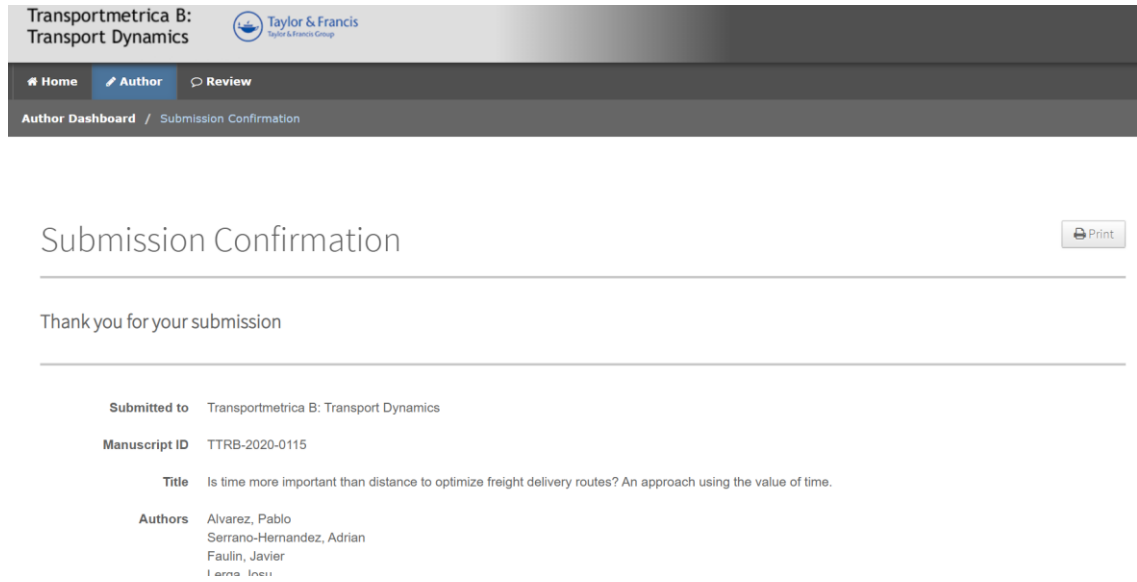


Figure 21. Submission to “*Transportmetrica B: Transport Dynamics*”

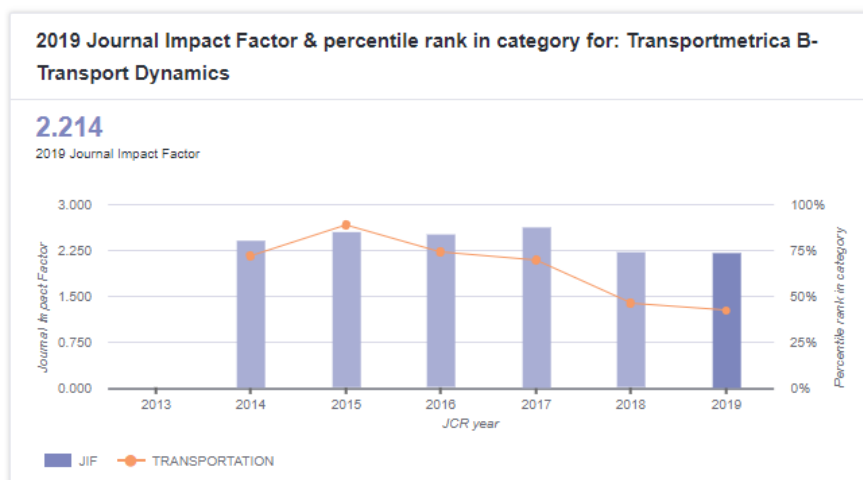


Figure 22. Impact Factor for *Transportmetrica B: Transport Dynamics* (Clarivate Analytics)

Work in progress / under review, as first author (see 5.2)

Article 7: Alvarez P., Serrano A., Faulin J., Lerga I. Modelling and simulation of last mile deliveries using the VRP in urban areas. Paper in progress. See section 5.2.

5.2 Article 7, in progress: Alvarez, P., Serrano-Hernandez, A., Faulin, J., Lerga, I. Modelling and simulation of last mile deliveries using the VRP in urban areas.

Note: this article is still work in progress.

INTRODUCTION

By 2050, almost 70% of the world's population is predicted to live in cities that are smart (United Nations, 2015), putting increased strain on urban infrastructure and transport systems. This population growth is leading to an exponential increase in the level of congestion within our metropolis (JRC, 2012), which is producing, on the one hand, several negative externalities within our transport systems such as pollution, noise or accidents. On the other hand, the increased travel times caused by congestion creates transport inefficiencies that also affect urban logistic activities, which are a key sector for worldwide economics (European Commission, 2016). Considering that we live in the one-click era, where online shopping and on-demand deliveries are changing the way we understand logistics activities within urban areas, it is easy to understand that the way we deliver goods within our urban areas must change too.

With the growth of e-commerce, the planning process of last mile deliveries is getting more complex. Nowadays, it is not always feasible to plan routes days in advance as the product demand, the driver availability, or the mode of transport (van, truck, tricycle...) is not always known. Urban conditions are also dynamic, and accidents, road closures, weather, and traffic congestion affect how routes are optimized. In general, companies plan delivery routes according to their experience, or following traditional approaches in which a distance-based cost function is minimized. However, considering traffic congestion and dynamic conditions of the urban network is important to better optimize delivery routes and get cost savings in a market that is fiercer every day. Although big logistics companies can build their own tools or buy software that allow them to optimize routes, small companies cannot always afford it, which leads to higher-than-optimal vehicle-kilometers due to their inefficient route planning (Jiang & Mahmassani, 2014).

In parallel, sustainable urban mobility plans are defending the shift from the internal combustion engines vehicles to electric ones, although the massive use of these electric vehicles will not solve other problems that urban logistics is facing in our current cities: traffic congestion, accidents, limited access to our city centres and lack parking spaces (Boussier, Cucu, Ion, & Breuil, 2011). Therefore, public authorities are also trying to enhance the liveability of our city centres by limiting the access to motor vehicles, which adds a higher level of complexity to a scenario where cyclelogistics seems a potential solution for last mile deliveries. However, logistics activities are often forgotten in many urban and mobility plans (Hall & Hesse, 2013) (Dablanc, 2009). There exist modelling and simulation tools that help transport planners, for example, to understand how to better design public transport networks or how to reduce traffic congestion in some roads. Nevertheless, the modelling tools focusing on freight transportation are very scarce, and usually these do not have the required level of granularity (microscopic level) to assess how specific transport or urban policies will affect last mile distribution, especially nowadays considering, as mentioned before, the dynamism of the urban networks where everything is in constant change.

Therefore, this paper shows a new approach in which the vehicle routing problem is intertwined with modelling and simulation techniques in order to analyse different urban scenarios. Through this methodology, an urban area can be modelled with nodes and links that have different real-time attributes (distance, travel time, congestion, CO₂ emissions), and last mile delivery operations can be simulated

through an ad-hoc tool. The methodology presented in this paper will provide a new tool that can be used by different stakeholders; by logistics companies to optimize delivery routes in real time considering existing conditions in the network, and also by transport planners and policy makers to understand how transport and urban policies (pedestrianization, traffic bans, incentives for cyclelogistics, etc.) will affect freight distribution in our city centres. This approach is flexible and adaptive (for different use cases in different cities), scalable (improved and more complex algorithms can be installed), and ready to be used in the smart city context, where sensors can provide real-time information to feed the models.

MODEL DEFINITION

In order to simulate a logistics urban network with real-time information and where several scenarios can be run, the model developed in this paper consists of four main modules.

- 1) The first module is the instance generator, which has been programmed in Visual Basic. Through the instance generator different simulation runs can be performed in two different modes: a random mode in which the variables (depot location, number of customers, customer location, demand, vehicle capacity....) are randomly generated, or a fixed mode in which the variables are predefined (for example to define a real situation) and in every simulation run the only variables slightly changing are the transit times (congestion) and service/stop times to consider stochasticity effects. With the instance generator it is also possible to select the scenario / network to run, the type of inputs used (real-time data or fixed data), the time of the day, the vehicle used, and the type of cost function to minimize (distance, time, gradient, CO2...). Furthermore, it is also possible to applied calibration factors (see section *Model calibration*).
- 2) The second module is the network model, which is set in QGIS. Here, the topology of the network is defined using links and nodes. This network model is not only used for visualization purposes, but the table from QGIS contains all the information (attributes) for each link of the network which is needed to run the model (distances, travel times, gradient, etc.).
- 3) The third module, built in JAVA, takes the real-time information data for each link of the network model using the Google Maps API. It would be possible to adapt this module to get the data from other sources (for example public data from the city council). Also, if the model is being run with fixed inputs instead of real-time data, for example, for a specific what-if scenario, this module does not run.
- 4) The fourth and final module, also built in JAVA, integrates the previous modules, generating the defined instances and running the VPR algorithms in the selected networks that have been updated with the real-time (or fixed) attributes. Although it is possible to install different algorithms depending on the complexity required, in this model, the Dijkstra, Clarke and Wright, and Tabu search algorithms are used. First, the origin-destination (OD) matrix (with travel times) is generated and used by the Dijkstra's algorithm to obtain the costs between the depot and all the customers. Then, the Clarke and Wright's Savings algorithm (CWS) is implemented in order to obtain the best preliminary solution. This solution is the initial solution for the Tabu Search algorithm, which is run to improve the preliminary solution. This metaheuristic guides the local search heuristic algorithm to explore the space of solutions beyond local optima.

Figure 1 shows the model with its different modules.

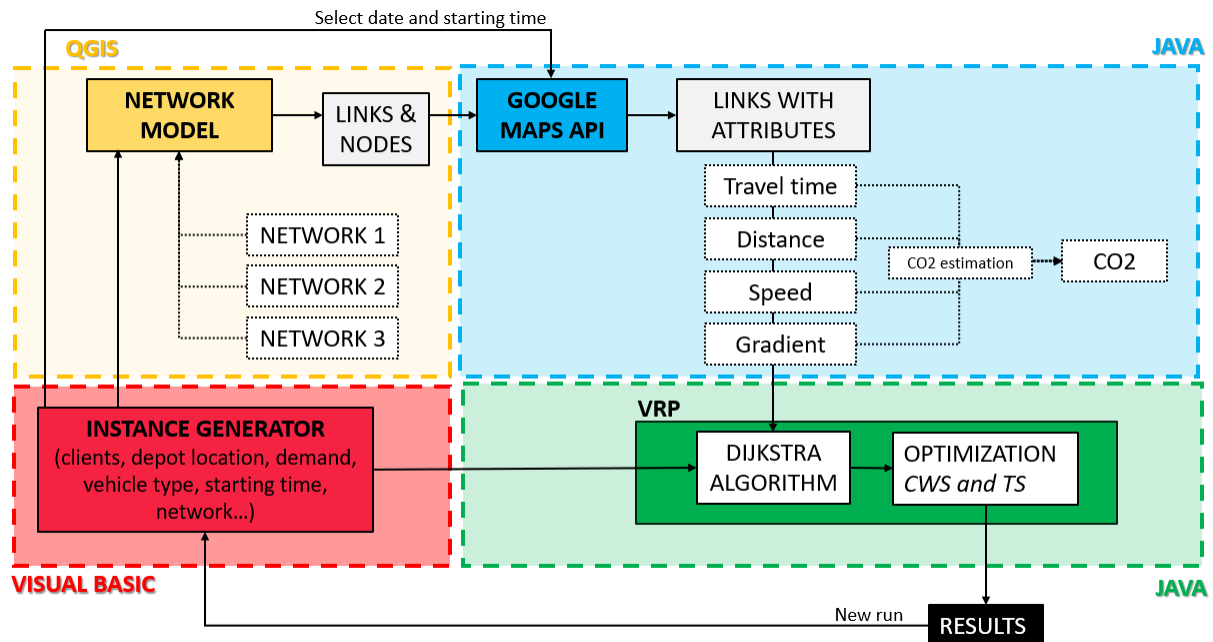


FIGURE 1 Diagram showing the developed model

DATA COLLECTION

Some of the inputs are needed to run the model as they are the attributes of each link of the model network (key inputs). However, other inputs are used for calibration and validation purposes and they do not directly feed the model (auxiliary inputs).

The below list presents all the key inputs needed to run the model, although depending on the simulations to be performed, some of them may not be necessary.

- **Distance** between two nodes. In this paper, it comes from Google data through the Google Maps API, although other sources could be used.
- **Travel time** for each link, also obtained from Google. This input can be download in real-time, or from past or future scenarios depending on the scenario that is being analyzed. The difference between the travel time in free-flow conditions (for example at 2AM) and the specific time corresponds to the traffic congestion at that time. Other sources of information such as street sensors or other tools could be used.
- **Speed** in each link derived from the travel time and distance, although it could be also obtained from street sensors.
- **Gradient**, also obtained from Google.
- **CO₂ emissions** can be estimated also for each link using speed, distance, and gradient, although there are other methods that are more sophisticated, for example considering also the load of the vehicle in each link.

In this paper, the above inputs are obtained automatically every time the model runs, and they also depend on the type of vehicle that is being modelled (truck, van, or tricycle).

As for the auxiliary inputs used for calibration and validation purposes, we have:

- **Speed** measurements of trucks and vans performed in different parts of the network. For this research, speed was recorded in 4 different zones with a total of 15 different and representative links of the network.
- **Traffic counts** to know 1) the number of delivery vehicles per day entering and leaving the delivery area (in this case, Old Town of Pamplona), and 2) how much time they drive within the delivery area. For this purpose, surveyors were placed in all the entrances and exits of the delivery areas, and the number of vehicles passing was recorded together with the time, the type of vehicle and the first four characters of the number plate. Figure 2 shows the template used by each surveyor.
- **Route tracking.** 10 different trucks and vans were followed to track their route, measuring service time (the time taken to deliver the parcel once the vehicle has arrived to the destination), total travel time, and number of stops per route.

To run the simulations, the demand was randomly generated ($U[0,1]$), and the capacity of each vehicle was set to 50 units. This could be manually set according to reality.

OBSERVADOR: PABLO		HORA INICIO 8:00		OBSERVACIONES: Nublado, sin lluvia, 4°C											
LUGAR: CALLE NUEVA		HORA FIN 11:00													
HORA	ENTRADA / SALIDA	VEHÍCULO	VEHÍCULO DE REPARTO										MATRÍCULA	EMPRESA	
			Coche reparto	Furgoneta	CAMIÓN				CICLOLOGÍSTICA			Otro			
					2-rígido	3-rígido	3-articulado	Otro	Bicicleta	Cargo-bike	Triciclo				
8:07	ENTRADA	Camión			X									7HDL	DONUTS
8:11	ENTRADA	Camión			X									1FZW	TABERNA
8:11	ENTRADA	Furgoneta		X										0JWR	AYTO
8:11	ENTRADA	Camión			X									5KCN	COCACOLA
8:11	ENTRADA	Camión			X									4DCC	COVIRAN
8:17	ENTRADA	Camión			X									0JWR	AYTO
8:17	ENTRADA	Furgoneta		X										3DBM	IZURA
8:29	ENTRADA	Furgoneta		X										1JWR	AYTO
8:46	ENTRADA	Furgoneta		X										1CCR	AYTO
8:48	ENTRADA	Furgoneta		X										4FVJ	AYTO
8:49	ENTRADA	Furgoneta		X										4FWD	MRW
8:52	ENTRADA	Furgoneta		X										6CCK	SALTOKI
8:54	ENTRADA	Furgoneta		X										4FWD	MRW
8:57	ENTRADA	Furgoneta		X										3DTT	AYTO
9:00	ENTRADA	Furgoneta		X										7CMJ	ARRASATE
9:27	ENTRADA	Furgoneta		X										6HCJ	AYTO
9:39	ENTRADA	Furgoneta		X										6CMT	ALTUNA

FIGURE 2 Template designed to count delivery vehicles.

NETWORK DESIGN

In this paper, the model has been applied to the Old Town of Pamplona (Navarra, Spain). The reason to model this area of Pamplona is its saturated zone of shops and bars, with about 1,500 in 1.4 km² (ANET, 2015). Furthermore, the city council has been investigating the pedestrianization of some streets and studying how to change the way freight is distributed, therefore this model could be also useful for policy makers.

The network has been delimited knowing where most of the last mile activities occur (ANET, 2015). The software QGIS has been used to model the network (see Figure 3). The network is composed of 140 nodes and 390 links which give enough granularity for the purpose of the model. For every pair of nodes A and B there are two links A→B and B→A to consider bi-directional traffic. Each link has a table of attributes associated to it such as distance, travel time (depending on the hour of the day and

- **Travel times.** To calibrate travel times, speed measurements have been used. Speeds derived from the inputs from Google (distance and time for each link) have been compared with the speeds recorded in four different zones of the Old Town, in a total of 15 links with a total of 75 records (5 records per link). In this specific case, we could see how the speed given by Google was slower than the one observed, therefore calibration factors were applied to the travel times of vans and trucks derived from Google, depending on the zone. This calibration exercise could have been done using data from induction loops or other sensors installed by the city council, but we did not have access to those.

	Speed (Km/h)	Data from Google	Observed data	Calibration factor
Zone 1	average	11,0	16,1	1,5
	SD	2,5	2,7	
Zone 2	average	11,0	15,9	1,4
	SD	3,8	2,3	
Zone 3	average	11,4	13,6	1,2
	SD	3,8	2,2	
Zone 4	average	11,9	16,7	1,4
	SD	3,7	3,3	

Table 1 Speed and travel time calibration

- **Clients visited per route.** Although the number of clients visited per route can be randomly generated through the instance generator, it is needed to know the average number of clients served in a route. Several real delivery routes were tracked and recorded using bicycles to follow vans and trucks and having interviews with delivery companies to gather information on the type of routes they do. After this, we estimated that the average number of clients per route is between 4 and 12, so we applied this constraint in our model. The instance generator also allows to input a specific set of customers. This is useful in real cases need to be analyzed.
- **Service time.** The service time is defined in this paper as the difference between the time when the vehicle has arrived to a client, and the time when the vehicle leaves to the next client. It is the time needed to deliver the parcel once the carrier is with the client. Through a route tracking exercise, we saw that the service time in the Old Town of Pamplona is, on average, 6.6 minutes with a standard deviation (SD) of 5.35 minutes. The goodness of fit analyses performed with MiniTab showed that the service time follows a lognormal distribution with $\mu=1.6185$ and $\sigma=0.79452$. This distribution (truncated) was inserted in the instance generator module, so this time has been added every time a client was visited.
- **CO₂ emissions.** In this model, a simplified estimation for the CO₂ emitted has been used, although other formulas could be applied if the level of detail requires it. In this paper, the CO₂ g/Km emitted by diesel trucks (rigid, <7.5tn) in urban areas is 369.25, and for diesel vans it is 287,14 g/Km (Oficina Catalana del Cambio Climático, 2011). This is in line with the data used by other researchers (Figliozzi, 2011).
- **Total route time.** The total times of the simulated routes have been validated with real route times obtained from the traffic counts performed. Our records show that average time per route in the Old Town of Pamplona is 37.9 min which is in line with the results obtained.

SCENARIOS

To test this model, the following scenarios have been designed:

- **Scenario 1.** Vans and trucks vs. tricycles. In this scenario, we compare urban deliveries using vans (subscenario 1A), and using tricycles (1B). Motor vehicles have traffic restrictions in some streets of the Old Town of Pamplona, and in all of them they can only travel in one direction. On the other hand, tricycles or bicycles can use all the streets in all directions, therefore the goal is to see if time reduction is relevant if cyclelogistics is used, and how much CO₂ could be saved.
- **Scenario 2.** Traffic bans (pedestrianization) in some streets. Here, we compare the current scenario (2A), with a what-if scenario (2B) in which some streets are closed to traffic due to the pedestrianization of some streets of the Old Town. The goal is to understand how this urban policy would impact freight distribution.
- **Scenario 3.** Depot location. We simulate two different scenarios in which the depot (urban microconsolidation platform) is located in a different place (3A and 3B). These depots location have been selected in this scenario as they are considered feasible options because i) they are close to the main dense activity area, ii) they have connectivity with the rest of the network, iii) there are parking infrastructures already in those locations that could be used for this purpose. In all the scenarios (except 3B) the depot used to run the simulations has been A.

Figure 4 below shows the different variations of the network in the different subscenarios.

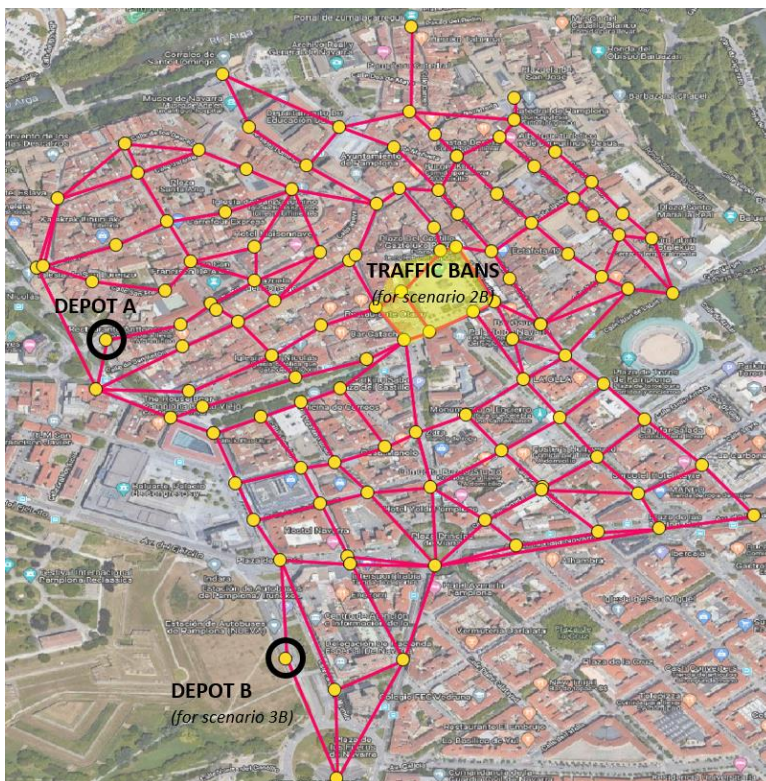


FIGURE 4 Network in the Old Town of Pamplona with the different subscenarios.

Due to the versatility of the model, it is possible to model more scenarios, for example using CO₂ as an objective function instead of time, using gradient (useful for cyclelogistics in places where gradient is a constraint) or adding new attributes to the links such as “population”, or “pedestrian density” so that we optimize routes considering how neighbours and pedestrians are affected. This flexibility can be

of great help to both logistics companies and policy makers to plan business strategies and to guide urban and transport plans.

SIMULATION AND RESULTS

For each subscenario, the program simulates and runs 10 different random routes with 4 to 12 clients each. Each route was run 5 times to consider stochasticity effects (changes in service time, demands, etc.). Therefore, in total, each subscenario has been run a total of 50 times. Thus, Table 2 shows the average results for each scenario.

	Avg time per route (min)	Avg CO₂ emitted per route (Kg)
Scenario 1A - vans	37.5	1.91
Scenario 1B - cyclelogistics	22.1	0.00
Scenario 2A - current network	36.4	1.74
Scenario 2B - some streets closed to traffic	39.2	1.93
Scenario 3A - Depot in zone A	35.3	1.65
Scenario 3B - Depot in zone B	40.3	2.04

Table 2 Simulation results

As it can be observed for Scenario 1, if tricycles were used instead of vans, the average time per route would decrease by 41% (from 37.5min to 22.1min). This is in line with other studies, for example a simulation of DHL deliveries in Berlin that showed that using bikes instead of trucks could lead to a reduction in operating time of 58% (Zhang et al., 2018), or another study in Grenoble that showed that mileage can be reduced by 55% if cyclelogistics is implemented (Hoffman et al., 2017). Considering that the avg CO₂ emitted per route in Kg in all the scenarios where vans are used is around 1.9Kg, and that our records show that there were around 694 vans entering each day in the city center, the CO₂ emitted by delivery routes in the Old Part of Pamplona is around 1.3 tons per day, or 483 tons per year. Although it is true that it is not possible to implement cyclelogistics in all the delivery routes (for example to deliver barrels, or very heavy materials, or refrigerated food), some studies show that bikes and tricycles could replace vans and trucks in up to 30% of the routes (Cairns and Sloman, 2019), therefore the potential to reduce emissions in the Old Town of Pamplona supporting cyclelogistics activities is huge.

As for Scenario 2, we see that if some streets are pedestrianized, the time needed per route would increase by 8% and, as the distance travelled also increases, the CO₂ emissions would be 11% higher. This shows that this model could be useful for public authorities, as sometimes some measures are taken without considering how they impact other sectors. For example, the pedestrianization of some streets could reduce traffic congestion, but in parallel this measure is pushing delivery companies to perform longer routes which, at the end, also increases emissions.

Regarding Scenario 3, we see that the location of the depot (urban consolidation center) is important as it directly affects distance travelled, time consumed, and emissions. Locating the depot in area B would increase travel time by 15%, and emissions by around 20%.

DISCUSSION AND CONCLUSION

This paper shows how some heuristics algorithms can be intertwined with transport modelling and simulation techniques to create models that are not only useful for logistics companies, but also for public organisms to drive urban policies (Javier et al., 2019). This methodology composed of four different modules gives enough flexibility to simulate different scenarios under different variables, using real-time data taken from Google, or from other sources if necessary. It is also possible to simulate scenarios with random attributes (demands, clients, capacity, vehicles...) for example to be used in what-if scenarios, or with real ones in case a specific known scenario needs to be analyzed. Although we have applied it to the Old Town of Pamplona, the network can be built to represent different areas, and the model can be also calibrated and validated using secondary sources of data, which is critical if the tool is intended to be used to drive business or political decisions.

In this specific use case of the Old Town of Pamplona, we have shown that bikes and tricycles could be more efficient than vans in this part of the city where distances are shorter and where the existing traffic bans in some streets affect deliveries with motorized means. Using bikes and tricycles in comparison to vans or trucks will not only reduce travel time, but will also have a positive impact on emissions. Of course, tricycles are feasible if they are part of a network departing from an urban consolidation center. Therefore, this model has also analyzed how the location of this hub impacts urban logistics activities. Finally, we have demonstrated that this model can be used to drive urban and transport policies. In this case, we have modelled a scenario in which some streets are pedestrianized to understand the impact for delivery companies.

Our cities are currently experience higher levels of traffic congestion, and public authorities are pushing to penalize motorized vehicles in city centres, for example through cordon charging schemes, by pedestrianizing some streets, by setting traffic bans in some streets, or by supporting green modes of transport like electric vehicles or bikes. In parallel, e-commerce is growing fast, especially after the Covid-19 crisis, which is increasing the need to access our city centers to deliver parcels. However, as seen in the introduction, logistics activities are often forgot in urban plans and transport policies, even when it is known that almost 15% of the traffic of a city is caused by logistics activities (Cairns and Sloman, 2019). Therefore, this paper presents a tool that could be useful to improve how logistics activities are planned in urban areas.

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