A PATH SELECTION ALGORITHM THAT INCORPORATES CONFLICTING CITY LOGISTICS STAKEHOLDERS' OBJECTIVES

Master's Thesis

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Abstract

This research created an algorithm to provide city logistics stakeholders with insights into the possibilities of reducing the negative impact of city logistics. Many large trucks and home delivery vans drive through cities while passing vulnerable objects and thereby negatively influencing the liveability of cities. Both stakeholder groups acknowledge the importance of mitigating these negative externalities of city logistics. However, public stakeholders want to maximize liveability while private stakeholders want to enter and leave the city as fast as possible. To incorporate these conflicting stakeholders' objectives, a multi-criteria optimal path algorithm has been designed. Stakeholders should assign weights to the different criteria, which results in the optimal path between an origin and destination. The algorithm is also capable of handling constraints on travel time. The algorithm was applied to a case study where the public and private stakeholders were represented by the municipality of Tilburg and an anonymous Dutch retailer, respectively. Routing data of the Dutch retailer in Tilburg was used to apply the algorithm. This showed that multiple conflicting stakeholders' objectives could be incorporated into a routing solution that generates the optimal path between an origin and a destination. A small detour compared to the fastest path already results in higher liveability. The stakeholders should decide the specifics of the algorithm in a public-private partnership or covenant such that all city logistics stakeholders' objectives are incorporated.

Keywords:
Multi-criteria, city logistics, liveability, path

Executive Summary

City logistics are essential to satisfy the consumer needs of the people living inside cities. However, the number of urban freight movements is increasing which leads to an increase in negative externalities such as congestion, air pollution, and noise pollution (Gevaers, Van de Voorde, Vanelslander et al., 2009; Bozzo, Conca & Marangon, 2014; Demir, Huang, Scholts & Van Woensel, 2015). These negative externalities harm the liveability of cities. Liveability is defined as the degree to which a city is suitable and attractive for living. A liveable city supports quality of life, safety, accessibility, and environmental sustainability (Tennakoon & Kulatunga, 2019). To mitigate the negative effects, stakeholders have to be engaged in implementing a solution (Viu-Roig & Alvarez-Palau, 2020). However, the conflicting stakeholders' objectives make it difficult to find a solution in which all objectives are considered. This research was executed to provide city logistics stakeholders with insights into the possibilities of reducing the negative impact of city logistics. For this purpose, the following main research question was formulated:

Which solution minimizes the negative impact of city logistics on the liveability of a city while satisfying private stakeholders' preferences?

Many solutions have already been treated in literature such as electrification, infrastructure management, and urban consolidation centres or rules such as restrictions on time access, noise, and vehicle weight (Holguín-Veras, Leal, Sánchez-Diaz, Browne & Wojtowicz, 2020). These city logistics initiatives were primarily used as alternatives which were evaluated within a multi-criteria decision analysis. These alternatives were evaluated according to economic, environmental, and social criteria. Another solution direction is applying multi-criteria analysis to vehicle routing. Methods that have been applied before are the weighted sum method and Pareto-optimal frontiers.

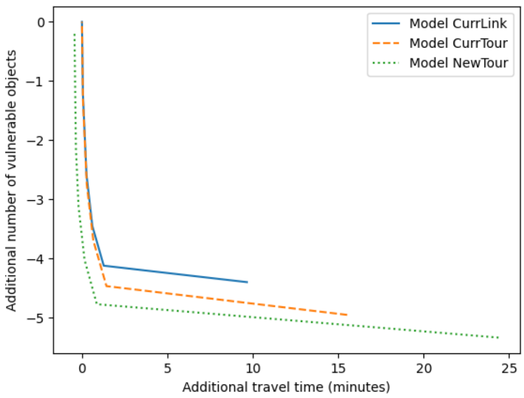
A descriptive analysis of a case study was performed to evaluate the current situation with regard to the impact of city logistics. The case study included the municipality of Tilburg as the public stakeholder and a Dutch retailer as the private stakeholder. The name of this retailer is concealed because of confidentiality. Routing data from this retailer has been used to execute the analysis. The analysis confirmed that different stakeholders have conflicting interests. Public stakeholders want to increase the liveability of a city while private stakeholders want to enter and leave the city as fast as possible. The analysis also showed that many large trucks and delivery vans visit the city multiple times a day. In addition to the aforementioned negative externalities, it was shown that during their visits vulnerable objects are passed which should actually be avoided. However, the stakeholders are currently unable to implement a structured solution for this.

Electrification, infrastructure management, and urban consolidation centres were identified as viable solutions for the negative externalities to explore except that the implementation would not be possible in the short term. Moreover, restrictions were not suited for this research since these do not incorporate the different stakeholders' objectives. On the other hand, a routing solution is capable to incorporate conflicting stakeholders' objectives. More specifically, a routing solution was designed which creates the optimal path between an origin and a destination.

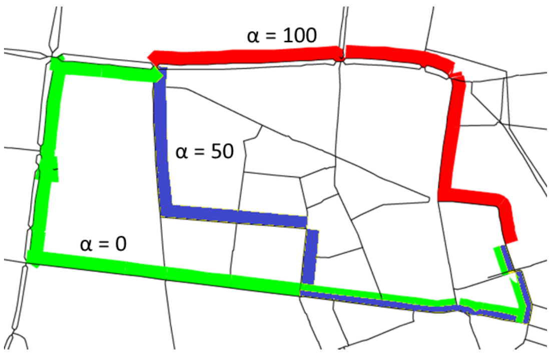
It was chosen to apply the weighted sum method which assigns weights to criteria because of its low computation time. Additionally, a maximum travel time feasibility test and Dijkstra's algorithm have been used. The former was essential for the evaluation of driving routes for supermarket replenishment and time window feasibility. The maximum travel time for the path from the highway to a supermarket can be defined by the stakeholders. The maximum travel time feasibility test was also used for the home delivery channel to ensure stop visitations within the time windows. Dijkstra's algorithm was used to obtain the optimal path for a given set of weights according to the logic of Hua and Abdullah (2018).

All these constructs have been combined into a multi-criteria optimal path algorithm. This algorithm has been used to create the three models CurrLink, CurrTour, and NewTour, which analyse current links, current tours, and new tours. These models were applied to the case study which was extended with the following criteria: travel time, travel distance, number of on-route vulnerable objects, and number of on-route residents. The former two were identified as most important by the private stakeholder. Moreover, travel time was an essential criterion for the algorithm to be able to incorporate travel time constraints. The latter two criteria were included based on available data and the lack of inclusion in the existing literature.

The models were applied to the case study through a trade-off analysis and bargaining power analysis. For this purpose, routing data from the Dutch retailer was used in combination with data from the traffic model of Tilburg. An example of a trade-off analysis is shown in the picture below. Considering only one stakeholder's objective by assigning full weight to one criterion would result in very disappointing values for the other criteria. For example, an extreme such as completely minimizing travel time resulted in low liveability whereas completely maximizing liveability resulted in very high travel times. The former is what is happening in the current situation. However, by slightly increasing the travel time, a big benefit was obtained in terms of liveability.



Only a small detour was necessary to make the city more liveable while still satisfying private stakeholders' preferences. An example is shown in the picture below. The alpha denotes the weight assigned to the travel time criterion. This means that the path with $\alpha = 100$, $\alpha = 50$, and $\alpha = 0$ regard the fastest path, the intermediate option, and the path that minimized the number of on-route vulnerable objects.



In addition to implementing a detour between an origin and destination, solutions for supermarket replenishment routes and home delivery have been tested. These solutions have been evaluated with the models that were constructed in this research. Public and private stakeholders can discuss which highway exit to take for each supermarket. However, this is highly influenced by the maximum allowed travel time from the highway to the supermarket. Therefore, this should be determined beforehand. For home delivery, time windows can be enlarged, two consecutive stops can be swapped, and a completely new visitation order could be established. Larger time windows and swapping did not result in big changes. A new visitation order resulted in large improvements compared to the current situation. This observation was obtained by executing the model NewTour. However, it should be noted that the evaluation of this solution neglected time windows, which should not be neglected in real-life.

In conclusion, creating detours by applying the multi-criteria optimal path algorithm is the solution that minimized the negative impact of city logistics on the liveability of a city while satisfying private stakeholders' preferences. Stakeholders should establish a public-private partnership or covenant in which the specifics and the application of the multi-criteria optimal path algorithm are discussed. The weights assigned to the criteria should be determined such that all stakeholders' objectives are considered. This will lead to a systematic approach to guide private stakeholders through the city without the imposition of rules. Additionally, the stakeholders should determine the maximum allowed travel time from the highway to each supermarket, which can be used as input for determining which highway exit to take.

This advice also holds for the case study of this research. The municipality of Tilburg and the Dutch retailer should establish a public-private partnership such as a covenant. The Dutch retailer can use the multi-criteria optimal path algorithm to construct the paths between stops. Both stakeholders should establish the weights that will be assigned to the criteria. Establishing the use of the algorithm in a covenant makes sure that the municipality of Tilburg does not impose additional rules. However, Tilburg should create an additional incentive for the Dutch retailer to use the algorithm. Tilburg could assist in financing electrification or could make an exception for the Dutch retailer when it comes to access and time restrictions.

Contents

List of Tables 6

List of Figures 7

List of Abbreviations 8

1 Introduction 9
1.1 Problem description . . . 9
1.2 Research questions . . . 9
1.3 Report structure . . . 10

2 Literature review 11
2.1 Multi-criteria analysis in city logistics . . . 11
2.2 Evaluating city logistics initiatives . . . 11
2.3 Vehicle routing . . . 13
2.4 Conclusion literature review . . . 14

3 Analysis 15
3.1 Case study description . . . 15
3.2 Route characteristics prioritization . . . 16
3.3 Data . . . 20
3.4 Current situation . . . 20
3.5 Conclusion analysis and diagnosis . . . 26

4 Conceptual design 28

5 Detailed design 31
5.1 Multi-criteria optimal path algorithm . . . 31
5.2 Model CurrLink . . . 33
5.3 Model CurrTour . . . 34
5.4 Model NewTour . . . 35

6 Case Study 36
6.1 Data . . . 36
6.2 Methods . . . 38
6.3 Results . . . 39
6.4 Discussion on results . . . 44

7 Conclusion 46
7.1 Future research . . . 47

References 48

Appendices 51

A Redundant analyses 51

B Data set preparation for analysis section 54

List of Tables

1 Criteria from literature review regarding city logistics initiatives evaluation 12
2 Criteria from literature review regarding vehicle routing 14
3 The average number of stops for the SC channel 22
4 The average number of stops for the HD channel 24
5 Number of vulnerable objects per priority level per supermarket in Tilburg 26
6 Illustration of the matrix modification procedure for model CurrTour 34
7 Final list of criteria for the multi-criteria optimal path algorithm 36
8 Numerical evaluation of the trade-off analysis regarding example trip 1 40
9 Numerical evaluation of the trade-off analysis regarding example trip 2 40
10 Travel times and distances per transport type for the SC channel 51
11 The average number of stops and stop times for the SC channel 52
12 Overview of data set references 54
13 Description of stop data sets for the SC and HD channels 54
14 Data subsets denotion 55
15 Data (sub)sets overview 56

List of Figures

1 Visualization of the scope of the data with regard to the supply chain of the Dutch retailer 15
2 Example home delivery route travelling through Tilburg 16
3 Entity-relationship diagram of the routing data of the Dutch retailer 20
4 Bar plots of the number of transports per weekday per transport type for the SC channel 23
5 Histograms of the arrival time of trucks per transport type for the SC channel 23
6 Visualizations of timing KPIs for the HD channel 24
7 Alternative driving route for supermarket 06 29
8 Visualization of models' scopes 30
9 Visualization of the multi-criteria optimal path algorithm 31
10 Maximum travel time feasibility test visualization 32
11 Visualization of model CurrLink: link analysis 33
12 Visualization of model CurrTour: tour analysis 34
13 Visualization of model NewTour: new tour generation 35
14 Entity-relationship diagram of the routing data and traffic model 37
15 Visualization of the geographical segmentation of Tilburg 37
16 Visualization of the trade-off analysis 40
17 Geographical visualization of possible routes for example origin-destination links 1 and 2 41
18 Bar plot for highway exit evaluation with a maximum travel time of 0 minutes 42
19 Bar plot for highway exit evaluation with a maximum travel time of 60 minutes 42
20 Visualization of detour time evaluation for supermarket replenishment routes 43
21 Visualization of the effect of larger time windows on the trade-off analysis 43
22 Visualization of the effect of swapping on the trade-off analysis 44
23 Histograms of the stop duration per transport type for the SC channel 52
24 Histogram of the stop duration of vans for the HD channel 53

List of Abbreviations

AHP	Analytical Hierarchical Process.
BBMA	BrabantBrede ModelAanpak.
DC	Distribution Centre.
ERD	Entity-Relationship Diagram.
FR	Functional Requirement.
GIS	geographic information system.
HD	Home Delivery.
KPI	Key Performance Indicator.
LCB	Logistics Community Brabant.
MCDA	multi-criteria decision analysis.
MCDM	multi-criteria decision-making.
PUP	Pick Up Point.
SC	Supply Chain.
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution.
TSP	Travelling Salesman Problem.
UCC	Urban Consolidation Centre.
UML	Unified Modeling Language.
VRP	Vehicle Routing Problem.
WSDA	Weighted Sum-Dijkstra's Algorithm.
WSM	Weighted Sum Method.
ZEZ	Zero Emission Zone.

1 Introduction

1.1 Problem description

The number of people living in cities is rapidly increasing. In 2020, 56% of the world's population lived in cities and this percentage is expected to become 70% by 2050 (*Urban Development Overview*, 2020). Because of this increase, the number of logistics vehicles within a city is increasing as well. These urban goods movements are required to satisfy consumers' needs. Stakeholders such as shippers and carriers play an important role in this context. They attempt to satisfy customers by providing freshness and high product availability. For example, perishable goods may lose value over time (Blackburn & Scudder, 2009). Therefore, city logistics are essential to enable the offering of high-quality products.

It can be observed that in recent years store replenishments and home deliveries were executed more often and with larger quantities (Gevaers et al., 2009). Along with these increasing urban goods movements, negative externalities are increasing as well. Social and environmental problems like air, water, and noise pollution; traffic congestion; greenhouse gases; and land use are becoming more important to solve (Bozzo et al., 2014; Demir et al., 2015). To mitigate these negative effects, a collaboration between different stakeholders is essential (Viu-Roig & Alvarez-Palau, 2020).

Rześny-Cieplińska and Szmelter-Jarosz (2020) showed that all stakeholders in city logistics acknowledge the importance of sustainable city logistics. In general, reducing greenhouse emissions and increasing the quality of life were among the most important variables. However, which factors are perceived as important varies per stakeholder group. City logistics stakeholders can either be classified as public or private (Rześny-Cieplińska & Szmelter-Jarosz, 2020). Public stakeholders include administrators and authorities. Shippers, carriers, receivers, and residents belong to the category of private stakeholders.

Private stakeholders aim to satisfy the customer's needs by focusing on technological preferences such as costs and reliability (Rześny-Cieplińska, Szmelter-Jarosz & Moslem, 2021). Meanwhile, they pay little attention to the aforementioned negative externalities. For example, routes are mainly optimized by minimizing travel times and travel distances. However, to increase a city's liveability, other characteristics should also be considered. This is in accordance with the objective of local governments: improving the city's liveability for their residents by controlling city logistics. Municipalities want to increase the efficiency of urban freight and reduce the number of trucks in the city (Katsela & Pålsson, 2019). Freight is an important topic for municipalities. However, different cities copy each other's ideas without evaluating their applicability to their own city (Van Duin, 2005). Local governments have little experience with the operational aspects of urban freight transport. However, a municipality should take the initiating role (Taniguchi, Thompson, Yamada & van Duin, 2001; Katsela & Pålsson, 2019; Rześny-Cieplińska & Szmelter-Jarosz, 2020; Viu-Roig & Alvarez-Palau, 2020). The difficult task of the municipality is to find a solution in which all conflicting stakeholders' objectives are incorporated.

1.2 Research questions

A solution will be designed which mitigates the negative externalities of city logistics while considering the conflicting objectives of stakeholders. The solution will provide insight into possible actions that can be taken by the different stakeholders. This guides the stakeholders in cooperating and making decisions in which every stakeholder is represented. Public-private partnerships are essential to accelerate city logistics towards sustainability and liveability (Taniguchi, 2014). For example, instead of opposing rules, cooperation through covenants would be beneficial for all stakeholders (Browne, Nemoto, Visser & Whiteing, 2004).

To guide this research, the following main research question is formulated:

Which solution minimizes the negative impact of city logistics on the liveability of a city while satisfying private stakeholders' preferences?

The main research question is divided into several sub-questions. The first section focuses on the factors and constructs that represent the impact of city logistics on the liveability of cities. Liveability is defined as the degree to which a city is suitable and attractive for living. A liveable city supports quality of life, safety, accessibility, and environmental sustainability (Tennakoon & Kulatunga, 2019). Which solutions and criteria that have been treated within the literature should be investigated. Additionally, it should be examined which criteria are relevant for the stakeholders.

RQ1a. Which existing solutions for the negative externalities of city logistics can be obtained from the literature?
RQ1b. Which criteria representing the economic, social, and environmental impact of city logistics have been treated by scientific literature?
RQ1c. Which criteria represent the social and environmental preferences of public stakeholders with regard to city logistics?
RQ1d. Which criteria represent the economic preferences of private stakeholders with regard to city logistics?

In addition to defining the criteria, it is important to know how these factors can be obtained from the available data and how they should be modelled. For modelling the criteria, it is important that different path characteristics are made comparable. To accommodate this, specific modelling choices will have to be made. The following question can be formulated with regard to modelling the criteria:

RQ2. How can the criteria from research question 1 be modelled and obtained from the available data?

The criteria obtained by answering the first two research questions will be used to evaluate different alternatives. It is investigated how previous academic works generated and evaluated alternative solutions. This will answer the following sub-question:

RQ3. Which methods have been applied in the literature to generate and rank alternative solutions for the negative impact of city logistics which incorporate liveability and private stakeholders' preferences?

Lastly, an alternative generation method and alternative evaluation method should be selected. These two methods will be used as input for the solution which will be designed in this research. For this purpose, the last sub-questions can be formulated as shown below.

RQ4a. Which method is the best option for city logistics to generate alternatives which incorporate liveability and private stakeholders' preferences?
RQ4b. Which method is the best option for city logistics to evaluate the alternatives?

1.3 Report structure

The following section of this report presents academic works that have already been conducted regarding reducing negative externalities in city logistics while considering conflicting objectives. This will answer research questions 1a, 1b, 2, and 3. Section 3 includes an analysis of the current situation to answer research questions 1c, 1d. Additionally, the analysis will create a framework for research questions 4a and 4b. These will be answered in section 4, which describes the conceptual design. Followingly, section 5 regards the detailed design. In this section, the proposed algorithm and models are presented. These are applied to a case study in section 6. Lastly, a conclusion is presented in section 7. This section also includes a recommendation for future research.

2 Literature review

In this section, existing literature is presented that focuses on incorporating conflicting interests in city logistics. This overview should assist in answering research questions 1a, 1b, and 3. For research question 2, the literature review assists in presenting options for criteria modelling. Firstly, a general description of multi-criteria analysis in city logistics is presented. The second paragraph focuses on multi-criteria analysis applications in the evaluation of city logistics initiatives. The last paragraph focuses on multi-criteria analysis applications in vehicle routing. Both paragraphs examine solutions and methods that have been used in the literature and also include a description of which criteria received attention from which researchers.

2.1 Multi-criteria analysis in city logistics

City logistics is also referred to as a combination of the following words: city, urban, last-mile, logistics, freight, transport, delivery, and distribution. For example, both urban freight transport and last-mile delivery can be used to refer to the same logistical activities. Researchers do not agree on which terms reflect which parts of city logistics. Cardenas et al. (2017) showed that some researchers view urban freight transport as a subset of city logistics whereas others argue that the two constructs overlap. In this research, the definition from Savelsbergh and Van Woensel (2016) is used: "city logistics is about finding efficient and effective ways to transport goods in urban areas while taking into account the negative effects on congestion, safety, and environment". Nevertheless, Strale (2019) showed the majority of academic works still prioritize industrial challenges rather than environmental and social issues. However, the awareness among researchers, private stakeholders, and public stakeholders of the importance of mitigating the negative externalities is increasing (Viu-Roig & Alvarez-Palau, 2020). This is confirmed by the number of city logistics initiatives in recent years (Holguín-Veras et al., 2020). These initiatives include, for example, infrastructure management such as ring roads; loading area management; and vehicle-related strategies such as electrification, noise regulations, time access restrictions, and traffic control.

In order to evaluate city logistics, multi-criteria analysis is frequently used. Multi-criteria analysis is also known in the literature as multi-criteria decision-making (MCDM) and multi-criteria decision analysis (MCDA). Multi-criteria analysis is used to support decision-makers in choosing from different alternatives which are evaluated by multiple conflicting criteria (Hanzl, 2020). These criteria reflect the preferences of the stakeholders. Multi-criteria analysis has been applied in logistics by many researchers before (Khan, Chaabane & Dweiri, 2018). In particular, city logistics is used more often as a research area in the last few decades to apply multi-criteria analysis methods to (Hanzl, 2020). Two main directions have been observed: evaluation of city logistics initiatives and vehicle routing. Each construct is separately discussed in the following paragraphs.

2.2 Evaluating city logistics initiatives

Within multi-criteria analysis, three categories can be distinguished in the literature which evaluated city logistics initiatives: people, planet, and profit. This classification is widely used in scientific literature and is also known as the framework called the triple bottom line (Elkington & Rowlands, 1999). However, researchers in city logistics use another terminology where people, planet, and profit are described as social, environmental, and economic factors respectively. In this context, the social and environmental categories primarily regard the interests of the public stakeholder. The private stakeholder's interests are represented by the economic class. The social, environmental, and economic categories can be further divided into criteria. Followingly, it will be discussed which solutions and criteria were discussed by previous academic works.

Shiau and Liu (2013) created an indicator system for local governments to evaluate the sustainability of transport in cities. However, it should be noted that they also included the transport of individuals. Therefore, not all criteria are relevant to this context. For example, air pollution is relevant but the ratio of parking lots for park and ride compared to the total number of parking lots is not.

Jamshidi, Jamshidi, Ait-Kadi and Ramudhin (2019) reviewed several research papers which performed resembling studies regarding a multi-criteria decision-making approach to evaluate the sustainability of city logistical initiatives. They combined quantitative and qualitative techniques to involve stakeholders in setting criteria weights and ranking alternatives. Especially the papers from Awasthi and Chauhan (2012); and Parezanović, Pejčić Tarle and Petrović (2014) show great resemblance in criteria usage. The city logistics initiatives they considered can be summarized as vehicle weight restrictions, congestion charging, clean urban logistics, and access timing restrictions. They also looked at city distribution plans such as the implementation of an urban distribution centre. On the other hand, Tadić, Zečević and Krstić (2014) ranked four different city logistics concepts according to economic, social, and environmental factors. Their method combined multiple fuzzy MCDM approaches to select the city concept which would be the most suited for the stakeholders.

Bandeira, D'Agosto, Ribeiro, Bandeira and Goes (2018) created a multi-criteria model for evaluating the sustainability of urban freight transportation. For this purpose, they performed a literature review which shows resemblances to the one from Jamshidi et al. (2019). However, some evaluated sources included passenger transport. The criteria from these sources were filtered to obtain a list of criteria relevant to urban freight transport. Lebeau, Macharis, Van Mierlo and Janjevic (2018) presented a multi-criteria analysis focusing on the conflicting objectives of stakeholders. The presented objectives can be interpreted as criteria to evaluate different scenarios. These scenarios were constructed by alternating between trucks or vans, and diesel or electric. Additionally, the scenarios were identified by the implementation of a road tax and the authorisation of night distribution. Pryn, Cornet and Salling (2015) did not use many criteria but reasonably constructed a relevant list of indicators. For example, it was argued that CO_2 is not included as a separate criterion but is correlated to and a good indicator of air pollution. A summary of criteria usage by the authors from this subsubsection is given in Table 1.

Table 1: Criteria from literature review regarding city logistics initiatives evaluation

		Authors						
Category	**Criterion**	Shiau and Liu	Awasthi and Chauhan	Tadić et al.	Parezanović et al.	Bandeira et al.	Lebeau et al.	Pryn et al.
Economic	Customer coverage		x		x			
	Load factor	x	x		x		x	
	Revenues and costs		x	x	x		x	x
	Service quality		x	x	x		x	
	Trip efficiency		x		x	x		
	Volume of freight handled		x		x	x		
Environmental	Air pollution	x	x	x	x	x	x	x
	Energy consumption	x	x		x	x		
	Land use / space occupancy		x	x	x		x	
	Noise pollution		x		x	x	x	x
Social	Accessibility / mobility	x	x		x			x
	Accidents	x	x	x	x	x		
	Congestion		x		x		x	
	Freeing of public space		x		x			
	Safety			x			x	

2.3 Vehicle routing

Multi-criteria analysis can also be used to create routes which are more personalized as was done, for example, by Niaraki and Kim (2009) and Nadi and Delavar (2011). Both models make use of geographic information system (GIS). The former used the Analytical Hierarchical Process (AHP) to model a combination of preferences whereas the latter focused more on decision strategies to be able to provide users with multiple options. Both researchers went beyond conventional methods such as Dijkstra's algorithm (Dijkstra, 1959), primarily because this algorithm operates on single-attribute edges. Dijkstra's algorithm finds the shortest path from an origin to a destination node.

Roghanian and Shakeri Kebria (2017) solved the single edge attribute problem by combining Dijkstra's algorithm with The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to create a multi-attribute Dijkstra's algorithm. Roghanian and Shakeri Kebria (2017) mentioned alternative shortest-path search algorithms such as A*, Bellman-Ford, and Floyd-Warshall. A* is a generalized Dijkstra's algorithm since it explores a subset of nodes (Hart, Nilsson & Raphael, 1968). Researchers do not fully agree on the computational performance and general applicability of this search algorithm (Zeng & Church, 2009). Bellman-Ford can process negative edge weights but is slower than Dijkstra's algorithm (Bang-Jensen & Gutin, 2008). Floyd-Warshall is also slower since it computes the shortest path between every combination of nodes (Bang-Jensen & Gutin, 2008).

Another solution for the single-attribute edge problem was taken by Hua and Abdullah (2018). They combined Dijkstra's algorithm with the Weighted Sum Method (WSM) to create the Weighted Sum-Dijkstra's Algorithm (WSDA). Both WSDA and TOPSIS with Dijkstra's algorithm have been implemented by other researchers. The former has been applied to a data set from Indonesia by Rosita, Rosyida and Rudiyanto (2019). They used the vector technique for data normalization. Sarraf and McGuire (2020) used TOPSIS and four alternative decision-making methods instead of WSDA. Their data normalization approach is called the linear sum technique. It has been argued that data normalization should be applied to obtain resembling scales for all criteria to be able to compare them. Neither Rosita et al. (2019) nor Sarraf and McGuire (2020) explicitly mentioned why they selected the normalization technique used. However, it shows that many alternatives exist (Vafaei, Ribeiro & Camarinha-Matos, 2016). For example, linear max, linear max-min, and logarithmic normalization.

In addition to Dijkstra's algorithm, many other methods have been applied to routing. For example, Chen, Cai and Wolf (2015) used Pareto-optimal (efficient) frontiers assuming criteria weights are not known beforehand. The drawback is a large computation time. Pacheco and Martí (2006) applied the tabu search heuristic in order to incorporate the conflicting objectives of route length and the number of buses. In order to find the optimal path, Pradhan, Agarwal and De (2022) and Pahlavani and Delavar (2014) incorporated driver's preferences. The former applied a genetic algorithm whereas the latter used a locally linear neuro-fuzzy model and a modified invasive weed optimization algorithm. Multi-criteria analysis has also been widely applied to the Vehicle Routing Problem (VRP) (Jozefowiez, Semet & Talbi, 2008; Gupta, Heng, Ong, Tan & Zhang, 2017). The literature review of Kim, Ong, Heng, Tan and Zhang (2015) revealed multiple City VRPs which are characterized by considering different stakeholders' objectives. Most of these studies have focused on objectives such as time windows and air pollution. Other widely used objectives are environmental, travel, driver, or fixed costs; travel distance or time; service time; and fleet size. Within the domain of multi-criteria for VRP, many methods have been applied such as game theory and the genetic algorithm (Belhaiza, 2016; Ferreira, Costa, Tereso & Oliveira, 2015).

The academic works that implemented multi-criteria optimal path selection have used their own sets of criteria. A summary of the predominant criteria has been shown in Table 2. The sources regarding VRPs have been excluded because some of their objectives can not be taken into account in multi-criteria path selection. Additionally, the papers of Chen et al. (2015) and Pacheco and Martí (2006) have been excluded because their criteria are irrelevant for city logistics.

Most of the criteria are self-explanatory except for the degree of difficulty. This criterion reflects the road type; quality, width, and slope of the road; the number of turns; and the number of traffic lights. Together with congestion, this criterion has been used the least whereas costs, time, and distance have been described the most.

Table 2: Criteria from literature review regarding vehicle routing

	Authors								
Criterion	Hua and Abdullah	Khan et al.	Nadi and Delavar	Niaraki and Kim	Pahlavani and Delavar	Pradhan et al.	Roghanian and Shakeri Kebria	Rosita et al.	Sarraf and McGuire
Freight costs	x	x	x		x		x	x	
Time	x		x		x	x	x		x
Distance	x		x	x		x		x	x
Congestion			x	x				x	
Degree of difficulty			x		x	x			
Safety				x		x	x	x	x
Scenery / facilities			x	x	x	x			

2.4 Conclusion literature review

In general, existing literature mainly focuses on industrial challenges instead of taking environmental and social challenges into account (Strale, 2019). The small selection of papers that incorporate environmental and social factors either evaluate city logistics initiatives or create methodologies for routing. However, the existing solutions do not suffice in mitigating the negative externalities of city logistics to an acceptable level. City logistics stakeholders still indicate the need for improving the liveability of cities. Therefore, a novel methodology will be designed in this research which is capable of incorporating the conflicting objectives of city logistics stakeholders.

The methodologies discussed in this section will be used as inspiration for the solution that will be designed in this research. As will be shown later in this report, a vehicle routing solution is designed which creates the optimal path between an origin and a destination. The methodology is based on the approach of Hua and Abdullah (2018). However, their methodology has not been applied in a city logistics context yet. Additionally, the methodology will be extended with several constructs. The adapted algorithm is capable of handling timing constraints. Moreover, the adapted algorithm is capable to construct the optimal path for a tour with multiple stops. The adapted algorithm is also capable of suggesting new visitation orders through swapping consecutive stops and the application of the Travelling Salesman Problem (TSP).

The criteria related to city logistics initiatives as well as routing will also be used as inspiration. However, many criteria have not been treated in the literature yet but would be valuable to be incorporated into a solution. The solution that will be designed in this research will incorporate new social and environmental criteria which have not been used by researchers in the past. It will be shown later in this report that public data can be used to incorporate on-route vulnerable objects and on-route residents into the proposed solution.

3 Analysis

This section describes the analysis of the current situation. This is done for a specific case study which includes a municipality as the public stakeholder and an omnichannel retailer as the private stakeholder. A true omnichannel strategy implies the integration of the online and offline shopping experience (Frazer & Stiehler, 2014). The case study description is given in subsection 3.1. A description of their opinions about the importance of the characteristics of city logistics is provided in subsection 3.2. This answers research questions 1c and 1d. Subsection 3.3 describes the data that is used for the descriptive analysis in subsection 3.4. This section includes the analysis of the case study which is performed to investigate the current impact of city logistics vehicles. This will create a framework which will be combined with the information from the previous chapter to answer research questions 4a and 4b.

3.1 Case study description

The case study is characterised by a public and a private stakeholder. The municipality of Tilburg represents the public stakeholder and the private stakeholder will be represented by a Dutch Retailer whose name is concealed because of confidentiality. Since this retailer is active in omnichannel retailing, a clear distinction is made between transports for the Supply Chain (SC) and Home Delivery (HD). Which transports regard which channel is visualized in Figure 1. A rapid delivery warehouse, supermarket, hub, and Pick Up Point (PUP) are fulfilled by a Distribution Centre (DC). It should be noted that different types of DCs are used which are placed at different locations throughout the Netherlands.

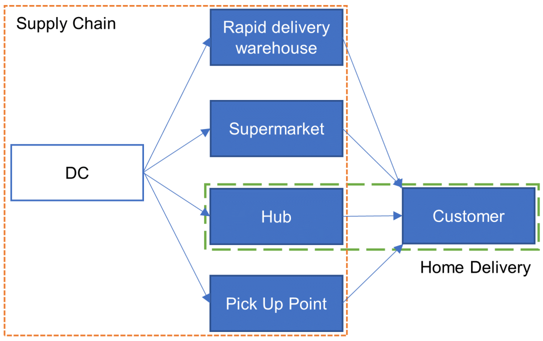


Figure 1: Visualization of the scope of the data with regard to the supply chain of the Dutch retailer

Based on the data and the different types of DCs, a threefold distinction can be made based on transport type: groceries/fresh goods, frozen products, and orders for a PUP. Deliveries with groceries and fresh goods are often combined into trucks and are, therefore, combined into one transport type in this case study. Each distribution centre is responsible for its own transport planning of outbound logistics. The routes are generated by software but evaluated by humans. For example, routes are adjusted to ensure the minimization of driving on narrow roads or through residential areas. This shows that possibilities exist to implement the outcomes of this research.

Scoping towards Tilburg

There are ten supermarkets in Tilburg of the Dutch retailer. Some of these supermarkets also function as a Pick Up Point. In addition to the supermarket, two other locations in Tilburg receive freight from the DCs. These regard a distinctive PUP and a warehouse for rapid deliveries in Tilburg. The supermarkets, PUP, and rapid delivery warehouse in Tilburg are supplied from DCs in many places in the Netherlands.

The distribution network for home deliveries in Tilburg is different from the distribution network for supermarkets. The DC in Den Bosch is where the customer orders are collected. This DC also functions as a hub.

The collected customer orders at the DC in Den Bosch either stay at the hub in Den Bosch or are transported to the hub in Breda. Customers in Tilburg can receive their groceries from both the hubs in Den Bosch and Breda. It is observed that approximately half of the home deliveries in Tilburg originate from Den Bosch and the other half are delivered from Breda. From which hub the deliveries are made, can change weekly.

It should be noted that the routes driven by delivery vans can cover multiple municipalities. This means that it is possible that the customers visited by a delivery van do not necessarily exclusively live in Tilburg. It can be distinguished what fraction of a tour is relevant. The difference is best explained with Figure 2. The location on the left is the home delivery hub in Breda and is not considered a stop. Therefore, the number of stops for the trip through Tilburg is equal to 11, whereas the number of stops exclusively in Tilburg is equal to 4.

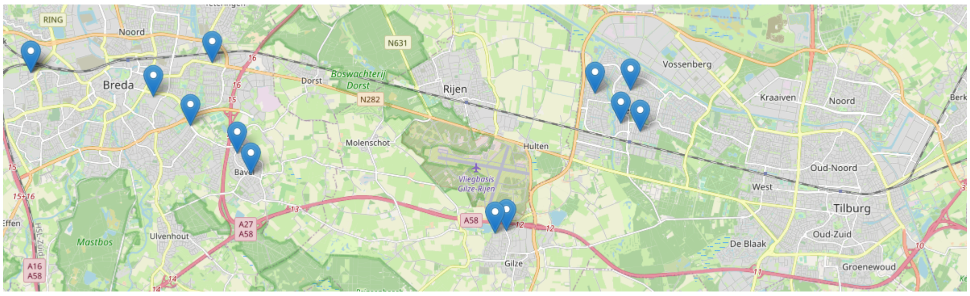


Figure 2: Example home delivery route travelling through Tilburg

3.2 Route characteristics prioritization

This subsection describes the current practices with regard to route characteristics that the public and private stakeholders focus on. Additionally, their ambitions for the future are examined. As mentioned before, the public stakeholder regards the municipality of Tilburg and the private stakeholder is represented by a Dutch retailer. Interviews with these stakeholders provided the insights generated in this section.

Public stakeholder

Local governments in the Netherlands act on behalf of their residents (Siebers, Gradus & Grotens, 2019). This is also the case for the municipality of Tilburg. Their main concern is the liveability of the city, which reflects the social and environmental categories from the triple bottom line. However, regarding the economic factors of city logistics, they explicitly mention that vehicles' load factors should be as high as possible. This notion can be explained by the preference for minimizing the number of vehicles inside the city. Tilburg initiated building an Urban Consolidation Centre (UCC) to bundle freight movements for the inner city of Tilburg which should reduce the number of vehicles. The municipality of Tilburg is doing this because of its focus on the perception of its residents. The main concerns are safety and air quality. It should be noted that many routing characteristics are correlated and can not be seen as individual constructs. For example, air quality and the number of trucks inside the city are related to each other. Fewer vehicles inside the city result in less air pollution (Holguín-Veras et al., 2020; Thondoo et al., 2020).

The growth of the Zero Emission Zone (ZEZ) is an example which assists in increasing the air quality inside the city. In the current situation, only the inner city of Tilburg is affected by an emission zone but from 2025 onwards, a larger region will be affected. The ZEZ regards the area within the four ring roads of Tilburg. This zone will be implemented because of regulations from the European Union with regard to air pollution and CO_2 emissions. It is clear that the undesirable fuel types are fossil fuels. Vehicles should be powered by environmentally friendly fuel types but it does not matter if a vehicle is, for example, powered by electricity or hydrogen gas.

The municipality of Tilburg has also emphasized that it is important where vehicles drive. The preferred roads are highways and ring roads. It is better to avoid residential areas. This can be achieved by entering the city as close as possible to the destination. This should also contribute to the avoidance of vulnerable objects. It is valuable to avoid these objects to increase safety and air quality. The vulnerability is evaluated based on traffic type and intensity. Currently, Tilburg primarily focuses on schools and hospitals. They mention that it is difficult to determine during which times to avoid these objects. For example, a university compared to an elementary school has no fixed opening and closing times. The best would be to avoid vulnerable objects entirely if possible. In addition to timing during the day, Tilburg has no preference regarding the timing of logistical activities during the week.

Supply Chain

Tilburg would like customers to shop at a supermarket and to supply that supermarket with one large truck. Making use of the SC channel would fit this preference. Nevertheless, they notice a change in shopping behaviour. Residents are increasingly using the convenience of home delivery and it is difficult to control this behaviour. However, the municipality mentioned negative characteristics of trucks driving for the SC channel. These trucks make noise and cause congestion easily. Noise is caused by the motor of the truck, possible cooling unit, and back-up alarm. An SC truck also pollutes and is difficult to convert to a more sustainable fuel type. Large trucks are seen as dangerous because of their size, weight, and braking distance. When this vehicle type is involved in an accident, the impact would be higher than when a delivery van is involved in an accident (Chang & Mannering, 1999). Therefore, it is more desirable that the SC truck is (un)loading than driving. When an SC truck is on the road, its negative impact is higher. Many of the aforementioned problems of SC trucks do not apply when it is standing still.

Home Delivery

HD vans drive through the entire city and make use of many different streets to arrive at their destination. Additionally, HD vans are not as safe as standard passenger cars, which is shown by many researchers. For example, Lefler and Gabler (2004) mentioned that the probability of pedestrians dying from an accident with a van is two to three times larger than when a pedestrian is struck by a car.

The impact of individual vehicles is only relevant when looking at the total number of vehicles. More HD vans are required to deliver the same amount of freight as an SC truck. Additionally, it is observed that many delivery vans are driving through Tilburg. This is confirmed by the number of accidents that occur with these vehicles. The province of Noord-Brabant also acknowledged this fact and started a designated project to reduce the number of accidents with delivery vans.

The difference between driving and (un)loading is less obvious for HD vans. When (un)loading, the placement of the van can be disturbing for other drivers. Especially considering the fact that an HD van has to stop at multiple locations. However, the time such a van is busy (un)loading is relatively short. Tilburg viewed driving delivery vans as normal road users. Whether this is a just opinion can be questioned because of the aforementioned safety decrease of vans compared to passenger cars.

Private stakeholder

Many routing characteristics are different for the two retail channels of the Dutch retailer as will be shown in the following paragraphs. However, both channels make use of diesel-powered vehicles. This creates an opportunity for improvement regarding environmental sustainability (Taniguchi & Thompson, 2018). Especially considering the aforementioned enlargement of the Zero Emission Zone (ZEZ) (*Ontheffing milieuzone - Gemeente Tilburg*, n.d.).

Supply Chain

The Dutch retailer explicitly mentioned that the most important routing characteristic is travel time. Travel time and congestion are not seen as separate characteristics since congestion is incorporated into the travel time. In addition to route planning, capacity planning is focused on efficiency by maximizing load factors and shift lengths of drivers. Routes are sometimes planned to maximize service levels but this is less common and preferred than efficient routes.

Other important factors in route planning are travel distance and timing. However, it is confirmed by the interim supply chain & transport manager of the Dutch retailer that time is more expensive than distance. For timing, it is important to spread the load over the day and week since the supply chain should be capable to process the busiest periods. For example, it would be valuable to perform SC transports at a time when few trucks are driving. Before 06:00 would be such a time. Timing is also incorporated into route planning by evaluating which objects are passed at which times to increase safety. This is not common practice yet but it is something that would be valuable for the Dutch retailer. Currently, route adjustments to avoid vulnerable objects are processed upon request. For example, a supermarket manager requests to supply another time so the supplying vehicle avoids an elementary school during opening or closing time. The same workflow is applied when a supermarket manager would like to request to change a delivery route. For example, to avoid specific residential areas or other places. The Dutch retailer would like to control preferred routes more systematically but with the currently available tools, this is not possible yet.

A small start to increase environmental sustainability has also been made for the supply chain but this only regards a few vehicles because of several reasons. Firstly, the infrastructure is not yet available at the distribution centres to be able to charge the trucks. Secondly, the range of electric trucks is not sufficient to make some of the trips. Lastly, the Dutch retailer needs more certainty about the rules from the government before they make big investments.

They are passively waiting for information from the government. An example of rules that are imposed is the aforementioned ZEZ that is currently being implemented in Dutch cities. The Dutch retailer is investigating how they are going to cope with these zones. Since an electric truck's range is insufficient, a possible solution could be to implement a city hub from which a few electric vehicles supply within the Zero Emission Zones.

Additionally, the vehicle type influences the type of disturbance that can be experienced by citizens. For example, noise pollution and congestion. Some trucks for the SC channel are cooled which produces additional noise compared to the noise from the truck itself. Supply chain transports are executed by large trucks which cause congestion easily (Campbell, 1995). To decrease the disturbance of SC trucks, the Dutch retailer tries to minimize the time at the supermarket. For example, they aim for planning the drivers' breaks at the distribution centre instead of at the supermarket or on the go. Minimizing the time at the supermarket is done to, for example, make way for other trucks and to decrease the disruption of the truck. The latter is confirmed by examining the types of (un)loading areas at each supermarket in Tilburg. Only a few possess indoor loading docks whereas the majority have reserved a spot in a parking lot or on the side of the road.

Lastly, the Dutch retailer focuses on the difference between the planned and realized times instead of preferring driving or (un)loading. A plan is made which incorporates time for travelling, brakes, parking, unloading, and loading if applicable. Time for (un)loading is calculated per unit that has to be (un)loaded.

Home Delivery

The overall objective in planning for the home delivery channel is minimizing the total travel time. Sometimes this objective is replaced by minimizing the number of trucks when the number of drivers is limited. If sufficient drivers are available, an additional vehicle could reduce the total travel time.

The planning phase for home delivery consists of two steps. The first step regards resource planning. During this step, it is determined which customers are assigned to which trips. The most important factor for this is the time window in which the customer has to be served. The Dutch retailer views this as a hard constraint because of the promise they made towards the customer. Additionally, time windows can be used to control the spreading of customer orders throughout the day. Subsequently, it is evaluated how much time is needed for each customer. This consists of a fixed time and a variable time based on the order size and the location of the customer. Larger orders take longer to deliver and it takes longer to deliver in the middle of Tilburg than in a rural area. It would be nice to be able to compute this time per postal code but this is currently not possible. The advantage would be to be able to judge based on postal code if somebody, for example, lives in a flat.

The second step in the planning phase regards the actual route planning. For this purpose, the information from the resource planning is used by the route planning software. The resulting routes are communicated through navigation devices to the drivers. The most important characteristic is travel time followed by travel distance. This is mainly the case because time is more expensive than distance. The route planning takes congestion into account.

For home delivery, the diesel-powered Renault Master is used. The Dutch retailer is engaged in increasing the environmental sustainability of its HD transport; they are electrifying the home delivery fleet. However, it is not attractive yet to electrify the entire fleet because of the smaller capacity and driving range of the electric alternatives. The only possible time to charge a vehicle would be overnight. The time between work shifts is not enough to completely charge the vehicle. Additionally, the electric versions of HD vans must be manually loaded instead of loading the van per trolley. This results in a higher handling time.

The Dutch retailer is putting too little attention on determining where vans should drive. They do not consider vulnerable objects or residential areas but they take into account two things: they are not allowed to drive across the border and they try to consider time restrictions. Driving internationally is not allowed because of certain goods such as alcohol and tobacco. The time restrictions are more difficult to take into account. Previously, these were not taken into account at all. The Dutch retailer could not prevent incurring a fine because it had to enter a forbidden area to deliver to a customer. The information about time and access restrictions in the Netherlands is not easily accessible, which makes it difficult to consider during planning. In Tilburg, the Dutch retailer tried to act on this by requesting exemptions for specific vehicles. Two specific vans are allowed to enter the city centre despite the time restriction. The Dutch retailer mentioned that another solution would be to allow the customer to order only for time slots which end before 11:00.

The Dutch retailer is also actively trying to increase the safety of HD vans. The routes that are travelled for home deliveries are constantly changing because of the constantly changing customer set that has to be visited. However, the behaviour of the drivers can be directed by informing them about the optimal driving route. Additionally, the Dutch retailer acknowledged that the time pressure would make the drivers go faster and this is something the Dutch retailer wants to prevent. They also want to prevent damage which, unfortunately, still happens daily. To nudge drivers to better driving behaviour, the Dutch retailer monitors four driving characteristics: travel speed, braking harshness, corner speeds, and whether a driver drives forward or backwards after (un)loading. The latter is important because vision is limited when driving backwards after being parked. Based on the four constructs a score is given to each trip which has to be maximized. This phenomenon is known as gamification (Steinberger et al., 2015).

Lastly, the Dutch retailer does not prefer an HD van either (un)loading or driving. They pay little attention to the disturbance the van can cause. Their main focus is on the difference between planned and realized timing. They mentioned, however, that the drivers have to turn off the engine when (un)loading to decrease noise pollution. An HD van does not have a cooling compartment, so the van does not produce any sound when (un)loading.

3.3 Data

Data collection

Routing data of the Dutch retailer has been collected through Logistics Community Brabant (LCB). This community engages enterprises, education, government, and researchers to innovate within the logistics sector in Noord-Brabant, a province in the Netherlands. The data was collected from 01-08-2022 until 30-08-2022. The representativeness of this sample is confirmed by the Dutch retailer. An overview of the data structure is given in Figure 3. This figure shows an Entity-Relationship Diagram (ERD) (Li & Chen, 2009). The Unified Modeling Language (UML) notation has been used. The figure shows that a trip can have one or multiple stops, whereas a stop adheres to only one trip. Between stops and locations, a one-to-one relationship has been denoted.

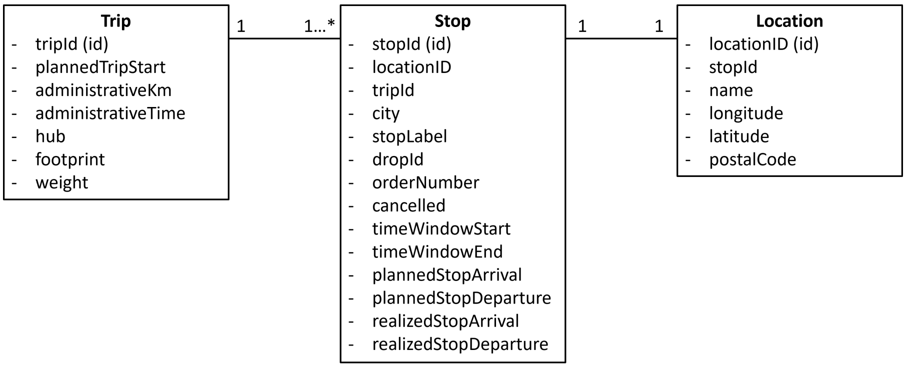


Figure 3: Entity-relationship diagram of the routing data of the Dutch retailer

In addition to this data, two special types of data have been used. The first special type of data is a few files which include written directions for driving routes from the DC in Breda to the supermarkets of the Dutch retailer in Tilburg. The second special type of data regards an online database has been used which includes locational data about vulnerable objects (*Externe veiligheid: kwetsbare gebouwen en locaties*, n.d.). These include, for example, offices, schools, health centres, sports centres, and daycare for children. The vulnerable objects can be classified into three categories based on the number of people present, duration of visit, and level of self-sustainability in case of an emergency.

The three classifications are very vulnerable, vulnerable, and limited vulnerable. To indicate these three levels of vulnerability, the classifications are characterized by priorities ranging from 1 to 3. Priority 1 regards the highest level of vulnerability. The regulation regarding these objects has been included in an environmental code to ensure protection from external risks.

Data preprocessing

A few data preprocessing steps have been taken. Data cleaning was applied to exclusively obtain stops that have not been cancelled. Secondly, data integration has been applied as can be seen in Figure 3. Different data sets were linked through data attributes. For example, stops are connected to trips through the data attribute "tripId".

3.4 Current situation

As mentioned before, the biggest influence on negative externalities inside the city is road transport (Demir, Syntetos & van Woensel, 2022; Ranieri, Digiesi, Silvestri & Roccotelli, 2018). The data from the Dutch retailer can be used to examine how vehicles in omnichannel retailing behave. The performance of the current situation is evaluated with regard to several Key Performance Indicators. A Key Performance Indicator (KPI) is a quantifiable measure of performance. The analysis of the KPIs is structured according to a threefold classification: supply chain, home delivery, and general KPIs.

For SC and HD, the KPIs that are investigated are categorized as the number of stops, volume, timing, and vehicle characteristics. Firstly, the number of stops is evaluated for stops in Tilburg and tours through Tilburg. The volume category regards the KPI number of vehicles. The timing category regards the timing during the day and week. Lastly, the category vehicle characteristics includes the KPI load factor. In addition to the KPIs for SC and HD, a general KPI is presented: the number of vulnerable objects.

Methods for current situation

It is briefly described how each KPI is obtained from the data. The data from 01-08-2022 until 28-08-2022 has been used to create fairness among the weekdays.

Number of stops

For the number of stops, it is both interesting to investigate tours which travel through Tilburg and the stops only in Tilburg. It should be noted that a stop is defined as an intermediate location that is visited to deliver freight. This means that the start and end locations were not included in the number of stops. This was done by excluding data entries for which "stopLabel" was equal to "S" or "E". Subsequently, for the SC channel, the number of unique location IDs was counted per "tripId". For the HD channel, the number of occurrences for trip IDs was counted. The average number of stops was calculated by taking the average of the number of stops per "tripId".

Volume

The number of stops shows the impact of individual trucks but the effect is even more substantial when the average number of trucks was calculated. It does not matter whether data subsets with tours through Tilburg or data subsets with stops only in Tilburg are used. For both the SC and HD channels, the number of unique trip IDs per day was calculated. This showed the minimum and the maximum number of vehicles per day. All values per retail channel were used to compute the average number of vehicles per day.

Additionally, for the SC channel, the average number of visits per transport type per supermarket per day was calculated. Duplicate trip IDs have been removed. The data entries were counted and summed which specified Tilburg as the city. The obtained summed values were divided by 24 days for frozen products and PUP orders because these are not transported on Sunday. According to the same reasoning, the summed values for groceries and fresh products were divided by 28 days to obtain the average number of vehicles per transport type per supermarket per day.

Timing

For all the KPIs in the timing category, stops exclusively in Tilburg are relevant. Firstly, the average number of vehicles per weekday has been examined. This was done by first removing duplicate values regarding the data attribute tripId. Subsequently, "realizedStopArrival" has been converted to numbers representing the weekdays. The obtained values have been used to generate bar plots. Secondly, the arrival time of vehicles has been investigated. This was done by extracting the time component from "realizedStopArrival". From these values, a histogram has been created.

In addition, a few additional KPIs for the home delivery channel have been evaluated with regard to time windows. It was first examined which time windows were used. Each possible combination of "timeWindowStart" and "timeWindowEnd" was requested. Followingly, data attributes "realizedStopArrival" and "realizedStopDeparture" were used to calculate the number of deliveries that were too early, too late, or delivered exactly within the time window. The average time too early was obtained by the average difference between "timeWindowStart" and "realizedStopArrival". The average time too late was obtained by the average difference between "timeWindowEnd" and "realizedStopDeparture".

Vehicle characteristics
The load factor for the SC trucks has not been based on data but was obtained through the interim manager of the supply chain & logistics of the Dutch retailer.

For the home delivery, on the other hand, the load factor was calculated for trips through Tilburg. This has been done by using "tripId" as a cross-reference. Subsequently, data attributes "hub", "weight", and "footprint" were used to calculate the average weight and footprint per trip per hub. However, the only relevant hubs are Den Bosch and Breda. The average weight and footprint were divided by the maximum possible weight and footprint to obtain the load factors. The maximum weight is equal to 800 kg. The maximum footprint is different for the different hubs because of the design of the fulfilment process at the EFC. The maximum footprints for hubs Den Bosch and Breda are equal to 102 and 99, respectively.

Vulnerable objects
For the evaluation of vulnerable objects, the digital database including vulnerable objects has been combined with the written directions for SC trucks. For each driving route to each supermarket, it was investigated which vulnerable objects are passed along that route. A distinction was made between the different priority levels.

Supply Chain KPIs

Number of stops
It is evaluated per individual truck how many stops are, on average, made per tour. The analysis for the number of stops is performed according to the threefold classification of transport types as seen in Table 3. The smallest number of stops were found for the transport of groceries/fresh goods. When driving through Tilburg, the average number of stops is equal to 1.5. This is the case since these types of trucks mainly visit one or two supermarkets per tour. When compared to the number of stops exclusively in Tilburg (1.2), it can be noticed that the difference is relatively small. Trucks delivering groceries/fresh goods mainly stay in Tilburg when visiting at least one supermarket in Tilburg. This is not the case for the transport of frozen goods or PUP orders. These transport types are more likely to visit multiple cities during one tour. Additionally, the average number of stops is much larger for these two transport types compared to the groceries/fresh transports. This can be explained by the order size of supermarkets. These transports include many visits with a small amount of freight per supermarket. Therefore, the trucks performing these transports have to stop more often.

Table 3: The average number of stops for the SC channel

		Groceries/fresh	Frozen	PUP
Average number of stops	**Tour through Tilburg**	1.5	10.3	7.5
	Stops only in Tilburg	1.2	4.1	1.8

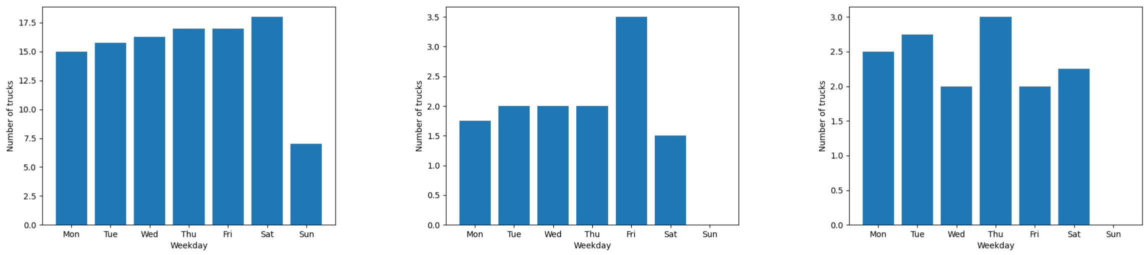
Volume
Between 2.0 and 17.0 trucks are on the road each day for the SC channel. On average, the number of SC trucks in Tilburg is equal to 11.0. These values can be put into perspective by calculating the number of visits per day per supermarket in Tilburg. This means that it will be evaluated how often the ten supermarkets, the Pick Up Point and the rapid delivery warehouse are visited. The number of visits of trucks delivering groceries/fresh products ranges from 0.9 to 3.1. The average number of frozen deliveries per location is bounded at one per day. However, the values are averages per day obtained from data covering a month. It is, therefore, possible that a location can receive multiple deliveries of frozen goods per day, but this is not standard practice. Lastly, the number of visits of trucks delivering PUP orders was evaluated. The Pick Up Point in Tilburg shows the highest number of PUP deliveries: 2 per day. It was confirmed that only a selection of supermarkets functions as a PUP. The rapid delivery warehouse receives on average 0.2 PUP deliveries per day.

Timing

A weekday analysis is performed for the three different transport types within the supply chain as shown in Figure 4. The peak days are distinguishable per transport type. For groceries/fresh goods, frozen products, and PUP orders, the peak days are Saturday, Friday, and Thursday, respectively. When examining the differences among transport types, the y-axes have not been standardized since large differences exist for the number of trucks per day. The order of magnitude is not the same for each transport type.

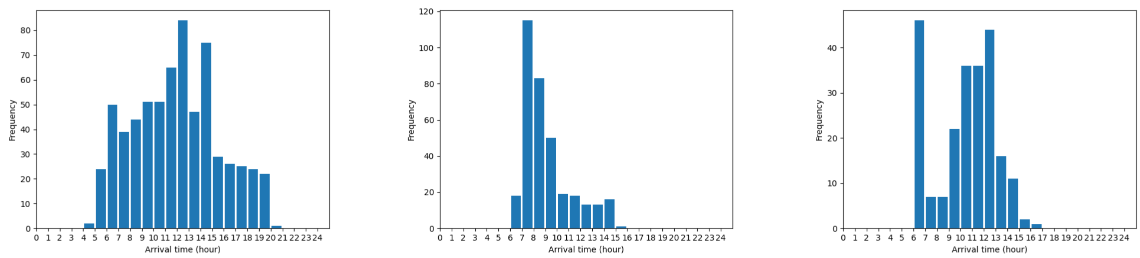
Especially the number of vehicles transporting groceries/fresh goods is relatively large. It can also be noticed that the number of transports is smaller for groceries/fresh on Sunday than on other days. Moreover, no trucks supply frozen products and PUP orders on Sunday. This can be explained by various reasons. For example, personnel costs are higher compared to other days. For the majority of drivers, Sunday is a day off which means that employment results in a higher hourly rate. Other reasons are supermarkets that are closed and cannot receive goods, suppliers that do not deliver goods on Sunday, or maintenance of software that is often planned on Sundays.

Besides the timing during the week, it is also important to gain insight into the timing during the day. Supply chain transports begin at 04:00 but are not executed after 21:00 as shown in Figure 5. Most of these deliveries are done between 06:00 and 15:00. After 15:00, there is a big drop in the number of SC transports in Tilburg. The only active transport type after 17:00 is the groceries and fresh category as shown in Figure 5a. Figure 5b and Figure 5c show a large peak at the beginning of the day for frozen products and PUP orders.



(a) Groceries/fresh goods (b) Frozen products (c) PUP orders

Figure 4: Bar plots of the number of transports per weekday per transport type for the SC channel



(a) Groceries/fresh goods (b) Frozen products (c) PUP orders

Figure 5: Histograms of the arrival time of trucks per transport type for the SC channel

Vehicle characteristics

Trucks for supply chain logistics are large trucks and most of these trucks are operated by full-time drivers who drive fixed predefined routes. Trucks driving for the supply chain can be categorized based on capacity. Mainly four different sizes are used by the Dutch retailer. Trucks can carry between 41 and 54 containers. City trucks can only contain 41 containers and are used to supply supermarkets when restrictions are in place for (un)loading.

Additionally, a different capacity is detected based on the type of temperature control. Trucks transporting goods at one temperature and trucks transporting goods that have to be stored at different temperatures do not have the same capacity. A slight difference is applicable to trucks that have different types of unloading mechanisms. This difference is equal to two containers. Despite available capacity, not all trucks are utilizing the maximum amount of space. The Dutch retailer strives for a load factor for large trucks of 93%, but the actual load factor is approximately equal to 90/91%. These numbers have been provided by the interim manager of the supply chain & logistics of the Dutch retailer.

Home Delivery KPIs

Number of stops

The number of stops is analysed. The values for these two KPIs are summarized in Table 4. The HD data show delivery routes of vehicles with, on average, 14.9 stops when travelling through Tilburg. Per tour, the average number of stops in Tilburg is equal to 6.7. This difference clearly shows that trips through Tilburg also visit customers outside of Tilburg.

Table 4: The average number of stops for the HD channel

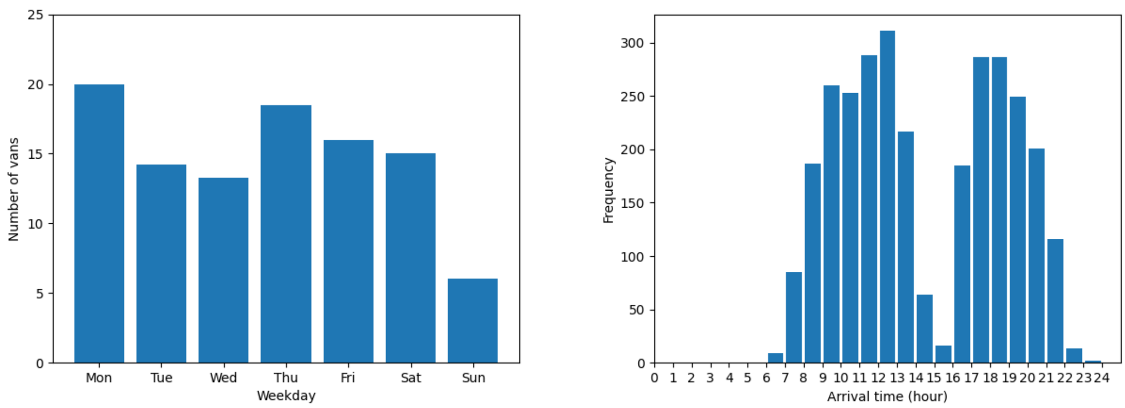
Average number of stops	**Tour through Tilburg**	14.9
	Stops only in Tilburg	6.7

Volume

Between 4.0 and 22.0 home delivery vans visit Tilburg every day. Per day, the average number of HD vans in Tilburg is equal to 14.8.

Timing

A visual representation of the number of vans for HD transports is shown in Figure 6a. It can be observed that the peak day for the HD channel is Monday. This can be explained by the number of companies ordering on Monday. Many companies have reserved a fixed time slot on Monday morning. This day is more difficult to plan than other weekdays since the average company's order size is larger than the average order size of consumers. Some large companies can even order up to the entire capacity of a van. On the other hand, Figure 6a shows that on Sunday the fewest vehicles are on the road. This can be explained by lower consumer demand and higher personnel costs compared to other weekdays. Additionally, hubs are only supplied in the morning on Sunday.



(a) Bar plot of the number of HD vans per weekday (b) Histogram of the arrival times of HD vans

Figure 6: Visualizations of timing KPIs for the HD channel

Besides the timing during the week, it is also important to gain insight into the timing during the day. For this purpose, Figure 6b is created. This figure shows that home delivery vans deliver between 06:00 and 24:00 in Tilburg. These times are especially important when considering time access restrictions for logistical vehicles. For example, freight in the inner city centre of Tilburg is only allowed between 06:00 and 11:00 (*Verkeersontheffing - Gemeente Tilburg*, n.d.).

A clear distinction can be observed between morning and afternoon deliveries; there is a large drop in the number of deliveries between 14:00 and 16:00. This notion can be explained by the time windows that are used. In total, 11 different time windows are used of which some overlap. Overlapping is used to smooth the customer demand during the day. Multiple time windows can be used per trip, which creates more flexibility. All time windows in the morning end before 14:00 and the time windows in the afternoon all start after 16:00.

No time windows are in place between this interval because of changing from the morning to the afternoon shift. In this interval, vans return to the hubs to be reloaded and, in most cases, change drivers. The home deliveries between this time interval are either late deliveries of the morning time windows or early deliveries of the afternoon time windows. Particularly, 79.1% of home deliveries are served within the specified time window in Tilburg. Deliveries can arrive before the prespecified time window or depart after the time window. In 8.4% of the cases, home deliveries arrive too early with an average of 20.8 minutes. HD vans depart too late in 12.5% of the deliveries with an average of 24.0 minutes. It was also calculated that 87.7% of the deliveries departed before the end of the time window and 12.3% departed after the end of the time window. The average time departing before the end of the time window was equal to 70.7 minutes.

Vehicle characteristics
The load factor for home delivery is difficult to compute. An HD van is constrained by two constructs: weight and volume. The maximum allowed weight for the van is equal to 800 kg. This type of capacity is more often the bottleneck than the volume of the van. The maximum weight is determined based on the maximum allowed weight a driver with a standard driving license is allowed to drive. Comparing this value with the average weight of a van, a load factor of 81.3% is obtained. Based on the maximum footprint of a delivery van, calculations show that the load factor with regard to volume is equal to 72.0%.

This confirms the fact that an HD van is more often capacitated by weight than volume. Additionally, the low values for the load factors can be explained by the planning of routes. For example, sometimes a driver executes two tours during one work shift. The second tour is smaller in order to not exceed the end of the driver's work shift. This results in a low load factor.

General KPI

Vulnerable objects
When performing city logistical activities, many buildings such as schools, offices, and health centres are passed. The Dutch government aims to protect these vulnerable objects by including them in the environmental codes of cities (*Externe veiligheid: kwetsbare gebouwen en locaties*, n.d.). Municipalities should ensure protection from external risks. Currently, the municipality does not take action to ensure the avoidance of vulnerable objects regarding logistical movements. It is only considered where to place vulnerable objects. For example, the municipality tries to avoid placing schools next to busy roads.

Vulnerable objects can be classified into three categories based on the number of people present, duration of visit, and level of self-sustainability in case of an emergency. The three classifications are very vulnerable, vulnerable, and limited vulnerable. For the ten supermarkets of the Dutch retailer in Tilburg, it is evaluated which vulnerable objects are passed by trucks which perform supermarket replenishment. The routes that are travelled are fixed per supermarket.

Eight supermarket replenishment routes take exit 11 on the highway. For one supermarket, exit 12 is taken and for the last supermarket, exit 10 is taken. These choices are made to ensure that trucks drive as long as possible on the highway and that the time inside the city is minimized. A summary of the vulnerable objects that are passed is given in Table 5. The number of vulnerable objects is evaluated for a single trip from the highway to the supermarket. It can be observed that every path passes at least one vulnerable object. The maximum number of vulnerable objects is equal to 8 for supermarket 05.

Table 5: Number of vulnerable objects per priority level per supermarket in Tilburg

	Number of vulnerable objects		
Supermarket	Priority 1	Priority 2	Priority 3
01	0	1	0
05	3	4	1
06	2	2	0
08	0	1	0
25	1	2	0
30	3	2	0
31	1	4	0
56	3	1	0
60	2	0	1
65	2	2	1

3.5 Conclusion analysis and diagnosis

The analysis confirmed that the objectives of city logistics stakeholders differ. The municipality of Tilburg acts on behalf of its residents and tries to increase the liveability of its city. As shown in the literature review, these domains have received little attention compared to industrial challenges (Strale, 2019). Increasing safety and air quality are the main priorities of the municipality of Tilburg. To achieve this, the public stakeholder tries to reduce the number of vehicles inside the city. It is also important where these vehicles drive. Residential areas should be avoided. Large trucks cause noise and air pollution which has a negative effect on the residents. Vulnerable objects such as hospitals and schools should also be avoided. Currently, Tilburg can only control this through access and timing restrictions.

The Dutch retailer prioritizes travel time. Environmental sustainability is considered to a certain extent. The majority of the vehicles are powered by diesel. For large trucks, electrification is difficult because of infrastructure, driving range, and uncertainty about rules from the government. For delivery vans, electric vehicles are a little less difficult to implement, but still less attractive than diesel-powered vehicles because of capacity and driving range. In addition to environmental sustainability, the Dutch retailer tries to increase liveability as a whole. They focus on increasing the safety of delivery vans by monitoring the driving behaviour of employees. They also wish to increase the liveability of cities by determining where large trucks and delivery vans drive. Currently, the fixed driving routes of large trucks can be changed upon requests from supermarket managers. However, the Dutch retailer would like to implement a systematic solution for both retail channels.

The preferences of the stakeholders have been used to analyse the current situation. This showed that many large trucks and delivery vans of the Dutch retailer enter Tilburg every day while making multiple stops per tour. The analysis also showed that the paths from the highway to the supermarkets pass between 1 and 8 vulnerable objects. This illustrates that the liveability could be increased. The range still allows the avoidance of vulnerable objects.

Lastly, both stakeholders indicated that the timing of vehicles is important. Not only because of vulnerable objects but also because of congestion and the disturbance of residents. Vehicles of the Dutch retailer visit Tilburg between 04:00 and 24:00 since timing restrictions are only in place for the inner city centre. Both the municipality of Tilburg and the Dutch retailer would like to find a solution to mitigate the negative externalities of city logistics without imposing rules. The following chapter will evaluate different types of solutions and proposes the design of the best option. The implementation of this solution can be benchmarked to the values which were calculated in the analysis from this section.

4 Conceptual design

This section presents the scope of the system by setting boundaries. Functional requirements are used to define which processes are incorporated into the design. A Functional Requirement (FR) is a specification of how a system should behave. This section also shows the feasibility of the set of functional requirements by combining the literature review with the analysis from the previous section.

The analysis showed that many vehicles drive through cities for supermarket replenishment and home delivery. The literature review showed that this number of urban freight movements is increasing. Measures are required to limit the impact of these movements on the liveability of a city. Especially considering the fact that road transport is the most commonly utilized mode of transportation. Additionally, road transports show the biggest negative impact on the liveability of cities (Demir et al., 2022; Ranieri et al., 2018). The analysis also showed that city logistics pass vulnerable objects which should actually be avoided as much as possible as stated by the stakeholders. All stakeholders acknowledged the importance of mitigating the negative externalities of city logistics but are currently incapable of systematically implementing solutions. They also acknowledged the importance of public-private partnerships for the successful execution of suitable solutions. As shown in the literature review, many solutions for the negative externalities of city logistics exist. The type of solution that will be implemented should be feasible and acceptable for each stakeholder. These two requirements are the basis of the FR set.

The first option for a solution is clean urban logistics. This could be achieved by, for example, environmental zones and electrification of the fleet. However, as shown in the analysis, electrification is not a feasible solution for the short term. Implementing this type of solution would take at least a few years since the infrastructure is not readily available to convert the entire fleet from diesel to electricity. The same reasoning can be applied to infrastructure management. This solution can not be implemented in the short term. Additionally, public stakeholders are already actively managing the infrastructure. For example, the municipality of Tilburg is trying to reduce the number of vehicles in the city centre by making it less attractive for vehicles by increasing the number of one-way streets. Urban distribution centres could be used to minimize the number of urban freight movements. For supermarket replenishment, this solution would not significantly reduce the number of vehicles because of the high load factors in the current situation. For home delivery, an urban consolidation centre could be beneficial. However, its implementation would be difficult because of time windows. Lastly, public stakeholders could impose rules on private stakeholders such as congestion charging or restrictions on time access, noise, and vehicle weight. However, time access restrictions have a counterintuitive effect since their use does not result in a decrease in emissions but rather an increase (Quak & De Koster, 2006). Moreover, all these types of rules are unsuitable for a public-private partnership because the objective of the private stakeholder would not be taken into account.

A solution that would incorporate multiple stakeholders' objectives is adjusting vehicle routes. A different routing strategy could be beneficial because of its influence on many negative externalities such as congestion, emission, safety, and liveability (Holguín-Veras et al., 2020). To verify the feasibility of this solution, the set of FRs is constructed as shown below. Followingly, the feasibility of the requirements is evaluated.

- As few route changes as possible
- Consideration of multiple stakeholders' objectives
  - Private stakeholder: Minimize travel time
  - Private stakeholder: Deliver within time windows for home delivery
  - Public stakeholder: Maximize liveability

The first functional requirement is that the vehicle routes should change as little as possible. This would allow for a fast implementation of the routing solution. The implementation would have a low impact on the operations of a private stakeholder while considering the objectives of a public stakeholder. This can be achieved by changing driving routes between stops. Instead of using conservative techniques such as creating the fastest or shortest path, more advanced paths can be created by considering the different criteria. In the remainder of this report, routing will be referred to as the procedure of selecting a path in a network along which a vehicle can travel from origin to destination. This solution would also be able to satisfy the second functional requirement; the literature review showed that multiple conflicting criteria could be handled when generating vehicle routes between an origin and a destination. So it is methodologically possible, but it should also be evaluated whether it is practically possible as well.

As an example, it is evaluated whether it is possible to change the current situation by adjusting a supermarket replenishment route. This is shown in Figure 7. Route A is the current route that is travelled by trucks, whereas route B is an alternative route which avoids two vulnerable objects. The first number of kilometres is for both routes the same. Therefore, a starting point has been chosen closer to the destination. Route B would decrease priority levels 1 and 2 with one vulnerable object each. The two remaining vulnerable objects are unavoidable. For example, both routes will pass a shopping centre that must be visited since the supermarket is in the middle of this shopping centre. The downside of route B is an increase in travel distance of 2.2 km.

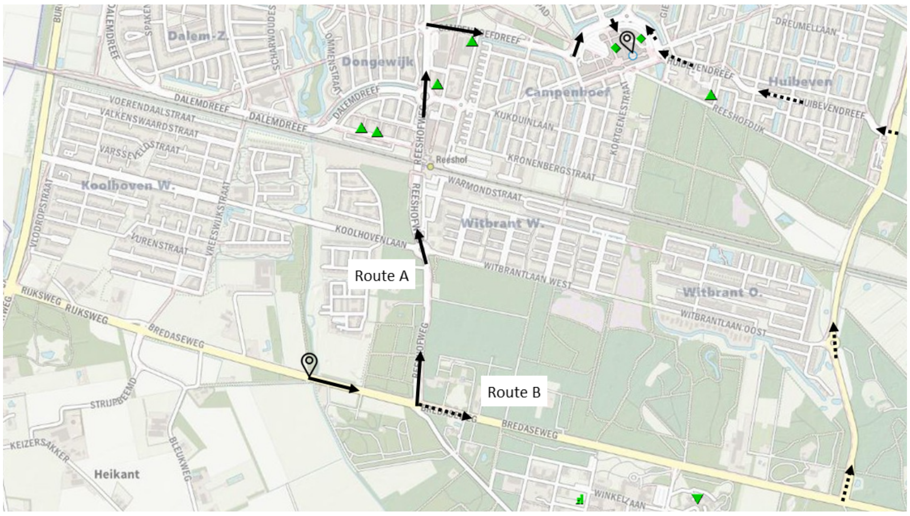


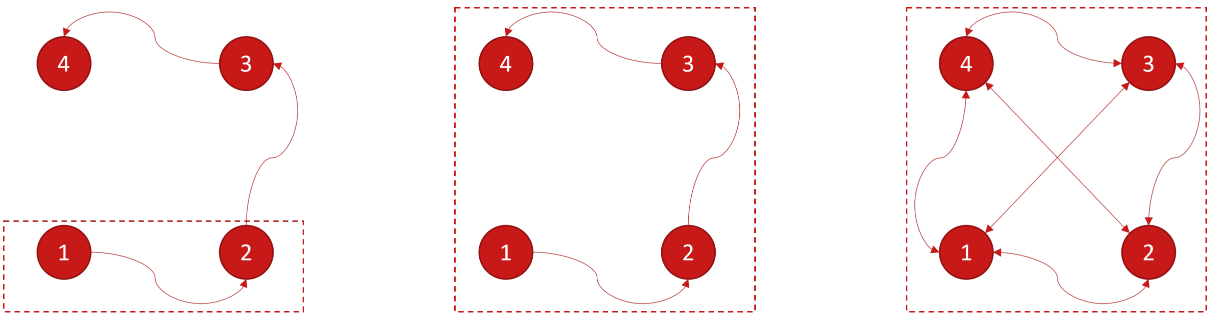
Figure 7: Alternative driving route for supermarket 06

This shows that a detour is possible. However, for home delivery, a special functional requirement was added regarding time window feasibility. Taking a detour implies additional travel time and a later arrival at consecutive stops. However, the analysis showed that most of the home deliveries depart before the end of the time window. For these deliveries, the average spare time was equal to 70.7 minutes, which is a sufficient amount of time which could be spent on taking a detour.

It has been shown that increasing the liveability of city logistics is possible, but it is unknown what the trade-offs are with opposing criteria. It has also been shown that a city can become more liveable by adjusting the paths taken by city logistics vehicles between subsequent stops. The private stakeholder is prepared to take a detour but is currently unable to implement this in a structured way. Additionally, both stakeholders are currently unaware of the implications of driving different routes.

The literature review showed that several methods can be applied to find an optimal driving route. Heuristics such as tabu search and genetic algorithms could be applied. These solutions will not be implemented because a large number of iterations are required to obtain a solution. The second disadvantage is the high number of tuneable parameters. Another solution suggested in the literature review is a neuro-fuzzy model to learn driver preferences. However, this is not the objective of the required solution in this research. On the other hand, the model was extended with Pareto-optimal frontiers. This method would be a relevant option if its computation time would be lower. Because of the high computation time, this solution is not implemented. The last unsuitable solution is the VRP. This method is not implemented because a VRP optimizes a set of routes, whereas the solution that is proposed in this section focuses on driving routes between an origin and destination. The solution that is capable of doing this within a reasonable amount of time is called the weighted sum method.

The weighted sum method is an MCDM method and creates alternative driving routes by assigning different weights to criteria. For a specific set of weights, the optimal alternative can be obtained by applying Dijkstra's algorithm according to the logic proposed by Hua and Abdullah (2018). Based on their method, an algorithm can be constructed which also ensures the feasibility of the time window requirement. The detailed design of this multi-criteria optimal path algorithm is explained in the following section. The multi-criteria optimal path algorithm can be adapted to several scenarios. Three scenarios can be constructed where each scenario is represented by a designated model. Models CurrLink, CurrTour, and NewTour regard the analysis of the current link, current tour, and new tour, respectively as shown in Figure 8.



(a) Model CurrLink (b) Model CurrTour (c) Model NewTour

Figure 8: Visualization of models' scopes

The first model resembles the solution proposed in this section the most. It constructs the optimal path between an origin and a destination. This model only changes the path taken between consecutive stops and does not change the visitation order. This is done in order to satisfy the first functional requirement. Model CurrLink will also take a maximum travel time into account. This maximum travel time can be decided on by a decision maker or can be calculated in the case of home deliveries with time windows. The latter can be done to satisfy the functional requirement of meeting time window restrictions.

The second model calculates the optimal path between each origin-destination link from the current situation. It also does not change the order of visitation to meet functional requirement 1. However, this model is capable of evaluating which link results in the highest benefit. For example, it is capable of assigning additional travel time to specific links for which the highest number of vulnerable objects can be avoided.

Model NewTour is introduced to evaluate the impact of changing the visitation order. This model violates most functional requirements but will give insight into the effect of neglecting static orders of visitation and timing constraints.

5 Detailed design

This section describes the algorithm and models as suggested in the previous section. Firstly, the multi-criteria optimal path algorithm is explained, which includes a description of Dijkstra's algorithm, weights and the maximum time feasibility test. Subsequently, each model is elaborated on in a designated subsection. This includes three models: CurrLink, CurrTour, and NewTour. Additionally, an extension of the model CurrTour is presented which enables swapping two consecutive stops.

5.1 Multi-criteria optimal path algorithm

The algorithm that is proposed uses multiple criteria to generate the optimal path for a set of nodes. An overview has been given in Figure 9. The algorithm assumes that tours are known in advance. Therefore, from the set of nodes, the time slack and locations of the origin, destination, and intermediate stops are derived. Time slack is used as input for the maximum travel time feasibility test which ensures that the minimum required weight is assigned to the travel time criterion to obtain a feasible path. Time slack and the maximum time feasibility test are denoted by different shapes compared to the other constructs in Figure 9 since the algorithm can be used without executing the maximum time feasibility test. If this test is used, it influences the weights assigned to the criteria. Through these weights, one weighted matrix is generated. The weights have been denoted by a different shape in Figure 9 since this is where stakeholders can exercise their influence. The locations are combined with the weighted matrix in Dijkstra's algorithm to compute the optimal path. In the remainder of this subsection, every part of the algorithm is explained in further detail.

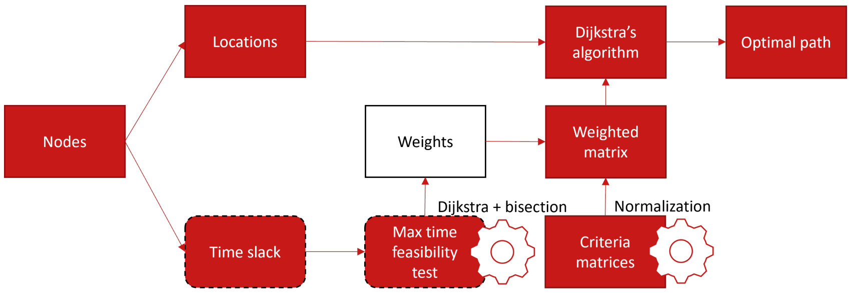


Figure 9: Visualization of the multi-criteria optimal path algorithm

Locations and criteria matrices

The locations and criteria matrices apply to a geographical region that is divided into areas. A customer location represents one of the areas. A criterion matrix includes values for each combination of areas. Consequently, each matrix resembles a dissimilarity matrix. The model requires the matrices to be normalized because different criteria matrices have varying data ranges (Hua & Abdullah, 2018). Normalization is essential to ensure comparability between the different criteria. At least two criteria matrices have to be provided: one regarding travel time and a second criterion matrix regarding liveability. The travel time criterion is necessary for the consideration of time windows. Adding multiple criteria in addition to travel time is possible.

Dijkstra's algorithm

The multi-criteria optimal path algorithm uses Dijkstra's algorithm at multiple steps. It is both used for the maximum time feasibility test and to construct the optimal path when all input has been preprocessed. Dijkstra's algorithm has been chosen as it has proven its applicability to similar contexts. Dijkstra's algorithm finds the shortest path from a specific origin area to every other area. The algorithm outputs a list which denotes the predecessor for each area. This list can be used to construct the shortest path for each destination from the specified origin.

Weights

Weights have to be assigned to the criteria that are provided. These weights can be assigned by decision-makers or an expert group sampled from the stakeholders. A distinction is made between the time criterion and non-time criteria. This is done to be able to apply the bisection method for the maximum travel time feasibility test as will be described in another subsubsection. The weight for the time criterion is denoted as α and the weight for the non-time criteria is denoted as β. Both weights should add up to 100%. The non-time criteria can be given weights per individual criterion. This set of sub-criteria is denoted by S. Subsequently, the weights can be defined as w_s. For these weights, it also holds that they should add up to 100%. In conclusion, the complete set of weights can be computed according to Equation 1.

$$\text{weights} = [\alpha, \frac{\beta \cdot w_1}{100}, ..., \frac{\beta \cdot w_{|S|}}{100}] \tag{1}$$

Time slack and maximum travel time feasibility test

The multi-criteria optimal path algorithm should be able to process maximum travel times and time windows. This is implemented through the definition of a maximum travel time which influences the weights. To find which sets of weights are feasible, the weights α and β from the previous subsubsection are used. The maximum travel time feasibility test should find the value for α for which the travel time does not exceed the maximum allowed time, which is called the feasibility percentage. For this purpose, the bisection method is applied. The procedure of this method can be explained with Figure 10. The feasibility percentage is found through bisection, which is denoted by y in Figure 10.

Point a corresponds to the current situation where travel time is the most important and receives a weight of 100%. Point b corresponds to the situation where no attention is paid to travel time. It can be argued that point a represents the objective of the private stakeholder and point b represents the objective of the public stakeholder. Points a and b are used as input for the bisection method. In addition, bisection requires a function as input. When this function is larger than zero, the maximum time is larger than the travel time and a detour is possible. The opposite is true when the function is smaller than zero. In that case, no detour is possible. The bisection method attempts to find the point for which the function is exactly equal to zero.

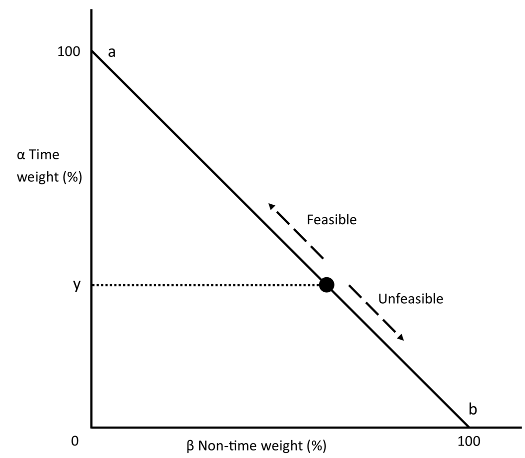


Figure 10: Maximum travel time feasibility test visualization

The procedure of the maximum travel time feasibility test is described as pseudocode in Algorithm 1. It first defines points a and b. It evaluates if a full focus on travel time results in an infeasible solution. If this is the case, the feasibility percentage is set to 100. If this is not the case, it evaluates if no focus on travel time results in a feasible solution. If this is the case, the feasibility percentage is equal to zero. If both statements are not satisfied, it will apply the bisection method. This is denoted by the while loop in Algorithm 1. Point y regards the point in the middle between a and b. Subsequently, the function value at y is calculated. Based on the sign of this value, either point a or b is updated. This cycle is executed until either the function value at y is equal to zero or if the interval between a and b is small enough.

Algorithm 1 Maximum travel time feasibility test in pseudocode

$f(x)$ = maximum allowed travel time - travel time
$a \leftarrow 100,\ b \leftarrow 0$
if $f(a) \leq 0$ **then**
    $y \leftarrow 100$
else if $f(b) \geq 0$ **then**
    $y \leftarrow 0$
else
    while $f(y) \neq 0$ and $\frac{|b-a|}{2} > 0.01$ **do**
        $y \leftarrow \frac{a+b}{2}$
        if $\text{sign}(f(y)) = \text{sign}(f(a))$ **then**
            $a \leftarrow y$
        else
            $b \leftarrow y$
        end if
    end while
end if

In a home delivery setting, each stop within a tour has been given a time window. Therefore, just applying a set of weights to the multi-criteria optimal path algorithm is not always possible. It should be evaluated which sets of weights ensure that taking a detour still ensures departing before the end of the time window of a destination. If in the current situation, the departure was before the end of the time window, time is available for a detour. The maximum time available is defined as the current travel time from origin to destination plus the non-negative difference between the departure at the destination and the end of the time window of the destination. This is also shown in Equation 2.

$$\text{max time} = (\text{arrival}_{\text{des}} - \text{departure}_{\text{ori}}) + (\text{end time window}_{\text{des}} - \text{departure}_{\text{des}})^+ \tag{2}$$

5.2 Model CurrLink

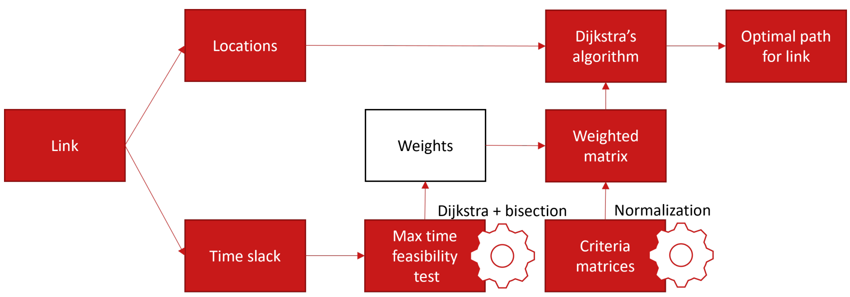


Figure 11: Visualization of model CurrLink: link analysis

The first model analyses links from the current situation. An overview is given in Figure 11. The model views the time window of each customer as a hard constraint. This is done by analysing each link individually. The disadvantage is that causality within tours is neglected. For example, taking a detour between stops 1 and 2 implies later arrivals at every stop succeeding number 2.

5.3 Model CurrTour

The second model analyses tours from the current situation. An overview is given in Figure 12. This model calculates the time slack per link and aggregates this into a maximum allowed travel time for the entire tour. The model can decide on the allocation of detour time to specific links. The disadvantage is that stops may not be visited within the time window.

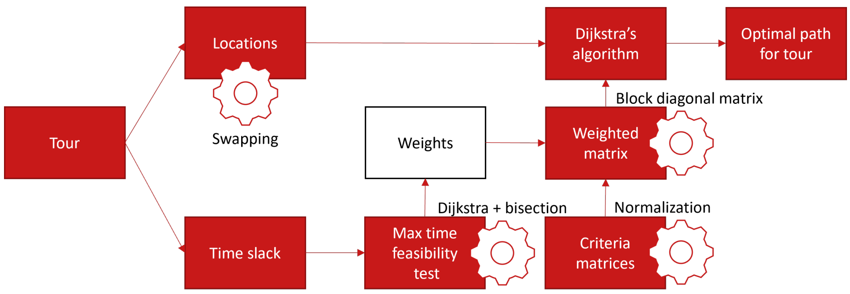


Figure 12: Visualization of model CurrTour: tour analysis

Additionally, the weighted criteria matrix has to be modified: a block diagonal matrix has to be created. Each main-diagonal block represents one link. Therefore, the number of main-diagonal blocks is equal to the number of links within a tour. As opposed to standard block diagonal matrices, the off-diagonal blocks are not zero matrices but matrices filled with big M values. This is done as these entries should not be picked by Dijkstra's algorithm. However, a few values should be changed to zero to ensure the connection between links.

This can be illustrated with an example tour: $1 \rightarrow 2 \rightarrow 3$. For this tour, a block diagonal matrix with two main-diagonal blocks is created according to the logic shown in Table 6 on the left side. The upper left corner represents the matrix for the first link. The lower right corner represents the matrix for the second link. The off-diagonal blocks are matrices filled with big M values except for (2, 2) in the upper right corner. This value is set to zero to ensure the connection between links 1 and 2. The actual block diagonal matrix is shown in Table 6 on the right side. The value for (2, 5) has to be set to zero since index 2 is the destination of link 1 ($1 \rightarrow 2$) and index 5 is the origin of link 2 ($2 \rightarrow 3$).

Table 6: Illustration of the matrix modification procedure for model CurrTour

Area		Area 1	Area 2	Area 3	Area 1	Area 2	Area 3
Area	1	Link 1 ($1 \rightarrow 2$)			M	M	M
	2				M	0	M
	3				M	M	M
	1	M	M	M	Link 2 ($2 \rightarrow 3$)		
	2	M	M	M			
	3	M	M	M			

Index		1	2	3	4	5	6
Index	1	a	b	c	M	M	M
	2	d	e	f	M	0	M
	3	g	h	i	M	M	M
	4	M	M	M	a	b	c
	5	M	M	M	d	e	f
	6	M	M	M	g	h	i

Model CurrTour can be extended to include swapping. This modification iteratively executes model CurrTour by evaluating a selection of stop visitation orders. The new sequences that are considered are obtained by each possible swap between two consecutive stops. Model CurrTour with the swapping extension evaluates each possible swap and returns the optimal path.

5.4 Model NewTour

The third model creates new tours based on the current tours. An overview is given in Figure 13. This model analyses each possible link given the stops in a current tour and subsequently determines the optimal order of visitation. The optimal path between each possible link is obtained through the multi-criteria optimal path algorithm without considering a maximum travel time. The optimal order of visitation is obtained through the Travelling Salesman Problem (TSP).

It should be noted that model NewTour creates a tour which returns to the origin in opposition to models CurrLink and CurrTour. Therefore, when comparing the obtained optimal path with the current situation, a translation should be made since the tour in the current situation does not return to the origin.

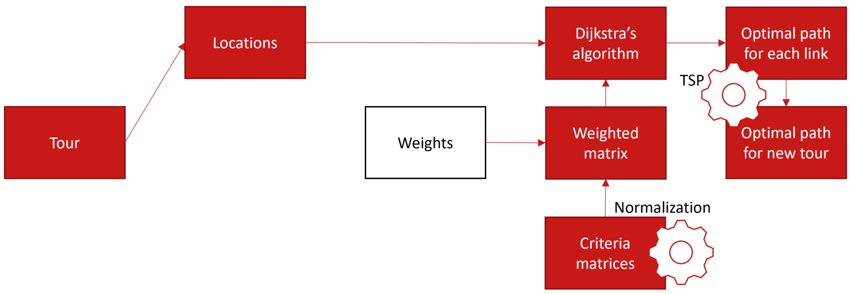


Figure 13: Visualization of model NewTour: new tour generation

The TSP that has been implemented is shown below. It minimizes the costs of the links that are used. For this purpose, decision variable x_{ij} is introduced. This variable is equal to 1 if link i, j is used and 0 otherwise. Stops i and j are part of the vertices set V. Links i, j are part of the links set A. Set S includes the subsets of V. Constraints 1 and 2 ensure that the tour arrives and departs at each stop, respectively. Constraint 3 is the sub-tour elimination constraint as proposed by Dantzig, Fulkerson and Johnson (1954).

$$\min \sum_{(i,j)\in A} c_{ij} x_{ij}$$

$$\text{s.t.} \quad \sum_{i\in V, i\neq j} x_{ij} = 1 \qquad \forall j \in V \qquad (1)$$

$$\sum_{j\in V, i\neq j} x_{ij} = 1 \qquad \forall i \in V \qquad (2)$$

$$\sum_{i\in S} \sum_{j\notin S} x_{ij} \geq 1 \qquad \forall S \text{ s.t. } 1 \leq |S| \leq |V| - 1 \qquad (3)$$

6 Case Study

This section applies the algorithm and models from the previous section to the case study that has been introduced in the analysis. The algorithm and models proposed in the previous sections can incorporate many criteria, but a selection will be made for the application to the case study. The first subsection describes which data has been used. Subsection 6.2 describes the methodology that has been applied to obtain results, which are presented in the subsection 6.3. The last subsection discusses the interpretation and limitations of the results.

6.1 Data

Objectives selection

Not all criteria as shown in Table 1 and Table 2 are suitable for this context. Therefore, some changes will be made to obtain a final list of highly applicable criteria as shown in Table 7. Travel time and distance will be used because of their importance for the private stakeholder. Additionally, travel time is essential as mentioned before. This criterion is required for the consideration of maximum travel times. Especially for the home delivery channel, a maximum travel time is crucial to be able to deliver within the specified time window.

For the public stakeholder, two criteria were added based on the data. Two criteria regarding liveability called exposure and disturbance will be added, which have also not been treated in the literature yet. These criteria can be obtained from the available public data. Exposure regards the number of on-route vulnerable objects of the highest priority a vehicle passes during a trip (*Externe veiligheid: kwetsbare gebouwen en locaties*, n.d.). These include, for example, schools, health centres, and day-care for children. It would be valuable to redirect logistical vehicles to contribute to the protection of vulnerable objects. Only the highest priority level will be considered because these are the most valuable to avoid. The analysis showed that stakeholders think it is important to avoid these vulnerable objects as much as possible. However, a structured approach was not yet possible but can be achieved by implementing this criterion into the algorithm and models.

The same holds for the second criterion which is called disturbance. This criterion regards the number of on-route residents. These people experience disturbance from city logistical activities. This criterion is added because it has not been treated by existing literature but it does relate to many other criteria that have been treated in academic works. Residents can, for example, experience disturbance in the form of noise- and air pollution. By minimizing the number of on-route residents in the algorithm and models, the number of people suffering from noise- and air pollution is optimized as well. Additionally, the inclusion of this criterion also satisfies the preferences of the stakeholders to minimize the time inside the city. For example, more residents live inside the city than close to highways. By minimizing the number of on-route residents, the algorithm and models attempt to maximize the distance travelled on highways. As was shown in the analysis, this is preferred by both the public and private stakeholders.

Table 7: Final list of criteria for the multi-criteria optimal path algorithm

Criterion	Description
Travel time	Travel time in minutes between origin and destination
Travel distance	Travel distance in kilometres between origin and destination
Exposure	Number of on-route vulnerable objects
Disturbance	Number of on-route residents

Data collection

To construct the models for the case study, data sets of home delivery were used. In addition, a few data sources have been added as shown in Figure 14.

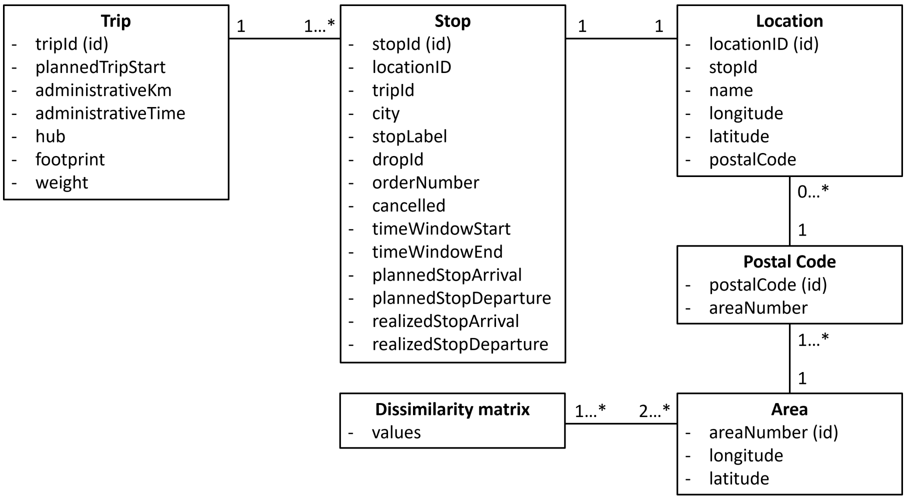


Figure 14: Entity-relationship diagram of the routing data and traffic model

The additional data sources revolve around the traffic model for the province of Noord-Brabant called the BrabantBrede ModelAanpak (BBMA). This model was created by Goudappel. Four regions can be distinguished in this model: West, Northeast, Southeast, and the middle of Brabant. The latter is to which Tilburg belongs. Tilburg is geographically segmented into 609 areas as shown in Figure 15. For each area, it is evaluated which postal codes are present within that area. So each area consists of multiple postal codes. Each area is identified by a centroid which is the centre of that area. The network formed by areas is asymmetrical because, for example, Tilburg has implemented one-way streets.

Dissimilarity matrices have been provided by Goudappel and Stratopo. Goudappel provided matrices which include travel times and travel distances between each combination of two centroids. Stratopo used the traffic model of Goudappel as input to construct matrices including data about vulnerable objects and residents. These matrices have been developed by generating the 370,881 (609 x 609) routes. Each vulnerable object/collection of residents was assigned to the closest route.

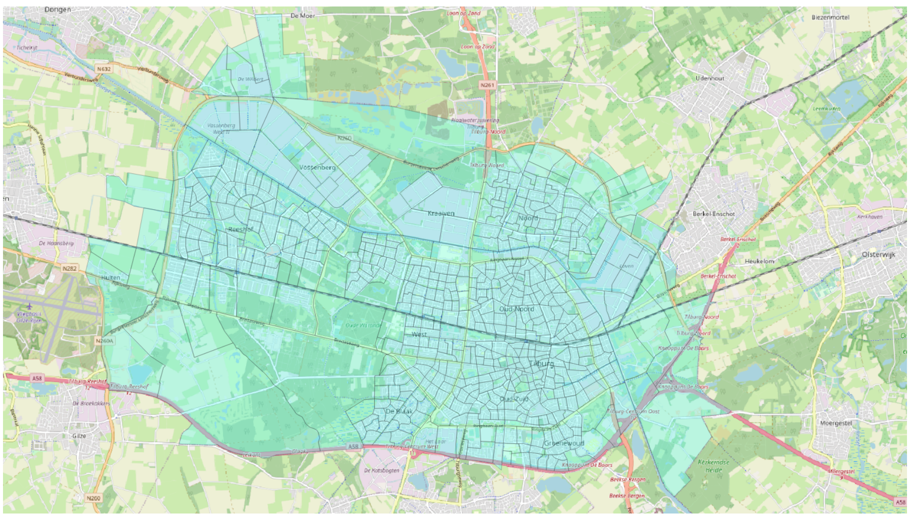


Figure 15: Visualization of the geographical segmentation of Tilburg

Data preprocessing

A few data preprocessing steps have been executed. Data integration was executed to link different data sources. For example, area number was used to connect areas with postal codes. Secondly, data cleaning has been applied to remove trips which included interchanges. These data entries negatively influenced the data because the location IDs of these stops were all equal to zero so cross-referencing locational data was impossible for these points. The entire trip was deleted because exclusively deleting these stops would make the data biased. For the remaining trips, stops have been removed which were not in Tilburg since no data regarding the criteria was available for these stops. Because of this, an additional transformation had to be applied to the maximum time calculation for model CurrTour. The logic behind Equation 2 was still used. However, not all consecutive stops in the cleaned data actually succeed each other. Therefore, Equation 2 was used for consecutive stops in Tilburg in the uncleaned data. Subsequently, the maximum travel time was corrected by multiplication with the following factor: the number of links in the cleaned situation divided by the number of links in the uncleaned situation. The last data cleaning step regarded the removal of trips with less than 2 stops in Tilburg. The reasoning behind this was the inability of creating routes if only one stop had to be visited in Tilburg. Data cleaning was also applied to the dissimilarity matrices from Stratopo since areas 93, 310, and 528 were missing from the data. The data provider could, unfortunately, not solve this. This has been solved by inserting a big M for these areas.

Data reduction has been applied to all dissimilarity matrices. Only areas 76-693 were relevant as was clarified by Goudappel. This was the case because of their traffic modelling technique. For example, the traffic model of Tilburg is part of a bigger traffic model. To obtain this extract, some areas at the border of Tilburg had to be cut off but are connected to the traffic model of Tilburg to be able to model the flows. However, these areas are not relevant in this context. The last data reduction step applies to model NewTour. Only a subset of data has been used. This subset contained 50 trips to obtain an acceptable computation time for the results. These 50 trips were randomly selected from the data set. However, tours that have been selected included less than 11 stops because the Gurobi solver that was used is not able to process a model with more than 2000 constraints. Because of the sub-tour elimination constraint, this limit would be exceeded for some tours.

6.2 Methods

Trade-off analysis

Since different weights can result in different optimal paths, a trade-off analysis has been performed to gain insight into the criteria's correlations. Primarily, the correlation between travel time and the number of on-route residents; and travel and the number of vulnerable objects has been investigated. This has been done because travel time is more important than travel distance to the private stakeholder. In addition, travel time was more interesting to gain insight into because of the effect on time windows. The presented analysis, however, can also be repeated for travel distance. Additionally, it should be noted that the trade-off analysis compares the optimal route obtained through the models with the fastest route which is driven in the current situation. Subsequently, the differences are converted to average values per origin-destination link to be able to compare the different models.

The trade-off analysis has been performed for all three models. In order to execute the analyses, a set of weights had to be identified. This was done by selecting values for $\alpha \in [0,100]$ and $w_1, w_2, w_3 \in [0,100]$. The variables α, w_1, w_2, and w_3 represent the weight on travel time, travel distance, number of on-route vulnerable objects, and number of on-route residents, respectively. For models CurrLink and CurrTour, some values for α result in time window infeasibility. Enough weight should be assigned to the travel time criterion in order for stops to be visited within the time window. Through the maximum time feasibility test, the minimum required value for α was found. This value is called the feasibility percentage. For the weight sets where α is below this feasibility percentage, the algorithm was executed with α equal to the feasibility percentage.

Geographical visualizations of a selection of routes between an origin and destination have also been created. These visualizations have been generated by executing the multi-criteria optimal path algorithm without a maximum time feasibility test. The criteria that were used are travel time and the number of on-route vulnerable objects. Different driving routes have been obtained by assigning the following weights to the criteria: 0%, 50%, and 100%. The green, and often the longest route, represents the route where the weight on travel time (α) equals 0. This regards the route that avoids as many vulnerable objects as possible. On the other hand, the red line represents the fastest route where α equals 100. Lastly, the intermediate option is denoted by the blue line for which α equals 50.

Bargaining power for the stakeholders

If a city has the potential for higher liveability by changing city logistics routes, it would mainly become the responsibility of the private stakeholder to operationalize the new routes. However, the public stakeholder should create an incentive for the private stakeholder to make a public-private partnership such as a covenant work. Guidance can be provided to the stakeholders regarding tools for negotiation. It has been investigated which possibilities exist. According to the logic of the trade-off analysis, the interactions between travel time and the number of on-route residents; and travel time and the number of vulnerable objects were used. Two measures for the supply chain channel and two measures for the home delivery channel were identified.

Supply Chain

For the SC channel, the stakeholders are able to choose which highway exit to use to enter the city for each supermarket of the private stakeholder. Secondly, they can choose the maximum amount of time to travel from the highway exit to the supermarket. For these two measures, the route from the distribution centre to the highway exit is out of scope. This is reasonable since the supermarkets are supplied from many different DCs across the Netherlands.

For the evaluation of highway exits, all possible combinations of each highway exit and each supermarket were evaluated for the number of residents and vulnerable objects. For this purpose, the general multi-criteria optimal path algorithm with the maximal travel time feasibility test has been used. The weights were defined as follows: $\alpha = 0$, and either w_2 or $w_3 = 100$. Model CurrLink was used for the investigation of time for detours. Different maximum travel times were given to the model to evaluate changes in the number of residents and vulnerable objects. Subsequently, the average of all supermarkets has been calculated.

Home Delivery

For the HD channel, the private stakeholder can increase the length of the time windows and change the order in which customers are visited. All three models were used to evaluate the impact of larger time windows. It has been analysed what the effects on the number of on-route residents and on-route vulnerable objects were when increasing time windows. To investigate the implications of changing the order in which customers are visited, two approaches were taken. The first approach was swapping two consecutive stops and the second approach was creating an entirely new visitation order. Model CurrTour was compared to model CurrTour with the swapping extension for the first approach. Model CurrTour was compared to model NewTour for the second approach.

6.3 Results

Trade-off analysis

Two examples of the trade-off analysis for the criteria travel time and the number of on-route vulnerable objects are shown in Table 8 and Table 9. It can be observed that high additional travel times were obtained for all models when alpha was equal to zero.

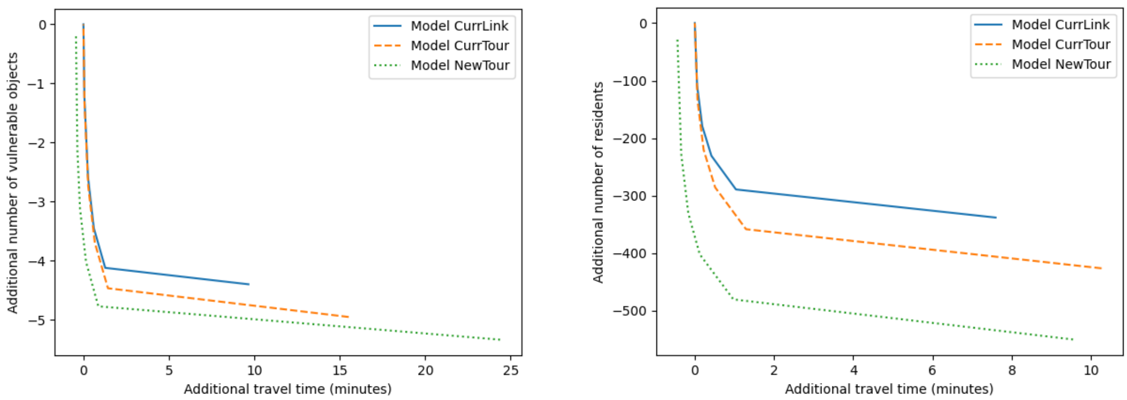
Table 8: Numerical evaluation of the trade-off analysis regarding example trip 1

	Additional travel time (minutes)			**Nr vulnerable objects avoided**		
Model → Alpha ↓	CurrLink	CurrTour	NewTour	CurrLink	CurrTour	NewTour
0	14.2	28.5	20.9	33	33	33
20	2.7	2.7	-5.0	32	32	32
40	2.1	2.1	-7.4	31	31	30
60	0.7	0.7	-8.5	27	27	27
80	0.1	0.1	-9.1	24	24	21
100	0	0	-9.1	0	0	21

Table 9: Numerical evaluation of the trade-off analysis regarding example trip 2

	Additional travel time (minutes)			**Nr vulnerable objects avoided**		
Model → Alpha ↓	CurrLink	CurrTour	NewTour	CurrLink	CurrTour	NewTour
0	23.3	152.0	178.0	31	44	46
20	4.9	6.2	4.7	27	37	44
40	4.9	6.2	0.6	27	37	41
60	3.4	4.6	-2.6	24	34	32
80	0	0	-2.9	0	0	29
100	0	0	-3.8	0	0	-3

A large drop was obtained by slightly increasing alpha. On the other hand, high values of alpha lead to small additional travel times and small numbers of vulnerable objects avoided. Moreover, negative values were obtained for models CurrTour and NewTour. These models were even capable of simultaneously reducing multiple criteria at once. Models CurrLink and CurrTour were only able to achieve non-negative additional travel times or non-negative numbers of vulnerable objects avoided. Additionally, the models produced more varying results in example 2 than in example 1. For example, when alpha was equal to zero, the same number of vulnerable objects were avoided by all models whereas these values varied in example 2.



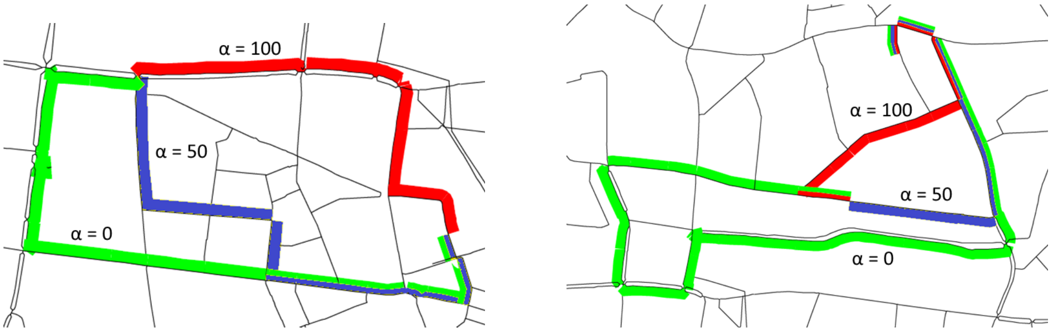
(a) Vulnerable objects

(b) Residents

Figure 16: Visualization of the trade-off analysis

The trade-off analysis was performed for multiple trips which enabled visualizing models CurrLink, CurrTour, and NewTour as shown in Figure 16. The three models show similar patterns. A large drop on the left side of the graph and a long tail towards the right side of the graph. It can be noticed that regarding liveability, model CurrTour performed better than model CurrLink. Moreover, model NewTour performed better than models CurrLink and CurrTour. The left sides of the graphs are marked by points (0, 0) for models CurrLink and CurrTour. This is not the case for model NewTour. This is in accordance with the values shown in the tables. It is also confirmed that model NewTour was capable of reducing the travel time compared to the fastest tour. Therefore, the line of model NewTour passes the left side of the vertical line where the additional travel time equals zero.

Geographical visualizations of a selection of routes are shown inFigure 17. The fastest route, intermediate route, and route that avoids all vulnerable objects are denoted by the red, blue, and green lines, respectively. It can be observed that the intermediate route is slightly longer than the fastest route, whereas the most liveable route takes a significant detour. This is especially the case for the origin-destination link from Figure 17b.



(a) Example origin-destination link 1 (b) Example origin-destination link 2

Figure 17: Geographical visualization of possible routes for example origin-destination links 1 and 2

Bargaining power for the stakeholders

Supply Chain

The first measure to gain bargaining power was the choice of a highway exit. The preference for one highway exit over the other regarding liveability was strongly influenced by the amount of time available for driving. This can be shown by executing the evaluation for different values for the maximum travel time. Figure 18 indicates the number of on-route residents and vulnerable objects per supermarket per highway exit when the maximum allowed time was equal to zero. This means that the algorithm automatically calculated the fastest route from each highway exit to each supermarket. The number of residents and vulnerable objects along these routes have been shown in Figure 18. It can be noticed that the fastest routes from highway exit 10 to supermarket 8, from highway exit 11 to supermarket 1, and from highway exit 10 to supermarket 5 do not pass any vulnerable objects. Regarding the number of on-route residents, these highway exits are the best options for the respective supermarkets.

On the other hand, Figure 19 shows the same type of figure except that the maximum travel time equals 60 minutes. The differences between highway exits per supermarket become a lot smaller. This can be explained by the large amount of time that is available for avoiding residents and vulnerable objects. Especially the number of on-route vulnerable objects was truly minimized. Exclusively the route to supermarket 31 passes a few vulnerable objects. On the other hand, avoiding all residents was not possible.

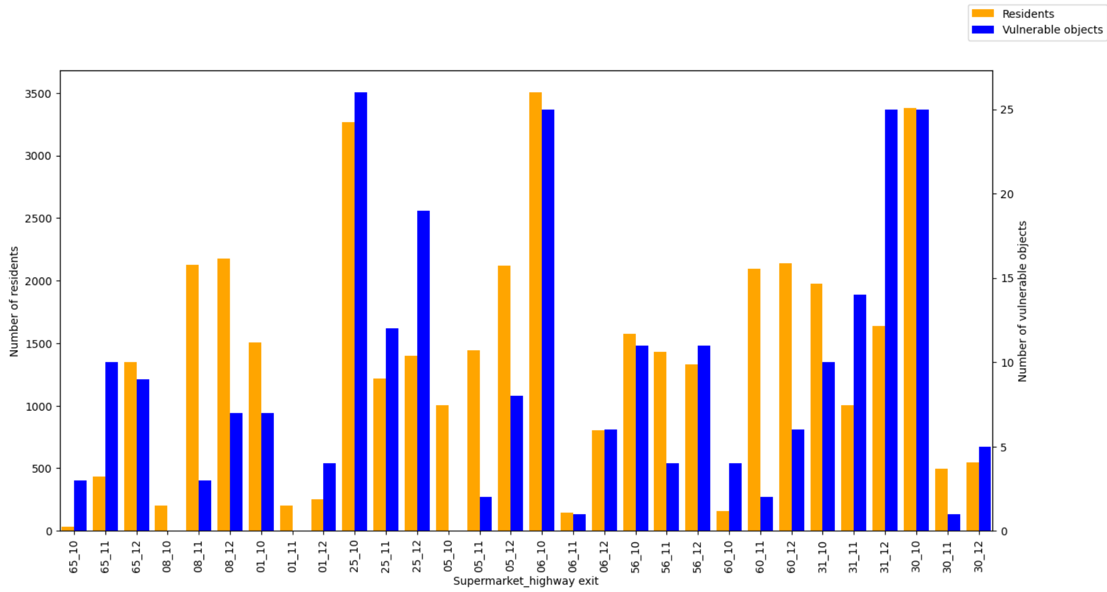


Figure 18: Bar plot for highway exit evaluation with a maximum travel time of 0 minutes

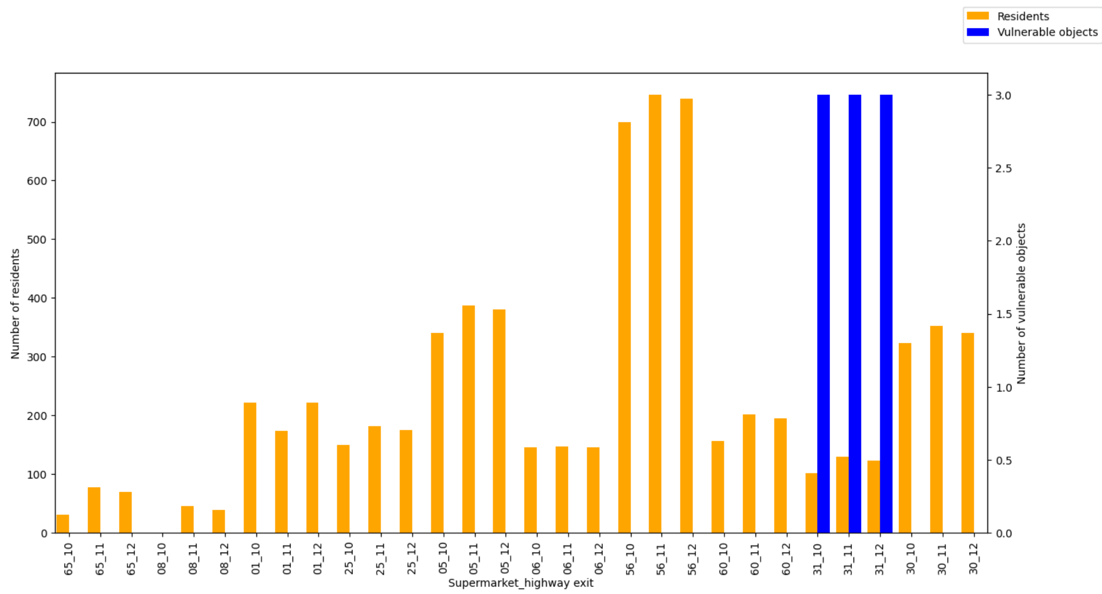


Figure 19: Bar plot for highway exit evaluation with a maximum travel time of 60 minutes

The second measure is the definition of the preparedness of travelling for additional minutes. The analysis performed for this measure is shown in Figure 20. The dotted line is steeper than the other line. This means that to avoid vulnerable objects, the required amount of time was less than when avoiding residents. Additionally, the tail of the line representing residents is longer than the tail of the other line. Extra travel time led to small improvements for higher values of additional travel times.

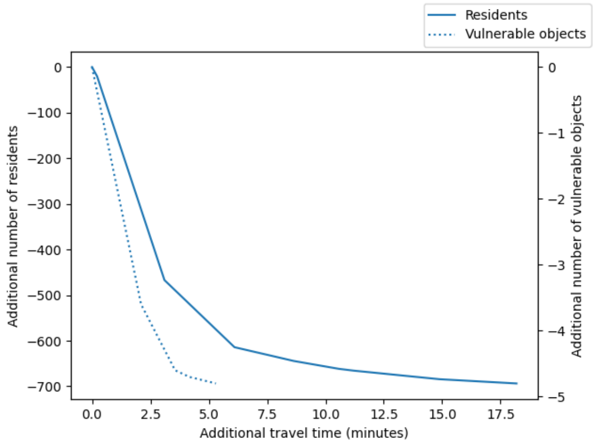
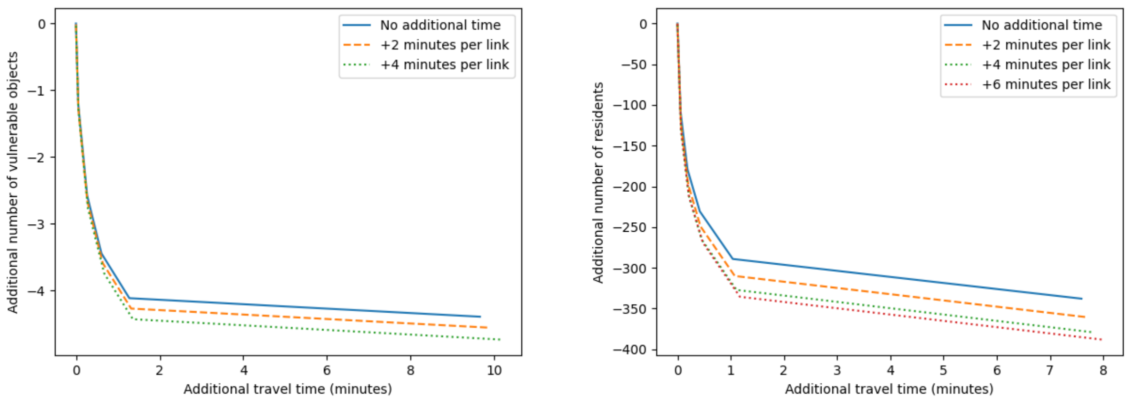


Figure 20: Visualization of detour time evaluation for supermarket replenishment routes

Home Delivery

The first measure for the home delivery channel is increasing the length of the time windows. This analysis has first been performed with model CurrLink as visualized in Figure 21. As expected, slight increases in travel time led to increasing liveability. It should be noted that model CurrLink regards the analysis of links, not tours. Therefore, a recalculation should be executed to incorporate the causality of detour time within tours since a detour at the beginning of a tour implies later arrivals at all subsequent stops. The analysis section showed that the average number of stops was equal to 14.9. This means that the average number of links within a tour was equal to 13.9.



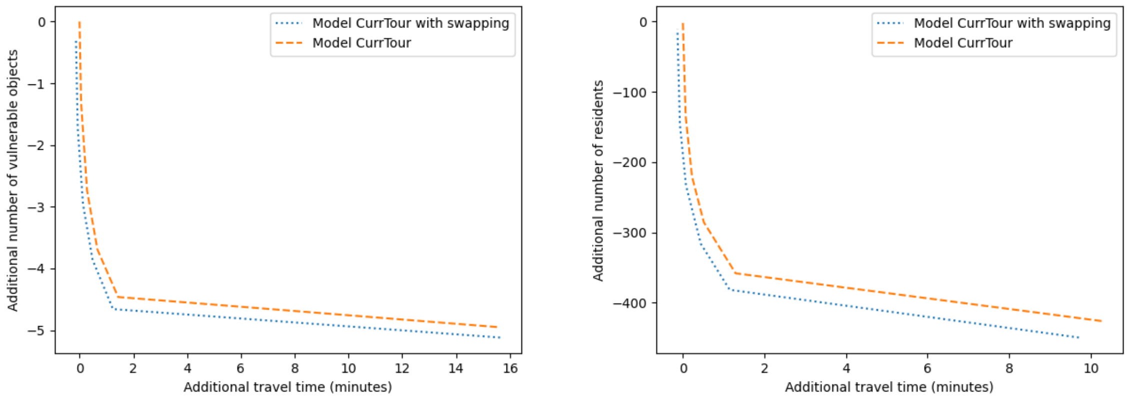
(a) Vulnerable objects (b) Residents

Figure 21: Visualization of the effect of larger time windows on the trade-off analysis

Subsequently, it can be reasoned that increasing time windows by 2, 4, and 6 minutes per link represents an average time window increase of 27.8, 55.6, and 83.4 minutes per tour, respectively. Larger time windows would not be reasonable. The same type of analysis was performed with models 2 and 3. However, very small differences were obtained for model CurrTour and no differences were obtained for model NewTour. Therefore, these visualizations are not presented here.

The last suggested measure was changing the order in which stops are visited. The trade-off analysis showed that an entirely new visitation order resulted in a higher number of vulnerable objects and residents avoided compared to the visitation order in the current situation.

To evaluate swapping, visualizations have been created as shown in Figure 22. This figure shows the differences between model CurrTour and model CurrTour with the swapping extension. Figure 22a and Figure 22b show that swapping was primarily beneficial for the number of residents. The difference in the number of vulnerable objects avoided was relatively smaller.



(a) Vulnerable objects

(b) Residents

Figure 22: Visualization of the effect of swapping on the trade-off analysis

6.4 Discussion on results

Interpretation

The trade-off analysis can be used to gain some interesting insights. First of all, extremes are not preferable options. For example, a complete focus on minimizing the number of on-route vulnerable objects results in high values for additional travel time. A more feasible vehicle route can be obtained by slightly increasing the weight assigned to the travel time criterion. This was confirmed by the numerical evaluations of the trade-off analysis and the geographical visualizations. More specifically, the visualizations of the trade-off analyses revealed that an additional travel time of 2 minutes would lead to a significant decrease in the number of on-route vulnerable objects and residents.

This shows that opportunities exist between the extremes where multiple stakeholders' objectives can be addressed to a certain extent. The algorithm and models are capable of simultaneously optimizing different opposing criteria. This finding can be extended from origin-destination links to entire tours. By considering the interdependencies of stops within tours, it can be reasoned that an additional travel time of 2 minutes per link results in an average additional travel time of 27.8 minutes per tour. The average number of stops per tour (13.9) from the analysis has been used for this calculation.

For the stakeholders to obtain bargaining power, the implications of additional travel time can be evaluated per supermarket. The results indicated that also for these routes, only a small additional travel time is required to avoid a significant number of vulnerable objects and residents. On average, 5 additional minutes would already result in the maximum number of vulnerable objects that can be saved. This time is slightly larger for the number of on-route residents. The amount of additional travel time prepared to travel can be used as input for the highway exit evaluation. It was demonstrated that the maximum travel time has a big influence on which highway exit results in the smallest number of on-route vulnerable objects and residents.

For the home delivery channel, the length of time windows can be increased to obtain additional travel time. It was shown that small improvements were possible for the number of on-route vulnerable objects and residents. Larger time windows resulted in bigger improvements. However, increasing time windows by more than 83.4 minutes would not be reasonable for the private stakeholder. An increase of 27.8 minutes or 55.6 minutes would be more reasonable but these resulted in small improvements regarding the number of vulnerable objects and residents avoided. Additionally, only model CurrLink produced significant improvements as opposed to models CurrTour and NewTour. The reason for this is that model CurrLink was more often constrained by time windows than model CurrTour. Model NewTour does not consider any time windows at all. Another measure which can be used as bargaining power for the home delivery channel is changing the order of visitation. By swapping two consecutive customers, the operation impact is low but a small improvement in liveability was obtained.

Limitations

The first limitation is a bias that was created in model NewTour. Since this model creates an entire tour, an additional link is evaluated in the trade-off analysis compared to models CurrLink and CurrTour. A one-on-one evaluation is, therefore, biased. Additionally, there were four limitations with regard to the data. The traffic model separated Tilburg into areas. Because of this, inaccuracies exist within the criteria values between stops. For example, the actual travel time from one stop to another stop may deviate from the travel time from the area where the first stop is to the area where the second stop is. Secondly, the tours were reduced as such to only include stops in Tilburg. A lot of valuable information is lost because of the removal of stops outside of Tilburg. Thirdly, the execution of model NewTour was limited by the Gurobi solver since large problems could not be handled. Lastly, the size of the subset forms a limitation. Only 50 tours were used to generate the results.

7 Conclusion

This section presents a clear overview of the research findings. A brief summary of key results is given to answer the main research question. Lastly, recommendations for future research are presented.

It was observed that the number of urban freight movements is large and keeps on increasing along with the number of people living inside cities. Many large trucks and delivery vans visit the city multiple times a day. These city logistics are essential but also endanger the liveability of a city. City logistics vehicles pass vulnerable objects and have a big impact on other negative externalities such as congestion, air pollution, and noise pollution. It was found that different stakeholders have conflicting interests. Public stakeholders want to increase the liveability of a city while private stakeholders want to enter and leave the city as fast as possible. A public-private partnership is required to mitigate the negative externalities of city logistics. This collaboration should be used to implement a solution which considers all stakeholders' objectives. This research aimed at satisfying the need of the stakeholders to find a systematic solution. For this purpose, the following main research question was formulated:

Which solution minimizes the negative impact of city logistics on the liveability of a city while satisfying private stakeholders' preferences?

Imposing rules such as time access restrictions would not be suitable since these do not meet the criteria of private stakeholders. Other solutions such as electrification, infrastructure management, and urban consolidation centres were viable options but not suited for short-term implementation. A more feasible solution was the incorporation of conflicting stakeholders' objectives into a routing solution. Multiple routing solution methods are capable of considering multiple conflicting objectives. It was chosen to apply the weighted sum method which assigns weights to criteria. Additionally, a maximum travel time feasibility test and Dijkstra's algorithm have been used to obtain the optimal path between an origin and destination. All these constructs have been combined into a multi-criteria optimal path algorithm.

Based on this algorithm three models have been constructed that analyse current links, current tours, and new tours. The application of these models to the case study resulted in some interesting insights. Considering multiple conflicting stakeholders' objectives is a feasible and attractive solution. Considering only one stakeholder's objective by assigning full weight to one criterion would result in very disappointing values for the other criteria. For example, an extreme such as completely minimizing travel time resulted in low liveability whereas completely maximizing liveability resulted in very high travel times. The former is what is happening in the current situation. However, by slightly increasing the travel time, a big benefit can be obtained in terms of liveability. Only a small detour is necessary to make the city more liveable while still satisfying private stakeholders' preferences.

In addition to implementing a detour between an origin and destination, solutions for supermarket replenishment routes and home delivery have been tested. These solutions have been evaluated with the models that were constructed in this research. Public and private stakeholders can discuss which highway exit to take for each supermarket. However, this is highly influenced by the maximum allowed travel time from the highway to the supermarket. Therefore, this should be determined beforehand. For home delivery, time windows can be enlarged, two consecutive stops can be swapped, and a completely new visitation order could be established. Larger time windows and swapping did not result in big changes. A new visitation order resulted in large improvements compared to the current situation. However, it should be noted that the evaluation of this solution neglected time windows, which should not be neglected in real-life.

Creating detours by applying the multi-criteria optimal path algorithm is the solution that minimized the negative impact of city logistics on the liveability of a city while satisfying private stakeholders' preferences.

Stakeholders should establish a public-private partnership in which the specifics and the application of the multi-criteria optimal path algorithm are discussed. The weights assigned to the criteria should be determined by the stakeholders such that all stakeholders' objectives are considered. This will lead to a systematic approach to guide private stakeholders through the city without the imposition of rules. Additionally, the stakeholders should determine the maximum allowed travel time from the highway to each supermarket, which can be used as input for determining which highway exit to take.

This advice also holds for the case study of this research. The municipality of Tilburg and the Dutch retailer should establish a public-private partnership such as a covenant. The Dutch retailer can use the multi-criteria optimal path algorithm to construct the paths between stops. Both stakeholders should establish the weights that will be assigned to the criteria. Establishing the use of the algorithm in a covenant makes sure that the municipality of Tilburg does not impose additional rules. However, Tilburg should create an additional incentive for the Dutch retailer to use the algorithm. Tilburg could assist in financing electrification or could make an exception for the Dutch retailer when it comes to access and time restrictions.

7.1 Future research

Researchers should focus more on environmental and social issues than on industrial challenges. However, this does not mean that industrial challenges should be neglected. This research showed that methods can be applied that incorporate these conflicting objectives. However, future research should be executed in several directions. First, the algorithm and models could be applied to a different context. It would be valuable to verify their applicability to other cities and different route data sets. Secondly, multiple extensions could be created. Additional criteria could be added to the models such as congestion and air pollution. Another extension would be implementing the algorithm in a dynamic environment by altering travel times in real-time. For example, changing the travel time to big M when a road is closed due to maintenance.

Lastly, it was shown that the largest benefit could be achieved by new visitation orders. This could be implemented into a solution which creates sets of routes which incorporate time windows. The multi-criteria optimal path algorithm can be adapted to serve as input for a Vehicle Routing Problem. Incorporating time windows would result in the most accurate representation of reality. A recommended approach would be to formulate a linear program to obtain optimal results.

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Appendices

A Redundant analyses

Travel time and distance

In order to calculate the average travel time and distance for the SC channel, duplicate trip IDs have been removed. Subsequently, travel time and distance have been calculated by taking the average of data attributes "administrativeTime" and "administrativeKm", respectively. For HD, these data attributes are unavailable and another approach was applied. For each trip, the difference between "realizedArrivalTime" of the start location and "realizedDepartureTime" of the end location has been calculated. The average travel time has been calculated using all travel times. The travel distance per trip was obtained by calculating the euclidean distance between each subsequent location and adding the values per trip. To approximate the travel distances based on the euclidean distances, a correction factor of 4/3 has been used. This factor is used to convert the euclidean norm to the Manhattan norm. The average travel distance was calculated by taking the average of all the travel distances of the trips.

Supply chain

Analyzing all SC transports results in an average travel time and distance of 3.4 hours and 99.0 kilometres, respectively. However, the values for both these KPIs for groceries/fresh goods, frozen products, and PUP orders show big differences as shown in Table 10.

Table 10: Travel times and distances per transport type for the SC channel

	Groceries/fresh	**Frozen**	**PUP**
Travel time (hours)	2.6	7.1	6.1
Travel distance (km)	74.3	217.7	177.0

Home delivery

The average travel time for a home delivery van is equal to 5.6 hours. The average travel distance is equal to 95.4 km.

Stop duration

For the duration of stops, exclusively the stops in Tilburg are relevant. It is not interesting how long a vehicle takes to (un)load outside Tilburg. For the SC and HD channels, data subsets 1E, 1F, 1G; and 2H have been used, respectively. The duration per stop was calculated by the difference between "realizedArrivalTime" and "realizedDepartureTime". The averages for the SC and HD channels have been calculated by taking the average of all stop durations in the respective retail channel.

Supply chain

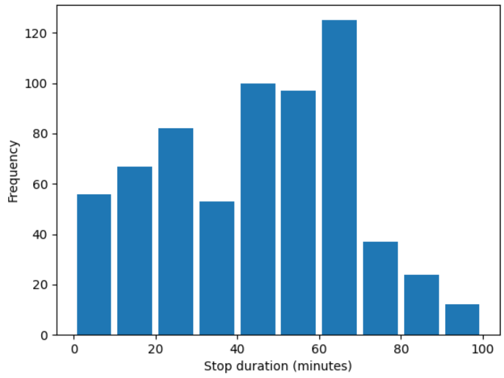
Trucks for the SC channel have high (un)loading times as shown in Table 11 and Figure 23. This is especially the case for vehicles transporting groceries/fresh goods which take, on average, 44.4 minutes per stop. The average duration of the stops for frozen and PUP transports is lower compared to the transports of groceries/fresh goods. This is intuitive when taking into account the number of stops. Trucks delivering frozen products and PUP orders stop more often, deliver less freight per location, and, therefore, have to stop for a shorter amount of time. The histograms showing the duration of stops for frozen products and PUP orders show similar patterns as can be noticed in Figure 23b and Figure 23c. Most of the trucks do not take longer than 40 minutes to (un)load. The largest peak for both transport types is shown for a stop duration between 15 and 20 minutes.

Table 11: The average number of stops and stop times for the SC channel

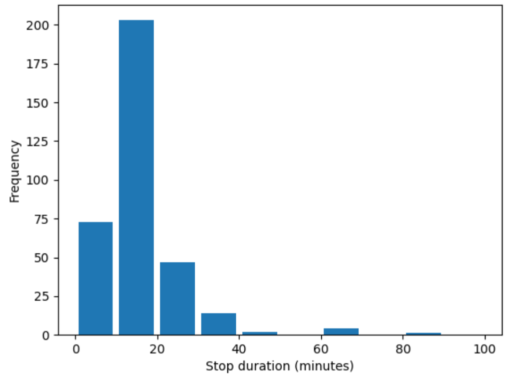
	Groceries/fresh	**Frozen**	**PUP**
Average stop duration (minutes)	44.4	16.7	16.9

Home delivery

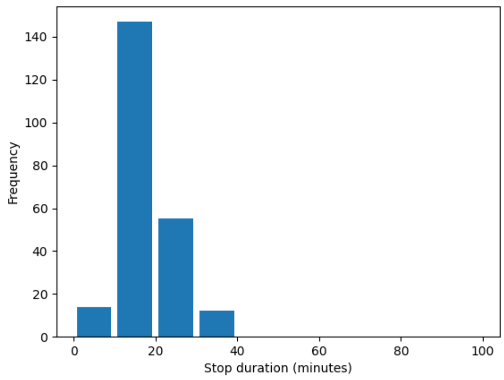
Each stop in Tilburg takes, on average, 10.9 minutes. To elaborate on the duration of stops, Figure 24 has been created. This figure depicts the frequency of each stop duration per HD van. It can be noticed that most of the vans do not stop for longer than 20 minutes. The largest peak is found for a stop duration between 8 and 10 minutes. This is in accordance with the average time available for (un)loading as was confirmed by the Dutch retailer. This time is calculated based on a fixed component and a variable component which is based on the order size and the customer's location.



(a) Groceries/fresh goods



(b) Frozen products



(c) PUP orders

Figure 23: Histograms of the stop duration per transport type for the SC channel

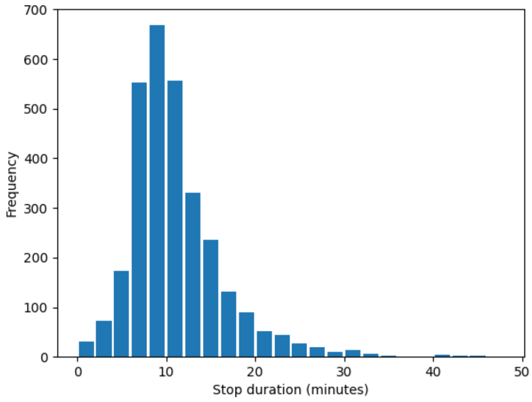


Figure 24: Histogram of the stop duration of vans for the HD channel

B Data set preparation for analysis section

The first data set contains information about Supply Chain (SC) transports. This data set will be denoted by data set 1 according to Table 12. This table has been generated to create a clear overview of the different data sets that are available and which will be described in this section. The second data set contains information about the Home Delivery (HD) channel of the Dutch retailer and will be denoted as data set 2. The main difference between the data sets is which parts of the supply chain are represented as mentioned before.

Table 12: Overview of data set references

Data set number	Data set name	Retail channel
1	Stop data	SC
2	Stop data	HD
3	Locational data	SC
4	Locational data	HD
5	Trip data	HD

Table 13: Description of stop data sets for the SC and HD channels

Data quality				
SC	**HD**	**Data attribute**	**Data type**	**Example**
✓	✓	tripId	Integer	8861_20220801_2
✓	✓	stopId	Integer	20220730_164
✓	✓	stopLabel	Integer or string	1
✓	✓	plannedTripStart	Datetime	2022-08-01T04:15:00.000Z
✓	✓	dropId	Integer	6033046928
✓	✓	orderNumber	Integer	6033046928
✓	✓	locationId	Integer	6033046928
✓	✓	cancelled	Boolean	FALSE
✓	✓	timeWindowStart	Datetime	2022-08-01T05:00:00.000Z
✓	✓	timeWindowEnd	Datetime	2022-08-01T06:00:00.000Z
✓	✓	plannedStopArrival	Datetime	2022-08-01T05:00:00.000Z
✓	✓	plannedStopDeparture	Datetime	2022-08-01T05:08:26.000Z
✓	✓	realizedStopArrival	Datetime	2022-08-01T04:50:01.000Z
✓	✓	realizedStopDeparture	Datetime	2022-08-01T05:08:31.000Z
✓	x	administrativeKm	Integer	156
✓	x	administrativeTime	Datetime	03:46:00
✓	x	extraKm	Integer	111
✓	x	extraKmReason	String	Extra kms ivm rondrit
✓	x	extraTimeInMinutes	Integer	30
✓	x	extraTimeInMinutesReason	String	Wachttijd file

The data within these first two data sets are mostly similar. The main difference is the quality of data attributes "administrativeKm", "administrativeTime", "extraKm", "extraKmreason", "extraTimeIn-Minutes", and "extraTimeInMinutesReason" as shown in Table 13. These attributes have been recorded for supply chain transports but not for home delivery. Table 13 gives an overview of the data attributes of data sets 1 and 2. Each data entry represents a location which is part of a tour. A tour has a start and end node which are denoted by "S" and "E" for the attribute "stopLabel", respectively. The locations between the start and end nodes are called stops and are denoted by integer values.

Two other tables containing locational data are available; one for the SC channel and one for the HD channel. These sets will be described as data set 3 and 4, respectively. These data have also been collected from 01-08-2022 until 30-08-2022. Data set 3 contains the following data attributes: "locationId", "name", "longitude", "latitude", "locationType", and "city". Data set 4 contains the following data attributes: "locationId", "longitude", "latitude", "locationType", "city", and "postalCode". Sets 3 and 4 can be cross-referenced to data sets 1 and 2, respectively. This can be done through "locationId".

The last data set has been provided by the Dutch retailer and contains trip data. This set also represents data from 01-08-2022 until 30-08-2022. This data set will be denoted as data set 5. This set contains the following data attributes: "hub", "tripId", "date", "footprint", and "weight". This data set can be cross-referenced to data set 2 through "tripId". Footprint regards the volume that is occupied. Most of the groceries are transported in crates. However, large case packs are transported without the use of crates. Fresh products are transported in cooled boxes. Frozen products are transported in plastic bags which are placed with multiple bags into a cooled box. At last, all valuables per trip are transported in one plastic container. For all of these transporting units, a footprint has been defined.

Additionally, data subsets have been created. For data set 1, this has been done in two directions as shown in the first four columns of Table 14. The letters in this table are combined with the numbers from Table 12 to denote which data subsets are referred to. The first direction regards trip relevancy; a distinction is made between the aforementioned total trip through Tilburg and stops in Tilburg. This distinction has been executed by using the data attribute "locationId" in data sets 1 and 3 and "city" in data set 3. For stops in Tilburg, only the data entries are selected for which "city" is equal to Tilburg. From this data set, the trip IDs are stored in a list. For tours through Tilburg, data set 1 is filtered by only selecting the data entries for which the trip IDs are in the stored list.

Table 14: Data subsets denotion

	SC			**HD**
	Groceries/fresh	**Frozen**	**PUP**	
Tour through Tilburg	A	B	C	D
Stops only in Tilburg	E	F	G	H

The second direction for creating subsets is a split in transport type. A distinction should be made between three different transport types: groceries/fresh, frozen, and PUP. This distinction is made because these three categories are transported by separate trucks. Additionally, the descriptive analytics will confirm the discrepancies between the different transport types. The distinction in transport types has been executed by evaluating data attributes "dropId" and "tripId". The subsets for frozen products have been created by selecting data entries for which the data attribute "dropId" contained "DIEPVRIES". Subsequently, the subsets for PUP orders have been generated in two steps. Firstly, data entries have been selected for which "tripId" contained "A". This logic could be applied because the distribution centres transporting frozen products and PUP orders use other planning software compared to the distribution centres transporting groceries and fresh products. Both planning software modules generate different formats for "tripId". Secondly, data entries were excluded for which "dropId" does not contain "DIEPVRIES".

For HD data set 2, two subsets have been created according to the trip relevancy as can be noticed in Table 14. To create the subsets for data set 2, data attributes "city" in data set 4 and "locationId" in data sets 2 and 4 have been used. For the stops in Tilburg, exclusively the data entries are selected for which "city" is equal to Tilburg. From this data set, the trip IDs are stored in a list. For tours through Tilburg, data set 2 is filtered by only selecting the data entries for which the trip IDs are in the stored list.

Data set 5 is filtered such that it only includes tours through Tilburg. This is done by cross-referencing with data subset 2D through "tripId". Subset 2D regards data set 2 with stop data for the HD channel but solely including tours through Tilburg. The obtained data subset is denoted as 5D.

A summary of all the data (sub)sets has been given in Table 15.

Table 15: Data (sub)sets overview

Data (sub)set	Data set name	Trip relevancy	Channel	Transport type
1A	Stop data	Tour through Tilburg	SC	Groceries/fresh
1B	Stop data	Tour through Tilburg	SC	Frozen
1C	Stop data	Tour through Tilburg	SC	PUP
1E	Stop data	Stops only in Tilburg	SC	Groceries/fresh
1F	Stop data	Stops only in Tilburg	SC	Frozen
1G	Stop data	Stops only in Tilburg	SC	PUP
2D	Stop data	Tour through Tilburg	HD	-
2H	Stop data	Stops only in Tilburg	HD	-
3	Locational data	-	SC	-
4	Locational data	-	HD	-
5D	Trip data	Tour through Tilburg	HD	-