INSTITUTE OF RETAIL ECONOMICS

ON DEPLOYING eCOmpass:

A DECISION SUPPORT TOOL FOR ENVIRONMENTALLY FRIENDLY RETAIL LOCATIONS

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On Deploying eCOmpass: A Decision Support Tool for Environmentally Friendly Retail Locations

Kenneth Carling*, Vijay Paidi*, and Niklas Rudholm‡

Abstract: Much focus in the joint retailing and transportation domain has been on the transition to e-tailing and the reformation of supply-chain logistics. However, traditional retailing, where consumers visit stores for shopping, dominates and will continue to do so for the foreseeable future. Retailers continuously expand, contract, and reconfigure their store network for strategic reasons. This paper reports on a project aiming to facilitate the incorporation of environmental consequences into the retailer's reconfiguration decision process. It describes the design and deployment process of eCOmpass, an online decision support tool that enables retailers to estimate the change in transportation-related CO_2 emissions caused by a reconfiguration of their store network. This description encompasses the judgmental choices of data acquisition, optimization technology, and user interface.

Keywords: CO2 emission estimation, *p*-median modeling, spatial data, user testing, web-based service

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1 Introduction

Location analysis is concerned with the problem of locating service points (e.g., schools, stores, offices, or production plants; hereafter facilities) to effectively serve demand points (i.e., a spatially dispersed population or set of users or consumers). It is presumed that the users utilize a transport network to fulfill their service demand in space and time. Here, we focus on road transportation and demand points, which have highly persistent networks and spatial distributions, respectively. Therefore, the facilities' localization intrinsically affects how the road network is utilized.

While some facilities are under public control, most facilities and their location are under the management and decision-making of private entities. A comprehensive understanding of the location decision is hard to obtain due to the business interests of the private actors. However, it seems sensible to assume that most location decisions follow a systematic analysis of key factors, albeit not as sophisticated as the analyses suggested in the scholarly literature (e.g., Kuo et al. [2002]).

Kimelberg and Williams (2013) reported key factors that determine the location decision of offices, manufacturing plants, or retail stores, while Turhan et al. (2013) reviewed key factors for the location decision specifically for retailers. Both papers noted that multiple factors determine the retailers' location decisions. However, none considered the environmental aspect of transportation a critical factor in the entry decision. In the market context of this research, Swedish consumers travel on average 30 km to brick-and-mortar stores when shopping for durables (Trafikanalys, 2013). Almost all these trips are made by car, and these shopping trips account for about a sixth of the total travel by private car in Sweden. Therefore, the impact of retailing on the environment has been debated in Sweden, with CO_2 emissions caused by the retailing sector being a societal concern.

Most retailers have historically not considered their environmental impact when choosing locations, which might not be a significant problem if consumer travel to and from stores was efficient from an environmental perspective. However, last-mile retail transport from retail stores or e-tailing outlets is still dominated by consumers' private cars, making last-mile delivery the most expensive, least efficient, and most environmentally problematic part of the overall delivery process (Vanelslander et al., 2013; Mommens et al., 2021). An early study by Carling et al. (2013) analyzed the locational optimality of brick-and-mortar stores for a selection of durable goods stores in the Swedish region of Dalarna. They found that CO_2 emissions were, on average, 22% higher than necessary for sub-optimal locations than for environmentally optimal locations, and notably, they were up to 35% higher for consumer electronics. Moreover, transportation by professional carriers to retail chain stores or e-tailing outlets was more environmentally efficient than last-mile transportation by consumers (Carling et al., 2015b). Zhao et al. (2017) also demonstrated the importance of good locational choices and sound urban planning to reduce CO_2 emissions. In general, these studies jointly indicate a considerable potential for reductions in CO_2 emissions if retailers could choose the locations of new stores and outlets based on their existing store and outlet networks to limit the need for last-mile transportation.

However, the location that minimizes the need for last-mile transports and, thus, CO_2 emissions is rarely known to the retail chain, and the mathematical tools needed to solve the optimization problem are not readily applicable to most retail chain managers. Retailers could use consultants to address this problem, but at considerable cost and inconvenience since the analysis would have to be redone for each new store entry or exit cycle they are contemplating.

Therefore, this paper draws on a research project to build a publicly available decision support system, comprising a web-based tool and detailed instructions, for retailers in Sweden who wish to minimize the need for last-mile transports in their location decisions, which we have called eCOmpass.

This web application can be easily accessed with any browser, regardless of the operating system. Some commercial software, such as ArcGIS and Maptitude, provide functions for optimized facility location, although abstracted from the CO_2 emissions aspect. The eCOmpass tool has been developed to facilitate environmentally attractive location decisions in Sweden. It is open source and may thus be used for location decisions beyond retailing, and it uses open-source tools such as open street maps to illustrate the locations. Moreover, it may easily be transferred to other geographical markets, provided that the market's spatial distribution of demand points and road network is available. For

European Union (EU) member states, the Infrastructure for Spatial Information in Europe (INSPIRE) directive should ensure that such data is of good quality.

The contributions of this work include the insights from and implementation strategy of this tool and the opportunity to use and transfer it to other facility location problems and countries.

This paper is organized as follows. Section 2 outlines the locational problems the eCOmpass tool should solve and its architecture. Section 3 discusses possible data sources with their pros and cons and reports on what is implemented in the eCOmpass tool. Section 4 explains how the optimization method was implemented in the eCOmpass tool, while Section 5 reports the user testing. Section 6 illustrates applying the eCOmpass tool to an expanding grocery store network in a Swedish municipality. Finally, Section 7 provides a concluding discussion where we consider some miscellaneous implementation issues and compare the impact of using the eCOmpass tool to other efforts toward reducing CO_2 emissions.

2 The archetype of the decision support tool

Let Q be the number of demand points[1] indexed by $q = 1, \dots, Q$; P be the number of existing facilities; and N be the number of facilities to be added (N is a negative integer when removing facilities). For the indexing facility, we use $p = 1, \dots, P, P + 1, \dots, P + N$. The Euclidian distance, road network distance, and produced CO_2 emissions per trip between demand point q and facility p are denoted $e(q, p)$, $d(q, p)$, and $c(q, p)$, respectively.

There are two types of business decisions to be supported. The first is the exploratory case. Here, the retailer chooses N and requests the N facility locations that would minimize $\sum_{q \in Q, p \in (P+N)} c(q, p)$ under the condition that the P existing facilities remain. The tool's response to this request would support the retailer in combining the environmental

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[1] At the most granular level, each Swede constitutes a demand point in space. However, some practical implementation aspects had to be introduced to enable real-time computation and an efficient optimization process (see Section 4 for details).

impact of the location decision with other deciding factors to narrow the potential locations for further investigations, such as land availability and cost.

In the second exploiting case, the retailer intends to locate N facilities at predetermined candidate locations, S, where $N \leq S$. Here, the tool returns the relative environmental impact of selecting a specific subset of N candidate locations out of S to other subsets or the existing locations only. By default, it is assumed that the retailer intends to maintain the P facilities; however, this assumption may be relaxed. The response is used for the counterfactual analysis of the finite potential location decisions.

The explore or exploit cases are further separated on a geographical (market) level. In the version of the tool built, the retailer chooses between location analysis on a municipal, regional, or national level.

Figure 1 shows the architecture of the eCOmpass tool. There is a user interface (UI) for data inputting by the retailer. The input should be the choice between exploring or exploiting and the market level. In addition, existing facilities (P) and their locations and the number of additional facilities (N) are to be inputted. Moreover, in the exploiting case, the number of candidates (S) and the candidate locations are to be submitted as well.

The eCOmpass tool then outputs the estimated change in produced CO_2 emissions attributed to the retailer's modified facility network in addition to the location of the new facilities. The counterfactual computations and the optimizations are executed on an origin-destination (OD) matrix for $e(q, p)$, $d(q, p)$, and $c(q, p)$.

We followed a systematic software development approach when developing the eCOmpass tool. When developing the UI, we relied on a methodology we had previously applied when developing a matching tool for consumers and parcel delivery companies in e-tailing (Paidi et al., 2020). The method, called Waterfall, is one of the most widely used and reliable software development methods (Royce, 1970; Bassil, 2012). The sequential development phases of Waterfall are conception, initiation, analysis, design, construction, testing, deployment, and maintenance, with each subject to review and verification before proceeding to the next phase. We conducted conception, initiation, and analysis as we developed the engine (i.e., the data processing part of Figure 1).

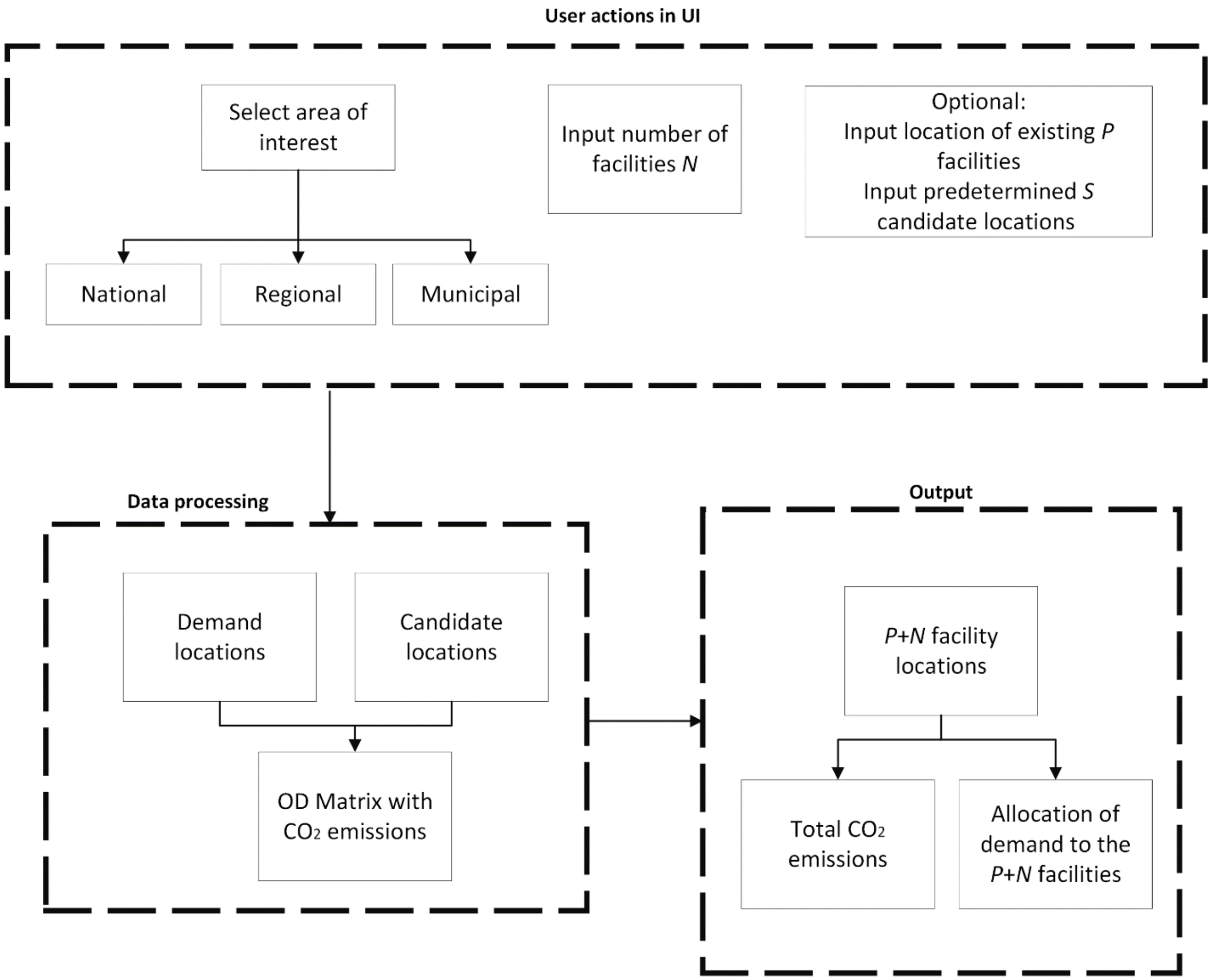

Figure 1. A representation of the architecture of the eCOmpass tool, where OD refers to origin-destination.

For design, construction, testing, and development, we opted for a user case in the form of IKEA's expansion in Sweden from its first store in 1958 to its latest in 2015, and the results are reported in Carling et al. (2024).[2] The counterfactual analysis in this user case estimates the impact on CO_2 emissions and traveled distances caused by rolling out the latest seven stores in Sweden in this millennium. Therefore, our test case is the network of IKEA stores during the period 2000–2015. This user case is provided in detail jointly with user instructions for the eCOmpass tool on the website: https://ecompass.se/.

The focus was on the eCOmpass tool's user-friendliness and ascertaining its open-source characteristics, meaning that, for instance, sufficient documentation is published for users that want to develop the application further. Regarding maintenance, it is imperative for the project's business and environmental benefits that the eCOmpass tool continues to function after the project's completion. As such, the Institute of Retail Economics commits to ensuring that the eCOmpass tool is properly maintained for at least five years after the project's completion.

3 Data acquisition and the trade-off between potential data sources

The eCOmpass tool requires data on the service (i.e., facility) and demand points as well as the generation of an OD matrix. This section explains how we acquired these data and discusses options.

We start with the service points (i.e., the location of existing facilities and candidate locations for the new facilities). We considered identifying the geocoded locations of the existing facilities in the WGS84 (ESPG:4362) coordinate system via either Google Maps or web-scraping the retailer's webpage. This solution would simplify the tool's utilization for the retailer. However, upon testing this approach, it proved to be too prone to errors. Therefore, the retailer is required to submit a list of geocoded existing facilities. This list can either be in the coordinate system or addresses. In the exploiting case, the retailer is further required to provide a list of the S geocoded candidate locations in a similar manner. In the exploring case, all existing demand points are considered candidate locations. This choice is motivated by two reasons. The first is the result of Hakimi (1964),

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[2] The eCOmpass tool was also open to a chosen set of users from August to December 2023, which is further reported in Section 5.

which implies that optimal locations are at the road network nodes. The second is that, based on a large set of location problems in Sweden, Rebreyend et al. (2014) noted that optimal locations were consistently at populated candidate nodes.

Regarding the demand points, we used the entire Swedish population as of December 31, 2022. The geocoded population data is publicly available through Statistics Sweden (www.scb.se), where each resident is geocoded in a 1 × 1 km grid with the center of each grid square given in the SWEREF99 coordinate system. We converted these coordinates to WGS84 to conform to the coordinate system of the facility locations and road network. Each grid square was then assigned to a region and municipality based on the 2023 geocoded regional and municipal boundaries, which are publicly available through Statistics Sweden.

The population's geodata provided by Statistics Sweden exist because of the EU INSPIRE directive (www.inspire-geoportal.ec.europa.eu/). All EU member states are under the INSPIRE directive. Therefore, in principle, it should be possible to replicate this approach for any EU country or any combination of EU regions.

The transportation between a demand point and a facility generates CO_2 emissions. The Euclidian distance is the simplest distance measure between these two points, which is readily computable from the coordinates of the two points. As noted by Francis et al. (2009) in their survey (see also Hillsman and Rhoda [1978]), this has historically been the predominant distance measure used in location analysis. The second most common is the rectilinear distance, also called the Manhattan distance, which is a good measure in urban areas comprised of blocks. However, in his early and seminal paper investigating competing distance measures, Bach (1981) considered the network distance in addition to the travel time and cost. To our knowledge, Jia et al. (2013) were the first to implement a detailed measure of CO_2 emissions generated by transportation on a road network.

Carling et al. (2012) replicated Bach's (1981) investigation in a setting comprising mixed urban, peri-urban, and rural areas. Their conclusion indicates that the Euclidian and Manhattan distances are inadequate measures of the distance traveled on the road network. Therefore, we discourage using the Euclidian and Manhattan distances unless the location analysis is limited to an urban area comprised of blocks, with the prototypical example being the Manhattan borough of New York City.

The most complete digital representation of the Swedish road network is the so-called NVDB (National Road Database) by the Swedish Transport Administration. For location analysis, Carling et al. (2015a) built the road network of a Swedish region, and Meng et al. (2018) built the road network of the entire country from the NVDB. This building is time-consuming and complex. The experiences of these two projects and the paper by Rebreyend et al. (2014) indicate that this approach is overly ambitious since a less detailed road network tends to generate comparable location analysis results.

More readily available and transferable alternatives to the NVDB are OpenStreet, Google, and Bing maps. For each of these three alternatives, there are open-source, off-the-shelf tools that allow for computing $d(q,p)$. Jia et al. (2013) studied how customers travel to retail stores using GPS-tracking data and discovered that they tend to use the shortest distance and the routing option that produces the least CO_2 emissions. Therefore, as is customary in location analysis using road network distance, we imposed that the routing between a demand point and a facility be the shortest. Dijkstra (1959) solved the non-trivial problem of rapidly finding the shortest route between two nodes in a road network. Both the Bing and Google application programming interfaces use this algorithm to provide the shortest route in real-time. Similarly, the Python library Osmnx provides a means to compute the shortest road distance for OpenStreet.

Consequently, there are data sources and computational methods and tools that provide $e(q,p)$ and $d(q,p)$ with reasonable accuracy, making the construction of the OD matrix computationally feasible. The eCOmpass tool uses OpenStreet to construct the OD matrix. The primary reason for this choice is its pure open-source characteristics relative to the other two mentioned options.

Zhao (2017) carefully studied the micro-level CO_2 emissions produced by transportation by GPS-tracking individuals using various modes of transportation on the road network with both observational and experimental study designs. Furthermore, Paidi et al. (2022) complemented GPS tracking with camera-based motion detection in a parking lot. The

CO_2 emissions depend on the vehicle's type and engine and the driver's behavior. However, while traveling, the CO_2 emissions follow an irregular pattern, primarily due to changes in traffic flow due to intersections, congestion, and speed limits. Jia et al. (2013) provides a map (cf. their Figure 7) classifying road segments as low, medium, and high CO_2 emissions. An exact calculation of $c(q, p)$ would be greatly facilitated by such a map or comprehensive market-wide GPS-tracking data of the users when travelling between demand points and facilities. However, such sources are not generally available. Therefore, as suggested by Carling et al. (2015b), we follow the transferable approach to calculate $c(q, p)$, as a reasonable trade-off between precision and general applicability. A similar recommendation was suggested by Stead (1999) based on British travel data.

An OD matrix is required for both the exploring and exploiting cases. Since the OD matrix may be large, we have preconstructed and stored it for general use (Figure 1). Computing $c(q, p)$ for all q and existing and candidate p in real-time would be intolerably slow for the tool's user. To reduce computational time, we have preconstructed OD matrices for each market (geographical level), meaning that there is a unique OD matrix for each region and municipality (except for the least populous municipalities).

4 The optimization engine of the tool

The eCOmpass tool identifies optimal facility locations considering the demand points and their associated driving routes and distances. At the most granular level, each Swede constitutes a demand point in space. However, some practical implementation aspects were introduced to enable real-time computation and efficient optimization.

First, the demand points depend on the selected geographical level: municipal, regional, or national. A municipality is an area of a region, and the national level includes all regions. As mentioned in Section 3, geocoded population data on 1×1 km^2 grids are available from Statistics Sweden. At the municipal level, these grids are considered the demand points, with the center point of each grid square defining the geographical position of the demand point. The original grid squares are aggregated into 5×5 km^2 grids at the regional level and 20×20 km^2 grids at the national level.

The computational benefit of this aggregation comes from the substantial reduction in functional calls required and the drastic reduction in the storage requirement for the OD matrices.

Second, the population grids are also used to define eligible candidate locations. Meng et al. (2018) stressed that a location without a settlement does not make sense as a candidate due to a lack of demand and workers to operate the facility. Therefore, candidate locations are only those grid center points constituting a demand point with the same geographical granularity as above. However, we impose an additional requirement that the grid should have at least 100 inhabitants at the municipal and regional levels and 1,000 inhabitants at the national to be an eligible candidate location. When converted into grid average population density, this reflects a minimum of 100, 4, and 2.5 inhabitants per km^2, respectively. Practically, this imposed requirement implies that municipal localizations are limited to peri-urban and urban areas of the municipality, whereas regional and national localizations may also be in rural areas.

Third, the maximum number of existing facilities that can be added to the eCOmpass tool is 100.[3] This restriction reduces the complexity and computational costs of the application. It also reminds the user to consider selecting a lower geographical level for the location analysis whenever this makes business sense.

Fourth, the OD matrix was in the first version of the eCOmpass tool generated at each instance. However, the real-time user experience of the tool was hampered by the unpredictability of processing time. Therefore, OD matrices have been precomputed and stored for many of the about 320 geographical options in Sweden. However, the

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[3] In Section 6 below, we use the grocery chain COOP as an example. COOP is one of the largest grocery store chains in Sweden, with some 800 stores. However, the retailer is divided into local divisions based on geography. The market studied in this paper, Borlänge municipality, belongs to COOP Mitt, with 93 stores in the regions of Gästrikland, Hälsingland, Dalarna, Uppland, Närke, and Västmanland. As such, there are very few examples in Sweden of retailers having 100 or more stores at the relevant geographical levels for location analysis.

OD matrix is still computed in real-time for some municipalities with very small populations and, consequently, a low-dimensional OD matrix.

Fifth, the OD distance matrices are converted to CO_2 emissions matrices based on the approximation proposed by Carling et al. (2015b), where 1 km = 0.15 kg of CO_2. The emissions and traversed distance are generally highly correlated unless electric vehicles are utilized; however, only 4% of private cars are currently electric in Sweden. Therefore, this emissions approximation works well, especially in the optimization problem, as elaborated in Section 3.

Sixth, in the explore mode, the problem of identifying environmentally optimal new locations is an *NP*-hard problem. This issue is solved in the eCOmpass tool by applying the branch-and-cut algorithm of the PULP Python library on the OD matrix. We chose this option since it reduces search complexity, improves efficiency, and facilitates global optimality, as discussed in Labbé et al. (2004).

5 UI choices and the validation testing

The eCOmpass tool can be accessed using a mobile or personal computer. However, a personal computer is better suited to using the tool due to the data inputting step. eCOmpass uses HTML for the front-end and Flask and Redis for the back-end tasks. HTML is a popular hypertext markup language that is used to structure and display content on a webpage. Flask provides a web framework that facilitates integrating the Python programming language and creating the web application part of the eCOmpass tool. Python was chosen because it is a versatile, high-level language with a wide range of libraries and services that bridge software development and data science. One such example is the PULP library, which provides a solver that utilizes mixed integer and branch and cut algorithms to solve the optimization problem of identifying the candidate facility locations that minimize CO_2 emissions.

The OD matrices and the auxiliary data required for the explore and exploit modes are moderately large, which made us choose GitHub as a database to store demand points along with their weights and other relevant data. Redis is a remote dictionary server that supports job queues and asynchronous tasks. It supports multi-threading, which helps to reduce processing time. Finally, the developed prototype of the eCOmpass tool was deployed for testing using Microsoft's Azure web services, a cloud platform that supports building, deploying, and managing web applications.

Since the eCOmpass tool works with spatial data, visualizing these locations on a map is desirable. For this purpose, open street maps are provided when the WGS84 coordinate system is used. As mentioned above, the user can submit the existing (and predetermined candidate) facility locations as addresses or coordinates. However, using coordinates is recommended to avoid any potential errors in geocoding. As mentioned in Section 4, the spatial aggregation of the demand points varies based on the geographical level of the analysis. The visualization is consistent with this aggregation in that each facility location identified by the eCOmpass tool is displayed as a position and buffer area, with the latter's size contingent on the concerned aggregation. The circular buffer area size is 1 km at the municipal level, 5 km at the regional level, and 20 km at the national level. We chose these sizes based on the amount of aggregation of the demand points used for the respective geographical level.

The user interacts with the eCOmpass tool using HTML forms, where they choose the geographical level and whether the analysis is in explore or exploit mode. In the same form, the user uploads a comma-separated values (CSV) file with either the addresses or coordinates of, if applicable, existing facilities and, if applicable, predetermined candidate locations, where existing facilities are tagged with a ”1” and predetermined candidate locations are tagged with a “0”. Furthermore, the number of recommended locations is also provided in the HTML form. In the output, the submitted locations are visualized on a map with existing facilities depicted by blue icons to allow the user to promptly visually verify the correctness of the submitted data. Predetermined new locations and new locations suggested by the eCOmpass tool are depicted by red icons instead.

The eCOmpass tool prototype has undergone both static and dynamic testing, consistent with the recommendations by Kaur and Singh (2014) and Hooda and Chhillar (2015). The developer mainly conducted the static testing, performing a review and walkthrough of the code. Functionality and user acceptance testing was performed dynamically, engaging some 15 external users over a two-month period. These external users had varied experience with location analysis but either had some expertise in either transportation or economic geography or were IT professionals. The feedback from these external users was iteratively collected and assessed for revisions of the eCOmpass tool. As an additional test of the eCOmpass tool, a complete analysis of the historical roll-out of IKEA's store network in the current millennium was conducted (Carling et al., 2024) and is provided on the eCOmpass website for instructional use, as already described in Section 2.

6 Illustrating eCOmpass with a synthetic use case

As mentioned above and in Section 2, an illustration with user data and instructions for IKEA's national location analysis is provided on the eCOMpass website. Here, we provide another illustration using a local (municipal) location analysis of the store network of the grocery chain COOP (www.coop.se), a national food cooperative. The COOP began in the late eighteenth century and is one of the oldest grocery store chains in Sweden. It is connected to the internationally dispersed cooperative movement in which members (customers) collectively own and manage the business. Therefore, the customer base distinguishes itself from other grocery stores, making it relevant businesswise to use the eCOmpass tool for COOP stores separate from other grocery stores. In Sweden, the COOP has approximately 800 stores nationwide and 30 in Dalarna. We examined CO_2 emissions relating to the locations of its two current COOP stores in the Borlänge municipality in Central Sweden. Borlänge is a municipality of slightly more than 600 km^2 with a population center of 35 km^2 and a total population of 52,193 inhabitants concentrated along the river that flows through it in a northwest-to-southeast direction. The OD matrix for the Borlänge municipality is a 60 × 60 matrix since there are 60 1 × 1 km grids with 100 or more inhabitants. These 60 grid squares contain 46,645 inhabitants, or 90% of the entire population of the municipality, and are the permissible candidate locations in the municipality, as explained in Section 4.

In Figure 2, the two existing COOP stores are depicted by square icons. As provided in Table 1, the northern store currently serves 43% of the population and the central 57%.

The average distance to the serving store is 3.13 km, resulting in average CO_2 emissions of 0.47 kg. These outputs were found by uploading the CSV file with the coordinates of the two stores, selecting the choice of exploit mode, and setting $N = 0$.

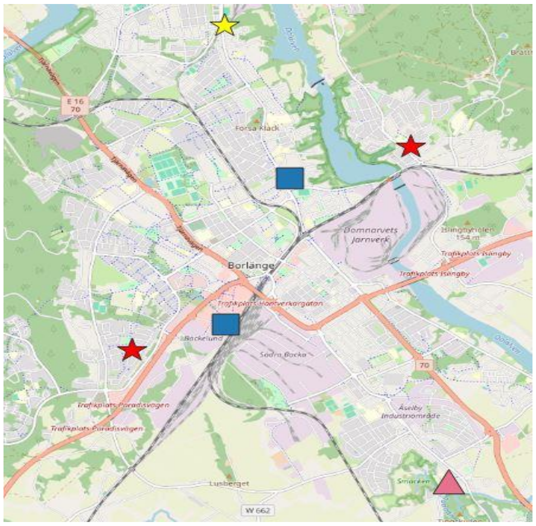


Figure 2. Existing COOP locations (blue icons) in Borlänge and some eCOmpass suggestions after adding one additional store in the municipality.

Now, assume that COOP was contemplating adding a store to their network in the municipality. In a first exploit case, it is assumed that they consider three predetermined locations, S. In Figure 2, these three candidate locations are marked by star icons. We selected these three locations because they represent the three major family home residential districts in Borlänge. This case was evaluated by running the eCOmpass in exploit mode, with $N = 1$, and the CSV file containing the coordinates of the two existing stores and the coordinates of the three (S) predetermined candidate locations. Of the three candidates, the northwestern candidate location (yellow star icon) was identified as the one that minimizes CO_2 emissions. Among other things, the outputs (Table 1) inform that the average CO2 emissions of 0.47 kg would decrease to 0.43 kg, about a 10% reduction. Such a third store would serve about 15% of customers (Table 1), with demand primarily shifting from the central store to this new one. This prediction might seem surprising since Euclidian-wise, the northern store appears more accessible for customers in the western and southwestern districts than the northwestern store. However, it can be explained by flow being highest, and thereby CO_2 emissions being lowest, on the two orange-indicated expressways crossing Borlänge, thereby achieving environmentally friendly routes.

It comes naturally to benchmark the solution above with the best possible location of a new store. In this thought experiment, it is assumed that the third store may be located anywhere in the municipality. This assumption was tested by uploading the locations of the existing stores to the eCOmpass tool, choosing the explore mode, and setting $N = 1$. The output provided the location given by the triangle icon in Figure 2 and suggested a 15%–20% reduction in both average distance and CO_2 emissions, where, for instance, the average CO_2 emissions would be further reduced to 0.40 kg. It also balances the distribution of customers across the three facilities, as provided in Table 1.

Table 1. The eCOmpass outputs for the existing two COOP stores in Borlänge and exploiting and exploring an additional store.

	Exploit		Explore
Facility no. (% served)	$P = 2$	$P = 2; N = 1$	$P = 2; N = 1$
1	43	43	27
2	57	42	45
3	*n. a.*	15	28
Average distance (km)	3.13	2.87	2.67
Average CO_2 emissions (kg)	0.47	0.43	0.40

In Figure 3, we compare the locations of the current COOP stores and the locations suggested by the eCOmpass tool for the examined exploit and the explore cases. It includes the visualizations provided by the eCOmpass tool in its output, where the blue color highlights existing stores and the red highlights the new store locations it identified. The locations are indicated as both a position and a buffer circle with a radius of 1 km for this geographical level to properly account for the spatial error introduced by the spatial aggregation of demand points and candidate locations.

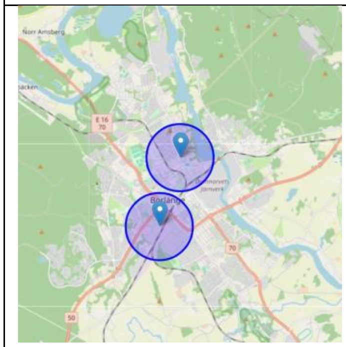
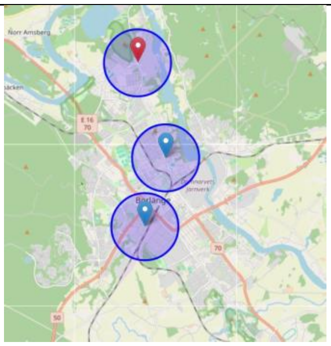
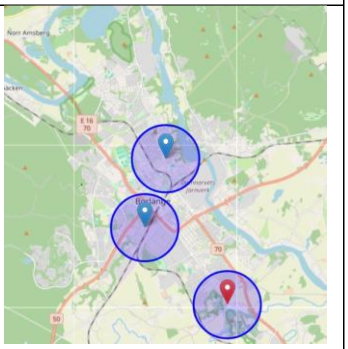
Exploit		Explore
$P = 2$	$P = 2; N = 1$	$P = 2; N = 1$
 (a)	 (b)	 (c)

Figure 3. The existing COOP locations (blue icons) in Borlänge and some eCOmpass solutions after adding additional store(s) in the municipality.

7 Discussion

One set of location problems is known as on-the-flow localization, where the business intends to serve the customers on route. A typical case is gas stations. The eCOmpass tool is not applicable to such problems; it is intended for localization problems where the facility attracts customers to itself. Many retailers are of this kind, but so are many other facility types, such as schools, sports arenas, and veterinary clinics. The eCOmpass tool may be used for location analysis of such facilities without further amendments.

One current restriction of the eCOmpass tool is that it is applicable only to the Swedish market. As discussed in this paper, its open-source nature and building blocks ensure its transferability to other markets. We consider the only critical data source to be the digital, spatial representation of demand in the concerned market. In principle, the EU INSPIRE directive should mean that at least all EU member states should have access to comparable data to Sweden; however, we do not know whether this is the actual case. Most European markets have substantially smaller areas and greater customer densities than the Swedish market. We recommend deciding on any spatial aggregation of demand points and candidate locations based on the particular market rather than re-implementing those applied here for Sweden.

The eCOmpass tool was developed as a web application for ease of use. A web application does not depend on any operating system, and anyone can access it using a web browser. Since the processing occurs on a server, it does not impact the user's computer resources. The web application can also be accessed using a mobile browser, although it is better suited to a desktop. Nonetheless, we plan to also develop a desktop version since frequent users would likely prefer such a solution.

The computational cost of the eCOmpass tool is highest when computing the OD matrix or running the optimization algorithm in the explore mode in highly populated areas. The processing time can vary from a few seconds to minutes or even hours based on the chosen N and the market's population. This computational complexity led us to implement a background worker like Azure cache. Since online websites do not maintain the connection to the server beyond 180 seconds, using background workers enables the retaining and printing of outputs even after the server connection is terminated. Problems of this kind are further exacerbated by multiple users concurrently accessing the tool. When the CPU is occupied on a longer-running task, the next user will experience a noticeable delay unless memory is allocated to concurrent users. However, the latter would be expensive to maintain for long periods. The deployment presented in this paper utilizes cloud resources like Azure, creating these multi-user issues. Consequently, we intend to use a local instead of a cloud server in the future. Using a local server might create some restrictions in scalability, but the costs of hosting and maintaining the website would be significantly reduced.

Can the eCOmpass tool impact CO_2 emissions? The COOP illustration suggests a scope of reducing the CO_2 emissions per store trip by 15%–20%, which is the low end of the many retail cases we have examined over the years. A reduction of 25%–35% would be more common. To put this opportunity into perspective, several political and public efforts have been made to reduce transport-related CO_2 emissions. In 2009, the EU Renewable Energy Sources (RES) directive set the goal of 10% of member states' transportation-related energy consumption being from renewable resources by 2020. To achieve this goal, the EU attempted to stimulate the transportation sector's uptake of biofuels and electricity. Besides direct regulation and emission taxation, the EU also implemented other emission mitigation strategies, such as Eco-driving, by educating drivers in efficient driving techniques. A report by the Swedish National Road Administration (Vägverket, 2009) reported that about 1% of Swedish drivers had been trained in eco-driving over a 10-year period. Moreover, the Netherlands, which had the world's most ambitious eco-driving strategy, achieved about 20% of drivers adopting eco-driving but at the cost of 30 million euros. The Dutch strategy resulted in a 2% reduction in CO_2 emissions by motorists.

Several cities have also implemented congestion charges to reduce congestion and related CO_2 emissions. In Sweden, congestion charges were implemented in Stockholm in 2007, and their societal impacts have been extensively studied and stimulated similar policies in other cities. For the Stockholm case, a 14% reduction in CO_2 emissions by inner-city traffic was reported, translating to a general reduction of 2%–3% in metropolitan Stockholm (Eliasson et al., 2009). While some retailers in Stockholm expressed concerns that introducing the charges would negatively affect their sales, this was not the case, and their introduction seems to have mainly had positive environmental effects (Daunfeldt et al., 2009, 2013).

Comparing transport-related CO_2 emissions in Sweden in 2009, the year the RES directive was implemented, to today, it can be argued that the political and public initiatives have been successful since CO_2 emissions have fallen by about 35% (The Swedish Environmental Protection Agency, www.naturvardsverket.se). However, driven by public initiatives, this reduction might now and in the future be leveraged by the private actors responding to consumers' demand for sustainable products. We believe that the eCOmpass tool can achieve a comparable reduction in CO_2 emissions by targeted location analysis.

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