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Net CO_2-emission effects of relocating freight facilities to free up land for urban development in central and semi-central urban areas

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ABSTRACT

This article investigates net CO_2 emissions effects of relocating freight facilities (wholesale warehouses) away from central areas and replacing them with more area-effective activities (mix of dwellings and workplaces) that would otherwise have been located more peripherally. This development is ongoing in many urban regions, and it is often part of land use strategies aimed at reducing CO_2 emissions from transport. However, whether this strategy is efficient has not been investigated much. The study contributes empirical research on two Norwegian regions, where net differences in total CO_2 emissions between two scenarios were analysed. In Scenario 1, wholesale warehouses have remained in their central location, and new dwellings and workplaces have been developed in relevant peripheral areas. In Scenario 2, centrally located warehouses have relocated to peripheral areas, and they have been replaced by dwellings and workplaces. The main finding is that relocating warehouses away from central and semi-central urban areas, to make land available for dwellings and workplaces, results in reduced net transport-related CO_2 emissions. The effects are stronger when the warehouses were originally more centrally located and the alternative locations of dwellings and workplaces are more peripheral. If warehouse relocations cause detours, the effects are somewhat reduced.

1. Introduction

A key issue in strategic land use and transport planning is allocating space in ways supporting societal goals, like reducing CO_2 emissions from transport. This latter goal is high on the agenda, but it has proven hard to achieve (European Commission, 2011; European Environment Agency, 2019; Ministry of Transport and Communication, 2017; Norwegian Environment Agency, 2015). Steering land use development in directions aimed at reducing transport demand and traffic volumes, by stopping urban sprawl and facilitating densification and transformation in and close to central urban areas, is understood as a key strategy for success (European Commission, 2013; Ministry of Local Government and Modernisation, 2014; UN Habitat, 2013). These strategies rely on convincing amounts of research demonstrating that traffic volumes and transport-related CO_2 emissions per inhabitant and per employee increase with distance from dwellings and workplaces to the city centre (for instance, see Næss, 2012; Newman & Kenworthy, 2015; we return to this in Section 2). Research results concerning the effects of location of various kinds of freight facilities, such as wholesale warehouses (hereafter, 'warehouses') and terminals on traffic and CO_2 emissions, are less unanimous (Koç, Bektas, Jabali, & Laporte, 2015; Nuzzolo & Comi, 2015); however, several studies have found that freight facilities generate more traffic and CO_2 emissions when located away from central urban areas (Dablanc & Rakotonarivo, 2010; Pinchasik, Hovi, Wangsness, & Tennøy, 2019; Sakai, Kawamura, & Hyodo, 2015).

Across many urban regions, a clear tendency has been found in which several types of freight facilities are relocating to areas further from city centres (Allen, Browne, & Cherrett, 2012; Dablanc, Ogilvie, & Goodchild, 2014; Dablanc & Ross, 2012; Pinchasik et al., 2019; Sakai et al., 2015). There are multiple causes of this, including businesses' optimisation and organisational and technological change in the logistics industry. Further, developmental pressure in central parts of cities is often high, especially in rapidly growing urban regions, causing increasing land prices that may motivate space-demanding freight facilities to relocate to less expensive urban fringe areas. This development can be desirable from city authorities' perspectives as it frees up land for urban development and contributes to making cities and urban

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regions more attractive and liveable (Lindholm, 2012); for instance, this can be seen when centrally located port areas are transformed to areas for housing, workplaces, shopping and leisure. Strategic land use and transport plans also suggest that relocating space-demanding freight facilities away from central areas—to give room for more area-intensive urban development—could be part of the strategy to reduce traffic volumes and transport-related CO_2 emissions (Oslo Municipality and Akershus County, 2015; Trondheimsregionen, 2015). Such a strategy involves an assumption that the net CO_2 emissions will be reduced.

We have, however, not seen empirical investigations concerning the effects on net CO_2 emissions of relocating freight facilities from central to more peripheral areas and replacing them with dense urban development (dwellings, workplaces, retail, leisure, etc.) that would otherwise have been located in less central areas. The aim of this article is to contribute to the existing literature with results from an empirical study on two Norwegian urban regions (Oslo and Trondheim), in which these net effects are investigated. It aims at answering the following research questions: *What are the net CO_2 effects of relocating wholesale warehouses away from central and semi-central areas, replacing them with new dwellings and workplaces that would otherwise have been located in more peripheral areas, in Oslo and Trondheim? How do the more specific locations of warehouses, as well as dwellings and workplaces, influence these effects?* While the analyses are based on data from Norwegian urban regions, we think the results are also relevant for other cities, regions and countries striving to reduce traffic volumes and transport-related CO_2-emissions.

2. Theoretical framework

To address the research questions, two scenarios were developed, and the difference in total CO_2-emissions between them was calculated. In *Scenario 1*, warehouses have remained in central areas, while dwellings and workplaces have been developed in hypothetical but relevant peripheral areas. In *Scenario 2*, warehouses have been relocated to peripheral areas, and a combination of dwellings and workplaces have been developed on the central plots freed up when the warehouses were relocated. The scenarios are illustrated in Fig. 1.

Key assumptions are that warehouses relocating from more to less central areas are replaced by new dwellings and workplaces, and these dwellings and workplaces would otherwise have been developed in more peripheral locations. These assumptions are valid in both our cases, which cover urban regions that are experiencing rapid population growth, which results in high development pressure. An objection against the assumptions is that they imply full substitutability, while warehouses may be located in areas that are not suitable or attractive for urban development for various reasons. Another assumption made here is that new developments in peripheral areas do not displace other activities to even more remote locations.

Constructing and comparing the above scenarios is obviously a strong simplification of the complex systems urban regions, land use and transport development—as well as interactions between land use and transport—represent. They are also only two out of many potential and relevant scenarios. We could have instead compared scenarios, for instance, where all new development was located either in central or peripheral locations. When choosing to compare these two scenarios, the idea was to simplify the problem in ways allowing for investigating how different mechanisms, activated by different locations of warehouses and urban development, play out in concrete contexts. The choice of scenarios was also motivated by our understanding that they represent strategic choices considered in overall and integrated land use and transport planning and decision making, as well as ongoing development that can either be supported or staggered through land use planning.

Three mechanisms that may be activated when warehouses are relocated from central to more peripheral areas are considered; these are as follows: *i*) changed distances for local distribution transports, *ii*) changed long-haul transport distances and *iii*) modal changes if access to rail terminals and ports is altered. Whether, and with what strength, these mechanisms act out and affect CO_2 emissions is context dependent. Relocations can result, for instance, in shorter transport distances if the new location is along existing transport routes and longer distances if the new location causes detours. They can also either improve or worsen access to ports and rail terminals, which can affect modal splits.

Concerning urban development, the current study focusses on how different locations of dwellings and workplaces in the urban structure affect average daily travel distances by car and public transport for inhabitants and employees. Existing literature has found that inhabitants travel averagely longer distances and make a higher share of trips as car-drivers, the further from the main city centre they live (Elldér, 2014; Ewing & Cervero, 2010; Hartoft-Nielsen, 2001a; Næss, 2012; Næss, Strand, Wolday, & Stefansdottir, 2019; Newman & Kenworthy, 2015). Likewise, workplaces tend to generate more car traffic with greater distance from the city centre, as car-driver shares are lower among employees the closer to the main city centre their work-place is located (Hartoft-Nielsen, 2001b; Næss, 2012; Næss, Tønnesen, & Wolday, 2019; Tennøy, Øksenholt, & Aarhaug, 2014). The literature theoretically explains these tendencies as the result of a complex mix of causal mechanisms, where proximity to a variety of activities and (thus) the accessibility by different modes of transport are key issues (Banister, 2011; Næss, Hansson, Richardson, & Tennøy, 2013; Næss, Strand, et al., 2019; Newman & Kenworthy, 2015). The city centre is normally the area in a city that is best connected to other parts of the city and the urban region by public transport, and it has the highest number of people living within distances that make walking and bicycling a convenient mode of transport when engaging in different activities. Moving outwards in the urban structure, densities become lower, activities more separated and the spatial structure more fragmented. Travel distances increase, public transport services become poorer, fewer trips are short enough to be made by foot or bicycle and conditions for car-usage improve. This results in longer travels and

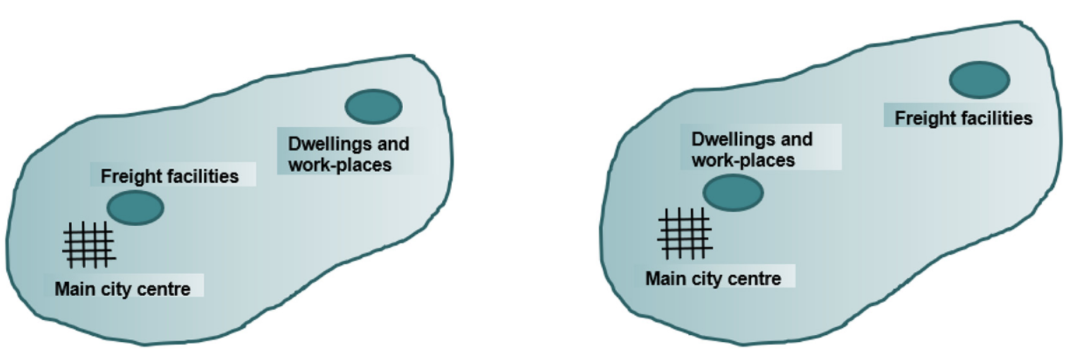

Fig. 1. Illustration of Scenario 1 (left) and Scenario 2 (right).

higher shares of trips done as car drivers, and hence, higher traffic volumes per inhabitant and employee. For similar reasons, dense cities and urban regions generate less traffic per inhabitant and per employee than sprawling cities do (see Newman & Kenworthy, 2015).

3. Research design, data and methodology

3.1. Overall research design

The research questions, together with the multi-causal nature of the problem and our focus on investigating how defined mechanisms play out in concrete contexts, call for in-depth empirical case studies and a mixed-methods approach (Yin, 2003). We selected two Norwegian urban regions as cases, where the use of land in central and semi-central areas is a debated issue in ongoing strategic land use and transport planning, where relocation of freight facilities more generally is an important part of these debates and where there is an observed ongoing sprawl of wholesale warehouses (Pinchasik et al., 2019). These regions are the Norwegian capital Oslo, with about 700,000 inhabitants in the municipality and about 1,000,000 in the urban region (the morphological city), and Trondheim, the third largest city in Norway, with about 200,000 inhabitants in the municipality and 280,000 in the urban region. Two concrete and context-related scenarios were constructed, and the differences in total CO_2 emissions between the two scenarios were calculated.

3.2. Calculating CO_2 emissions generated by wholesale warehouses in different locations

Using the Central Register of Enterprises (Statistics Norway, 2017a) and considering the availability of data on freight flow patterns from commodity flow surveys (see below), we identified relevant freight-generating firms that had relocated from central to peripheral areas in the urban regions in the period 2008–2014, as well as their current and previous locations. In Oslo, this included eight wholesale warehouses relocated from central areas to peripheral locations about 14–42 km *north* of the Oslo city centre and 12 warehouses that had relocated from similar areas to peripheral locations about 10–40 km *south* of Oslo city centre. The distinction between the northern and southern periphery is made to account for potentially different effects with respect to the geographical location of the main road transport route from Europe and the south of Sweden to Norway. In Trondheim, the sample included 12 warehouses relocated to a peripheral location about 13 km south of the city centre. See the maps in Fig. 2. The above selection requirements resulted in our case sample consisting of space-demanding and freight-generating firms with NACE classification 46 (wholesale trade). In addition to this case sample, other logistics facilities may have relocated as well. However, this cannot always be tracked, for example due to changes in organisation numbers when moving/consolidating/expanding.

Transport activity (tonne-km) generated by the warehouses was calculated for both the central and peripheral locations. This was done using a national freight model (NFM) for Norway (Grønland, 2015; Hovi, 2018; Jong, Ben-Akiva, & Baak, 2013; Madslien, Steinsland, & Grønland, 2015). The NFM is a strategic freight transport network model (Jonkeren, Francke, & Visser, 2019) using basic data from commodity flow surveys and foreign trade statistics (see below) to generate aggregate annual commodity flows between zones of origin and destination. The NFM optimises delivery frequencies, shipment size, transport routes, mode chains, transfer zones and size of vehicles to minimise logistics costs, and distributes commodity flows accordingly. Outputs are commodity flows (in tonnes) between defined zones, by different modes of transport, and transport performance (in tonne-km) by mode. As such, the NFM calculates transport to and from the warehouses and origin and delivery points (mainly urban distribution to shops, restaurants, etc., later termed *domestic flows*) and the part of transport on Norwegian territory that stems from foreign trade, that is, between the Norwegian border and the domestic warehouses (later termed *foreign flows*). For confidentiality reasons, we could not calculate CO_2 emissions generated by specific warehouses. Instead, we used data for commodity flows to and from firms in the same central and peripheral locations as our case firms. A strength of the NFM is that it allows shifts in modes of transport, vehicle size, delivery frequencies and so on when warehouses relocate. A weakness, at least in this study, is its relatively aggregated geographical level (post-zone level), dividing Oslo and Trondheim into 12 and 8 zones, respectively; this reduces the precision of the calculations.

Input to the NFM analyses of the *domestic transport flows* were commodity flow (basic) data from Statistics Norway from 2015 at the post-zone level for firms at both the origin and destination. The commodity flow dataset is based on a large stratified sample survey among firms within manufacturing industry and wholesale trade, including deliveries from the eight largest freight forwarders in Norway. Data for missing firms are imputed by Statistics Norway. In total, the survey included data on around 53 million shipments and 12,000 delivery firms. We assessed data for firms within and outside the study areas to cover the full effects of different locations through both incoming and outgoing freight flows. In analyses of *foreign transport flows*, a similar

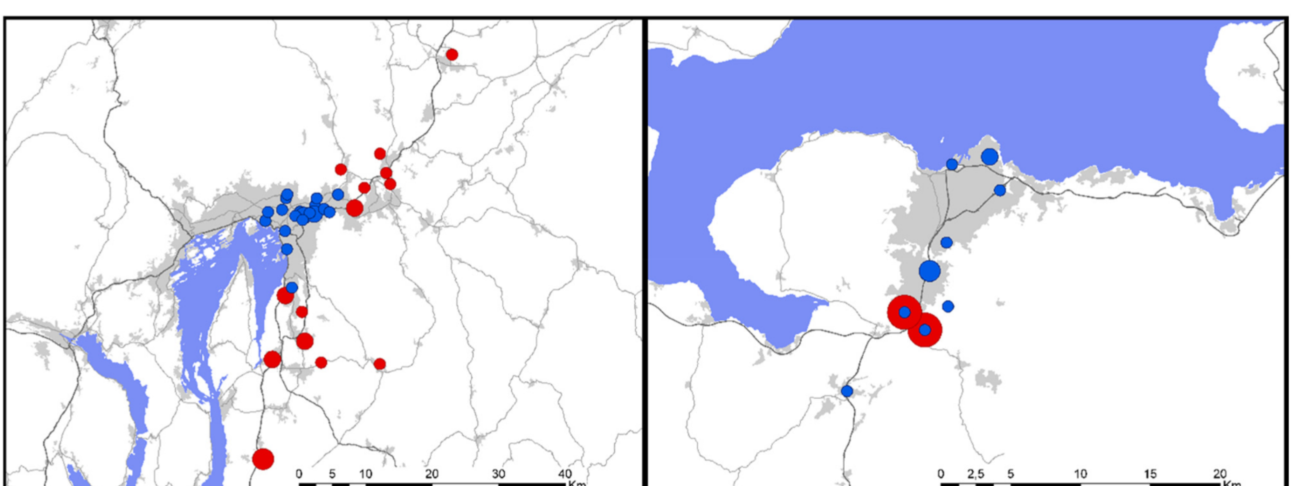

Fig. 2. Previous (blue dots) and current (red dots) locations of warehouses included in the study, in Oslo (left panel) and Trondheim (right panel). Larger dots indicate a greater number of firms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

input was formed by basic data from the Norwegian Foreign Trade Statistics.

CO_2 emissions from freight transport were derived from the NFM transport flow outputs (tonne-km, based on mode-specific tonne-km and CO_2 intensities per km, including vehicles of different sizes) and the average capacity utilisation of each mode. Transport distances between each zone pair in the central areas were based on the level of service matrices from the National Transport Model (NTM) for passenger transport in Norway (i.e., zones at the so-called NTM6 level, constituting approximately 1600 zones for Norway; see Rekdal et al., 2014; Steinsland, Fridstrøm, Madslien, & Minken, 2018). Transport activity and CO_2 emissions generated by domestic and foreign transport flows generated by the warehouses were then summarised for the central and the peripheral locations, respectively. Differences between locations were found by subtracting the figures for the previous central locations from the figures for the current peripheral locations. The results were used as inputs when analysing differences in total CO_2 emissions between the scenarios.

Data on plot sizes for the warehouses (that had relocated) in their current (peripheral) locations were retrieved from the Norwegian land register, which is '*the official register of legal rights and obligations associated with real property and housing cooperatives*' (Norwegian Mapping Authority, 2018). We found data for 4 of 12 firms in Trondheim, with plot sizes varying from 1500 to 18,000 m^2 and an average size of about 11,000 m^2. We found data for six out of eight firms that had relocated to Oslo north, varying in plot size from 5300 to 141,000 m^2, and an average size of about 32,000 m^2. For firms that had relocated to Oslo south, we found data for 10 out of 12 firms, varying in size from 3500 to 140,000 m^2, with an average size of about 33,000 m^2. We decided to use the average plot sizes for all Oslo firms, 33,000 m^2, in the calculation of the Oslo cases, with 11,000 m^2 for the Trondheim cases. These figures were used when calculating the average CO_2-emission differences for the warehouses (see results in Table 4).

The main uncertainties in these calculations lie with the differences in CO_2 emissions for warehouses in different locations and with plot sizes. Plot sizes are uncertain because data were not available for all relevant warehouses, as well as because data on plot sizes in the previous central locations were not available. Relocation of warehouses often also entails other changes (organisational, land-use efficiency, and hence, plot sizes) that affect what one could term 'freight-activity per m^2'. Hence, comparing plot sizes in the central and peripheral localisation would have been problematic even if complete data were available. This was an argument for the decision to use the average plot size. We conducted sensitivity analyses in which plot sizes, as well as differences in CO_2 emissions generated by the warehouses in different locations, were varied by ± 50%.

3.3. Calculating CO_2 emissions generated by dwellings and workplaces in different locations

Analyses of differences in transport-related CO_2-emissions generated by dwellings and workplaces (later termed *urban development*) in central and peripheral locations, resembling locations warehouses, were also required when analysing differences in total transport-related CO_2 emissions between the two scenarios. In Trondheim, the central area was defined as the city centre and the core city within 2.5 km from the city centre (Fig. 3). The peripheral area in Trondheim included the suburban area Heimdal, located about 10–14 km from the city centre. The Oslo urban region is larger and more complex than the Trondheim urban region is. Hence, for Oslo, we defined a central area, a semi-central area and several peripheral municipalities—located at different distances from the core city—as peripheral areas; these areas can be described as follows (Fig. 3):

- Central area: the area including the city centre and stretching about 5.5 km from the city centre through the inner city towards the eastern border of the dense city;
- Semi-central area: the suburban area east of Oslo (Groruddalen), stretching from about 5.5 km to 13 km from the city centre, towards the north-eastern municipal border;
- Peripheral areas north: Three municipalities located in different distances north-east of Oslo city centre—Skedsmo (centre located 24 km from Oslo city centre by road), Sørum (37 km) and Ullensaker (45 km); and
- Peripheral areas south: Four municipalities located at different distances south of the Oslo city centre—Oppegård (centre located 16 km from Oslo city centre by road), Ski (30 km), Ås (39 km) and Vestby (41 km).

When analysing the effects of different locations of urban development in Oslo, we distinguished between all these areas. When analysing the effects of different locations of warehouses, the central and semi-central areas in Oslo were analysed as one area.

For each area, vehicle kilometres (vkm) by private car and passenger kilometres (pkm) by public transport generated per inhabitant living in the area and per employee working in the area were calculated. For this, we used geo-coded data from the National Travel Survey (NTS) from 2013/14, comprising reports from about 60,000 persons nationwide (Hjorthol, Engebretsen, & Uteng, 2014). Modal splits for trips to and from workplaces and to and from dwellings (all kinds of trips) in each area were analysed. For journeys between homes and workplaces located in the same area, we split the work trips and counted trips from home to workplace as trips related to the workplace and the trips from workplace to home as trips related to the home. In this way, we included most trips without double counting any trips. Trips that neither started nor ended at the home or the workplace were omitted, but these represented a low share of trips. For trips performed as car drivers and public transport passengers, we also calculated the average travel lengths per trip. The NTS provided data on average numbers of trips per day.

The data (modal splits and average trip lengths on car-driver trips and public transport trips) were used when calculating traffic volumes (vkm) and public transport passenger volumes (pkm) generated per employee per year at workplaces located in the different areas; see Eqs. (1) and (2):

$$\begin{aligned}&\textit{Vkm per employee per year}\\&\quad = \textit{Car driver share} \times \textit{Average travel distance per car trip} \times 2\ \textit{trips a}\\&\qquad \textit{day} \times 230\ \textit{work days per year}\end{aligned} \tag{1}$$

$$\begin{aligned}&\textit{Pkm per employee per year}\\&\quad = \textit{Public transport share}\\&\qquad \times \textit{Average travel distance per public transport trip} \times 2\ \textit{trips a}\\&\qquad \textit{day} \times 230\ \textit{work days per year}\end{aligned} \tag{2}$$

Vkm and pkm generated per inhabitant per year (all kinds of trips) were calculated as in Eqs. (3) and (4):

$$\begin{aligned}&\textit{Vkm per inhabitant per year}\\&\quad = \textit{Car driver share} \times \textit{Average travel distance per car trip} \times 3,26\ \textit{trips a}\\&\qquad \textit{day} \times 365\ \textit{days per year}\end{aligned} \tag{3}$$

$$\begin{aligned}&\textit{Pkm per inhabitant per year}\\&\quad = \textit{Public transport share}\\&\qquad \times \textit{Average travel distance per public transport trip} \times 3,26\ \textit{trips a}\\&\qquad \textit{day} \times 365\ \textit{days per year}\end{aligned} \tag{4}$$

Calculations of transport-related CO_2 emissions per inhabitant and per employee required data for CO_2 emissions per vkm (private car) and pkm (public transport). Clearly, exact and certain data for this are not available. We used figures estimated in previous projects (Tennøy et al.,

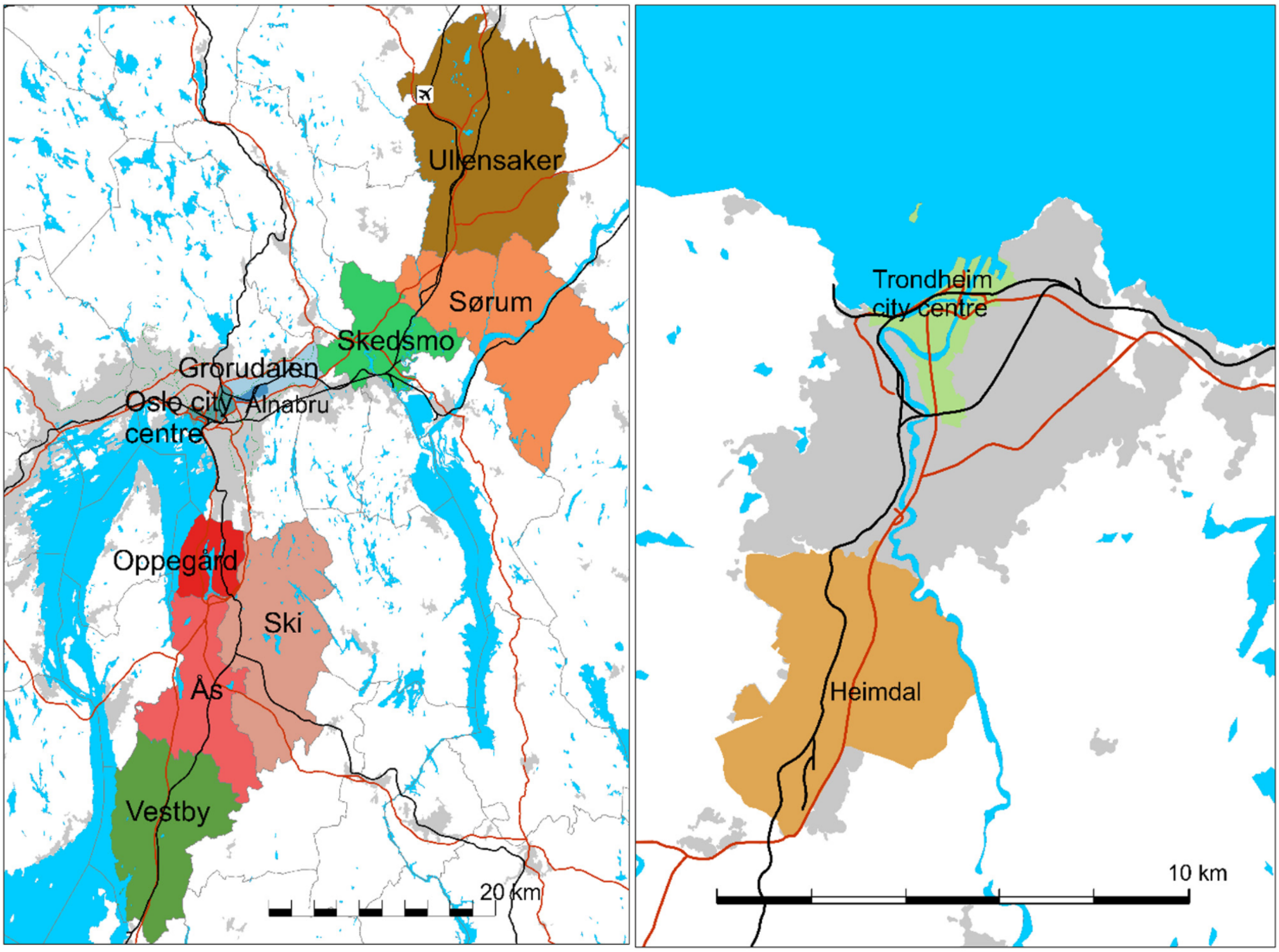

Fig. 3. Illustration of defined areas in Oslo (left) and Trondheim (right) used in the analyses of differences in CO_2 emissions generated by dwellings and workplaces in different locations.

Table 1
Figures for CO_2 emissions per vkm (private car) and pkm (public transport) in Oslo and Trondheim.

	CO_2-emissions per vehicle kilometre (kg)	CO_2-emissions per passenger kilometre (kg)
Oslo	0,15	0,00396
Trondheim	0,15	0,02508

2014; Tennøy, Øksenholt, & Aarhaug, 2013) based on the available statistical data (Kolshus, 2015; Monserud & Brunvoll, 2011; Statistics Norway, 2013) as the basis. These data were adjusted, with the help of the best available expertise, in terms of improved motor technologies, a strong increase in shares of electrical vehicles and increased use of bio-diesel in public transport in the Oslo region. CO_2 emissions from bio-diesel are not included as CO_2 emissions in our calculations. The figures for CO_2 emissions per public transport pkm are far higher in Trondheim than they are in Oslo. This is because public transport in Trondheim mainly runs on fossil fuels, while major shares of public transport in the Oslo region run on electricity and bio-fuels. For private cars, we used the same CO_2 emissions per vkm, as there was no evidence of significant differences between the regions. The figures used in the calculations are listed in Table 1.

CO_2-emissions per inhabitant and per employee per year could now be calculated *for each of the defined locations*, as in Eqs. (5) and (6) below.

$$\begin{aligned}&CO2\ emissions\ generated\ per\ inhabitant\ per\ year\\&\quad = (Vkm\ per\ inhabitant\ per\ year \times CO2\ emissions\ per\ Vkm)\\&\qquad + (Pkm\ per\ inhabitant\ per\ year \times CO2\ emsissions\ per\ Pkm)\end{aligned} \tag{5}$$

$$\begin{aligned}&CO2\ emissions\ generated\ per\ employee\ per\ year\\&\quad = (Vkm\ per\ employee\ per\ year \times CO2\ emissions\ per\ Vkm)\\&\qquad + (Pkm\ per\ employee\ per\ year \times CO2\ emssions\ per\ Pkm)\end{aligned} \tag{6}$$

Differences between CO_2-emissions generated per inhabitant and per employee in the different geographical areas could now be calculated by subtracting CO_2-emissions generated in central and semi-central areas from emissions generated in various peripheral areas (see results in Table 5).

Finally, we needed data for densities of employees and inhabitants in existing central and semi-central areas, to define how many inhabitants and work-places/employees we could assume there would be room for on the plots freed up when warehouses relocate from central areas. Geo-coded data from the Central Register of Enterprises (Statistics Norway, 2017a), including all units in Norway with economic activity, were used when analysing densities of employees in different areas. Population statistics (Statistics Norway, 2017b) were employed when analysing densities of inhabitants. Densities used in the calculations are listed in Table 2.

We used plot sizes of 33,000 m^2 in Oslo and 11,000 m^2 in Trondheim (see Section 3.2). With all the necessary data assembled, we could now analyse the differences in CO_2 emissions generated by a defined number of inhabitants and employees located in central, semi-

Table 2
Densities (population and employees) in central and semi-central areas in Oslo and Trondheim (data from Statistics Norway, 2017a and 2017b).

Area	Employees per km^2	Population per km^2
Oslo central	21,569	6060
Oslo semi-central	2187	3065
Trondheim central	9779	3121

central and various peripheral areas in the urban regions, as in Eq. 7 (see results in Table 5):

$$\Delta CO2\ emission\ urban\ development = (population\ density \times plot\ size \times \Delta CO2\ emission\ per\ inhabitant) + (employee\ density \times plot\ size \times \Delta CO2\ emission\ per\ employee) \quad (7)$$

The main uncertainties in these calculations lie with the CO_2 emissions per vkm and per pkm. Densities used could also be discussed, as new urban development in central and semi-central areas will often be denser than it is in the current situation. For these reasons, we conducted sensitivity analyses, varying figures for differences in CO_2 emissions between areas and for densities, by ± 50%, to investigate how this affects results and conclusions.

3.4. Comparing scenarios

Through the steps described in Sections 3.2 and 3.3, differences in CO_2 emissions generated by urban developments in plots of defined sizes, located in different areas (*ΔCO2 emissions urban development*), as well as differences in CO_2 emissions generated by warehouses in different areas (*ΔCO2 emissions warehouses*), were found. These findings were used as input when analysing differences in total transport-related CO_2 emissions between scenarios, as in Eq. (8) (see results in Table 6):

$$CO2\ differences\ between\ scenarios\ (total) = \Delta CO2\ emissions\ urban\ development - \Delta CO2\ warehouses \quad (8)$$

3.5. Sensitivity analyses

Sensitivity analyses were executed by increasing and decreasing figures by 50% for variables with uncertainty, as identified in Sections 3.2 and 3.3: Differences in CO_2 emissions per warehouse in different locations, plot sizes left in central areas by warehouses, differences in CO_2 emissions per inhabitant and employee in different locations and urban development densities. Further, multivariate sensitivity analyses were conducted where several variables were set conservatively to arrive at the lowest reductions. The results are listed in Tables A1, A2 and A3 in Appendix A.

4. Results

4.1. Effects of different locations of warehouses

Results from calculations of effects of relocating warehouses in the two urban regions are presented in Table 3, which shows transport volumes (1000 t-km per year) and CO_2 emissions (tonnes per year) in central and peripheral locations, as well as the differences between them. We distinguish between domestic volumes (between the warehouses and origin and delivery points in Norway, mainly urban distribution to shops, restaurants, etc.) and foreign volumes (i.e. between the Norwegian border and the domestic warehouses).

In total, relocation of the warehouses from central to peripheral locations resulted in increased transport volumes and CO_2 emissions from transport in both cases. In Trondheim, a marginal reduction in domestic transport volumes and a 0.9% increase in foreign transport volumes resulted in a 0.3% increase in total traffic volumes. Many deliveries have start- or end-points in the peripheral area south of Trondheim, meaning that warehouses relocating to a more peripheral location have relocated along the main transport route from the south. Modal changes for domestic and foreign transport were only marginal. CO_2 emissions from domestic transport increased by 0.3%, while emissions increased by 2.0% for foreign transport, resulting in a 0.5% total increase.

In Oslo (total), domestic transport volumes (in tonne-km) increased by 1.7%, while foreign transport volumes decreased by 3.2%, resulting in a 0.9% total increase. The growth in domestic transport volumes is explained by longer distances from warehouses to delivery points in the Oslo area. The reduction in foreign transport volumes is explained in that many warehouses have relocated to areas south of Oslo and closer to the main border crossing for road transport from the south of Sweden and Europe to Oslo, meaning that part of the transport shifted from foreign to domestic (as defined here). CO_2 emissions increased by 2.4% for domestic transport and 9.4% for foreign transport, resulting in a 2.7% total increase. The stronger increase in CO_2 emissions than in transport volumes was caused by modal changes from sea to road, as road transport is more CO_2-emissions intensive on average.

Separate analyses for the warehouses relocated to the north and south of Oslo showed clear differences. The effects were significantly weaker for warehouses relocated to the south, along major transport routes, and stronger for warehouses relocated to the area north of Oslo, where relocation generated substantial detours. Focussing on CO_2 emissions, the total increases were 5.6% for northern relocations and 1.9% for warehouses relocated to the south of the city. Although the results depend on the characteristics of the sample firms (e.g. demand patterns), and therefore, will vary between firms, these findings demonstrate that the more specific location of warehouses matters.

When analysing differences in total transport-related CO_2 emissions between scenarios (in Section 4.3), results are needed in terms of tonnes of CO_2 emissions per warehouse. Average differences in CO_2 emissions per relocated warehouse were calculated, as listed in Table 4.

4.2. Effects of different locations of dwellings and workplaces

When calculating differences in transport-related CO_2 emissions generated per employee and per inhabitant located in central, semi-central and peripheral areas (as described in Section 3.3, Eqs. (1)–(7), we arrived at the results presented in Table 5.

These figures are used when calculating differences in transport-related CO_2 emissions generated by the same number of inhabitants and employees when located in central, semi-central and different peripheral areas (as described in Section 3.3 and Eq. (7)). The numbers of inhabitants and employees used in those calculations are defined by the plot sizes left for urban development in the central areas of the urban regions (Table 6, column 6: *Plot-size* (m_2)*;* see also Section 3.2) and the densities of employees and inhabitants in the different areas (see Table 2). The resulting differences are listed in column 3 in Table 6.

4.3. Comparison of scenarios

Differences in total transport-related CO_2 emissions between the scenarios can now be analysed, and the results are presented in Table 6, column 5: *Total difference, tonnes of* CO_2. Total differences were found by subtracting differences in CO_2 emissions *per warehouse* when relocating from central and semi-central areas to peripheral areas (in column 4: *Difference in tonnes of CO2 for warehouses*, figures from Table 4) from CO_2 emissions saved when defined (by plot sizes) as numbers of employees and inhabitants are located in central or semi-central areas instead of in different peripheral areas (column 3: *Difference in tonnes of CO2 for urban development*; see Eq.(8) for explanation).

In all the cases investigated, the findings show that relocating

Table 3
Differences between transport volumes and CO_2 emissions generated by warehouses in central and peripheral locations in Trondheim and Oslo for the samples identified in Section 3.2.

	Transport volumes (1000 t-km per year)			CO_2 emissions (tonnes per year)		
	Domestic	Foreign	Total	Domestic	Foreign	Total
Trondheim*						
Central location	39,202	26,103	65,305	3340	543	3882
Peripheral location	39,165	26,345	65,510	3348	553	3902
Difference (absolute)	−37	242	205	9	11	19
Difference (%)	−0.1%	0.9%	0.3%	0.3%	2.0%	0.5%
Oslo total*						
Central location	311,044	58,612	369,656	34,879	1757	36,636
Peripheral location	316,315	56,728	373,043	35,717	1922	37,640
Difference (absolute)	5271	−1884	3387	839	165	1004
Difference (%)	1.7%	−3.2%	0.9%	2.4%	9.4%	2.7%
Oslo north						
Central location	76,899	6156	83,055	7998	204	8202
Peripheral location	79,825	6521	83,346	8412	244	8657
Difference (absolute)	2926	365	3291	414	41	455
Difference (%)	3.8%	5.9%	4.0%	5.2%	20.1%	5.6%
Oslo south						
Central location	234,145	52,456	286,601	26,880	1553	28,434
Peripheral location	236,490	50,207	286,697	27,305	1678	28,983
Difference (absolute)	2345	−2249	96	425	124	549
Difference (%)	1.0%	−4.3%	0.0%	1,6%	8,0%	1,9%

Figures under headings marked '*' have previously been published in Pinchasik et al. (2019).

central and semi-central warehouses to more peripheral locations, to give room for urban development on the freed-up plots in central and semi-central areas that would otherwise have been developed in peripheral areas, contributes to reducing transport-related CO_2 emissions. The findings also show that the CO_2-emission reduction effects of relocating warehouses are stronger with a more central original location, as well as a more peripheral alternative localisation of urban development. This is mainly caused by differences in travel behaviour, where inhabitants and employees generate more traffic and CO_2 emissions the further from the main city centre their dwellings and workplaces are located, as discussed in Section 2.

4.4. Sensitivity analyses

The findings presented in Table 6 are the results of analyses requiring data and assumptions that are uncertain for various reasons (as discussed in Section 3). To test the strength and soundness of the results, sensitivity analyses were executed by increasing and decreasing the following variables by 50%: differences between CO_2 emissions per warehouse in different locations, differences between CO_2 emissions per inhabitant and per employee in different locations, plot sizes left by warehouses, and densities of inhabitants and workplaces. Multivariate sensitivity analyses are also conducted, where two, three and four of the variables listed above are set conservatively to minimise CO_2-emission reductions.

4.4.1. Varying CO_2 effects of relocating warehouses

We found that a 50% increase in differences between CO_2 emissions generated by warehouses in central and peripheral locations resulted in negative figures (meaning increased total CO_2 emissions) in the cases where new urban developments are located in the nearest municipalities to the south (Oppegård) and north (Skedsmo) of Oslo rather than semi-central areas (see Appendix A, Table A1 for the results). These municipalities are located closest to the semi-central areas, meaning that differences in travel behaviour are small. Cases with more peripheral alternative locations of the urban development, as well as where warehouses are relocated away from central areas, still result in substantial reductions in CO_2 emissions.

4.4.2. Varying plot sizes, densities and CO_2-emission differences for passenger transport

When assuming 50% smaller plot sizes freed up for urban development by relocated warehouses, total CO_2 emissions increase in several cases where warehouses are relocated from semi-central to peripheral locations (see Appendix A, Table A2 for results). Relocation of centrally located warehouses still results in substantial reductions in CO_2 emissions in all relevant cases.

From Eq. (7) in Section 3.3, it is clear that increasing and decreasing the variables of 'densities' and the 'CO_2-emissions difference for passenger transport' by 50% will produce the same results as increasing and decreasing plot sizes by 50%. As discussed above, one could claim that densities in new urban developments in semi-central areas can be expected to be higher than those found in the current situation, and Table A2 shows that this would result in stronger CO_2-emission reductions in cases where warehouses are relocated away from semi-central areas. The table also demonstrates that decreasing differences in CO_2 emissions generated by inhabitants and employees located more and less centrally reduces the amount of CO_2 emissions.

Table 4
Average figures for differences in tonnes of CO_2 emissions per warehouse per year, when relocated from central to peripheral locations in Trondheim and Oslo.

Warehouses relocated to	Average figures (differences in tonnes of CO_2 emissions per warehouse per year)	Differences in tonnes of CO_2 emission per year, all warehouses in each area	Number of warehouses in each area
Trondheim peripheral	1.6	19	12
Oslo peripheral south	46	549	12
Oslo peripheral north	57	455	8

Table 5
Differences between CO_2 emissions per year generated per employee and per inhabitant in different locations in Trondheim and Oslo, in absolute (tonnes of CO_2) and relative (%) figures.

Comparing locations	Differences (tonnes of CO_2 emissions)		Differences (%)	
	Per employee	Per inhabitant	Per employee	Per inhabitant
Trondheim central versus:				
Trondheim peripheral	0.26	0.52	76	109
Oslo central versus:				
Semi-central location	0.42	0.21	119	40
Peripheral locations south				
Oppegård	0.58	0.63	166	117
Ski	0.98	0.72	278	134
Ås	0.76	0.79	215	147
Vestby	0.82	1.62	234	301
Peripheral locations north				
Skedsmo	0.54	0.81	153	150
Sørum	1.12	1.56	317	289
Ullensaker	0.86	1.39	245	258
Oslo semi-central versus:				
Oslo central	−0.43	−0.21	−55	−29
Peripheral locations south				
Oppegård	0.16	0.41	20	55
Ski	0.55	0.51	71	67
Ås	0.33	0.58	42	77
Vestby	0.39	1.41	50	187
Peripheral locations north				
Skedsmo	0.11	0.59	14	79
Sørum	0.69	1.34	88	178
Ullensaker	0.43	1.17	56	156

Table 6
Differences between total transport-related CO_2 emissions in different scenarios.

Comparing		Difference in tonnes of CO_2 for urban development	Difference in tonnes of CO_2 for warehouses	Total difference, tonnes of CO_2	Plot-size (m^2)
Central/semi-central	Peripheral				
Trondheim central	Trondheim peripheral	46.5	1.6	44.9	11,000
Oslo central	Oslo semi-central	348.1	–	–	33,000
	Oppegård	542.0	46.0	496.0	33,000
	Ski	840.8	46.0	794.8	33,000
	Ås	697.1	46.0	651.1	33,000
	Vestby	909.9	46.0	863.9	33,000
	Skedsmo	544.7	57.0	487.7	33,000
	Sørum	1105.5	57.0	1048.5	33,000
	Ullensaker	891.8	57.0	834.8	33,000
Oslo semi-central	Oslo central*	−52.7	–	–	33,000
	Oppegård	53.2	46.0	7.2	33,000
	Ski	90.8	46.0	44.8	33,000
	Ås	82.2	46.0	36.2	33,000
	Vestby	170.9	46.0	124.9	33,000
	Skedsmo	67.8	57.0	10.8	33,000
	Sørum	185.5	57.0	128.5	33,000
	Ullensaker	150.0	57.0	93.0	33,000

*Differences when comparing Oslo semi-central with Oslo central are smaller than those when comparing Oslo central with Oslo semi-central because lower densities in Oslo semi-central mean that there are fewer inhabitants and employees included in this calculation.

4.4.3. Multivariate sensitivity analyses

Sensitivity analyses where two, three and four variables were set to minimise the CO_2-reducing effects of the scenarios were conducted (see results in Table A3 in Appendix A). In all three analyses, the differences in CO_2 emissions per warehouse in different locations were increased by 50%. In the 'Minimum 1' analysis, one of the variables discussed in Section 4.4.2 (plot size, densities, CO_2-emissions difference for passenger transport) was decreased by 50%; in 'Minimum 2', two of the variables were decreased by 50%; and in 'Minimum 3', all three variables were decreased by 50%.

Cases where warehouses were relocated from central areas resulted in total CO_2-emissions reductions in almost all cases, as was the case when all four variables are set conservatively. Hence, in our understanding, it is a sound finding with a high degree of certainty that relocating warehouses to free up land in central areas for urban development that would otherwise have been located to more peripheral areas can be expected to result in reduced CO_2 emissions. The findings also emphasise that the effects of relocating warehouses from semi-central areas to free up land for urban development in these areas are more context-dependent and uncertain. As described in Section 3.2, in our cases, 'central areas' include not only the city centres but also most of the core areas in the cities, within 5.5 km from the city centre in the Oslo case and 2.5 km in the Trondheim case (when analysing urban development). When analysing warehouses, 'central areas' also include semi-central areas, meaning that it includes the whole municipality in the Oslo case.

5. Discussion and concluding remarks

The aim of this study was to contribute to the following research interests: *i)* investigating the net CO_2 effects of relocating wholesale warehouses away from central and semi-central areas, replacing them with new dwellings and workplaces that would otherwise have been located in more peripheral areas, and *ii)* how the more specific locations of warehouses, as well as dwellings and workplaces, influence effects. The analyses were conducted as case studies in the two Norwegian urban regions, Oslo and Trondheim, where two different scenarios were compared using empirical data from the case regions.

All the cases investigated resulted in reduced net CO_2 emissions from transport. Both warehouses and urban development generated more CO_2 emissions the further from the city centre they were located, but the differences were larger for urban developments than they were for warehouses. The effects were stronger the more centrally the warehouses were originally located, as well as the more peripherally new urban development was alternatively located. This is mainly related to effects of location on travel behaviour, where inhabitants and employees generate more traffic and related CO_2 emissions the further from the main city centre their dwellings and workplaces are located; this has been theoretically explained and empirically documented in previous research (see Section 2). In the Oslo case, separate analyses of warehouses located to the north and south of the core city showed clear differences. The increases in CO_2 emissions were significantly stronger for warehouses relocated to the north than to the south, mainly because locations north of the city cause detours while locations to the south are along major transport routes from Sweden and Europe to Oslo. As there were uncertainties related to several variables in the analyses, multivariate sensitivity analyses were conducted. These analyses showed that relocating warehouses away from central areas to give room for urban development resulted in CO_2-emission reductions in almost all investigated cases, including when all four key variables were set conservatively (least CO_2 reducing). The effects of relocating warehouses from semi-central areas to free up land for other development in these areas were more context dependent and uncertain.

The results in this article open discussions concerning other land-use developments than those included in the scenarios investigated. As expected, the calculations showed that both warehouses and urban development generate fewer CO_2 emissions when located more centrally. Using these results in the optimisation of land-use development with the aim of minimising CO_2 emissions would result in suggestions for developing both warehouses and urban developments as densification and transformation in more central locations rather than allowing or facilitating sprawl.

An issue not discussed here is the effect of reorganising logistics by locating smaller consolidation points in or close to the city centre, which could enable last-mile deliveries with smaller or zero-emission vehicles. This would often imply a combination of larger freight facilities in the periphery and small consolidation points in the city centre. Although such organisational changes could be an important part of solving problems related to deliveries in the city centre, and to make deliveries more efficient, it may also increase logistics costs due to the extra reloading. Nordtømme, Bjerkan, and Sund (2015) found that an obstacle to introducing this in Oslo was carriers and end receivers not acknowledging the need for such solutions and perceiving economic consequences to be negative.

We believe the findings in this article are relevant in land use and transport planning. Plans for the urban regions studied here suggest relocating freight facilities away from central areas to give room for dense and mixed urban development in those areas as part of their strategies for reducing urban sprawl, traffic volumes and CO_2 emissions from transport (Oslo Municipality and Akershus County, 2015; Trondheimsregionen, 2015). Our findings suggest that these strategies are efficient in contributing to achieving these goals, given the need to prioritise between activities. If municipalities could find ways of developing both freight facilities and urban developments as densification and transformation, rather than allowing or facilitating sprawl of any activity type, this could contribute even more to goal achievement. The strategic plans for Trondheim and Oslo urban regions suggest locations of freight facilities that will cause detours. Our results show that this may result in freight transport generating more traffic and CO_2 emissions than if located along main transport routes. Like other countries, Norway is experiencing more rapid growth in CO_2 emissions generated by road freight transport than for passenger transport (Statistics Norway, 2018). If decision makers and planners more properly considered the specific locations of freight facilities, in the investigated regions and elsewhere, growth could be reduced.

We think that the research and findings presented here have relevance beyond the Norwegian context as reducing CO_2 emissions from transport is a major issue in cities, regions and countries across the globe (European Commission, 2011, 2013; European Environment Agency, 2019; Norwegian Environment Agency, 2015; UN Habitat, 2013). Although the interrelation between knowledge and action in planning and decision making is far from obvious (Krizek, Forsyth, & Slotterback, 2009; Tennøy, Hansson, Lissandrello, & Næss, 2016), it could be maintained that knowledge is a necessary condition for enabling planners and decision makers to steer development in directions contributing to achieving prioritised societal goals.

CRediT authorship contribution statement

Aud Tennøy: Supervision, Project administration, Funding acquisition, Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Daniel Ruben Pinchasik:** Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Frants Gundersen:** Formal analysis, Visualization, Data curation, Writing - original draft. **Inger Beate Hovi:** Funding acquisition, Conceptualization, Formal analysis, Data curation, Methodology, Writing - review & editing.

Declaration of competing interest

None.

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Appendix A. Results from sensitivity analyses

Table A1
Results from sensitivity analyses where differences between CO_2 emissions for warehouses in different locations are increased and decreased by 50%, in different scenarios.

Comparing		Total difference in CO_2 emissions		
Central/semi-central	Peripheral	Original	50% increase	50% decrease
Trondheim central	Trondheim peripheral	44.9	44.1	45.7

(*continued on next page*)

Table A1 (*continued*)

Comparing		Total difference in CO_2 emissions		
Central/semi-central	Peripheral	Original	50% increase	50% decrease
Oslo central	Oslo semi-central			
	Oppegård	496.0	473.0	519.0
	Ski	794.8	771.8	817.8
	Ås	651.1	628.1	674.1
	Vestby	863.9	840.9	886.9
	Skedsmo	487.7	459.2	516.2
	Sørum	1048.5	1020.0	1077.0
	Ullensaker	834.8	806.3	863.3
Oslo semi-central	Oslo central			
	Oppegård	7.2	−15.8	30.2
	Ski	44.8	21.8	67.8
	Ås	36.2	13.2	59.2
	Vestby	124.9	101.9	147.9
	Skedsmo	10.8	−17.7	39.3
	Sørum	128.5	100.0	157.0
	Ullensaker	93.0	64.5	121.5

Table A2

Results from sensitivity analyses where assumed plot sizes freed up by relocated warehouses are increased and decreased by 50% in different scenarios.

Comparing		Total difference in CO_2 emissions		
Central/semi-central	Peripheral	Original (11,000/33000 m^2)	50% increase (16,500/49500 m^2)	50% decrease (5500/16500 m^2)
Trondheim central	Trondheim peripheral	44.9	68.2	21.7
Oslo central	Oslo semi-central			
	Oppegård	496.0	767.1	225.0
	Ski	794.8	1215.2	374.4
	Ås	651.1	999.6	302.5
	Vestby	863.9	1318.9	409.0
	Skedsmo	487.7	760.0	215.3
	Sørum	1048.5	1601.3	495.8
	Ullensaker	834.8	1280.7	388.9
Oslo semi-central	Oslo central			
	Oppegård	7.2	33.7	−19.4
	Ski	44.8	90.3	−0.6
	Ås	36.2	77.3	−4.9
	Vestby	124.9	210.4	39.5
	Skedsmo	10.8	44.8	−23.1
	Sørum	128.5	221.2	35.7
	Ullensaker	93.0	168.0	18.0

Table A3

Results from sensitivity analyses where two, three and four variables are set to minimise the CO_2-reducing effects of scenarios.

Comparing		Total difference in CO_2 emissions			
Central/semi-central	Peripheral	Original	Minimum 1	Minimum 2	Minimum 3
Trondheim central	Trondheim peripheral	44.9	20.9	9.2	3.4
Oslo central	Oppegård	496.0	202.0	66.5	−1.2
	Ski	794.8	351.4	141.2	36.1
	Ås	651.1	279.5	105.3	18.1
	Vestby	863.9	386.0	158.5	44.7
	Skedsmo	487.7	186.8	50.7	−17.4
	Sørum	1048.5	467.3	190.9	52.7
	Ullensaker	834.8	360.4	137.5	26.0
Oslo semi-central	Oppegård	7.2	−42.4	−55.7	−62.4
	Ski	44.8	−23.6	−46.3	−57.6
	Ås	36.2	−27.9	−48.5	−58.7
	Vestby	124.9	16.5	−26.3	−47.6
	Skedsmo	10.8	−51.6	−68.5	−77.0
	Sørum	128.5	7.2	−39.1	−62.3
	Ullensaker	93.0	−10.5	−48.0	−66.7

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