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The effects of geographical, operational and service parameters on WEEE transport networks

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Abstract

Efficiency in the collection and transport of waste electrical and electronic equipment (WEEE) is important for economic and environmental reasons. A detailed analysis of the logistical- and cost-effectiveness of the collection and transport of WEEE in Norway reveals regional geography to be a particularly important factor; it varies significantly across the country and heavily influences the cost of collection. The paper explores the influence of this, along with other parameters relating to operational effectiveness and customer service. Implications for all the key actors in the WEEE collection and transport business are outlined.

Key words: WEEE collection; geographical parameters; service parameters; route planning; transport cost analysis.

1. *Introduction*

The collection, transport and recycling of waste electrical and electronic equipment (WEEE) is an activity of ever-increasing importance in an increasingly technological world. Increasing scarcity of valuable resources, and the potential for significant environmental impact from electronic waste, drive the ongoing effort to improve the recycling supply chain. This includes elements at the beginning of the chain (e.g., encouraging consumers to recycle electronics at end of life) and at the end (e.g., ensuring environmentally sound treatment, eliminating illegal or undesirable export). This paper focuses on intermediate parts of the chain in Norway – specifically the transport of WEEE from initial collection points where it is deposited by the end-consumer to regional reception sites where it is either treated or aggregated for onward transport to specialist treatment facilities.

Collection and transport of WEEE have typically been considered as reverse-logistics processes, which more broadly are an area of decision-making / operational research that has a long history. Reverse logistics problems are often analysed as combinatorial optimization problems in integer programming frameworks, with a view to arriving at optimal design of a logistics network with respect to one or more cost-related criteria. Such approaches have been applied to collection networks for many types of waste, including vehicles (Vidovic et al. 2011), plastic waste (Bing et al. 2014), municipal solid waste (Akbarpour Shirazi et al. 2016) and hazardous wastes (Hu et al. 2002). Mathematically, such studies usually involve one or more optimisation calculations, often types of vehicle routeing problems (VRP) and/or facility location problems (FLP), for the optimal flows of vehicles between different facilities in a network, and the location of particular parts of a network (for example collection facilities or treatment plants) respectively.

With respect to WEEE, most studies are of the latter, facility-location, sort. The relatively early and widely-cited study of WEEE collection in Taiwan by Shih (2001) covered collection, transport, treatment and reclaimed materials in a cost / revenue perspective, using an integer programming approach to optimise facility location. Increasingly sophisticated mathematical formulations, encompassing many parts of the value chain in ever-more detail, have stemmed from this work (for example, Dat et al. 2012) but facility-location remains a prime focus.

Variations of scope include that in the Danish study of Gunrow and Gobbi (2009), which reflects the specific regulatory framework in Denmark whereby collection locations are allocated to take-back companies; the aim was fair and efficient allocation. Quieruga et al. (2008) attempted to evaluate the location of WEEE recycling plants according to a weighted combination of economic, legal and environmental factors. Gamberini et al. (2010) touched upon aspects that emerged as important in the present study, such as vehicle utilisation and capacity, in an Italian study that ultimately focused primarily on environmental factors.

More recent examples of broad and ambitious attempts to design a national network for WEEE include one in Portugal (Gomes et al. 2011). In some cases, these studies attempt to effectively design networks from scratch, particularly where there is little or no pre-existing formal infrastructure for WEEE, it instead being diverted along informal treatment paths. Recent studies in Turkey (Kilic et al. 2015, Aras et al. 2015) provide further broadly similar examples. The studies of WEEE collection in Greece by Achillas et al. (2010a, 2010b, 2011) provide an exception to the norm in that they consider some aspects of collection and transport cost, such as the use and availability of containers, in considerably more detail than the norm. Nonetheless the study essentially focuses on facility location over and above transportation cost optimisation.

Almost all of this work has at least one, and sometimes all, of the following features: the scope encompasses more of the value chain than just collection and transport, also including treatment and recycling; the focus may encompass factors other than logistical efficiency; modelling of parts of the value chain is quite broad-brush and general, with data seldom gathered directly from relevant actors; and the studies are predictive, focused upon designing new systems rather than evaluating existing ones. The broad modelling and parameterisation of transport, in contrast to the more detailed break-down of that part of the value chain in the present paper, is the most important of these factors. In addition, the geographical focus of such studies varies considerably. Many studies focus on local networks, perhaps at the level of an individual city or county / region. Others have a broader, often national, geographical scope. More detailed studies of the efficiency of transport-logistical problems, most importantly those directly involving the relevant actors, are much less common.

Bø and Hammervoll (2010), in a study of the wholesale grocery sector, found that both providers and purchasers of transport logistics had a fair general understanding of the relevant cost drivers and pricing structures, such understanding was patchy and incomplete. As such, contractual and operational arrangements were both made to some degree on instinct. A decision support tool devised in the study, which derived detailed costs in the categories used in the present paper (fixed, variable and salary costs as previously outlined by Stock and Lambert, 2001), enabled both parties to better understand the sensitivities and hence raise operational efficiency. Related work (Hammervoll and Bø, 2010) focused on the relationship between actors and importance of transparent information exchange as a driver for improvement. At the outset of the project underpinning this paper, we identified a similar picture for the Norwegian WEEE sector, and concluded that a broadly similar overall approach was feasible.

Norwegian infrastructure for WEEE collection and transport – reception and treatment facilities – was already well-developed. Hence, redesign of the collection and transport network in terms of adding or repositioning facilities was not on the agenda and FLPs did not form part of the analysis. The focus is on the transport of WEEE between existing facilities and hence forms of VRP. The study’s essential and distinguishing elements include the level of detail in the cost elements and the active participation of the relevant actors.

Norway, whilst not a member of the European Union, has incorporated the major European regulations on WEEE, notably the WEEE Directive (2012) and the directive restricting the use of hazardous substances in electronic equipment (the RoHS Directive, 2011), into its own national regulation. Indeed Norway is seen as something of a pioneer regarding WEEE and its regulation, and the existing EU Directives are said to be modelled on earlier Norwegian regulations. Collection and ultimately recycling of WEEE proceeds via the implementation of Extended Producer Responsibility (OECD, 2001) for WEEE in Norway. Producers and/or importers of electronic equipment are obligated to make arrangements for and to finance the collection, sorting, transport and recycling of electronic waste. Take-back companies (otherwise known as Producer Responsibility Organisations or PROs) are membership organisations for electronics producers, certified by the Norwegian authorities, which undertake these tasks on a collective basis. The actors of interest are as follows:

- retailers or municipal facilities, who accept WEEE from end-consumers as they are required to do so by the regulations
- the PRO, who does not engage directly in collection, transport and recycling activities – instead fulfilling a coordination role
- specialist transport contractors, who undertake the transport work on behalf of the PRO

Figure 1 shows the chain of WEEE from the consumer through to treatment and recycling operations, including the three principal transport steps T1-T3. Via a combination of consumer bring and kerbside collection, WEEE is transferred from consumers to local collection points (T1). These include individual retail outlets obligated to engage in take-back and municipal collection points. There are many hundreds of these local collection points across the country. WEEE is assumed to be separated from other waste but is otherwise unsorted. The WEEE is then collected, on behalf of the PROs, by specialist transporters, and taken to regional reception points (T2) – of which there are perhaps a dozen across the country. Thereafter, it is separated into fractions and sent onwards – either in-country or overseas – to specialist treatment and recycling facilities (T3).

[Figure 1 near here]

Here, we are concerned solely with the T2 step and its logistical efficiency. Transport vehicles for WEEE originate at the regional reception centres and are filled as they travel to one or more collection points before returning to the reception centre to unload. The study analyses the transport work and particularly the cost factors involved in this part of the operation, with a view to designing and operating WEEE collection in as effective a fashion as possible.

Collection networks, for WEEE and other types of waste, are not necessarily designed with logistical efficiency in mind. The location and spread of collection and treatment facilities is generally motivated by factors other than transport logistics – for example, convenience for consumers in terms of retail facilities or the operations of waste operators that may consider other sorts of waste alongside WEEE. Also, Norway experiences particular issues relating to geography and demographics. The wide variations in population density are quite extreme, meaning that WEEE in some parts of the country is much more onerous and costly to collect (hence less attractive to PROs) than in others. Without careful oversight and control of costs, there is a considerable risk of the WEEE that is most easily collected being cherry-picked to fulfil collection quotas, and of WEEE in remote areas never being collected. Many aspects of Norwegian WEEE collection are organised according to county. In this paper, we analyse operations in three different counties which vary greatly in terms of geography, population and the collected mass of WEEE subject to analysis in this study, as shown in Figure 2.

[Figure 2 near here]

Oslo county is dominated by the nation's capital and is essentially urban, with an average population density of around 1400 inhabitants per square kilometre. In stark contrast, Finnmark in the far north is large but extremely rural and sparsely populated, with only 1.5 inhabitants per square kilometre. Oppland provides an intermediate geography – it has quite large rural areas but also the moderately-sized urban area of Lillehammer. Overall, the three counties capture a wide range of different geographies. The result, as will be shown below, is that the effective value of WEEE and the costs of collection vary greatly across the country; local geography is certainly a factor of prime interest.

We focus on the operations of Elretur AS, one of the key PROs in the Norwegian market and an active participant, along with its subcontractors, in ongoing research. It has about 30% overall market share and focuses mostly on WEEE from households rather than from businesses. Its WEEE collection operations are contracted-out to two companies on a regional basis, with transport and logistics being further subcontracted to a range of hauliers. Like all Norwegian PROs it has operations in all parts of the country, and it appears that its operations are reasonably representative of the market as a whole. For example, it is known that the same hauliers conduct operations for multiple PROs.

In examining Elretur's operations we have identified "service" levels as a further area of interest. This concerns how frequently (on average) WEEE is collected from customers, therefore effectively to what degree customers are willing and able to stockpile WEEE at the initial collection point. Perhaps obviously, frequency of collection in practice varies greatly from site to site and depends on factors such as the rate of WEEE being brought to the site, the facilities available for intermediate holding of the WEEE, the facility's location, and so on. As will be described below, the total costs of collection and transport are calculated as an important indicator of logistical effectiveness. These might be influenced by operational parameters relating to collection and transport, such as the efficiency of loading / unloading of vehicles, which will also be considered.

The aim of the study is to calculate the logistical, and ultimately financial, costs of performing a given WEEE collection and transport duty, also to assess sensitivities so as to improve our general understanding of important factors such as regional geography for the design and operation of WEEE transport and collection networks. The paper is organised as follows. The reverse-logistical model is described in section 2, which yields factors such as the total vehicle distance covered for a given WEEE collection duty under given conditions. This then feeds into the economic model described in section 3 which yields the overall cost of collection and transport as a function of geographical, operational and service parameters. A range of scenarios are explored and discussed in section 4, with the principal conclusions being outlined in section 5.

2. *Logistical modelling of WEEE collection and transport networks*

In each case, the WEEE collection and transport task in focus is to collect the annual quantity of WEEE for a single PRO from a number of pickup locations around the county, and transport this to a specified reception point - which may be, and often is, outside the county itself. The locations for Finnmark are illustrated for example in Figure 3, with the reception point being outside the county, in the city of Tromsø. In practice, the WEEE collection modelled in this study is actually a subset of the total for the county – this depended on the structuring of particular contracts between PRO and transporter. A basic cost per kilo of collection, and the sensitivity of that cost to various parameters, is determined. The mass of WEEE studied is relatively large (around 40% of the actual annual total for each county) and the geographical spread of pick-up locations is relatively wide across the region. It follows that the analysis is satisfactorily representative of the total function – to give a representative cost per tonne of collection, yet avoid the need for extremely complex and onerous calculations that an absolutely full analysis would entail.

[Figure 3 near here]

This study makes use of Elretur’s extensive electronic records of collections and deliveries, which establishes the range of WEEE collection points of interest and the masses of WEEE collected by date. The resultant calculations are framed entirely in mass terms. This is in accord with many aspects of WEEE collection and transport – including overall collection statistics and targets, the costing and pricing of collection, transport and treatment, the capacity and payload of vehicles and so on. In the study we assume that filling of vehicles is mass-limited, and that the collection duty is undertaken by a fleet of vehicles each with the same capacity. Mass-limitation is a reasonable assumption for some types of WEEE but somewhat dubious for others, notably large white goods where volume per unit mass of vehicular filling is often low. Nonetheless all contracts, targets and calculations remain in mass terms at present, so a mass basis for our study is inevitable. Elretur’s records and experience suggest that a fleet of uniformly-sized vehicles is reasonable, except for central Oslo which is often served by smaller-capacity vehicles.

The exercise proceeds by first calculating the minimum driving distance for the collection and transport task, subject to specific assumptions regarding the frequency of collection from any given point (i.e., the level of “service”). The overall amount of WEEE to be collected in any given year is known in advance, but the amounts available at individual collection points are not. The latter are projected from the corresponding data in Elretur's records from previous years, and collated in the form of an order book, which details the projected ongoing demand for collection from individual sites over the forthcoming year.

The calculation is performed using the Network Analyst extension of the ArcGIS software platform. The procedure is that for a vehicle routing problem (VRP) in a reverse-logistical configuration to fulfil the order book. This means that there are multiple sources of goods (depots, the WEEE collection points) and a single deposit point (the regional reception). The minimum transport work is achieved in part by ensuring that vehicles run fully-loaded as much as possible. The basic operations of optimising transport work by matching orders to vehicle capacity and pairing orders along particular routes proceed exactly as normal. However the configuration differs from many typical VRPs, in that the demand at each point at any given time often exceeds the full capacity of the vehicles. A simplified example involving just three collection points and a reception point is illustrated in Figure 4.

[Figure 4 near here]

In this example, the capacity of the vehicle is 15 tonnes and the amounts of WEEE at the three collection points are as shown in Figure 4(a). The first stage is to take full loads from each and every site which can supply them. Hence, Figure 4(b) shows a vehicle running empty to site C1, collecting a full 15 tonne load, and then returning to the reception point R. Figure 4(c) shows the procedure repeated for site C2, whose inventory falls from 20 tonnes to 5 tonnes. At this point there remains no collection point at which a full load remains, and it becomes a conventional VRP to determine the remainder of the total minimum driving distance. Not all three remaining loads can be accommodated together; in this case it is optimal to collect from C3 then C2 as in Figure 4(d) and finally the remaining WEEE from C1 as in Figure 4(e).

The final output from the calculations is a schedule of routes with collection and drop-off points, which gives the total driving distance for the collection and transport duty. The principal data and calculated results are shown in Table 1.

[Table 1 near here]

The range of transport distances calculated for each county arises from variations in service level, which is described below.

3. *Economic modelling of WEEE collection and transport networks*

Following earlier work (Bø & Hammervoll, 2010; Stock and Lambert, 2001) the economic model calculates and adds fixed, variable and salary costs to yield a total cost per tonne of WEEE collected. The transport work calculations described in the previous section provide a direct input to the variable and salary cost calculations and an indirect input to the fixed costs. The model is implemented in Microsoft Excel and allows a wide range of contributory parameters to be varied, analysed and visualised.

3.1. *Principal data and sources*

The main primary data underpinning the model and its parameters were gathered as follows:

- Direct from Elretur

    - Historical data on quantities of WEEE collected, locations, dates and service levels – the order books for the study then being generated from forward projections of these data
- Direct from the hauliers as part of an ongoing research investigation in conjunction with Elretur
    - Fixed cost elements (equipment purchase, effective lifetimes, insurance, administration, taxes)
    - Variable cost parameters (fuel, maintenance, tyres)
    - Average remuneration costs for staff (hourly rates)
- From direct observation of haulier operations
    - Numbers of stops, stop times, loading and unloading rates, average driving speeds

The first two parts of the data were supplied directly by the relevant party, supplemented by allowing us access to internal company databases and systems where appropriate. Observations of haulier operations was performed within a sub-project (Karlsen and Aannestad, 2015) and involved the researchers directly participating in the operations of two transport vehicles over a period of 10 working days, logging nearly 100 separate collections and deliveries with direct measurements of relevant times, quantities and speeds. All of the data collected directly was complemented by structured interviews and informal unstructured communication with the relevant parties, over periods of months and years.

3.2. *Data quality, ranges, uncertainty*

We are reasonably confident regarding the quality and representativeness of the assembled data. The most important elements relating to where and when WEEE is collected stem from very detailed and robust internal systems. Fixed cost data from the hauliers is less robustly supported by objective measurements but it emerges that it contributes relatively weakly to overall costs in any case. Both of these data-sets are nationwide. The direct observations of haulier operations are extensive but limited in scope (to a single haulier, in the Oslo area). Nonetheless our experience and contacts within the sector as a whole allow us to extrapolate with some confidence as necessary. We have had direct contact with – if not direct observation of – every relevant party to this study. There follows an assessment of data quality and reliability for individual parameters, where applicable.

With respect to driving speed, a range of 25-70 km/h is used in the study, which fairly obviously captures almost all of the range of realistic speeds in each region. It seems extremely unlikely that average speeds are as low as 25 km/h in rural areas although this may not be unreasonable for daytime collections in urbanised areas, conversely it seems unlikely average speeds as high as 70 km/h will be achieved in a large city, but they may be routine on reasonable roads in open country. Hence, the data should be regarded as giving a general sense of sensitivity to the speed parameter rather than specific results for any particular area.

The rate at which transport vehicles are loaded and unloaded was identified as a potentially significant cost driver. This was calculated in terms of loading / unloading time per tonne of WEEE, even if many aspects of vehicle loading are actually volume- rather than weight-limited. A base-case value was derived from specific observations as 27 minutes per tonne for loading and unloading combined (18.5 minutes for loading and 8.5 minutes for unloading), and a possible range of 20-35 minutes was assumed.

A further operational parameter identified in the model was a “fixed time for stop”, reflecting the interval between a vehicle arriving at a loading or unloading point and loading commencing - also any delay following loading/unloading before the vehicle left. This parameter reflects the infrastructure and procedure for receiving and processing vehicle arrivals and departures at loading and unloading points. An average of nine minutes per stop was estimated from observational data, and a range of between four and eighteen minutes per stop was chosen for sensitivity analysis - essentially doubling or halving the overall efficiency of operations.

The operational parameters in the economic model reflect the fact that duties are shared in practice, but only as an overall percentage of the vehicle’s activity. It was impossible in the field to determine the exact division of loading between different activities. Nonetheless, calculation of the appropriate cost per tonne depends strongly on this division, particularly with respect to sharing fixed costs – as the results below show. In this analysis we do not attempt to determine the division of effort between different tasks, but we show in general how such division, if it were included, affects the overall costs.

This is necessary because in practice the vehicles are not dedicated to the specific WEEE collection task - indeed, transporters’ operations would be inefficient if they were so dedicated, with limited overall utilisation and substantial amounts of empty running. This was noted directly in field observations (Karlsen and Aanestad, 2015) and also in our previous experience of observing the operations of Elretur and its contractors.

Firstly, as stated above, this paper analyses only a proportion of the total WEEE collection operation. Also, vehicles might also be deployed on WEEE work for other PROs, the conveyance of other goods, or other unspecified duties. By maximising the effective use of the vehicle, one should in principle be able to lower the effective cost for each specific duty, by sharing the costs between them. In effect, therefore, the overall utilisation of the vehicle is a further operational efficiency factor to be considered. The calculation neglects any revenue that might be derived from additional vehicle usage, merely spreading the fixed costs more thinly across a wider range of activities.

The total annual fixed cost of the vehicles includes capital costs in the form of annual depreciation, cost of capital, administrative and insurance costs. Thus far in this analysis, all of the calculations have effectively assumed that the vehicles *are* dedicated to the WEEE collection operation being studied – the costs are fully allocated to that operation. In the following analysis, only a proportion of the fixed costs are allocated to WEEE collection, according to the overall operational use of the vehicles in hours of operation per year.

The economic and GIS models combined give a total time of operation for the year for the WEEE collection duty, which varies according to region and service level between 644 and 2230 hours. For the purposes of this analysis, we assume that a vehicle can in principle be operational for 3700 hours per year – corresponding to two separate shifts each working 37 hour weeks for 50 weeks per year. This of course assumes that a significant proportion of the vehicle’s operations take place in non-regular hours (evenings, nights, weekends). We assume that this is possible for the sort of work undertaken by these vehicles, although we note that constraints of facility opening and closing times often feature in VRP problems of the sort we have tackled here – and we have assumed complete freedom from such constraints. The discussion thus far has implicitly assumed that the relevant duties are undertaken by a single vehicle. It should nonetheless be noted that the calculations remain valid, subject to the specific assumptions, even where in practice there are multiple vehicles undertaking the WEEE collection duty.

3.3. *Calculation procedure*

Following earlier work (Bø & Hammervoll, 2010; Stock and Lambert, 2001) the economic model calculates and adds fixed, variable and salary costs to yield a total cost per tonne of WEEE collected. The transport work calculations provide a direct input, in the form of total driving distance, to the variable and salary cost calculations and an indirect input to the fixed costs. The model is implemented in Microsoft Excel and allows a wide range of contributory parameters to be varied, analysed and visualised.

The annual fixed costs are those independent of distance driven, as follows:

$$C_f = \frac{P(1-v)}{L} + \frac{P(1+v)r}{2} + F_o \tag{1}$$

where C_f is the annual fixed cost, P the purchase price of the vehicle (excluding tyres, which are modelled through a variable cost), v is the residual value of the vehicle (as a fraction of the purchase price) after a lifetime of L years, r the effective interest rate and F_o is the average annual sum of other fixed costs. The three terms represent in turn the average annual depreciation of capital equipment (trucks and trailers), the average annual costs of capital, and the average annual insurance, administration and taxes.

Variable costs depend on distance driven, as follows:

$$C_v = (F + M + T)D \tag{2}$$

where C_v is the annual variable cost, F the average fuel price, M the average maintenance cost and T the average cost of tyre replacement, with all three parameters being calculated per driven kilometre. D is the total distance driven in kilometres, as calculated from the transport-logistical model as described above.

Salary costs are calculated based on average staff hourly rates and the calculated total operational time of the vehicle per year.

$$C_s = W\left[\frac{D}{S} + N_s t_s + M(t_l + t_u)\right] \tag{3}$$

where W is the annual average hourly staff wage, S is the overall average driving speed, N_s the number of stops per year and t_s the average fixed time per stop, M the total mass of WEEE collected in tonnes, t_l the average loading time per tonne and t_u the average unloading time per tonne.

Summing the costs in the different categories and dividing through by M gives a total cost per tonne collected.

4. Main results from economic model

The study addresses the complex interplay between geographical, operational and service parameters on the logistical and hence economic efficiency of WEEE collection and transport. The most important parameters are as follows:

- Geographical factors – as established in the discussion above, regional geography appears to be a fundamental underlying factor in most of the analysis. It feeds into the model via the geographical spread of demand points, and hence driving distances and times for collection. Results are calculated for the three counties described above (Oslo, Oppland and Finnmark).
- Operational parameters – these factors capture operational effectiveness and to some extent, in principle, can be controlled by the transporters. They include average speed in transport, loading and unloading rates, and the utilisation of transport vehicles.
- Service parameters – these capture the frequency with which WEEE is collected from customers. The study establishes two extremes of service level, a theoretical minimum and a maximum. Minimum service assumes that collection takes place wholly at the transporter's convenience – it implies that the customer can store any amount of WEEE indefinitely before it is collected. In terms of the logistical model, it establishes a single demand point at each site, containing the total annual amount of WEEE for that site. Maximum service level essentially assumes that WEEE is collected on demand (as it is reported). We know from historical data and field observations that the actual service level is somewhere near maximum in highly urban areas and much lower in rural ones.

Figure 5 shows the basic variation in cost with geographical factors, by presenting the overall cost of collection and transport for the different counties studied, at different service levels. Regional geography has a strong overall effect, with costs in rural Finnmark being several times higher than those in urban Oslo. There are a range of reasons for this, which will be explored further below – the much longer distances between collection and/or reception points are an obviously important factor. Figure 5 also illustrates the effect of service level in different geographies. The results show that for the urban and semi-urban geographies, the level of service has a very limited effect on costs, limited to a few percent. However, in the highly rural geography of Finnmark, there is a very strong variation in cost with service level, with overall costs more than doubling between the two levels of service.

[Figure 5 near here]

The economic model encompasses three main elements and a number of sub-elements of cost, as outlined above. Further insight into the cost drivers can be seen from a breakdown of costs into major categories, as shown in Figure 6.

[Figure 6 near here]

A number of points are immediately apparent. Firstly, the variable costs increase sharply for rural areas, particularly when the service level is high. The collection work requires large driven distances with consequent high costs for fuel, tyres and maintenance. Salary costs are also high, owing to long journeys to, from and between collection points – each tonne of WEEE takes on average 3-4 times longer to collect in Finnmark than in the other regions. Once again, this is a strong function of service level. There is relatively little collected in

Finnmark and hence the fixed costs per tonne collected are also high compared to other regions – but this cost element does not depend on service level.

The next stage of analysis looks at operational parameters, and their interplay with geographical ones). Figure 7 shows the basic sensitivity of cost to average driving speed, based on the minimum service level for each county.

[Figure 7 near here]

The absolute levels of cost obviously vary considerably, so the percentage variation is perhaps the best comparison across the three counties. For Oppland the cost varies by about 18% across the full range, in Finnmark it is 37% and in Oslo 9%. However, most of the difference in cost for Finnmark appears between 25 km/h and 50 km/h, which is probably outside the realistic range in practice.

Figures 8 and 9 show the sensitivity of cost to operational factors relating to stops, specifically loading and unloading rates, and fixed times per stop, respectively. As outlined above, these factors were observed directly in the field.

[Figure 8 near here]

Figure 8 shows that loading and unloading times could be a quite significant parameter, particularly in Oslo, where the overall cost varies by almost 25% over the range of times analysed. For Oppland the cost variation is 12% and for Finnmark only 5%.

[Figure 9 near here]

Figure 9 indicates that a plausible range of fixed times per stop does not have much influence on overall cost. There is a variation of only 0.5% in total cost for Finnmark, 1.2% for Oppland and 2.8% for Oslo.

The final operational factor considered in Table 2 concerns overall utilisation of the vehicles, and hence how the fixed costs of the vehicles are allocated to the WEEE collection being analysed.

[Table 2 near here]

With the exception of maximum service level in Finnmark, the fair allocation of fixed costs across a range of vehicle activities has a marked effect on the overall costs of WEEE collection. A reduction in costs of 40% or more is possible through effective utilisation of vehicles. We have already established that high service levels in highly remote areas such as Finnmark seem very unrealistic, and so this particular result arguably does not merit much attention.

5. Discussion and conclusions

The results show a clear interplay between geographical and other parameters. Geographical factors are always important and as such provide an anchor for the other factors – that is, variations of cost with other factors always have a geographical element which should be taken into account; geography should always be considered. With all other factors being equal, costs are around twice as high in semi-rural regions as in urban ones, and around six times as high in very rural areas.

In the following sections we discuss the significance of individual factors examined in the study.

5.1. *Effect of customer service level*

The calculations show that cost is only weakly sensitive to service level in urban and semi-rural geographies (Oslo and Oppland) but highly sensitive to service level in rural Finnmark.

Historical data, in the form of Elretur's collection and delivery records, show that realistic levels of service vary considerably. Maximum service levels imply frequent collections, often of relatively small amounts of WEEE, probably at short notice. This is seen to be reasonably feasible in urban environments with large numbers of closely-grouped customers. Collection vehicles are available at relatively short notice owing to other work in the vicinity, and so fast response to short-term demand is relatively straightforward. In marked contrast, for rural areas maximum service levels would imply very inefficient operations, with vehicles frequently covering very long distances to collect small amounts. Furthermore, from the customer perspective, it seems natural that urban customers may well face severe constraints in terms of space and the cost of real estate, and may not be able to store amounts of WEEE for any period of time before collection. In contrast, in rural areas such pressures may well be less severe, and customers may be able to store WEEE for some time before collection without undue difficulty. Longer-term storage does increase certain risks (including those of theft), these are not considered here but should also be noted.

Generally speaking, service levels in practice are at least moderate and may be high in urban and semi-rural areas, but are low in rural areas. This means that, overall, service level is not a particularly important factor for overall logistical efficiency and collection cost. The one caveat is if high service levels and frequent collections are demanded in rural areas – this would drive up costs sharply.

5.2. Effect of operational factors

Fairly naturally, the results show that variable and salary costs – rather than fixed costs – are the main drivers for increased overall costs per tonne of collection in semi-rural and rural compared to urban areas. In turn, these depend strongly on the routeing of vehicles and hence the overall driven distance. In principle, some of the underpinning factors can be consciously influenced to some degree by the transporter, and in some way are representative of "efficiency of operations". However, there are inevitably practical constraints on the range and variability of the parameters considered.

Average driving speed clearly depends in part on uncontrollable elements (such as terrain and topography, road quality, speed limits on the major routes) but may also be controllable to some extent – for example, average speeds in urban areas could in principle be increased by arranging collections at night and hence reducing problems of traffic. The results suggest that average speed is not a particularly strong driver for total cost across realistic ranges of speed in different areas - perhaps having an effect of up to 10% across a reasonable range of speeds. Stronger sensitivity is only seen across low ranges of speeds in open country.

Efficient loading and unloading of vehicles could have quite a significant effect on cost, particularly in urban and semi-rural areas where driving distances are short and hence the time the vehicle is stationary at loading and unloading points is relatively more significant. Costs could vary by up to around 20% depending on the efficiency of loading / unloading operations. Fixed times per stop (when the vehicle is being prepared for loading / unloading and otherwise when it is stationary but WEEE is not actually being moved) do not influence overall costs very strongly, no more than 2-3% overall. Clearly one can conclude that attempts to improve operational efficiency at the facilities in the collection and transport network should focus on the basic loading and unloading procedures over and above any other factors.

By far the biggest potentially controllable factor is the degree to which vehicles are on the road and working. Vehicle utilisation and consequent allocation of fixed costs is shown to have a very noticeable effect of up to 40% on total cost. In practice, the issues may lie on paper – within contractual arrangements and pricing structures – more than in operational reality. As discussed above, vehicles in practice may be engaging in more activities that are not reflected in cost allocation. This mirrors earlier studies of WEEE treatment and recycling (Mayers et al., 2013) which arrived at the identical conclusion that “paper” issues of cost allocation and financing are crucially important.

5.3. Assumptions and uncertainties in the study

Field observations show that a mass basis for some aspects of the operation is a somewhat dubious assumption. Probably the most important issue concerns the loading of vehicles for WEEE transport, which is almost certainly volume-limited rather than mass-limited in at least some cases. In future work this assumption could be relaxed by using variable effective vehicle capacities, probably depending on the specific types of WEEE being collected at any one time. For example, it seems that waste refrigerators, having large amounts of void space, are likely to pack quite differently onto collection vehicles than smaller types of WEEE.

Uncertainties in most of the operational parameters do not greatly affect the broad findings of the study. For the most part, the greatest sensitivity of costs to uncertainty in parameters coincides with relatively unrealistic ranges in those parameters (for example, across low ranges of driving speed in rural areas).

5.4. Comparison with other studies

As discussed above, much of the other work on WEEE collection and transport is not very similar in scope and approach to the present study so as to allow comparison. However, some of the more recent studies do merit some comparative analyses, at least for overall cost levels.

The studies of northern Greece by Achillas et al. (2010a, 2010b) predicted, depending on scenario, an average WEEE transportation cost of around 50-80 EUR / tonne (around 400-700 NOK / tonne at the exchange rate of the time). In the present study we have identified regional geography as a key parameter, manifest in local population density. For the region of Greece under study this was around 100/km^2 (2 million inhabitants in 20 000 km^2) which is well above Oppland but well below Oslo in the Norwegian context. Interpolating between the Oppland and Oslo cost figures suggests that a Norwegian estimate for a region of equivalent population density would perhaps be 500 NOK per tonne, which is quite similar to the Greek case. Extending the Greek study to the country as a whole (Achillas et al., 2011) saw costs rise to the region of 100 EUR / tonne (once again highly dependent on facility location scenarios) but the scenario is complicated by the fact that around 15% of the Greek population live on islands and therefore the WEEE value chain includes transport to the mainland, which presumably drives up costs. Kilic et al. (2015) performed a study of WEEE in Turkey, with similar overall population density to Greece of around 80/km^2. Once again, depending on facility location scenarios, a cost of around 40-50 EUR / tonne was projected.

Whilst these studies do not provide a breakdown of the transportation costs and the sensitivities as we do here – remembering that they are from predictive studies and give projections based on facility location problems – they nonetheless provide an anchor for our overall cost calculations, suggesting that WEEE transportation costs are broadly similar on a like-for-like (population density) basis.

5.5. Implications of the findings

The findings of the study have implications for all of the main actors in the value chain: governments and policy-makers, producer responsibility organisations and their members, and collection / transport agencies.

In the policy domain, the findings suggest that broader consideration of the funding of WEEE collection, transport and recycling is needed. Analysis of the funding flows for extended producer responsibility schemes for WEEE (Mayers et al., 2013) shows that the funding models are typically rather crude and coarse-grained, with costs allocated on a simple overall mass-averaged basis. The funding regime generally fulfils the ostensible purpose of ensuring that all the costs of collection and treatment are covered by producers, but fails to provide differentiated costs based on the actual collection, treatment and recycling of producers' products. Competition between producer responsibility organisations offers a further level of complication. Shortcomings of these funding arrangements are normally identified with respect to the recycling end of the value chain and the failure to close the loop to producers. Design for recyclability, the broad overall purpose of producer responsibility, is not seen to be particularly encouraged. The potential alternative of differential pricing / costing depending on actual rather than averaged costs has been identified as a potential driver for better recycling practice, specifically the enhanced recovery of plastics from WEEE (Baxter et al., 2015).

Our work here shows that differential costing (specifically, differential *funding*) could equally well apply to collection and transport as to treatment and recycling, particularly in the Norwegian context. The marked differences in difficulty and cost of WEEE collection which we have quantified in this paper have long been recognised in general terms. WEEE in different areas varies significantly in its attractiveness to PROs seeking to fulfil their obligations and those of their members. Specifically, small amounts of WEEE in remote areas assume effectively negative value and in a completely free market would never be collected. Note that here we are regarding WEEE as a whole - certain product groups are always intrinsically more valuable than others. The authorities recognise the danger regarding non-collection in remote areas and take steps to preclude it via regulatory means. Effectively, all producer responsibility organisations are compelled by the Norwegian waste regulations to operate in all areas of the country (Miljødirektoratet, 2013). Whilst this is understandable, it introduces a degree of inefficiency by design into the system. Duplication of effort and the reversal of economies of scale become inevitable. The analysis in this paper shows how such effects can significantly drive up overall costs, and future work will examine this specific issue in further detail. Establishing schemes for PROs to trade collection obligations – as has been seen for example in the UK with the Settlement Centre (UK Environment Agency, 2015)

– might provide a mechanism by which more efficient operation could be encouraged within a marketplace of multiple PROs. More generally, this paper shows that there is considerable scope for improved efficiency – not just in treatment and recycling but also collection and transport of WEEE – given a more sophisticated regulatory environment.

The above findings addressed principally at policy-makers also, of course, have significant implications for PROs. More specifically for that group, the study findings indicate to some degree that examining the structure and organisation of operations (tender processes, awarding of contracts, reporting structures and so on) may be beneficial for logistical and cost efficiency. For example, organising work on a county-by-county basis may be necessary or required for elements of reporting practice, but prove somewhat inefficient in terms of the collection and transport itself.

For transporters, the findings of the study should bring their existing knowledge of their cost base and the drivers for efficiency into focus. The effects of operational factors have been outlined in some detail, and these probably provide some scope for improvement. Route planning did feature in our calculations but does not factor strongly into the findings, for two reasons. Particularly in rural areas, vehicle routeing is often a highly constrained business since there are few degrees of freedom - there may be only one road between any two points, and most of the total driven distance is made up of such tightly constrained route sectors. Secondly, routeing is also somewhat constrained by the fact that collection of full vehicle loads from a single point is often common - in this case also there are obviously few degrees of freedom.

6. *References*

Achillas, C., Vlachokostas, C., Moussiopoulos, N., & Banias, G. (2010a). Decision support system for the optimal location of electrical and electronic waste treatment plants: a case study in Greece. *Waste Management*, 30(5), 870-879.

Achillas, C., Vlachokostas, C., Aidonis, D., Moussiopoulos, N., Iakovou, E., & Banias, G. (2010b). Optimising reverse logistics network to support policy-making in the case of Electrical and Electronic Equipment. *Waste Management*, 30(12), 2592-2600.

Achillas, C., Vlachokostas, C., Moussiopoulos, N., Perkoulidis, G., Banias, G., & Mastropavlos, M. (2011). Electronic waste management cost: a scenario-based analysis for Greece. *Waste Management & Research*, 29(9), 963-972.

Akbarpour Shirazi, M., Samieifard, R., Abduli, M. A., & Omidvar, B. (2016). Mathematical modeling in municipal solid waste management: case study of Tehran. *Journal of Environmental Health Science and Engineering*, 14, 8.

Aras, N., Korugan, A., Büyüközkan, G., Şerifoğlu, F. S., Erol, İ., & Velioğlu, M. N. (2015). Locating recycling facilities for IT-based electronic waste in Turkey. *Journal of Cleaner Production*, 105, 324-336.

Baxter, J., Wahlstrom, M., Zu Castell-Rüdenhausen, M., & Fråne, A. (2015). *Plastic value chains: Case: WEEE (Waste Electrical and Electronic Equipment): Part 2 Report*. Nordic Council of Ministers.

Bing, X., Bloemhof-Ruwaard, J.M. & van der Vorst, J.G.A.J. (2014). Sustainable reverse logistics network design for household plastic waste, *Flexible Services and Manufacturing Journal,* 26, 119-142

Bø, E., & Hammervoll, T. (2010). Cost-based pricing of transportation services in a wholesaler–carrier relationship: An MS Excel spreadsheet decision tool. *International Journal of Logistics: Research and Applications*, 13(3), 197-210.

Dat, L. Q., Linh, D. T. T., Chou, S. Y., & Vincent, F. Y. (2012). Optimizing reverse logistic costs for recycling end-of-life electrical and electronic products. *Expert Systems with Applications*, 39(7), 6380-6387.

Directive, RoHS (2011). 65/EU of the European Parliament and of the Council of 8 June 2011 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (recast). *Off. J. Eur. Union, 1.*

Directive, E. C. (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment, WEEE. *Official Journal of the European Union L*, 197, 38-71

Gamberini, R., Gebennini, E., Manzini, R., & Ziveri, A. (2010). On the integration of planning and environmental impact assessment for a WEEE transportation network—A case study. *Resources, Conservation and Recycling*, 54(11), 937-951.

Gomes, M. I., Barbosa-Povoa, A. P., & Novais, A. Q. (2011). Modelling a recovery network for WEEE: A case study in Portugal. *Waste management*, 31(7), 1645-1660.

Grunow, M., & Gobbi, C. (2009). Designing the reverse network for WEEE in Denmark. *CIRP Annals-Manufacturing Technology*, 58(1), 391-394.

Hammervoll, T., & Bø, E. (2010). Shipper-carrier integration: overcoming the transparency problem through trust and collaboration. *European Journal of Marketing*, 44(7/8), 1121-1139.

Hu T-L., Sheu,J-B & Huang,K_H. (2002). A reverse logistics cost minimization model for the treatment of hazardous wastes, *Transportation Research Part E: Logistics and Transportation Review*, 38(6), 457-473.

Karlsen, G-A. & Aanestad, H.O. (2015). A case study of costs and influencing factors for WEEE-collection in Oslo, *Master of Science in Business thesis, BI Norwegian Business School*

Kilic, H. S., Cebeci, U., & Ayhan, M. B. (2015). Reverse logistics system design for the waste of electrical and electronic equipment (WEEE) in Turkey. *Resources, Conservation and Recycling*, 95, 120-132.

Mayers, K., Lifset, R., Bodenhoefer, K., & Wassenhove, L. N. (2013). Implementing individual producer responsibility for waste electrical and electronic equipment through improved financing. *Journal of Industrial Ecology,* 17(2), 186-198.

Miljødirektoratet: Regulations relating to the recycling of waste (Waste Regulations) (2013), Retrieved October 12, 2015, from http://www.miljodirektoratet.no/no/Regelverk/Forskrifter/Regulations-relating-to-the-recycling-of-waste-Waste-Regulations/

OECD (2001), *Extended Producer Responsibility: A Guidance Manual for Governments, OECD Publishing, Paris*.

Queiruga, D., Walther, G., Gonzalez-Benito, J., & Spengler, T. (2008). Evaluation of sites for the location of WEEE recycling plants in Spain. *Waste management*, 28(1), 181-190.

Shih, L. H. (2001). Reverse logistics system planning for recycling electrical appliances and computers in Taiwan. *Resources, conservation and recycling*, 32(1), 55-72.

Stock, J. R., & Lambert, D. M. (2001). *Strategic logistics management* (Vol. 4). Boston, MA: McGraw-Hill/Irwin.

UK Environment Agency - Waste electrical and electronic equipment (WEEE): Evidence and national protocols guidance. (2015). Retrieved October 29, 2015, from https://www.gov.uk/government/publications/weee-evidence-and-national-protocols-guidance/waste-electrical-and-electronic-equipment-weee-evidence-and-national-protocols-guidance

Vidovic, M., Dimitrijevic, B., Ratkovic, B., & Simic, V. (2011). A novel covering approach to positioning ELV collection points. *Resources, Conservation and Recycling*, 57, 1-9.

Figures and tables

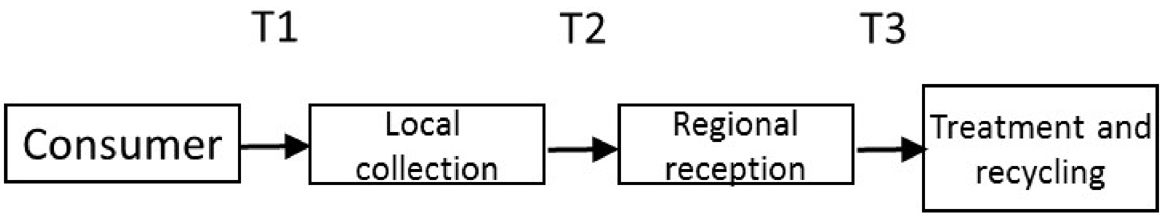

Figure 1: WEEE collection and recycling value chain

	Oslo	Oppland	Finnmark
	454 km^2	25 192 km^2	48 631 km^2

624 000 inhabitants	187 000 inhabitants	74 000 inhabitants
3311 tonnes WEEE	841 tonnes WEEE	422 tonnes WEEE

Figure 2: Counties analysed in the study

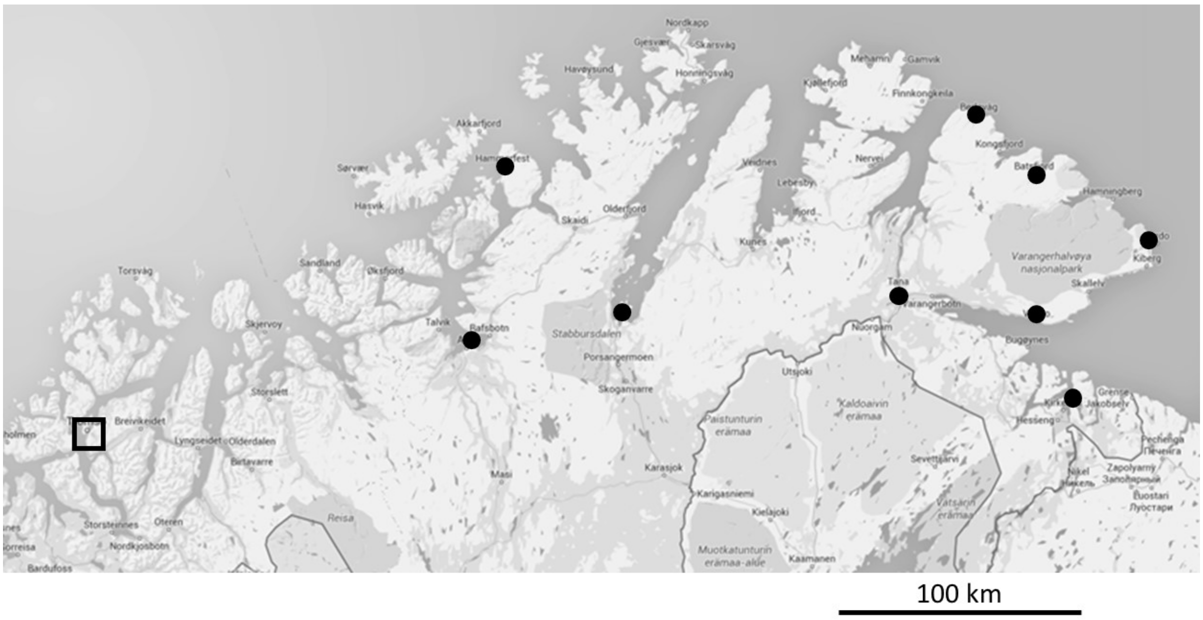

Figure 3: Collection (solid circles) and reception (open square) locations for Finnmark

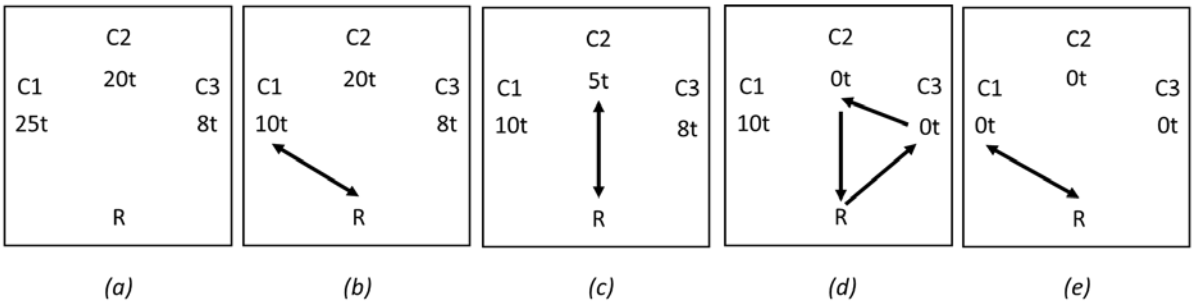

Figure 4: Simplified route planning example with three collection and one reception points

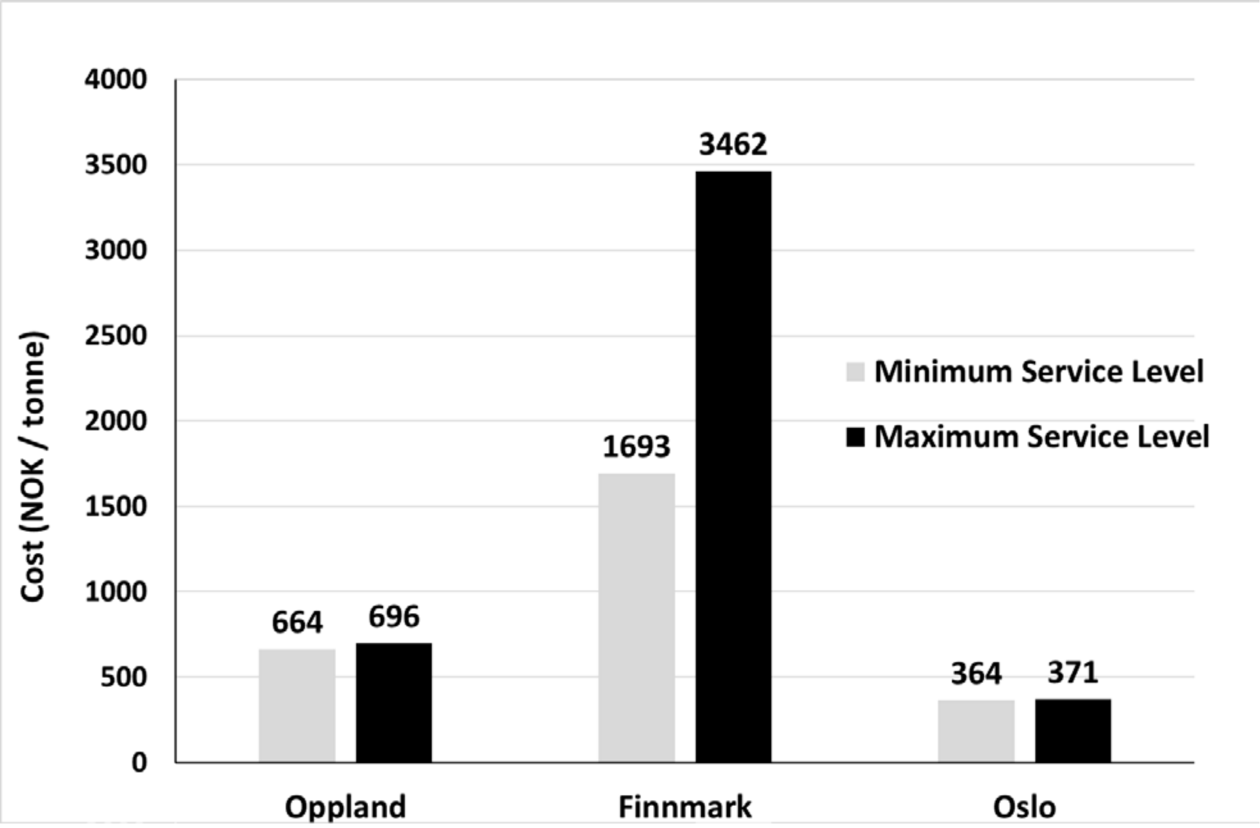

Figure 5: overall cost per tonne of WEEE (different service levels)

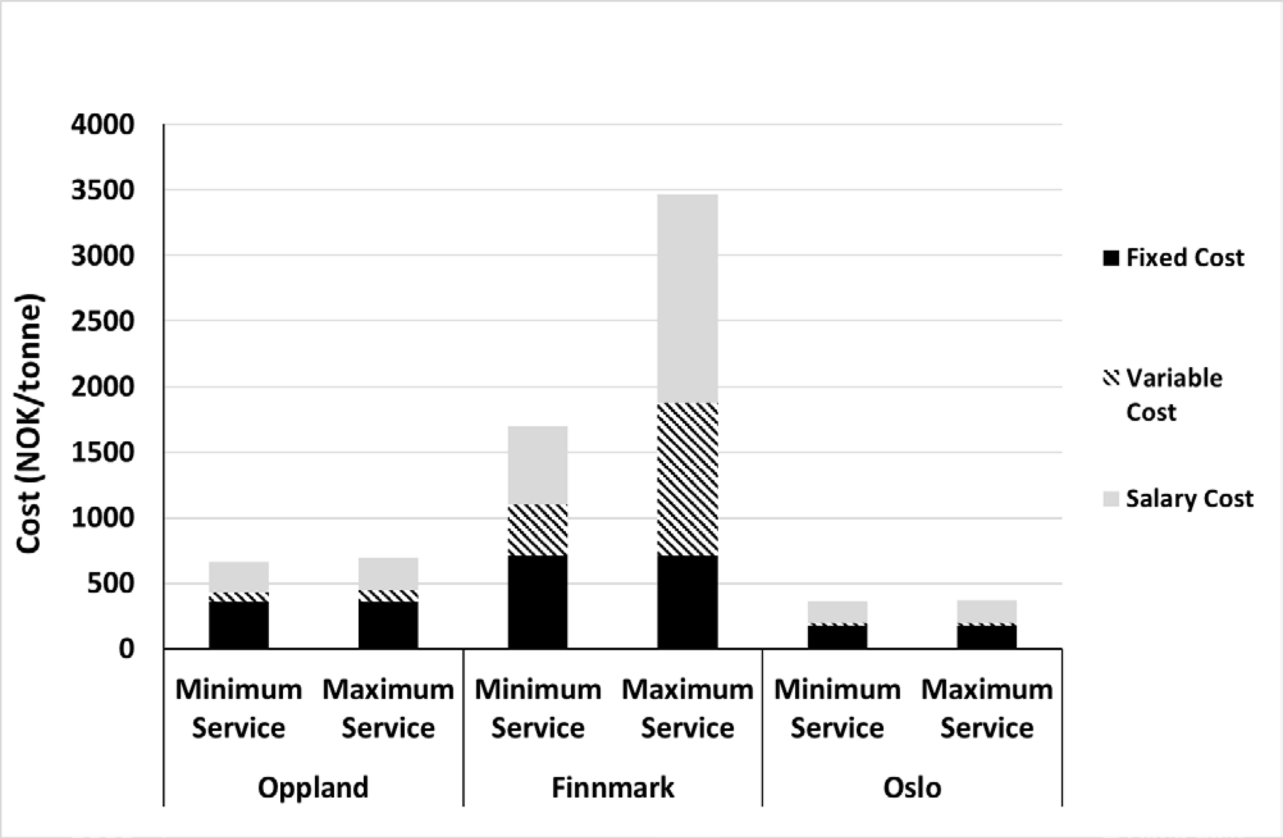

Figure 6: Breakdown of overall costs with service level and geography

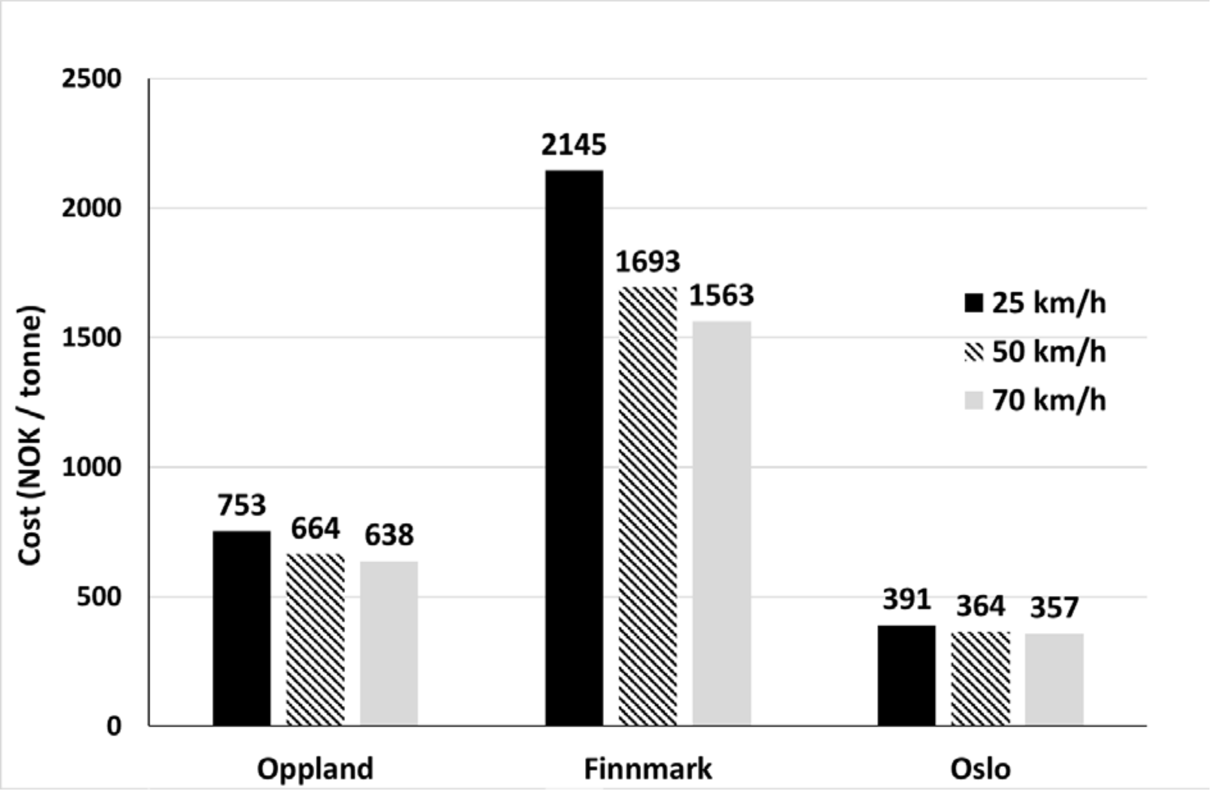

Figure 7: overall cost as a function of average vehicle speed (minimum service level)

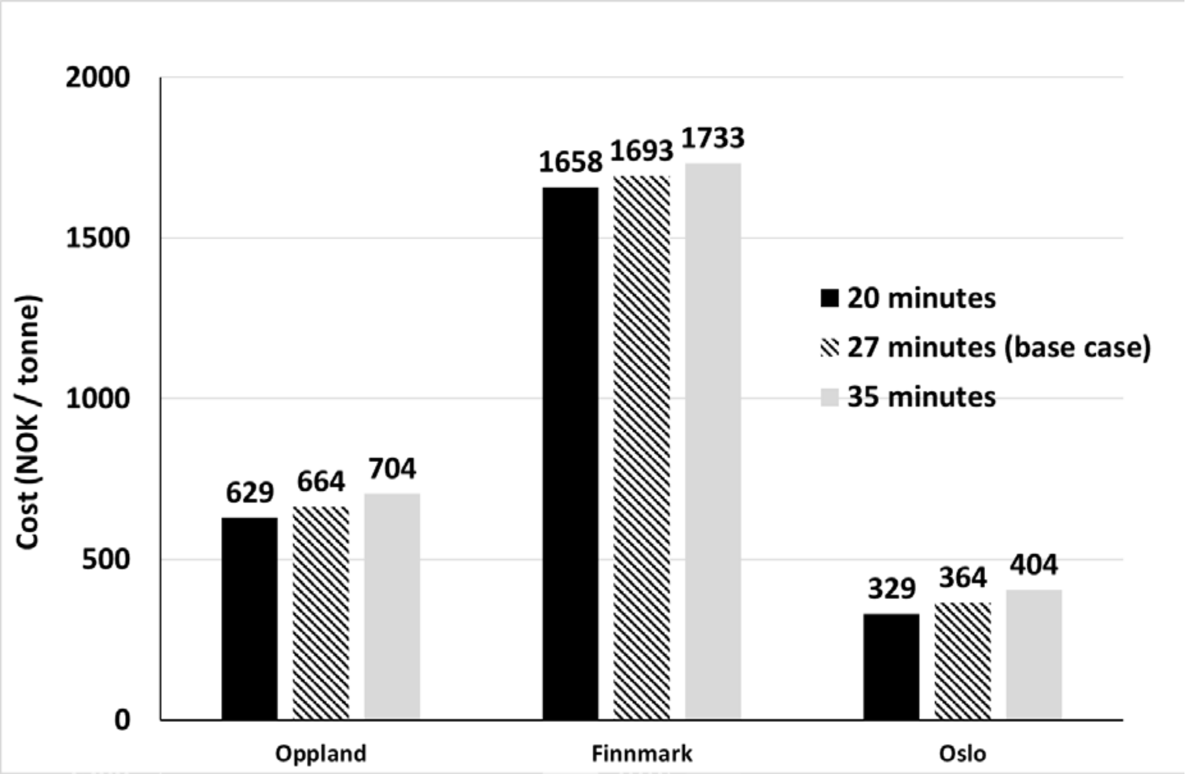

Figure 8: costs per tonne collected as a function of combined loading and unloading time per tonne

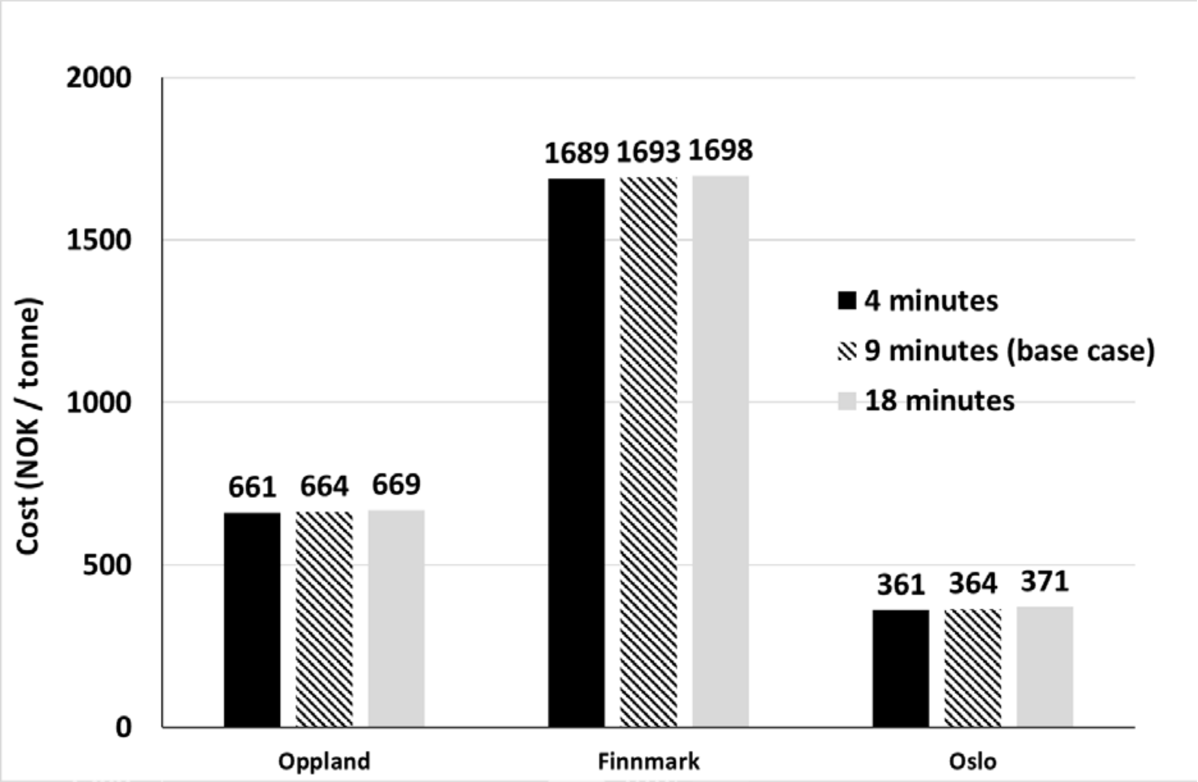

Figure 9: costs per tonne collected as a function of fixed time per stop

	Oslo (Outer)	**Oslo (Inner)**	**Oppland**	**Finnmark**
Vehicle capacity (kg)	17000	6000	17000	17000
Number of collection points	13	10	17	11
Total mass of waste collected (tonnes)	2908	403	841	422
Total distance driven (km)	10334 – 10930	4131 – 4916	12568 – 14848	31845 - 95707

Table 1: Principal data for transport-logistical calculations of WEEE collection and transport

Region	**Service Level**	**Calculated operation time (hours per year)**	**Cost, kr per ton, dedicated operation**	**Cost, kr per ton, non-dedicated operation (3700 hours)**	**Cost reduction for non-dedicated operation**
Oppland	Minimum	644	664	369	44%
	Maximum	696	696	406	42%
Finnmark	Minimum	835	1693	1142	33%
	Maximum	2230	3462	3180	8%
Oslo	Minimum	1853	364	234	36%
	Maximum	1900	371	241	35%

Table 2: effect of vehicle utilisation and fixed cost allocation on cost of collection