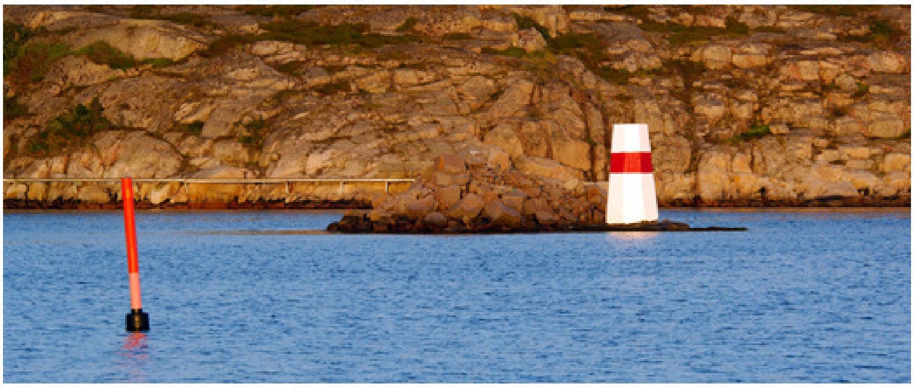

No. C 168
August 2016

Life cycle inventory of fairway channels

with examples from the Port of Gothenburg

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Funded by: VINNOVA
Photographer: Swedish Maritime Administration
Report number C 168
ISBN 978-91-88319-05-0
Edition Only available as PDF for individual printing

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This report has been reviewed and approved in accordance with IVL's audited and approved management system.

Introduction

The project 'Holistic environmental assessment of freight transport'[1] focuses on environmental impact from transport infrastructures. The environmental impact from several types of transport infrastructure on land has previously been considered in lifecycle assessment studies (e.g. Stripple, et al., 2010; Holmvik and Wallin, 2007, Stripple, 2001). However, infrastructures relating to shipping, such as sea ports and fairway channels, have not been subject to such studies. In the report 'Port Infrastructures in a System Perspective' (Stripple et al., 2016), from this project, environmental impacts from ports are described from a life cycle perspective. Other infrastructural requirements for shipping are related to the ship journey. Mainly relying on the buoyancy of ocean water, impacts from marine transport infrastructures are relatively low.

Certain measures are however taken by port states and ports in order to maintain a safe and reliable access to ports regardless of traffic density and weather conditions, and to safeguard the environment. Fairway channels[2] to and from ports are always equipped with lighthouses and navigation marks to guide visiting ships. Ice breakers keep fairways ice free and dredging keeps the fairway sailing depth and breadth as requested. In addition, pilots guide ships to quayside positions.

This report considers activities associated with fairways from an environmental perspective. Data on the energy use of ships and machinery servicing Swedish fairways have been acquired from the Swedish Maritime Administration and the Port of Gothenburg. The aim is to present generic data but port specifics can cause large variations in the need for the fairway channel maintenance, piloting and ice breaking needs. Care should therefore be taken before applying and using the presented data in a wider context.

The specific aim of this study is to quantify life cycle inventory (LCI) data on construction, operation and maintenance of fairway channels. The data collection is in most cases limited to energy input and emissions to air from fuel combustion for most included activities. The data are intended for use in life cycle assessment (LCA) models on transport infrastructures and calculations of emissions from transport chains. The activities included in this study are of different character and after the description of each of them follows recommendations of their further use. A life cycle consists of different life stages of a product or service. The lifecycle of a transport service crosses the lifecycles of ports, fairway channels and ships. A lifecycle of a port is described in the report Stripple et al. (2016) from this project.

This study covers the activities 'Dredging', 'Operation and maintenance of aids of navigation', 'Ice breaking' and 'Pilotage'. For practical reasons the use of the gathered data is recommended to be split between existing LCA calculation models: 'Dredging' and 'Operation and maintenance of aids of navigation' are recommended to be integrated into LCA models of ports, and 'Ice breaking' and 'Pilotage' should preferably be included in models on ship operations or a transport chain. All dredging activities can be assumed to be undertaken in the absolute vicinity of a port. It is also often port authorities that administer the dredging activity. The 'Operation and maintenance of aids of navigation' is also favourably integrated in port models. The fairway channels with marks, lights and lighthouses are established and maintained in order to provide ships safe passage to and from ports. They are essential for most ports which is the reason to include the lifecycle data on them in the port models. Important to note is that the length of the channel can vary considerably depending on the geography of a port. 'Ice breaking' and 'Pilotage' on the other hand, very much depend on ship and ship route. The 'Ice breaking' only occurs for ships in northern regions during winter and pilots are needed more often for larger ships than small and more for ships carrying dangerous goods than for others. Due to this, the data on these activities should be included in LCA models on ship operations. Figure 1 is a schematic picture of the relations of lifecycles of a transport chain and the lifecycles of ports, fairway channels and ships. The figure shows how activities during operation and maintenance of fairway channels are assigned to either the LCA model on port infrastructure, or to ship operation and transport LCA models.

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[1] Holistisk miljöanalys av godstransporter'- authors translation
[2] 'Fairway' is a term used frequently in Sweden that corresponds to a shipping lane or ship canal that has navigational aids and well measured depths. Fairways can be used by both merchant ships and leisure boats.

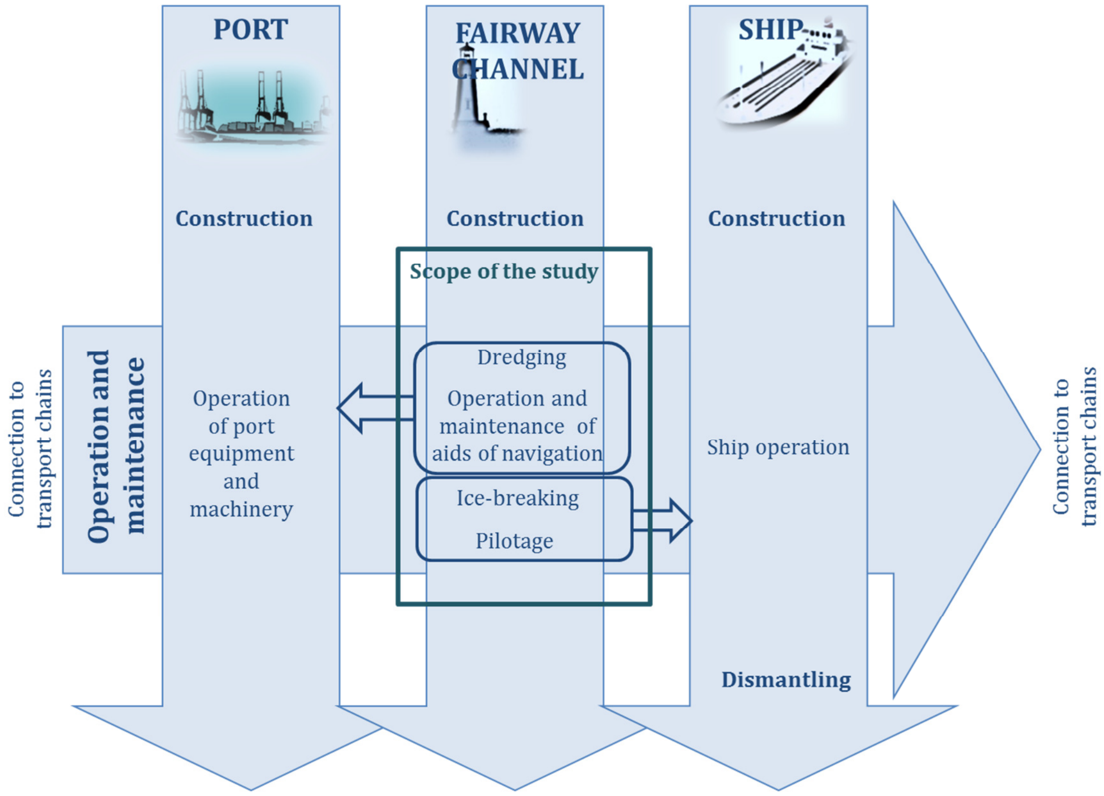

Figure 1. Schematic picture of lifecycles related to ship transport. The activities during operation and maintenance of fairways are assigned to connected LCA models.

Inland waterway infrastructure such as canals and locks are not included in this study but might be significantly influencing the results for inland waterway transport.

The impacts on the marine environment have been excluded from this inventory. There is a high complexity around impacts on marine life from mainly dredging when a lot of material is resuspended in the water column. Even estimating the amounts of hazardous substances being available for biological take-up was considered to be out of scope of this study. This exclusion is however not made based on the assumed effects on the environment. The effects on marine life may be more important than the contribution to emissions to air. However, the life cycle analysis method is most likely not the best method to determine this.

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Summary

Well-maintained fairway channels are necessities for a functioning marine transport system. In this report environmental aspects of construction and operation of fairway channels are described and analysed. Life cycle inventory data on energy use during dredging, maintenance of navigational aids, pilotage and ice breaking are presented. Impacts on the marine environment have not been included in the study. All data have been acquired from the Swedish Maritime Administration and the Port of Gothenburg.

The study is part of a greater project covering environmental life cycle aspects of a larger part of the transport infrastructure system, including ports. The data have therefore been modelled to fit in a life cycle assessment model, developed for the same project.

The aim is to present generic data for Swedish fairway channels. However, port specifics can cause large variations in the need for the fairway channel maintenance, piloting and ice breaking. Care should be taken before applying and using the presented data in a wider context. All the activities described in this report are for this reason accompanied with a brief recommendation on further use.

For use in LCA models with wider scopes, it is recommended that impacts from pilotage and ice breaking are related to models on ship operations, and that dredging, and maintenance of navigational aids are related to models on ports. A summary of the most important emissions to air from fairway activities are presented in the Table below. The results for Sweden are summarised both as a total including all activities in the inventory, and with pilotage and ice breaking subtracted. The latter values are intended for further use in LCA models on ports.

The results show that the main contributing activity to energy use and CO_2 emissions from a national perspective is dredging. For a single port, other activities may have greater influence. In the case study of Gothenburg, pilots contributed the most to CO_2 emission. However, the impacts from infrastructure activities in the fairway channel are minor in relation to the impacts from a transport chain as a whole.

Emissions to air from fairway channel construction and maintenance, presented in relation to the functional units 'fairway km' and 'port call', for Sweden in general and for Gothenburg specifically.

	Sweden	**Sweden**	**Gothenburg**
NOTE	**Total, including all activities in inventory**	**excl. ice breaking and piloting**	**excl. ice breaking and piloting**
PER FAIRWAY KILOMETER			
CO_2 (tonne)	11	9.5	49
CH_4 (kg)	0.091	0.081	0.37
N_2O (kg)	0.53	0.45	2.3
NO_X (kg)	230	190	990
HC (kg)	3.5	3.0	15
SO_2 (kg)	7.4	6.3	32
PM_{10} (kg)	0.68	0.58	3.0
$PM_{2.5}$ (kg)	0.58	0.49	2.5
PER PORT CALL			
CO_2 (tonne)	1.2	1.0	0.19
CH_4 (kg)	0.010	0.0085	0.0014
N_2O (kg)	0.056	0.047	0.0090
NO_X (kg)	24	20	3.8
HC (kg)	0.37	0.31	0.059
SO_2 (kg)	0.78	0.66	0.12
PM_{10} (kg)	0.072	0.061	0.012
$PM_{2.5}$ (kg)	0.061	0.052	0.010

Sammanfattning

Väl underhållna farleder är nödvändigheter för ett välfungerande marint transportsystem. I den här rapporten beskrivs och analyseras miljöaspekter av konstruktion och drift av farleder. Uppgifter om energianvändning under muddring, underhåll av navigationshjälpmedel, lotsning och isbrytning presenteras. Eventuella effekter på den marina miljön ingår inte i inventeringen. Alla data har erhållits från svenska Sjöfartsverket och Göteborgs Hamn.

Studien är en del av ett större projekt där livscykelanalyser av en större del av transportinfrastrukturen, inklusive hamnar, görs. Uppgifterna som samlats in har därför anpassats för vidare användning i en modell för livscykelanalys som utvecklats för samma projekt.

Syftet med arbetet är att presentera generiska data för svenska farleder. Däremot kan skillnaderna mellan hamnar vara stora, vilket leder till att hamnarna har olika behov av underhåll, lotsning och isbrytning. Om de data som presenteras skall användas bör hänsyn tas till detta och användningen ske med viss försiktighet. Alla aktiviteter som beskrivs i denna rapport åtföljs därför också av en kort rekommendation om fortsatt användning.

Om resultaten skall användas i LCA-modeller med större omfattning rekommenderas att påverkan från lotsning och isbrytning kopplas till modeller för fartygstransporter, och att påverkan från muddring och underhålla av navigationshjälpmedel kopplas till modeller över hamnar. En sammanställning över de viktigaste emissionerna till luft per farledskilometer, samt per hamnanlöp, presenteras i tabellen nedan. I tabellen visas dels de sammanlagda emissionerna för alla aktiviteter som ingår i inventeringen, dels ett fall då isbrytning och lotsning inte ingår. De senare värdena är användbara i LCA-modeller för hamnar.

Resultaten visar att för Sverige som helhet ger muddringen det största bidraget till energianvändning och CO_2-emissioner. Förhållandena mellan bidrag från olika aktiviteter kan dock se annorlunda ut om man tittar på specifika hamnar. I en fallstudie på Göteborg bidrog lotsningen med den största andelen CO_2-emissioner. Sett ur ett större perspektiv är dock miljöpåverkan från infrastruktur-aktiviteter i farleden små i förhållande till påverkan från en transportkedja.

Emissioner till luft från konstruktion och underhåll av farled presenteras i förhållande till de funktionella enheterna farledskilometer' och 'hamnanlöp'. Resultaten anges för svenska förhållanden i allmänhet och för Göteborg specifikt.

	Sverige	**Sverige**	**Göteborg**
NOTE	**exkl. isbrytning**	**inkl. isbrytning**	**exkl. isbrytning**
PER FARLEDSKILOMETER			
CO_2 (ton)	9,5	11	49
CH_4 (kg)	0,081	0,091	0,37
N_2O (kg)	0,45	0,53	2,3
NO_X (kg)	190	230	990
HC (kg)	3,0	3,5	15
SO_2 (kg)	6,3	7,4	32
PM_{10} (kg)	0,58	0,68	3,0
$PM_{2.5}$ (kg)	0,49	0,58	2,5
PER HAMNANLÖP			
CO_2 (ton)	1,0	1,2	0,19
CH_4 (kg)	0,0085	0,010	0,0014
N_2O (kg)	0,047	0,056	0,0090
NO_X (kg)	20	24	3,8
HC (kg)	0,31	0,37	0,059
SO_2 (kg)	0,66	0,78	0,12
PM_{10} (kg)	0,061	0,072	0,012
$PM_{2.5}$ (kg)	0,052	0,061	0,010

1 Life Cycle Inventory

In the life cycle inventory, data on the studied activities are gathered from literature and experts. The data are thereafter structured and presented in relation to potential functional units in a life cycle assessment (LC). A functional unit is used as the reference unit, to which all data are related in an LCA. In this inventory, data are presented in relation to a set of functional unit; per km fairway channel, per ship call in port, and per port. This is done in order to make the data possible to use in different analyses.

1.1 Pilots

Most ships are requested to use a pilot when approaching or leaving a port. Exceptions to this rule exist and while pilotage is compulsory for most large ships, smaller ships are often exempted. The Swedish Transport Agency presents regulations and general advice which are implemented by defined pilot areas (Transportstyrelsen, 2012). Ships are divided in pilotage categories primarily based on ships size and cargo. For ships that carry dangerous goods, smaller size classes of ships are requested to use a pilot than those that do not carry dangerous goods.

For ships in frequent traffic to a specific port a route dependent pilot exemption certificate can be acquired. The certificate is strictly bound to person and route. This is common for ferries and roro-ships in liner services.

The total number of ship movements engaging pilots in Sweden for the years 2011 to 2013 is presented in Table 1 together with the annual fuel consumption of the pilot boats. There was a significant decrease in pilotage between 2012 and 2013 which is most likely due to a general reduction in vessel traffic to and from Swedish ports. An average amount of 81 kg of fuel per pilot event is calculated. All data on total number of piloted events and fuel consumption have been obtained from the Swedish Maritime Administration.

Table 1. Number of piloted ship movements in Sweden in 2011, 2012 and 2013 and their respective total energy requirements.

Year	Number of piloted ship movements	Energy (TJ)	Fuel (MGO) consumption (tonnes)	Fuel (MGO) consumption per pilot event (kg)
2011	37781	114	2720	72
2012	34376	111	2650	77
2013	26052	103	2460	95
Average	**32736**	**110**	**2610**	**81**

Pilot assistance in connection to port calls depends on the ships' size and cargo carried. It is therefore recommended that in the environmental impacts associated with pilotage are coupled to a model of a ship journey rather than to a port or other infrastructure model. If a model of a transport chain or a ship journey is to include pilotage, the existing regulations should be considered and extra fuel penalty for ships using pilots should only be allotted to those ships requested to use a pilot.

1.2 Ice breaking

Data on fuel consumption of ice breakers during 2012 and 2013 have been acquired from the Swedish Maritime Administration (SMA, 2014). The data on total energy use can be allocated to the number of assisted ships or assisted distance in nautical miles (NM). No other environmental aspect than fuel use and combustion is included in this analysis.

The data for the two years indicate an approximate energy use per assisted ship of 280 GJ corresponding to CO_2 emissions of 21 tonnes/assisted ship. These are rounded values based on average energy use and assisted ships in 2012 and 2013. The data are presented in Table 2.

Table 2. Energy use for ice breaking in Swedish fairways 2012 and 2013 (SMA, 2014).

Year	Ice condition	Assisted ships (number)	Assisted distance (NM)	Energy (TJ)	Fuel (MGO) (tonnes)	Fuel (MGO) consumption (kg /ship)	Fuel (MGO) consumption (kg/ NM)
2012	Light ice winter	680	11 359	192	4580	6730	403
2013	Normal ice winter	1714	37 349	486	11600	6750	310
Average						**6740**	**360**

Ice breaking services are mainly needed in the most northern parts of the Baltic Sea and in the lakes where solid and compact ice form more easily than in the open seas with higher salt concentrations. The ratio between energy and distance gives a more accurate figure to use than energy use per assisted ship, since the distance might differ considerably per assisted ships. However, in order to incorporate energy use or emissions from ice breaking in a model of emissions from transport chains, the average values for assisted ships are most likely more practicable to use. Less detailed information on the actual transport length is then needed for the calculations. It is recommended to include data on icebreaking activities only for ship transports that are known to occur in icy sea conditions. Thus, it is also recommended that ice breaking is left out of any analysis of environmental impacts of transport chains unless the transport includes ship calls to the most northern parts of the Baltic Sea in winter conditions.

1.3 Operation and maintenance of navigational aids

The LCI of the navigational aids navigation marks, and lights and lighthouses are presented in this chapter.

1.3.1 Navigation marks

Each year the Swedish Maritime Administration surveys the fairways and replaces navigation marks that are damaged or altered in any way. In addition to the reoccurring survey, maintenance is done upon need. The SMA manages the maintenance and work on the fairways, and data on fuel consumption of the ships used in this service have been acquired from the SMA (SMA, 2014). No other environmental impact than that originating from the fuel use and combustion is included in this analysis.

The average yearly fuel consumption of the ships used in this service is 2200 m^3 based on fuel consumption from 2012 and 2013, Table 3. The reported fuel consumption from earlier years is significantly lower but is considered less accurate and complete, and has therefore been left out of the analysis. It can be assumed that the values for different years diverge significantly depending on e.g. weather conditions during the winter.

The total fuel consumption from these activities is allocated between merchant shipping and leisure boating. A ratio based on costs for personnel and materials for fairway maintenance in shipping and boating respectively is used as approximation. According to actual costs and expert judgement this ratio is approximately 1/3; i.e. 2/3 of total energy use in connection to fairway channel maintenance is allocated to merchant shipping.

The yearly totals need to be allocated to the ships according to a chosen principle. In this study two different approaches are compared. One approach allocates fuel use based on the length of fairways. For each port this length is different from another, and when the length to a specific port is known, this approach can provide a good approximation of fuel use from maintenance activities. Due to the different channel lengths to ports, there is an unequal distribution of work between them. The length of Swedish fairway channels, excluding passages on open water, is approximately 8500 kilometres. A division of the total fuel consumption with the channel length results in a factor of 160 kg fuel per kilometre and year. The other approach allocates fuel consumption on service ships based on total numbers of calls to Swedish ports. This approach is useful when actual fairway lengths are not known or when several ports are included in a study, to give two examples. In 2012 and 2013, Swedish ports were called by 82 400 and 78 467 ships respectively (Trafikanalys, 2013 and Trafikanalys, 2014) resulting in an average value on energy use per call of 16 kg. The choice of allocation principle thus has a large effect on the results. However, even the result from the latter approach is very low in relation to energy use from other activities included in the LCA of fairway channels. It is therefore not likely that the choice of allocation principle will have a significant influence on overall results in a transport chain study. An overview of the fuel consumption from ships used to maintain and establish fairways is presented in Table 3.

Table 3. Fuel consumption from ships used to maintain and establish fairways in Sweden 2012 and 2013 (SMA, 2014).

	Length of Swedish fairways channels (km)	Number of calls – Swedish ports total	Fuel consumption (TJ) marine gasoil, merchant shipping	Fuel consumption (tonnes) marine gasoil, merchant shipping	Fuel consumpti on per call (kg/call)	Fuel consumption per fairway km (kg/km)
2013	8500	78 467	59.5	1420	18	167
2012	8500	82 400	51.4	1220	15	144
Average			**55**	**1300**	**16**	**160**

Yet another option is to divide the fuel consumption in an even split between the 54 Swedish merchant ports, which results in 24 tonnes of fuel allotted to each port.

1.3.2 Lightening of fairway channels

Lightening of fairway channels are important aids for sea farers. Many different kinds of lights and lighthouses are used. In the following text the term lighthouse is used as a collective term, although most lightening aids are much simpler constructions.

Although the function of lighthouses for merchant ships has gradually been replaced by electronic devices on board the ship they remain an important navigational aid. Lighthouses can be of different character but in general produces two kinds of lights; one that signals through characteristic lights in intervals and one steady light that illuminates the facade of the lighthouse. The latter requires considerably more electricity than the former. The electricity for the signalling light is often produced by photovoltaic cells, although many of the large lighthouses are connected to shore side power production via electric cables.

The 1200 lights and lighthouses around the Swedish coastline have an annual electricity consumption of 3 500 000 kWh. Approximately half of them are powered by solar cells while the rest are supplied with electricity from shore. Old lamps are continuously replaced with more energy efficient light emitting diodes (LED). The copper cables have a total estimated length of 500 km with an average diameter of 10 mm^2. A total approximate volume of copper of 5 m^3 (or 45 tonnes) is thus used for this purpose. Further, all lights and lighthouses are equipped with batteries, mainly of nickel cadmium type. Allocation of electricity and material use for lights and lighthouses can be done based on fairway length, number of lighthouses, number of ports or number of calls. If the number of lights and lighthouses in the fairway channel to a port is known, the figures on kWh electricity and kg copper per lighthouse should preferably be used; number of lighthouses is the most accurate allocation base, which accordingly produces the most accurate value for further use. For very specific and detailed analyses of a port, an important parameter is however the electricity source of the lights since it is often generated by solar power. The countrywide values presented in this study are approximations. Fairway length as allocation base delivers values that are well functioning in larger geographical areas. These values should be used when the number of lighthouses is not known. The third allocation principle, ship calls, is less accurate than the previous two and should only be used if neither number of lights and lighthouses or fairway length is known. A fourth allocation principle where all electricity is divided equally between ports has also been considered. The accuracy of this principle is very low. An overview of the electricity consumption in lights and lighthouses and associated copper consumption in sea floor cables is presented in Table 4.

Table 4. Electricity consumption in lights and lighthouses and associated copper consumption in sea floor cables allocated on number of light(houses), fairway kms and calls respectively.

Activity		Amount	Merchant shipping*:
Number of lights and lighthouses in Sweden	(#)	1 200	n.a
Length of Swedish fairways channels (km)	(km)	8 500	n.a
Average calls to Swedish ports per year (2012 and 2013)	(#)	n.a	80 434
Number of public ports in Sweden	(#)	n.a	54
Electricity consumption	(kWh)	3 500 000	2 300 000
Copper consumption	(kg)	45 000	30 000
Electricity consumption per light(house)	(kWh/light(house))	n.a	1 900
Electricity consumption per fairway km	(kWh/km)	n.a	270
Electricity consumption per call	(kWh/call)	n.a	29
Electricity consumption per port	(kWh/port)	n.a	43 000
Copper consumption per light(house)	(kg/light(house))	n.a	25
Copper consumption per fairway km	(kg/km)	n.a	3.5
Copper consumption per call	(kg/call)	n.a	0.37
Copper consumption per port	(kg/port)	n.a	550

*2/3 of the total amount is allocated to merchant shipping

1.4 Dredging

The activities relating to dredging are divided into construction dredging, which includes construction of a new or significantly wider or deeper fairway channel, and maintenance dredging which signifies dredging reoccurring in more or less specified intervals.

1.4.1 Maintenance dredging

Maintenance dredging is required to maintain water depths in areas where sedimentation occurs. Many harbours are situated by river mouths which cause a constant settling and accumulation of runoff material transported by the river, on the sea floor in the harbour area and its vicinity. Regular dredging of fairways close to ports is therefore often necessary.

Different dredging technologies exist, a rough division into mechanic dredging and hydraulic dredging is common. In mechanic dredging, the sediments are removed by digging, scraping or cutting. Simple solutions consist of an excavator equipped with a bucket or clamshell dredger placed on a pontoon vessel. The clamshell type can reach large depths, the largest ones reaching down to approximately 25 meters. The masses are lifted to a barge or ship for transport to the discharge site. The mechanical dredgers are suitable for removing most kinds of sediment, and particularly suitable for precision work in small areas. However, solutions using open buckets cause a lot of resuspension of material in the water masses and can therefore be less suitable than other alternatives in ecologically sensitive areas. Hydraulic dredging is done by suction of free running material, like sand, with a high mixing ratio with water. Suction dredgers commonly reach around 15 to 20 meters depth. The most common type of hydraulic dredger is the so called trailing suction hopper dredger (TSHD). These are free sailing self-propelled ships that load the dredged material to holds (hoppers) on board the ship. After loading, the masses are transported to the disposal site and discharged via bottom opening doors in the hull bottom or by pumping. Some solutions use hydraulic transports of the solids or slurries from the digging in pipelines to the discharge site.

The input data to the estimates of energy requirements for dredging are gathered from a dredging episode in the fairway channel outside the Port of Gothenburg in 2014. Similar operations are repeated every fourth year and are of typical maintenance character. Approximately 330 000 m³ clay and silt were dredged. The masses were disposed of at two locations; 'Lundbyhamnen' at a 5 km distance from the dredging site and 'Vinga' at 17 km from the dredging site (Port of Gothenburg, 2014).

Three machines were used for the dredging, one excavator backhoe dredger and two trail suction hopper dredgers. The TSHDs transported the masses to the deposition location under its own power, while the masses from the backhoe dredger were loaded onto barges. Two barges served the excavator. In addition, three towing boats were in use during the dredging operations.

The average consumption of fuel per volume unit varied between 0.9 and 4.0 tonnes/m³, between the three dredgers, see Table 5. The TSHDs consume less fuel than the backhoe dredger per cubic meter dredged material. On average the THSDs consume 1.2 kg fuel per m³ (52 MJ/m³) and the excavator 4 kg fuel per m³ (170 MJ/m³). The fuel consumption of the barges is added to the excavator service and the fuel consumption of the tows are divided equally between the three dredgers.

Table 5. Fuel consumption of the dredging activities in the fairway to the Port of Gothenburg

		Produced volume of dredged material (m³)	Fuel consumption (tonnes)	Fuel consumption kg/m3	Fuel consumption (MJ/m3)
TSHD	Magni R	110 368	95	0.9	36
	Sif R	180 119	290	1.6	68
Backhoe excavator	Mjölner R	43 540	174	4.0	168
TOTAL			**559**		

The average values are suitable for further use in life cycle assessments of ports. The time interval between maintenance dredging and the amount of material removed should be known and included in the assessment. The dredging of a fairway channel is of central importance for the availability of a port; without the dredging the port cannot offer passage to berths for visiting ships. Therefore, it is not very reasonable to couple these data to visiting ships or even the density of ship traffic to a port. If little or nothing is known about dredging in a specific fairway channel, it is recommended that the absolute amount of fuel consumption presented for Gothenburg, 559 tonnes, is used. This amount should be distributed over the period between dredging the port, which is four years.

1.4.2 Construction dredging

In the years 2002 to 2004 a widening and deepening of the two fairway channels to Port of Gothenburg were undertaken. The project was aiming at offering safer passage to and from the port for large ships and by that become a more attractive choice for trans-ocean ship traffic in the future. Clay was mainly dredged by TSHDs and only to a minor amount by backhoe excavators. The amounts of removed material are presented in Table 6.

Table 6. Amounts of dredged material during the widening and deepening of the fairway channel outside Port of Gothenburg.

Activity	Amount (m^3)	Fuel cons. (kg/m^3)*	Fuel cons. (tonnes)*
Dredging – clay	11 800 000	1.25	14 750
Dredging – rocks	930 000 (barge volume)	4.0	3 720

*Calculated based on values presented in Table 5, rock is assumed to be removed with backhoe dredger and clay with THSD

It is important to set a reasonable lifetime for newly established or significantly changed fairway channels in order to fit it into larger LCI models. In the project 'Holistic environmental assessment of goods transport', the calculation period for port infrastructure is set to 60 years, roughly approximating the lifetime (Stripple et al., 2016).

Rocky grounds were also blasted at several locations. A total amount of dynamite of the make 'Gelamon 30', of 716 tonnes was used. The preparation of multiple drill-holes for the dynamite is not included in the LCI.

The widened channel was equipped with new beacons. In total, 33 steel beacons of 0.4 W each were installed. Electricity used by the beacons is not included in the analysis.

The data on construction dredging are suitable for further use in life cycle assessment studies of ports.

2 LCI Swedish fairway channels

As presented above, the inventory of data is rather limited to energy input to maintenance of Swedish marine infrastructure. A brief overview of total energy input and the emissions to air for Sweden as a whole for year 2013 is presented in Table 7. The main contributing activities to emissions to air from Swedish marine transport infrastructure are 'Dredging' and 'Ice breaking'.

Construction dredging is assumed to occur once for every port during a 60 year period.

Total amounts of copper and explosives are given in the table but not included in the calculations.

Table 7. Inventory of emissions to air from marine fuel and electricity from Swedish marine transport infrastructure. Values representative for 2013.

	Input/ Emission	unit	Pilot	Ice break.	Service ships	Light-houses	Dredging - maintenance	Dredging - construction	TOTAL
Note						Swedish electricity mix (2011)	All 54 ports dredge	Every port does a major construction dredging every 60th year in Sweden	
Lifetime						Electr. 1yr Cu 60 yr	4 yr	60 yr	
Input	MGO	tonnes	2 460	11 600	1 420		7 550	16 500	**39 500**
Input	Electricity	kWh				2 330 000			**2 330 000**
Input	***SUM-energy***	***TJ***							***1670***
Input	Copper	kg				750			**750**
Input	Explosives	tonnes						640	**640**
Output - emission	**CO_2**	tonnes	7800	37 000	4 500	250	24 000	52 000	**130 000**
Output - emission	**CH_4**	tonnes	0.048	0.23	0.028	0.19	0.15	0.32	**0.96**
Output - emission	**N_2O**	tonnes	0.37	1.8	0.21	0.0039	1.1	2.5	**6.0**
Output - emission	**NO_x**	tonnes	99	750	91	0.32	490	1 100	**2 500**
Output - emission	**HC**	tonnes	2.5	12	1.4	0.018	7.5	16	**39**
Output - emission	**SO_2**	tonnes	5.2	24	3.0	0.25	16	35	**83**
Output - emission	**PM_{10}**	tonnes	0.48	2.2	0.27	0.040	1.5	3.2	**7.7**
Output - emission	**$PM_{2,5}$**	tonnes	0.40	1.9	0.23	0.0050	1.2	2.7	**6.5**

Emissions from combustion of MGO dominate emissions of all species in the inventory. Methane (CH_4) is the only compound for which the electricity production gives a considerable contribution to total emissions. The values presented in Table 7 are based on the Swedish electricity mix. It is worth noting that with an assumption that the electricity was produced by natural gas power stations (an assumption often used for marginal electricity) the CH_4 emissions would increase significantly to approximately 4.6 tonnes per year. Methane has a strong global warming potential.

Values for fuel consumption from 2012 for pilots, ice breaking and service ships result in considerably lower total consumption and emissions than in 2013. As an example, CO_2 emissions are 95 000 tonnes in 2012 compared to 130 000 tonnes in 2013. This is mainly due to 2012 being a winter with light ice conditions, while in 2013 the ice conditions were more normal. The total energy input and emissions in 2012 are presented in Table 8.

Table 8. Total fuel and electricity input, and emissions for Swedish marine transport infrastructure, 2012.

		unit	TOTAL
Input	MGO	tonnes	29 900
Input	Electricity	kWh	2 333 000
Input	Copper	kg	750
Input	Explosives	tonnes	640
Input	***SUM - energy***	***TJ***	***1 260***
Output - emission	CO_2	tonnes	95 000
Output - emission	CH_4	tonnes	0.78
Output - emission	N_2O	tonnes	4.5
Output - emission	NO_x	tonnes	1 900
Output - emission	HC	tonnes	30
Output - emission	SO_2	tonnes	63
Output - emission	PM_{10}	tonnes	5.8
Output - emission	$PM_{2,5}$	tonnes	4.9

3 Case – LCI of fairway channel activities in Port of Gothenburg

A case study has been conducted on the activities in the fairway channel outside Port of Gothenburg for the year 2013. The main aim of this case study is to give examples of how the choice of allocation principle influences outcomes. Further, the case study makes it easier to study the environmental impact from the fairway channel activities in relation to both impacts from ship transport and other transport infrastructures. The Port of Gothenburg is Scandinavia's largest port and accommodates a variety of ship types including container vessels, oil- and chemical tankers, RoRo ships and Passenger ferries. It is situated on the west coast of Sweden in the mouth of River Göta. The port has approximately 8000 calls per year.

The principles followed in the calculations are:

1. All data are related to emissions and energy use for one year.
2. If exact data on activities on the specifics of the fairway channel outside the Port of Gothenburg are known these are applied in calculations.
3. The recommended allocation principles discussed for each activity are applied.

For the Gothenburg case study this means:

- Pilotage data have been calculated based on specific figures for the port and can therefore not be said to follow any allocation principle. Concerning the pilotage in the port, an average figure on fuel consumption per pilot event has been used and multiplied with the actual number of pilot events in Gothenburg 2013.

  As discussed previously in this report, impacts from piloting are tightly coupled to the port activities while dredging, and navigational aids and lighthouses are more connected to the ship route. However for the purpose of the case study, an analysis comprising all fuel consumption from pilotage to and from the Port of Gothenburg is conducted in order to relate impacts from the different investigated activities to each other.

- Ice breaking is rare in the fairway channel. Ice breaking data are therefore excluded from the analysis.

- Lighthouses data are treated differently than the information on other navigation aids. Detailed information on lighthouses in the fairway channel outside the Port of Gothenburg is known. It is therefore possible to use the recommended method for calculations which contains specific information. The average energy use for lighthouses is multiplied with the number of lighthouses.

  Other navigation aids have an environmental impact coupled to their maintenance and the use of service vessels. The recommendation is to use a known fairway channel length if available. This is done in the case study.

- Dredging activities are in the previous text exemplified by data from the Port of Gothenburg. These data are used; maintenance dredging data are divided in three in order to make them representative for one year; construction dredging data are divided by 60 years for the same reason.

In addition to using these recommended methods, at some instances comparisons using other allocation bases are made in order to illustrate the sensitivity of the results to different the choice of allocation.

The length of fairway channel, the number of calls, and the number of ship movements engaging pilot assistance for Gothenburg and Sweden as a whole are given in Table 9.

Table 9. Length of fairway channel, the number of calls, ship movements engaging pilot assistance, and lighthouses for Gothenburg and Sweden as a whole.

	Gothenburg	Sweden	Share Goth./Swed.
Approximate length of fairway channel (km)	29	8 500	0.3%
Number of calls 2013	6 798	78 467	9%
Number of piloted ship movements 2013	5 234	26 052	20%
Number of lighthouses	13	1 200	1%
Share port	1	54	2%

3.1 Pilotage in Gothenburg

Since it is recommended that energy use during pilotage should be analysed together with assessments on ships' environmental impact rather than studies on ports', it should be stressed that the average fuel consumption per pilot event is 81 kg.

If a port would want to use data on the fuel consumption per year, a multiplication of the average fuel consumption and the number of piloted ship calls per year can easily be calculated. The Port of Gothenburg reports around 5 000 ship movements accompanied by a pilot each year. This corresponds to 20 % of all piloted ship movements in Sweden this year. The total fuel consumption from pilot events in Gothenburg in 2013 is calculated to around 495 tonne based on 5234 calls with pilot assistance and the average value of 80 kg of fuel per pilot event, see Table 10.

Table 10. Fuel consumption for pilotage to and from the Port of Gothenburg 2013.

Piloted movements in Gothenburg 2013	5 234
Average fuel consumption per pilot activity (kg)	81
Estimated fuel consumption for pilotage to and from the Port of Gothenburg (tonnes)	**425**

3.2 Lighthouses and other navigation aids to and from Port of Gothenburg

The fairway channel outside the Port of Gothenburg is equipped with 13 lighthouses, and has an approximate length of 16 NM between the lighthouse 'Trubaduren' and 'Nya Älvsborgs fästning', which marks the sea side end of the port area. The length comprises both alternative fairway channels outside the port.

The total electricity consumption of the lighthouses is approximately 25 000 kWh and the total copper consumption for cables are 320 kg, Table 11.

Table 11. Annual electricity needs and copper consumption for lighthouses in the fairway channel outside the Port of Gothenburg.

Port of Gothenburg fairway	Total electricity	Total copper
Average electricity consumption per lighthouse	1900 kWh	25 kg
Lifetime	1 year	60 years
Electricity consumption, 13 lighthouses	**25 000**	**5.4**

The choice of allocation method significantly affects the outcome. An allocation of the total electricity consumption in Swedish lighthouses based on number of calls indicates an electricity need of 200 000 kWh for lighthouses in the fairway. Estimations based on the other allocation methods are between 7 900 and 43 000 kWh, see Table 12.

Table 12. Calculated electricity consumption from lighthouses in the fairway channel outside Gothenburg Port using different allocations of total electricity use.

	Average Sweden	*Gothenburg specifics*		**Result Gothenburg**
Electricity consumption per lighthouse (kWh)	1 944	*13*	*lighthouses*	**25278**
Electricity consumption per fairway km (kWh)	275	*29*	*km*	**7931**
Electricity consumption per call (kWh)	29	*6798*	*calls*	**197 206**
Electricity consumption per port (kWh)	43 210	*1*	*port*	**43210**

It is recommended that fuel consumption and emissions from service ships is allocated to specific ports with the channel length; a factor of approximately 160 kg of fuel per kilometre and year. The total amount of fuel allocated to Gothenburg is 4.5 tonnes when using this method, see Table 13.

Table 13. Annual fuel consumption by service ships, allocated to Gothenburg

SERVICE SHIPS	
Amount of fuel per fairway km (kg)	160
Amount of fuel Gothenburg (tonnes)	4.5

Another approach allocates fuel consumption on service ships based on total numbers of calls to Swedish ports. This approach is useful when actual fairway lengths are not known or when several ports are included in a study, to give two examples. Another option if little is known about the fairway length is to use one 54th of the total fuel consumption for Swedish conditions, for any studied port. There are 54 public ports in Sweden. This would result in 24 tonnes fuel allocated to the port.

3.3 Dredging

The dredging outside the port of Gothenburg is conducted every fourth year. The amount of fuel used for the dredging in 2014 was 559 tonnes. It is assumed that this amount is used every fourth year for the maintenance dredging. Construction dredging data from the widening and deepening of the fairway in 2002-2004 presented in 1.4.2 is used as the only construction dredging activity in a 60 years' time period. As a result, annual fuel consumption for maintenance dredging and construction dredging can be estimated to 140 tonnes and 300 tonnes, respectively, see Table 14.

Table 14. Annual fuel consumption from dredging activities.

Dredging type	Fuel consumption (tonnes)
Maintenance	140
Construction	300
TOTAL	**440**

3.4 Overall analysis – Gothenburg

Analysed together, the main contributing activities to energy consumption are related to pilots and dredging, see Figure 2. The contribution by service ships and electricity for the lighthouses are insignificant in an overall analysis.

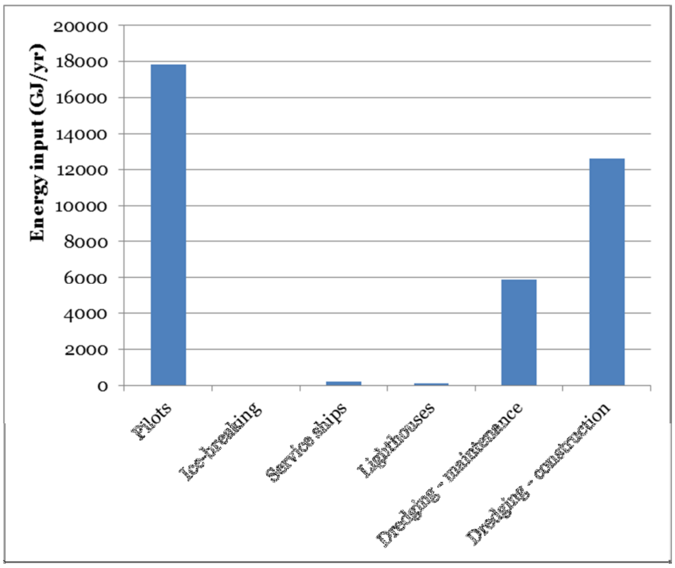

Figure 2. Energy use of activities in the fairway channel outside Port of Gothenburg.

As expected, the CO_2 emissions follow the same pattern as energy use, Figure 3. The only energy source for the studied activities is marine gasoil (MGO), except for lighthouses which use electricity. The Swedish electricity mix has relatively low emissions of CO_2 compared to fuel oil combustion.

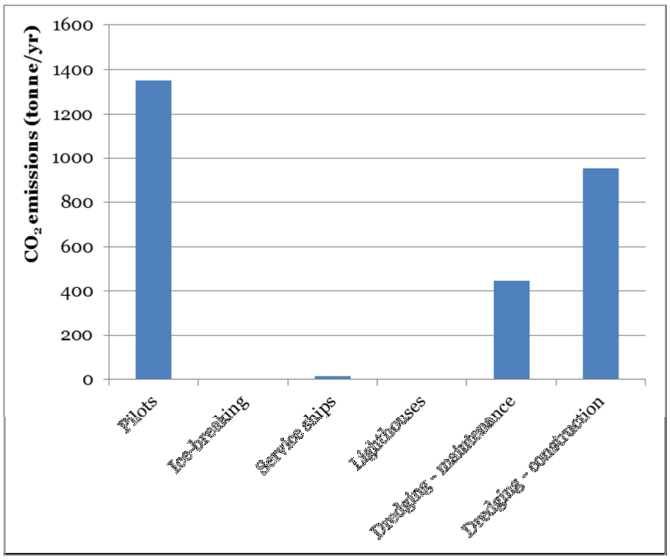

Figure 3. CO_2 emissions from activities in the fairway channel outside Port of Gothenburg.

These results can be compared to the energy used by ships during a call. Annual CO_2 emissions from the activities in the fairway channel has for this purpose been divided by the number of calls to the port, approximately 8000. The CO_2 emissions from the infrastructure activities are by this calculated to 0.35 tonnes per port call. A ship's CO_2 emissions during a port ship call is of course to a large extent depending on the power requirements of the ship; large ships and ships that have high steaming speeds have larger engines installed than smaller and slower ships. As an example, a small general cargo ship passing the port to or from destinations in Lake Vänern or River Göta is calculated to emit approximately 2 tonnes of CO_2 per call while large cruise ships with relatively long times at berth emits around 87 tonnes per call. Ships of the types 'Tankers' and 'RoRo/Ferries' cause emissions of on average 29 and 15 tonnes/call, respectively, see Table 15. The calculations behind these values include emissions from all engines and boilers on ships from the time they spend in the traffic area. The values are from emission inventories conducted for the Port of Gothenburg and are average values for three years.

Table 15. A comparison of CO_2 emissions from different ship types and the total CO_2 emissions from activities related to the fairway infrastructure.

	Average CO_2 emissions per call in Port of Gothenburg (tonnes)
All fairway infrastructure activities	**0.35**
Small general cargo ships*	2.3
Large cruise ships	87
Tankers- varying sizes	29
RoRo/Ferry	15

*no time at berth, only passing

The CO_2 emissions from fairway infrastructure activities are thus considerably lower than emissions from a ship call by any ship type seen from this perspective.

4 Concluding remarks

The total energy use for fairway maintenance and construction limited by the scope of this study has been calculated to 1670 TJ for 2013 and 1370 TJ for 2012. From a Swedish perspective, the dredging of the fairways is outstanding as major contributing activity to energy use and consequent CO_2 emissions.

From the perspective of a port the relative contributions of different activities are related to the number of calls by ships. In the Port of Gothenburg, the pilots contribute more to CO_2 emissions than dredging and the other activities. This is due to that Gothenburg is a busy port and uses pilot service frequently. Construction dredging is the second largest contributor to CO_2 emissions followed by maintenance dredging, in the case study of the port. The activities relating to ice breaking, service ships and lighthouses are much dependent on choice of allocation method. When using the recommended allocation principle, they are all of minor importance to total results for the Port of Gothenburg. For more Northern ports, ice breaking may however be a significant contributing factor.

The total electricity and fuel consumption and subsequent emissions included in this inventory are significantly less than emissions from the ships using the fairways and ports. The presented data are intended for inclusion in other models on studies with broader scopes and for environmental impact assessments. A generality of data has been aimed at, but significant differences between countries and individual ports are likely to exist. The data are therefore not to be used for detailed analysis of specific ports and fairway channels.

5 References

Holmvik, N., and Wallin, H., 2007., Användning av livscykelanalys och livscykelkostnad för vägkonstruktion inom Norden. Lund, Lund Institute of Technology, Department of Technology and Society, Traffic and Road. Thesis 155

Port of Gothenburg, 2014, personal communication with Ida Fossenstrand "Infrastructure", Port of Gothenburg

SMA, 2014, personal communication with Reidar Grundström "Sjöfartspolitiska enheten", Swedish Maritime Administration

Stripple, H., 2001, Life Cycle Assessment of Road; A Pilot Study for Inventory Analysis, IVL, IVL-reportB 1210 E

Stripple, H., Fridell, E., and Winnes, H., 2016, Port Infrastructures in a System Perspective A Part of the Project Environmental Calculations for Transport Infrastructure, IVL, IVL-report C128

Stripple H., Uppenberg S., 2010, Life cycle assessment of railways and rail transports - Application in environmental product declarations (EPDs) for the Bothnia Line, IVL, IVL-report B1943.

Trafikanalys, 2013, Sjötrafik 2012 (Shipping goods 2012), Statistik 2013:11, Sveriges officiella statistik

Trafikanalys, 2012 Sjötrafik 2013 (Shipping goods 2013), Statistik 2014:9, Sveriges officiella statistik

Transportstyrelsen, 2012, Transportstyrelsens föreskrifter och allmänna råd om lotsning, TSFS 2012:38 SJÖFART

Appendix

List of conversion factors used in the calculations

Marine Gasoil (MGO) density	903 kg/m^3
Marine Gasoil (MGO) lower heating value	42 MJ/kg
Marine Gasoil (MGO) CO_2 emissions at combustion	3.18 kg/kg
1 kWh	3.6 MJ
1 Nautical mile (NM)	1.852 km

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