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Ecological Assessment of Port Equipment for Container Terminals

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Environmental protection and energy efficiency are important topics for sea port management, which is characterized by long-term investments. To assess the environmental impact of port equipment, we investigate different equipment types with fossil, hybrid and electric drive technologies, in cooperation with our project partner Hamburg Port Consulting (HPC). An ecological assessment of port equipment will support terminal operators who aim to make sustainable investment decisions. We conduct a comparative life cycle assessment (LCA) of different port equipment types including the three above-mentioned drive technologies. Various LCA impact categories, such as climate change, terrestrial acidification and particulate matter formation, were calculated and compared. Thus, we aim to foster a more comprehensive understanding of the environmental performance of port equipment. The results show the contribution of each life cycle phase to the environmental performance of an equipment type within each impact category and thus allow for a comparison of different port equipment types. So far, little comprehensive research exists regarding sustainable port operations. Especially, port operators often lack knowledge about the environmental impact of port processes, whereof it is necessary to provide a good basis to fill in this gap.

Keywords: Ports; Sustainability; LCA; Straddle Carrier

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1 Introduction

In order to mitigate further climate change, efforts are ongoing to curb Greenhouse Gas (GHG) emissions across business sectors. The transport sector accounts for about 23% of global GHG emissions (Creutzig et al. 2015). However, some technologies that are associated with lower GHG emissions are also disputed because they are considered harmful in other environmental categories, such as acidification, resource depletion or eutrophication. In general, four different approaches to address the environmental impact of transport can be distinguished: reducing the total amount of transport, shiftin to less damaging modes of transport or forms of behavior, reducing the impact of specific modes of transport and improving the environment in terms of spatial planning (Hou and Geerlings 2016).

Before measures from any of these four approaches can be taken, it is important to identify the current environmental impact of transport and potentials for improvement with regard to a meaningful selection of environmental categories. Ports are central actors in the transportation and logistics sector, and their role in the sector's sustainability efforts receives increasing attention (Davarzani et al. 2016). Current legislative efforts targeting ports are e.g. aiming to curb emissions of sulphur and nitrogen oxides (Tichavska et al. 2017). Also, significant energy saving potentials can be exploited by improving operations, adopting energy efficien technologies and using renewable energy sources (Wang and Sarkis 2013). At the same time, ports and terminals may improve their "green" image by reducing emissions, which may be associated with direct and indirect benefits (Lam and Notteboom 2014).

While there is abundant research on the transportation to and from ports, only few studies focus on the role of port layout and equipment on the environmental impacts of entire supply chains. Stahlbock and Voß (2007) explain container logistics in ports and provide a comprehensive review on existing literature. Yang and Chang (2013) give an overview over different electric and diesel-electric Rail Mounted Gantry cranes (RTGs), with a focus on fuel consumption. They came to the conclusion that 68 % of carbon dioxide emissions and more than 80 % of energy can be saved through a substitution of diesel drive trains by electric drive trains. Also, Yang (2017) investigated carbon dioxide emissions in container terminals and received similar results as Yang and Chang (2013). He conducted a carbon footprint analysis of container handling in ports, which showed positive effects on time efficien y, carbon dioxide emissions and fuel consumption in terms of electrification of power trains. Agrawal et al. (2017) studied the inventory of air emissions especially for the port of Los Angeles. They investigated various equipment types (like RTGs, Straddle Carrier, Yard tractor etc.) of the port of Los Angeles mostly powered by diesel. Gottwald Port Technology et al. (2011) compared the environmental impact of conventional diesel-electric Automated Guided Vehicles (AGVs) for container handling with battery-electric AGVs. Vujičić et al. (2013) conducted a similar study for RTGs and utility tractor rigs (UTR). In both studies, the use phase causes the highest environmental impact within the whole life cycle of the equipment. Replacing diesel-electric equipment by battery-electric equipment could therefore significantly reduce GHG emissions in the use phase, if the equipment is operated with renewable electricity. The results for RTGs and UTR show notable differences in the production phase (Vujičić et al. 2013). While the production of one UTR leads to lower GHG emissions compared to an RTG, the radioactive waste from the production of an RTG is supposed to be higher than for an UTR (Vujičić et al. 2013).

Despite the increasing importance of improving sustainability in ports, there is currently a high level of uncertainty amongst the terminal operators and port authorities to find the most promising measures to achieve this aim (Wilmsmeier and Spengler 2016, The European Sea Ports Organization (ESPO) 2012). This is of particular importance since terminal handling equipment requires substantial financial resources and is usually deployed for more than 20 years. Investments into such equipment influences the whole terminal layout configuration, this is why one can consider it as ultra-long-term investment (ULLI) (Breuer et al. 2013).

Therefore, it is necessary to further investigate the environmental performance of container handling equipment. The project "Simulation-based evaluation of measures for the improvement of energy sustainability in port operations" (SuStEnergyPort), which is carried out by the Georg-August-Universität Göttingen and the Hamburg Port Consulting GmbH (HPC), aims at developing a structured, model-based methodology to identify suitable measures that port operators can use to improve their energy efficien y and their usage of renewable energy. A selection of promising measures for the abatement of CO_2 and other emissions will subsequently be implemented in a simulation tool covering both logistic and energetic aspects as well as a life cycle assessment.

In this paper, the production and the use phase of exemplary equipment types are compared to find the most sustainable layout for specific container terminals. The present study shows first results for the life cycle assessment (LCA) of a straddle carrier and also gives a first insight into results from the SuStEnergyPort project.

2 Structure, logistics and handling equipment of container terminals

This chapter gives a brief introduction to the structure and logistics processes of a container terminal. Furthermore, we point out which equipment is important for the logistic processes and should therefore be analyzed for potential improvement concerning environmental impact.

The main function of a seaport container terminal lies in handling of container arriving by truck, train or ship and in their temporary storage on the premises. A container terminal is an open and complex system which has two interfaces to the outside. First, there is the seaward interface (quayside) for loading and unloading of container ships and, second, the landside interface for loading and unloading trucks and trains. A container terminal always has container storage, the so called container yard, to store container after arrival. The intermediate storage is necessary to cope with different arrival and departure times of ships and land vehicles (Günther and Kim 2006).

The chain of operations for import container can be described as follows: After arriving at the port, the container ship is assigned to a berth equipped with quay cranes to unload or load container (ship operation area). Unloaded container are transported to the container yard by internal transportation equipment. Additional moves are performed inside the container yard before the container is loaded to a land side vehicle to leave the terminal (see Figure 1).

Several different types of cranes can be deployed on a container terminal. First of all, the quay crane or gantry crane for loading and unloading container from ships. Modern quay cranes can handle two 20ft container at the same time. They move the containers from ship to shore by putting them on the quay or on a vehicle and the other way around by moving the containers from the quay or vehicle onto the ship. Quay cranes can be powered by a diesel engine-driven generator located on top of the crane or by electric power from the dock. As a result, quay cranes can have different environmental impacts depending on their power supply.

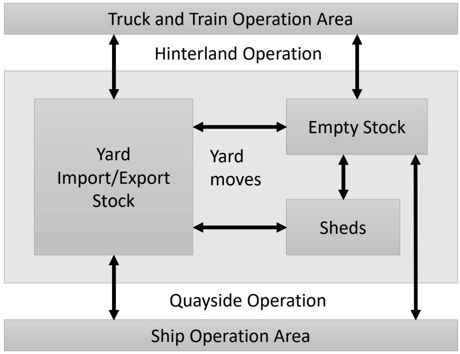

Figure 1: Operation areas of a seaport container terminal and flow of transports, see (Steenken et al. 2004)

Secondly, there are three different types of cranes with regard to yard management: The rail mounted gantry cranes (RMG), the RTG and the overhead bridge cranes (OBC). Gantry cranes usually span 8 to 12 rows in a yard and are able to stack up to 10 container. To improve operation speed, there can be up to three gantry cranes in one yard block (Steenken et al. 2004). All three types of cranes can be powered by either diesel engine-driven generator or by electric power. Since RTGs are not locally bound to one yard, they need a battery or a small diesel engine in addition to a static power supply. Depending on their power supply, the cranes can therefore have different environmental impacts locally and concerning their whole lifespan. In addition, changing the drive system of a crane can have a significant impact on the performance (Yang and Chang 2013).

Vehicles for horizontal transport can be divided into two categories: passive vehicles and active vehicles. Passive vehicles are not able to lift container by themselves. Loading and unloading of container is done by either gantry cranes or quay cranes. Typical vehicles in this category are trucks with trailers, multi-trailers and AGVs. Transport vehicles of the second category are able to lift container by themselves. Typical vehicles of this class are forklifts, reach stackers and straddle carriers (SC). The SC is a load carrying vehicle that carries its freight underneath (straddling) it, instead of carrying it on top. Concerning container terminals, SCs can be seen as cranes that are not locally bound to a stack or the quay. When deploying SCs, the container terminal does not need yard cranes or other transport vehicles, since the SC can move, stack and manage container in the terminal. Concerning their power supply, there are SCs with diesel drives, diesel-electric drive and battery-electric drives which leads to different environmental impacts for each type of SC.

To conclude, most of the energy of container terminals is needed for handling equipment during the processes described above (Geerlings and van Duin 2011). In addition to the ensuing environmental impact of this energy demand, the production of equipment generates an environmental impact as well. A decision about choosing or replacing equipment is complicated by the fact that several different types of equipment can be used for the same operations at port container terminals. To gain a better understanding of the environmental impact of some equipment types and the resulting effects of their usage on the overall sustainability of port terminal operations, our research aim is to investigate and compare various port terminal equipment types with a LCA, starting with SC.

3 General methodology of Life Cycle Assessment

The LCA is a method to estimate the environmental impact of a product system through its whole life cycle. In the 1970 the Society of Environmental Toxicology and Chemistry (SETAC) developed a methodology for the ecological product analysis (Klöpffer and Grahl 2014). The International Organization of Standardization (ISO) implemented the international standard EN ISO 14040 for the assessment of environmental impacts in 2006. This norm only gives a general framework for conducting such analyses, as LCA can be applied in relatively different contexts. In addition to product-specific analyses, services or individual processes within a firm can be assessed with regard to their environmental impact. The DIN EN ISO 14040 divides a LCA into the four major phases: goal and scope definition, life cycle inventory analysis, life cycle impact analysis and interpretation (see Figure 2).

In the first phase, a definition of goal and scope is required. This phase also includes the identification of an audience for the analysis. Our study comprises multiple product life cycle assessments for different port container terminal equipment types and focuses on a comparative analysis of these types. The overall aim of our study is to investigate the environmental impacts of the respective

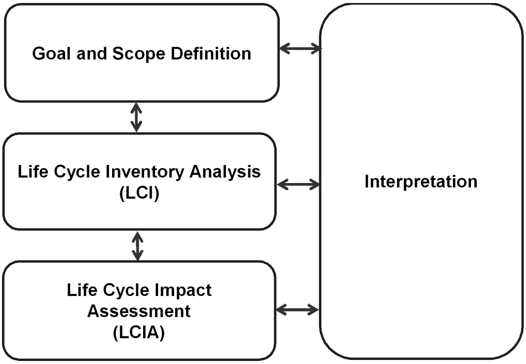

Figure 2: The four phases of life cycle assessments (DIN EN ISO 2006)

equipment types to advise port terminal operators regarding a sustainable port terminal layout.

The system boundaries should include all the input and output flows of material and energy that are relevant for the production system in question. Transparently communicating these system boundaries is of particular importance since the emission of certain parts of the life cycle will mean that these need to be attributed to other production systems in the course of a comprehensive analysis. In terms of our study, the boundaries include activities of selected equipment types for container movement within the gate of a port. Ideally, all energy and material flows needed to provide the equipment types with different drive trains and the infrastructure from ‘cradle-to-grave’ should be investigated. This means that the whole life cycle from the mining of raw materials, to production processes, transportation, use phase and the disposal of goods should be part of a proper LCA. E. g. in the container terminal case, it is important to consider the production phase, as the production of batteries may diminish the environmental benefits of electric drive trains in the use phase.

All results are expressed relative to a functional unit (FU) for comparison purposes. The FU should reflect the utility of the investigated products. The reference flow should correspond to the quantity of a product that is required to achieve this utility. Usually, multiple options for a FU exist. The major challenge within our project was to decide on a suitable FU that serves to compare different equipment types and enables the implementation of emission factors into the simulation tool. This way, port terminal operators can be advised before realizing ULLIs. The FU in our project is defined as using equipment over one working hour. Note that in this assessment we use a different FU because we present preliminary results of one equipment type: using equipment over the life time of one SC.

Only few industrial processes exclusively produce a single product, or are based on a linear relationship between input and output. Because of this, energy and material flows and the associated emissions have to be allocated to several products. In such cases, the following priorities are recommended by DIN EN ISO 14040:

1. Avoid allocation
2. Find a sound scientific reasoning for an allocation approach
3. Find a sound economic reasoning for an allocation approach

With regard to the quality of the data used for the LCA, the data should be accurate, comprehensive, consistent, reproducible and representative. Due to high effort required to obtain such data, port terminal operators often lack detailed knowledge about port terminal processes like the actual energy consumption of equipment. Additionally, manufacturers usually provide data sheets with generalized information about equipment, which is not detailed enough for a comprehensive LCA. These facts constitute the importance and the challenge to further investigate port activities.

In the second phase of the LCA, a life cycle inventory analysis is created. This inventory analysis serves to properly identify and quantify all input and output flows and indicates their interdependencies. As mentioned above, the development of a LCA usually demands detailed process knowledge, which creators of LCAs often lack due to a limited access to process information. Therefore, it is recommended to use LCA soft are. These LCA soft are solutions are usually combined with access to databases containing data from completed life cycle assessments. In this way, modular datasets supply process knowledge about e.g. upstream chains.

In the third phase, the life cycle impact assessment, the results of the inventory analysis are interpreted with regard to specific impact categories, such as climate change (classification), and corresponding impact indicators (characterization), such as carbon dioxide equivalents. Subsequently, the potential impacts of different port terminal equipment with different drive trains on the environment can be assessed.

In the fourth phase, the interpretation, the results from the inventory analysis are compared to the results from the impact assessment to allow for an interpretation concerning port terminal equipment as a whole. It should be kept in mind that a LCA is an iterative process, which requires a frequent review and reworking of initial phases whenever new insights are gained in the later phases of the process (DIN EN ISO 2006, Guinée et al. 2002).

4 Life Cycle Inventory Analysis of Port Terminal Transport Equipment

The assessment of environmental impacts of selected equipment types in container terminals is implemented in the soft are Umberto LCA+ using the ecoinvent database version 4.3 (IFU 2018). This model has been developed to quantify numerous categories of environmental impacts for a subsequent choice of the most fitting emission mitigation strategies for ports on the basis of the DIN EN ISO 14040 norm.

Following we conduct a simplified LCA-example of a SC (Christou 2012, Yang and Chang 2013) operating on port terminals. We model the SC with two different drive trains: diesel-electric and battery-electric. In the subsequent section, we compare the influences of these two drive trains on the overall LCA. The FU in this assessment is defined as using equipment over the life time of one SC. We will express all considered environmental impacts relatively to this FU.

1. Production:

The production of equipment includes all upstream parts of the supply chain, beginning from the cradle. Here, especially the production of raw materials and equipment parts like the diesel generator and electric diesel engines are modelled by customizing modular datasets (mostly so called ’unit processes’) from the ecoinvent database. The main component of the SC is the steel-gantry with a hoist system and a driver’s cabin. We assume that more than 90 % of the components of an SC are made of steel.

2. Transportation:

The equipment must be transported to the terminal before it can be used. These transport processes have not been included in our LCA so far.

3. Use phase:

An average use phase of an SC in port operation includes fuel/energy consumption for container transportation and empty driving and maintenance of the SC.

4. End of life:

This phase covers the disposal and recycling of equipment parts at the end of a SC´s life cycle. Recycling of the battery of a battery-electric SC has not been included so far.

We model an SC with a total weight of 70 tons, which rank among the bigger ones (Kalmar 2017). The modelled SC can carry one 20ft, one 40ft or two 20ft container (Kalmar 2017). We assume an overall life span of 20 years.

The diesel-electric SC runs with a diesel-generator and four electric motors at the wheels, whereas the battery-electric SC has a battery (4 t) and four electric motors. Our calculations, which are based on the inventory data shown in Table 1, consider a replacement of the battery after 3,000 recharging cycles, which means that within a life span of 20 years 3.19 batteries are needed. We create two scenarios of a battery-electric SC to compare two different electricity mixes, the German and the Icelandic, for power consumption. The electricity mix of Iceland is chosen as a reference because it consists of nearly 100 % renewable resources (Loftsdóttir et al. 2017). An overview about further technical data on both SC models is given in Table 1.

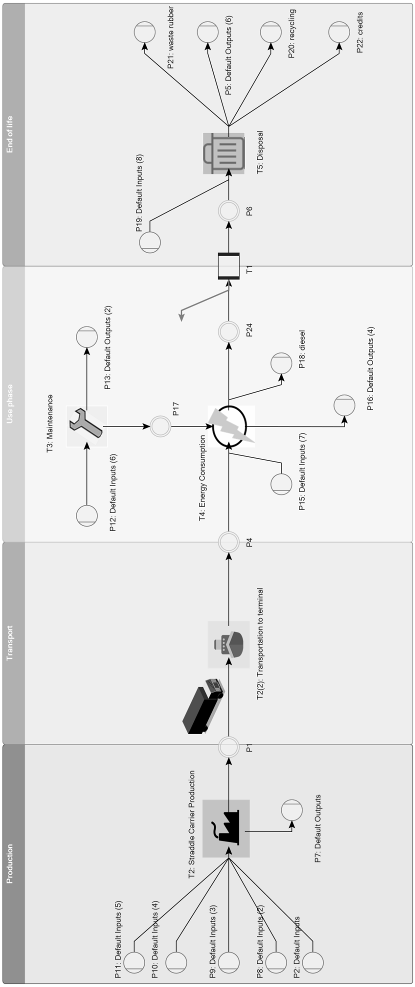

Figure 3: Life cycle phases of a straddle carrier

Table 1: Technical inventory data straddle carrier

	Diesel-electric	Battery-electric	Sources
Steel (gantry) [ton]	64.6	64.6	assumption
Life span [years]	20	20	assumption
Tires [number]	8	8	(Kalmar 2017)
Diesel-Generator [number]	1		(Kalmar 2017)
Electric motor [number]	4	4	(Kalmar 2017)
Working hours [h/y]	3,388	3,388	(Agrawal et al. 2017)
Fuel consumption [l/h]	20	–	(Froese et al. 2014)
Power consumption [kWh/h]	–	80	(Froese et al. 2014, Gottwald Port Technology et al. 2011)
Useful energy [kWh]	–	566	(Sterner and Stadler 2017)
Recharging cycles [number]	–	3,000	(Gottwald Port Technology et al. 2011)

5 Results of an Exemplary Environmental Impact Assessment for a Straddle Carrier

Most of the technical inventory data for our LCA (see Section 4) is derived from literature and research of other institutions. Therefore, our calculations are based on multiple assumptions and have to be treated as preliminary results. The planned future steps of our project with HPC will comprise a more comprehensive analysis of real data and conditions at Hamburg port terminals to produce more detailed results. Nevertheless, the LCA results already indicate the dimensions and interdependencies of port terminal equipment´s life cycles to operate ports more sustainable.

5.1 Life Cycle Impact Assessment and Interpretation of diesel-electric and battery-electric Straddle Carriers

For a concise presentation of the most relevant results, we chose the three impact categories ’climate change’, ’terrestrial acidification’ and ’particulate matter formation’. These impact categories cover the most relevant emissions (greenhouse gases, sulfur dioxides and particulate matter) for the port transportation sector (Naturschutzbund Deutschland (NABU) 2015, International Maritime Organization (IMO) 2016).

Figure 4 to Figure 6 show the results of our LCA for the diesel-electric engine and the battery-electric engine with the German (ger) and the Icelandic (ice) electricity mix. In all impact categories, the diesel-electric SC causes the highest pollution. The greatest environmental impacts originate from the use phase in all impact categories. Within the use phase, the fuel consumption causes significant quantities of environmentally relevant emissions. The end of life treatment shows negative values in all impact categories, which come from credits for recycling of steel and treatment of rubber. We assume that 100% of steel can be recycled to low-alloyed steel. Meanwhile the end of life treatment of rubber in an incineration plant generates electricity. The electricity from waste incineration substitutes electricity from other resources.

In the impact category ’climate change’ (see Figure 4), the electricity mix itself has a large influence on LCA results in the case of battery-electric engines. While the replacement of a diesel generator with an electric engine reduces the pollution

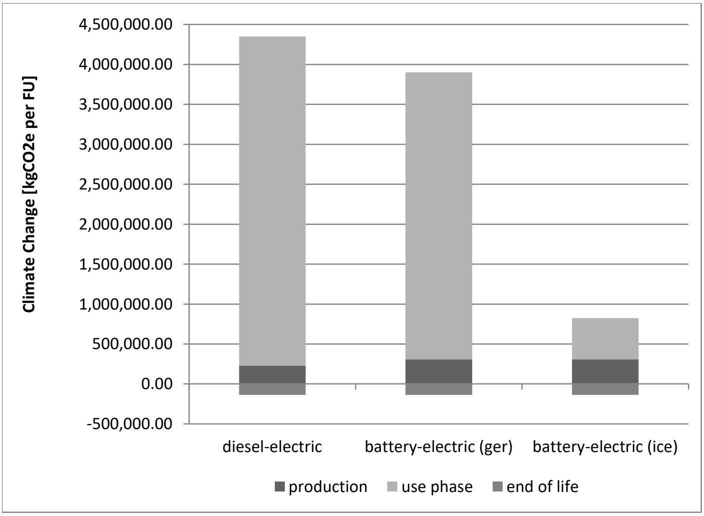

Figure 4: LCA results for the impact category 'climate change'

by about 13 % when assuming the German electricity mix, the green electricity mix of Iceland reduces the pollution by about 88 %.

A similar effect to the 'climate change' can be observed in the impact category 'terrestrial acidification' (see Figure 5). The diesel-electric SC has the largest influence on LCA results, while the battery-electric SC can significantly reduce emission from the use phase. Here again, the reduction potential depends on the electricity mix for power consumption in the use phase.

Foremost, the environmental impact of the production phase increases through the production of a battery for a battery-electric SC. The contribution of the use phase and the production phase to the 'particulate matter formation' (see Figure 6) by a battery-electric SC is very similar. Particularly for the battery-electric (ice) SC, the use phase causes only 13 % more emissions than the production phase. Nevertheless, emission reductions in the use phase switching from a

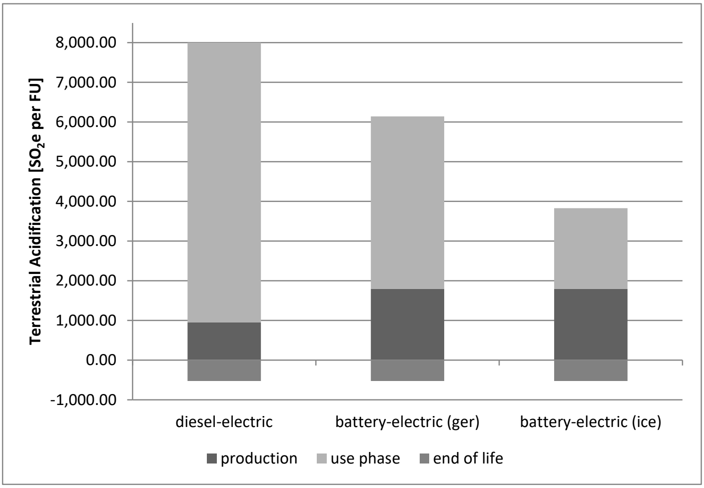

Figure 5: LCA results for the impact category 'terrestrial acidification'

diesel-electric to a battery-electric SC outweigh higher emissions caused by the production of the battery.

As battery recycling has not been modeled in our LCA, the end of life phase has no relevant effect on our results so far. As long as credits for recycling and impacts from disposal of rubber remain the same, there are no differences with regard to the disposal phase in the LCA results of our three SC models.

5.2 Conclusion based on findings

The scope of our project comprises a comparative analysis of feasible measures to improve the environmental performance of ports, especially with regard to the configuration and operation of equipment in the container terminal. The system boundaries have been set to enable a comparison of the relevant energy and material flows associated with specific types of terminal equipment. So far, we

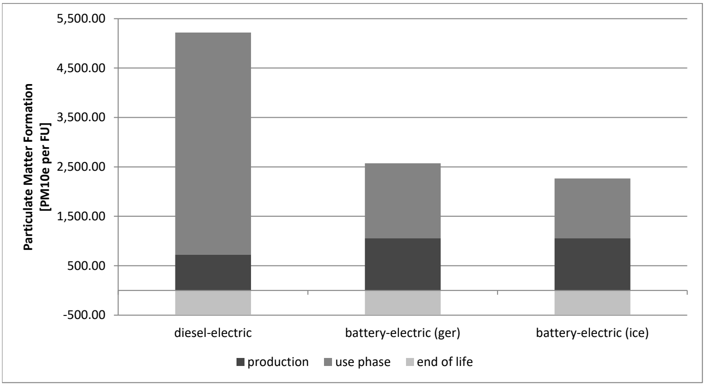

Figure 6: LCA results for the impact category ’particulate matter formation’

conducted one simplified LCA of an SC with a diesel-electric and one of an SC with a battery-electric drive train and two different electricity mixes.

Our preliminary results show the importance and the high impact of the use phase on the overall LCA results. Nevertheless, depending on the impact category, the production phase may also have an important impact on environmental pollution. The high relevance of the production phase confirms the findings of Vujičić et al. (2013), Agrawal et al. (2017) and Gottwald Port Technology et al. (2011). While it is not yet included in our LCA, it is likely that battery recycling will have an influence on the comparative LCA and may change our results in favor of battery-electric vehicles.

Further steps of our project will include a more detailed analysis of SC drive trains. A comparison of the SC with other equipment types for port terminal transportation like RTGs, RMGs and AGVs will also be taken into account to gain a better understanding of a sustainable port terminal layout. The overall aim is to develop emission factors for each equipment type and drive train per working hour. These factors will be implemented in a port operation simulation tool to serve as basis for further recommendations on sustainable ULLIs.

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References

Agrawal, A., G. Aldrete, B. Anderson, R. Muller, and J. Ray (2017). "Inventory of Air Emissions for Calendar Year 2016: Prepared for: The Port of Los Angeles: Prepared by: Starcrest Consulting Group, L. L.C." In:

Breuer, W., H. Dyckhoff, A. Hüwe, P. Letmathe, O. Lorz, R. Madlener, P. Thomes, and G. Walther (2013). *Ultralangelebige Investitionen, Definition und Problembeschreibung*.

Christou, I. T. (2012). *Quantitative Methods in Supply Chain Management: Models and Algorithms*. London: Springer Verlag.

Creutzig, F., P. Jochem, O. Y. Edelenbosch, L. Mattauch, D. P. van Vuuren, D. McCollum, and J. Minx (2015). "Transport: A roadblock to climate change mitigation". In: *Science* 350.6263, pp. 911–912.

Davarzani, H., B. Fahimnia, M. Bell, and J. Sarkis (2016). "Greening ports and maritime logistics: A review". In: *Transportation Research Part D: Transport and Environment* 48, pp. 473–487.

DIN EN ISO (2006). *Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen (ISO 14040:2006)*. Berlin.

Durrant-Whyte, H., D. Pagac, B. Rogers, M. Stevens, and G. Nelmes (2007). "Field and service applications - An autonomous straddle carrier for movement of shipping containers - From Research to Operational Autonomous Systems". In: *IEEE Robotics & Automation Magazine* 14.3, pp. 14–23.

Froese, J., S. Töter, and I. Erdogan (2014). *Green Efforts - Recommendations Manual for Terminals, Deliverable 12.1*.

Geerlings, H. and R. van Duin (2011). "A new method for assessing CO2-emissions from container terminals: A promising approach applied in Rotterdam". In: *Journal of Cleaner Production* 19.6-7, pp. 657–666.

Gottwald Port Technology, HHLA, ifeu, and RWTH Aachen (2011). *Abschlussbericht B-AGV, Forschung und Entwicklung batteriebetriebener Schwerlastfahrzeuge (AGV) und deren Erprobung in einem Feldversuch im Container-Terminal Altenwerder in Hamburg, im Rahmen des FuE-Programms "Förderung von Forschung und Entwicklung im Bereich der Elektromobilität": Projektlaufzeit: 01.06.2010 - 30.09.2011: Gefördert durch das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit*. Düsseldorf.

Guinée, J. B., M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H. A. de Udo Haes, H. de Bruijn, R. van Duin, and M. A. J. Huijbregts (2002). *Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards*. Dordrecht: Kluwer Academic Publishers.

Günther, H.-O. and K.-H. Kim (2006). “Container terminals and terminal operations”. In: *OR Spectrum* 28.4, pp. 437–445.

Hou, L. and H. Geerlings (2016). “Dynamics in sustainable port and hinterland operations: A conceptual framework and simulation of sustainability measures and their effectiveness, based on an application to the Port of Shanghai”. In: *Journal of Cleaner Production* 135, pp. 449–456.

IFU (2018). *Umberto LCA+: Institut für Umweltinformatik Hamburg GmbH (IFU); Institut für Energie- und Umweltforschung (IFEU)*. Hamburg/Heidelberg.

Kalmar (2017). “Kalmar Straddle Carrier Data sheet”. In:

Klöpffer, W. and B. Grahl (2014). *Life Cycle Assessment (LCA): A Guide to Best Practice*. Weinheim: Wiley-VCH.

Lam, J. S. L. and T. Notteboom (2014). “The Greening of Ports: A Comparison of Port Management Tools Used by Leading Ports in Asia and Europe”. In: *Transport Reviews* 34.2, pp. 169–189.

Stahlbock, R. and S. Voß (2007). “Operations research at container terminals: A literature update”. In: *OR Spectrum* 30.1, pp. 1–52.

Steenken, D., S. Voß, and R. Stahlbock (2004). “Container terminal operation and operations research - a classification and literature review”. In: *OR Spectrum* 26.1, pp. 3–49.

Sterner, M. and I. Stadler (2017). *Energiespeicher - Bedarf, Technologien, Integration*. Berlin, Heidelberg: Springer Berlin Heidelberg.

The European Sea Ports Organization (2012). *Green Guide - Annex 1: Good practice examples in line with the 5 Es*. Bruxelles.

Tichavska, M., B. Tovar, D. Gritsenko, L. Johansson, and J. P. Jalkanen (2017). “Air emissions from ships in port: Does regulation make a difference?” In: *Transport Policy*.

Vujičić, A., N. Zrnić, and B. Jerman (2013). “Ports Sustainability: A life cycle assessment of Zero Emission Cargo Handling Equipment”. In: *Strojniški vestnik – Journal of Mechanical Engineering* 9.59, pp. 547–555.

Wang, Z. and J. Sarkis (2013). “Investigating the relationship of sustainable supply chain management with corporate financial performance”. In: *International Journal of Productivity and Performance Management* 62.8, pp. 871–888.

Wilmsmeier, G. and T. Spengler (2016). “Energy consumption and container terminal efficien y”. In: *FAL Bulletin* 350.6, pp. 1–10.

Yang, Y.-C. (2017). “Operating strategies of CO 2 reduction for a container terminal based on carbon footprint perspective”. In: *Journal of Cleaner Production* 141, pp. 472–480.

Yang, Y.-C. and W.-M. Chang (2013). “Impacts of electric rubber-tired gantries on green port performance”. In: *Research in Transportation Business & Management* 8, pp. 67–76.