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Holistic framework for studying ship air emissions in a life cycle perspective

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ABSTRACT

This paper presents a novel mathematical framework which incorporates the life cycle approach with the objective to provide a holistic assessment of air emissions for ocean going ships. For the development of the framework, important elements of the Life Cycle Assessment method have been applied which is a methodology that considers the full life cycle of the system it examines (i.e. from the extraction of row materials to the final disposal/recycling). The paper presents some illustrative results from a case study on a Panamax oil tanker. The life cycle emissions inventory for this ship has been developed using the life cycle framework and results are presented and discussed accordingly.

1. Introduction

1.1. Motivation

Despite its international nature and enormous growth, the maritime transport sector, has been criticized for being rather slow in achieving global agreements for the reduction of its air emissions footprint. Recently (from 1.1.2013) regulations for greenhouse gases of shipping have entered into force through the MARPOL 73/78 regime. Recent figures from the third IMO Greenhouse gas study show that the international shipping sector while carrying over 90% of the world's trade contributes not more than 2.8% to the global anthropogenic CO_2 emissions (International Maritime Organization, 2014). Yet, in absolute terms, emissions from international shipping are significant and keep rising; moreover there is evidence that the impact of these emissions in some areas is not negligible (Corbett et al., 2007) and calls for further actions. It has been estimated that in the absence of emission reduction policies, a doubling to tripling of 2007 emission levels is expected by 2050 (International Maritime Organization, 2014).

Life cycle thinking is continuously earning acceptance in environmental assessments of industrial products and services as a response to the growing awareness of society about the long term impacts of human activities.

A well known method for life cycle systems examination is the Life Cycle Assessment (LCA), a structured and standardized technique under the framework of ISO. According to this international standard, the LCA is the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO, 2006). The method has been extensively used in different industrial sectors for measuring the environmental impacts of several products, but for the particular case of maritime transport it has a short application record so far, the main reason being the complexity of the ship system. There is a growing interest for the concept of LCA in recent years (Finnveden et al., 2009) which is confirmed by the fact that there are some official initiatives launched for this concept at European and global level. The European Platform of Life Cycle Assessment run by the Joint Research Centre (JRC) is the official EU initiative created to facilitate communication on life-cycle data and commence a co-ordination scheme involving both ongoing data collection efforts in the EU and existing harmonization projects. The other major initiative is cooperatively run by the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), namely the UNEP/SETAC Life Cycle Initiative. The mission of this initiative is to bring together different science-based Life Cycle approaches worldwide and explore the possibilities to achieve a global consensus on how the method should be conducted (Swarr et al., 2011).

1.2. Literature review

Life cycle studies in shipping were initially conducted during the 1990s. These studies have demonstrated that the LCA method may well be employed for the environmental life cycle evaluation of ships (Fet, 2002). The first LCA experimental studies highlighted

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the significance of the system boundaries selection which is a highly subjective process and may lead to contradicting results (Fet, 2002).

The National Maritime Research Institute of Japan has developed suitable software to examine the environmental impact of cargo vessels in this country (Kameyama et al., 2004). LCA is very successful for comparing the environmental impact of alternatives used for the same product (or process). The software SSD (Sustainable Ship Design) evaluates different green technologies in terms of environmental impacts from a life cycle perspective (Tincelin et al., 2010). Furthermore, two alternative materials for the superstructure of cruise ship (traditional steel and aluminum and new-type composite sandwich material) have been comparatively assessed with the LCA method (Hou, 2011). Chatzinikolaou and Ventikos (2015) have used elements of the LCA method to develop a holistic framework capable of producing ship air emission inventories in a life cycle perspective. The same authors have reported a life cycle impact assessment study on the hull subsystem of the ship (Chatzinikolaou and Ventikos, 2014b).

Recent life cycle studies have focused on the area of marine fuels. Ryste (2012) has used the LCA framework to conduct a life cycle analysis of the bunkering process of LNG as marine fuel looking, in particular, to the climate change impacts of this type of fuel. The International Council on Clean Transportation, ICCT (2013) has recently published an analysis of life cycle greenhouse gasses and the possible benefits of using LNG as an alternative marine fuel. A comparative LCA study has examined, in a life cycle perspective, the impact of LNG and HFO used as marine fuels (Laugen, 2013). Comparisons of different options of marine fuels (HFO, MGO, gas-to-liquid fuel, and LNG, combined with two exhaust abatement techniques) has been performed in another study, by using the life cycle approach with the necessary steps from extraction of raw material to transportation of one ton cargo in 1 km on a Ro–RO vessel (Bengtsson et al., 2011).

Finally, the environmental implications of additional ship scantlings for selected bulk carrier ship types have been studied to illustrate that more robust ships would be better protected from corrosion and that the resulted lower maintenance demands would in turn produce less CO_2 emissions during the ship life (Gratsos et al., 2010).

2. Material and methods

The overall goal is to model and examine air emissions of an ocean going ship in a life cycle perspective. The life cycle of the ship is divided in the following four stages: shipbuilding, operation, maintenance and dismantling. The important ship processes with respect to air emissions are identified in these four life cycle stages and algorithms are developed that can estimate air emissions at any life cycle stage, year in the life cycle and total life cycle as well. The focus of the study is on the modeling of ship processes in order to create adequate and reliable life cycle emissions inventories. Examination of life cycle impacts of these emissions (which is the last step of the LCA technique) is out of this scope of this paper.

2.1. *Ship life cycle analysis*

The authors have already reported a suitable system for life cycle analysis of ship systems (Chatzinikolaou and Ventikos, 2014a, 2014b, 2015). For this purpose the authors have used elements of Systems Theory and the Life Cycle Assessment (LCA) method (ISO, 2006). The ship is viewed as a system which can be detailed into subsystems and further into system elements. A subsystem is defined as an individual step that is part of the defined total system. Two subsystems are qualified as important sources of air emissions throughout the life of cargo ships namely the hull subsystem, and the machinery subsystem. The hull subsystem comprises of elements that have to do with the steel structure of the ship. The machinery main components subsystem includes the primary components of the engine room of a cargo ship: main and auxiliary engines and gen sets, and boilers.

At the system element level the important processes with respect to air emissions are identified and elaborated. This elaboration is done in an input–output context where inputs are raw materials and energy for the process and outputs are the air emissions produced throughout the process.

The processes included in the hull material system element are: 1. steel production, 2. steel cutting, 3. abrasive blasting, and 4. materials transport. The boundaries of the shipbuilding include the production of steel and a transportation scenario of the steel material from the production site to the shipyard. In the life cycle stage of operation no important processes in terms of emissions production are considered for this system element. The processes included in the maintenance life cycle stage are identical to the shipbuilding stage, although quantities of materials and resulting emissions are considerably less. The processes included in the recycling stage are steel recovery which takes into consideration the specific way that the steel is being recovered in the selected site (recycling in India, Alang) for which data has been made available.

The hull protection system element includes the coating application which is a major shipbuilding and ship repair process. Some spot painting may be also performed during the operational life of the ship but this is not considered important in terms of emissions production and therefore is excluded from the analysis.

The process of sacrificial anodes (on the hull, rudder and water ballast tanks) is also included in the hull protection system element in the stages of shipbuilding and ship maintenance. A transportation scenario is also considered for the transport of relevant materials to the shipyard. For the ship recycling stage the fate of materials used for the protection of the hull is not known. Therefore for this life cycle stage no process has been incorporated in the hull protection system element.

The structure of the system is shown in Fig. 1.

2.1.1. *Machinery construction*

2.1.1.1. Process: engines construction. Generally, the life cycle of engines before they are installed onto the ship is not known. A simplified scenario has been used for modeling the construction process of marine engines. This scenario includes materials (i.e. steel, fuels), and processes (i.e. assembly, welding, transport). Table 1 contains the quantities of materials and processes for the construction and installation of one main engine (2 stroke, 12,240 kW) and three auxiliary engines (4 stroke, 740 kW each) onboard the Panamax oil tanker case study which is presented in this paper.

Representative air emissions from this particular scenario of engines construction are presented in Table 2. These results derive from the use of specialized LCA databases (Eco-Indicator 99, 2014).

2.1.1.2. Process: engines shop tests. The process of shop tests of the engines before they are installed onboard produces air emissions due to the consumption of fuels in the tested engines. Information for fuel consumption during this process comes from the work of Alkaner and Zhou (2006). According to this study during the testing stage of engine manufacturing (specific diesel oil engine manufacturer), 0.350 kg/kW of marine diesel oil (MDO) and 1.886 kg/kW of heavy fuel oil (HFO) are consumed. Therefore the quantities of fuels used in the shop tests are made available (in kg)

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