Environmental and social valuation of shipping emissions on four ports of Portugal

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Abstract

Maritime sector is expected to continue growing significantly in line with world trade, however its impacts on environmental, social and human health are not yet fully known. Thus, this study aimed to estimate the external costs of in-port shipping emissions (NO_x, SO_2, CO_2, VOCs and $PM_{2.5}$) and accomplish a comprehensive eco-efficiency evaluation of four ports in Portugal (Leixões, Setúbal, Sines and Viana do Castelo) during 2013. External costs were based on the external cost factors from BeTa, CAFE and NEEDS projects and from Song (2014). Eco-efficiency evaluation was based on environmental, social and economic criteria. Results showed higher externalities for Sines and Setúbal (2.0E+02 million €), followed by Leixões (1.8E+02 million €), and Viana do Castelo (6.3 million €). NO_x, SO_2, and $PM_{2.5}$ were the pollutants with the highest externalities. Sines port showed the best overall eco-efficiency. Although Setúbal port showed higher performance than Viana do Castelo port based on the economic data, when social and environmental aspects were considered the results changed. This shows the importance of performing a more comprehensive analysis using social and environmental indicators. The combination of all these indicators is highly important to support the implementation of policies for the abatement of shipping in-port emissions.

Keywords: Emission costs; Shipping emissions; Eco-efficiency; Sustainable ports; Ports management

Conflict of interests

The authors declare no conflict of interests

1. Introduction

Maritime transport is commonly appointed as an efficient and environmentally friendly cargo transportation mode when compared to other modes of transportation, due to the capacity of tonnes transported per kilometre travelled. Despite this fact shipping emits large amounts of air pollutants (Bilgili and Celebi, 2016; Miola et al., 2009; Papaefthimiou et al., 2016). Hence, ship emissions have received great focus in recent years. Greenhouse gases (GHG) emissions from shipping accounted for approximately 2.4 % of global emissions in 2012 (IMO, 2015). Maritime sector is expected to grow significantly in line with world trade, thus environmental and human health impacts estimated due to shipping emissions will be even higher in the future (Antturi et al., 2016). In fact, it is expected that by 2050 without correct regulation of shipping emissions their CO_2 emissions may represent 17 % of the global (IMO, 2011; Papaefthimiou et al., 2017; Sanabra et al., 2014; Wan et al., 2018).

In the last years, emissions from ships have attracted the interest of researchers that have been making efforts to develop accurate emission inventories for ports (Saxe and Larsen, 2004; Deniz and Kilic, 2009; Tzannatos, 2010; Saraçoğlu et al., 2013; Liu et al., 2014; Song and Shon, 2014; Miluse Tichavska and Tovar, 2015; Nunes et al., 2017). Nonetheless, estimating shipping emissions is not sufficient to develop mitigation plans and effective regulatory requirements and to assist decision-makers (Zhang et al., 2017). In order to perform more complete and reliable analyses, it is also important to estimate the externalities of ship emissions and evaluate sea ports in terms of social-economic and environmental concerns (Antturi et al., 2016; Papaefthimiou et al., 2017; Song, 2014; Miluše Tichavska and Tovar, 2015)

In fact, estimation of ship emissions external costs may be helpful for diverse purposes, since it can give an indication of the total social costs associated with specific ship activities, projects or choices (Antturi et al., 2016). This information allows for better decisions to ensure that

25   social benefits of new operational conditions exceed their social and environmental costs.

26   Moreover, high external costs can serve as an indicator that a port should deserve more attention

27   for pollution prevention and control. Finally, external costs can be used to apply taxes or special

28   fees to promote the reduction of harmful emissions (Bickel and Friedrich, 2001; Matthews et

29   al., 2001).

30   Typically, port authorities assess their performance mainly through economic data (commercial

31   output of ports) underestimating the environmental and social impacts due to shipping

32   emissions. To perform a complete and reliable analysis of the port performance, it is important

33   to study their eco-efficiency. The Organisation for Economic Co-operation and Development

34   (OECD) designates eco-efficiency as "the efficiency with which ecological resources are used

35   to meet human needs" and defines it as a ratio between the value of products and services

36   produced and the sum of environmental pressures generated by a firm, sector, or economy as

37   whole (European Commission, 2010). Regarding ports, eco-efficiency can be evaluated using

38   indicators based on typical economic data (amount of general cargo, number of handled

39   containers, number of ship calls and annual income), oriented towards two main aspects: i)

40   environmental level, like the external costs related with in-port shipping emissions; and ii)

41   social level, like the external costs related with health impairment induced from the emissions.

42   This study intends to extend Nunes et al. (2017) study and analyses for the first time the external

43   costs of shipping and eco-efficiency of four ports in Portugal. The results allowed evaluating

44   seaports in terms of social-economic and environmental concerns.

45   The article is organised as follows: after the introduction in Section 1, a brief literature review

46   concerning the methods that are used to estimate external costs from ships at ports and the

47   studies that combine the estimation of external costs of shipping emissions with the evaluation

of the ports eco-efficiency is presented in section 2. Section 3 describes in detail the methodology to calculate the external costs and to assess the eco-efficiency of ports used in this study. Section 4 focuses on the external costs estimation and ports eco-efficiency analysis. Finally, in Section 5, main conclusions and future work are summarized.

2. Literature review and problem statement

Negative impacts of air pollution on health and the environment lead to high economic costs. Economic consequences of air pollution can be quantified as external costs through two approaches, a bottom-up and/or a top-down (Miola et al., 2009). Both approaches have advantages and disadvantages and inevitable sources of uncertainties. The bottom-up approach calculates the economic costs of air pollution (or the economic benefits of reduced air pollution) starting from emissions, followed by concentrations, exposure, biophysical impacts and valuation of the economic costs and is more appropriate to apply to marginal cost valuation (more precise and accurate, with potential for differentiation). The top-down approach estimates the external costs using cost factors from reference bottom-up studies (mostly for the United States of America and the European Union) and is more convenient to assess average costs (Miola et al., 2009; OECD, 2016; Tichavska and Tovar, 2017).

Under ExternE project a bottom-up approach, also called impact pathway approach (IPA) was developed for the first time. This approach is considered the most detailed methodology for calculating site specific air emissions external costs and it has been used in the context of an economic valuation of air pollution, mostly for the United States of America (USA) and the European Union (EU) (OECD, 2016).

70 For EU, IPA was used to study the benefits of several Directives and technology options aiming

71 to improve air quality (EC, 2013; ExternE, 1995; Holland, 2014a, 2014b; Vrontisi et al., 2016).

72 Moreover, it was used in major studies for external cost estimation in transport, such as the

73 Benefits Table database (BeTa) (Holland and Watkiss, 2002), the Clean Air for Europe (CAFE)

74 (European Commission, 2015; Holland et al., 2005), the Harmonised European Approaches for

75 Transport Costing and Project Assessment (HEATCO) (Bickel et al., 2006) and the New

76 Energy Externalities Development for Sustainability (NEEDS) (Korzhenevych et al., 2014).

77 External costs of shipping emissions are exclusively estimated through the methodologies from

78 BeTa, CAFE and NEEDS reports (Tichavska and Tovar, 2017). All of the methodologies

79 applied on these reports result from the application of IPA, which is considered the most

80 detailed methodology for calculating site specific air emissions external costs, however each

81 study has different methodological specifications on the emission cost calculation (Tichavska

82 and Tovar, 2017).

83 BeTa was created for the Environment Directorate-General of the European Commission by

84 netcen, taking as a starting point a set of data on pollutant chemistry and dispersion generated

85 for the ExternE Project (European Commission, 2016; Holland and Watkiss, 2002). This

86 database was created to provide a simple mechanism to estimate the external costs of emissions

87 from all sources in rural locations for 15 EU countries, for the emissions at ground level in cities

88 of different sizes and for the shipping emissions based on data for urban areas of various sizes.

89 For in-port shipping emissions, BeTa theorizes that the external cost factors (ECFs) are the sum

90 of the damage caused in urban areas with the same size of the port city considering the rural

91 externality value of the emissions for the country under study (Holland and Watkiss, 2002;

92 Tichavska and Tovar, 2017; Tzannatos, 2010).

93 Although BeTa provides a simple tool to estimate external costs (linking urban and rural

94 externalities) there was evidence that their rural ECFs underestimated real costs (Sanabra et al.,

95 2014; Miluše Tichavska and Tovar, 2015). Thus, in 2005 the estimates of marginal external

96 costs of air pollution were updated as part of the cost-benefit analysis of the Clean Air for

97 Europe Programme (CAFE), thus despite maintaining the approach used in BeTa, updated rural

98 ECFs from CAFE project started to be used (EC, 2016; Holland et al., 2005). The main updates

99 from CAFE project were the addition of ammonia (NH_3) to the pollutants considered, the

100 increase from 15 to 25 EU member states for which the results were provided and the use of

101 EMEP for modelling atmospheric pollutants dispersion (chemistry and meteorology were

102 updated), applied to a series of scenarios in which emissions were changed individually by

103 country and pollutant for the 2010 baseline scenario. Furthermore, in the CAFE program four

104 different sensitivity scenarios were considered with variations resulting from: i) methodologies

105 used to value mortality, ii) magnitude of health effects; and iii) cut-point for assessment of

106 ozone impact which varies in each scenario (European Commission, 2015; Holland et al., 2005;

107 Sanabra et al., 2014). NEEDS project has been cited in recent studies as the most updated

108 methodology for calculating external costs of maritime transport, since their ECFs are the most

109 recent and updated, covering all EU Member States, including all European sea regions, and

110 quantifying both health and side effects of NO_x and SO_2 on materials, biodiversity and crops

111 (Dragovic et al., 2015; Korzhenevych et al., 2014; Maragkogianni and Papaefthimiou, 2015).

112 The above-mentioned projects do not provide ECFs for CO_2, because considering the

113 impairment and global effects triggered by global warming, the location and how CO_2

114 emissions occur are indifferent. Thus, ECFs from global studies on external costs of transport

115 (Berechman and Tseng, 2012; van Essen et al., 2011) and/or regarding specific external costs

116 of shipping emissions at port (Song, 2014) are commonly applied to different countries.

117　As far as known, there are only three studies that combine or suggest the combination of the

118　estimation of external costs of shipping emissions with the evaluation of the ports eco-

119　efficiency (Papaefthimiou et al., 2017; Song, 2014; Miluše Tichavska and Tovar, 2015). Most

120　of the studies only perform the emissions inventory and evaluate their associated external social

121　costs (Berechman and Tseng, 2012; Dragovic et al., 2015; McArthur and Osland, 2013; Miola

122　et al., 2009; Sanabra et al., 2014; Tzannatos, 2010).

123　Song (2014) reported the calculation of in-port shipping emissions and their associated external

124　and social costs in Yangshan port of Shanghai during 2009. To make a more extensive analysis,

125　the author also studied the port performance regarding social-economic and environmental

126　concerns. In this study, Song (2014) used several values of ECFs from international studies to

127　adjust them for Shanghai social-economic reality.

128　Tichavska and Tovar (2015) estimated external costs and eco-efficiency parameters from

129　shipping emissions in Las Palmas Port, using emissions calculated on a previous study (Miluse

130　Tichavska and Tovar, 2015) and determined their associated costs using ECFs from BeTa,

131　CAFE and NEEDS. Results indicated that shipping emissions caused significant damages to

132　human health and built environment around the Port of Las Palmas.

133　Although Song (2014) and Tichavska and Tovar (2015) have analysed the port having into

134　account the eco-efficiency and the social-economic indicators the authors only considered the

135　emissions inventory per se as an environmental performance indicator. More recently,

136　Papaefthimiou et al. (2017) proposed a methodological approach integrating other

137　environmental indicators, such as general cargo per emissions, number of containers per

138　emissions, number of passengers per emissions, ship calls per emissions and emissions per

139　annual income. Even though in this study a complete characterization of ports was performed,

only BeTa project methodology was applied, and the authors compared ports based on information from previous studies with different methodologies for shipping emissions calculation. Thus, to overcome the lacks above referred, this study aimed to estimate the external costs of in-port shipping emissions based on the combination of the application of BeTa, CAFE and NEEDS projects, and accomplish for the first time (Tichavska and Tovar, 2017), as far as the authors knowledge goes, a comprehensive eco-efficiency evaluation based on environmental, social and economic criteria of four ports in Portugal. This was performed using the previously estimated emissions reported by the authors in Nunes et al. (2017), which is the only publication studying international shipping emissions for Portugal, namely concerning shipping emissions at port level.

3. Material and methodology

3.1 External cost of shipping emissions

To determinate the external costs of the in-port shipping emissions in the targeted ports of this study (during manoeuvring, considered the average time when the ship was inside the port in manoeuvre operations, and hotelling, considered all the time the ship was inside the port, with exception of manoeuvring operations), shipping emissions calculated in a previous study were used (Nunes et al., 2017). In their study Nunes et al. (2017) used the bottom-up approach quoted as Tier 3 in the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook 2016 based on the ship calls information provided by port authorities. A detailed description of the methodology can be found in Nunes et al. (2017).

162   Table 1 shows the in-port shipping emissions of NO_x, SO_2, CO_2, VOCs and $PM_{2.5}$ for Leixões,

163   Setúbal, Sines and Viana do Castelo in 2013. Leixões is the largest port infrastructure in the

164   Northern Region of Portugal, represents about 25% of Portuguese international trade (moves

165   about 14 million tonnes of goods per year) and annually receives about 3 000 port calls. Viana

166   do Castelo Port is located near the mouth of Lima River, incorporating an industrial port, a

167   commercial port, a marina and a fishing port. The industrial port consists of two plants: the

168   shipyards of Viana do Castelo (ENVC) and a component manufacturing industry for wind

169   turbines (ENERCON). The commercial port handle about 500 000 tonnes per year and receives

170   about 200 port calls annually. Setúbal Port is located at the junction of major routes of

171   intercontinental navigation North-South and East-West and is the Portugal national leader in

172   fractional general cargo transportation (about 43% of the national total) and in the Ro-Ro traffic

173   of the new light vehicles (around 90% of the national total), with annual incomes of about 3.5

174   million €. Annually this port receives about 1 200 port calls. As the main port on the Atlantic

175   coast of Portugal due to its geophysical characteristics, Sines Port is the largest artificial port in

176   Portugal, and a deep-water port. It is the Portuguese port with the highest annual incomes of

177   around 12 million € and receives about 2 000 port calls annually (APP, 2016). For each port

178   and air pollutant, the external costs of emissions produced during manoeuvring and hotelling

179   were estimated using the following Equation:

180    $$EC_{Port}(€) = E_{Port}(tonnes) \times ECF\left(\frac{€}{ton}\right), \qquad\qquad (1)$$

181   where EC_{Port} is the external cost of in-port shipping emissions for each pollutant in a particular

182   port (€), E_{Port} is the total in-port shipping emissions for each pollutant in a particular port

183   (tonnes) and ECF is the external cost factor for each pollutant (€/tonnes).

184 After conducting a literature review, in the present case study, a top-down approach using ECFs

185 from BeTa, CAFE and NEEDS projects (bottom-up studies) and from Song (2014) were used

186 to estimate the externality costs from shipping emissions. Although a bottom-up approach,

187 based on the Impact Pathway Approach, would be a better option for external cost estimation,

188 because it could be more localized and accurate, it would be more complex, involving higher

189 costs, more models and requiring intensive local data that was not possible to be collected

190 (Miola et al., 2009; Miluše Tichavska and Tovar, 2015). As for Portugal there are no

191 publications concerning external costs of shipping emissions, estimations based on top-down

192 approaches using ECFs from major European reports (BeTa, CAFE, NEEDS) were considered,

193 to fill the existing scarcity in this field of knowledge. Moreover, although it has associated

194 uncertainties, this methodology has been widely accepted (Berechman and Tseng, 2012;

195 Maragkogianni and Papaefthimiou, 2015; McArthur and Osland, 2013; Miola et al., 2009;

196 Sanabra et al., 2014; Song and Shon, 2014; Miluše Tichavska and Tovar, 2015). As stated by

197 BeTa project for in-port shipping emissions, ECFs results of the sum of the damages caused in

198 urban areas (short-range externalities) of the same size as the port infrastructure with the rural

199 externalities of the emissions for the country (longer-rage externalities) where the port is

200 located.

201 For urban impact estimation, urban externalities for $PM_{2.5}$ and SO_2 in a standard city with a

202 population of 100 000 people (33 000 €/tonne for $PM_{2.5}$ and 6 000 €/tonne for SO_2) are

203 multiplied by a scale factor, depending on the population in the port city. Population data were

204 obtained from the website of PORDATA – Base de Dados Portugal Contemporâneo

205 (PORDATA, 2017). Since the scale factors are linear up to 500 000 inhabitants, interpolations

206 were used to determine these factors for the cities of Matosinhos (Leixões Port) and Setúbal.

207 For the remaining cities, a value of 1 was assigned. Table 2 shows the number of inhabitants,

208 scale factors and external costs calculated for each city of this study. For rural impact

209 estimation, BeTa project rural ECFs of NO_x, SO_2, VOCs and $PM_{2.5}$ were estimated for several

210 European countries, including Portugal. According to BeTa project, rural external costs of NO_x,

211 SO_2, VOCs and $PM_{2.5}$ emissions for Portugal are 4 100 €/tonne, 3 000 €/tonne, 1 500 €/tonne

212 and 5 800 €/tonne, respectively. It should be noted that urban ECFs for NO_x and VOCs were

213 considered the same as the rural ones (Holland and Watkiss, 2002) which may cause

214 uncertainties.

215 According to the information previously described, updated rural ECFs from CAFE project

216 (considering four different sensitivity scenarios to attain more comprehensive results) were

217 used to update BeTa methodology.

218 In the present study, ECFs from NEEDS project were also used, because although not specific

219 to maritime ports, they include all major pollutants in EU member states and specific ECFs to

220 European maritime territories. Furthermore, this is considered by some authors as the most

221 updated methodology and has been referred as suitable for the calculation of external costs of

222 shipping (Maragkogianni and Papaefthimiou, 2015). Thus, external costs of NO_x, SO_2 and

223 VOCs emissions for Portugal used in this study were 1 957, 4 950 and 1 048 €/tonne,

224 respectively. For $PM_{2.5}$, ECFs were estimated for three different levels according to population

225 density (urban - population density of 1 500 inhabitants/km^2; suburban - population density of

226 300 inhabitants/km^2; rural - population density below 150 inhabitants/km^2). To assign the

227 values to port cities, data on population densities were obtained from Instituto Nacional de

228 Estatística (INE) website (INE, 2017). Consequently, for Leixões Port located in the city of

229 Matosinhos with a population density of about 2 811 inhabitants/km^2 (considered urban) an

230 ECF of 196 335 €/tonne was attributed. For Sines Port, located in the city of Sines with a

231 population density of about 70 inhabitants/km^2 (considered rural) an ECF of 18 371 €/tonne

232 was attributed. For Ports of Setúbal and Viana do Castelo located in the cities of Setúbal and

233 Viana do Castelo, with population densities of about 526 and 278 inhabitants/km^2, respectively

234 (considered suburban) an ECF of 49 095 €/tonne was attributed. Regarding CO_2 ECF, the value

235 of 29 €/tonne based on mean values from Berechman and Tseng (2012), USEPA (2010), World

236 Bank (2010) and IPCC (2006) was adopted (Song, 2014). Although Song (2014) also provided

237 ECFs for other pollutants, they were not used in this study because they were adapted to China

238 and Shangai's reality. All values mentioned above reflect non-updated year prices. To update

239 them to 2013 the Consumer Price Index (CPI) of Portugal from OECD country statistical

240 profiles were used. Table 3 shows updated ECFs for 2013 used in the present study.

241 *2.2 Ports eco-efficiency*

242 To make a complete evaluation of the performance of the studied ports, three characterization

243 criteria were considered based on economic data, and environmental-social criteria defined

244 through eco-efficiency indicators (Papaefthimiou et al., 2016).

245 The typical economic data such as the number of TEUs (handled containers), amount of general

246 cargo handled, number of ship calls and annual income were obtained from the official annual

247 reports available on the port's websites and from a report performed by the Mobility and

248 Transports Portuguese public Institute (Instituto de Mobilidade e Transportes, I.P. - IMT) (IMT,

249 2013). This data allowed the evaluation of ports' economic performance. Regarding

250 environmental and social domains, eco-efficiency indicators were considered based on

251 emissions and their associated external costs. Accordingly, at the environmental level the

252 following indicators were defined: i) amount of emissions during manoeuvring and hoteling

253 (Emissions); ii) amount of emissions per number of TEUs (Emissions/Containers); iii) amount

254 of emissions per amount of general cargo handled (Emissions/Cargo); iv) amount of emissions

255 per number of ship calls (Emissions/Calls); and v) amount of emissions per income

256 (Emissions/Income). At the social level, the following indicators were defined: i) external cost

257 of emissions (EC); ii) external cost of emissions per number of TEUs (EC/Containers); iii)

258 external cost of emissions per amount of general cargo handled (EC/Cargo); iv) external cost

259 of emissions per number of ship calls (EC/Calls); and v) external cost of emissions per income

260 (EC/Income). For the social indicators, total costs calculated through the urban ECFs from

261 BeTa and rural ECFs from CAFE (average results for the four sensitivity scenarios) have been

262 used. BeTa is the only report where the damages from in-port shipping emissions are considered

263 and, with the updated rural ECFs from CAFE an enhanced estimation is achieved. The same

264 approach has already been considered in the literature (Sanabra et al., 2014; Miluše Tichavska

265 and Tovar, 2015). Finally, to compare ports considering the three domains previously

266 mentioned, economic data and the calculated eco-efficiency indicators were rescaled using the

267 unity-based normalization method (Smithson and Verkuilen, 2006).

268 **4. Results and Discussion**

269 *4.1. External costs estimation*

270 The total external costs associated to the in-port shipping emissions at Leixões, Setúbal, Sines

271 and Viana do Castelo during 2013 are presented in Table 4. Figure 1 shows a more detailed

272 distribution of the external costs by type of pollutant. The highest external costs were found

273 when rural ECFs from CAFE for sensitive scenario 4 were used. As already mentioned, the

274 variation in the results of the different scenarios is mainly due to the evaluation of mortality,

275 the range of health effects and the cut-off point for the assessment of ozone impact. To

276 homogenize all the scenarios, an average scenario was considered (CAFE SC average).

277 Accordingly, external costs obtained using BeTa urban ECFs combined with ECFs from the

278 average scenario of CAFE were higher than those obtained when the rural and urban ECFs of

279 BeTa were used, as can be seen in Table 4. This result was expected because external costs

280   estimated using BeTa's rural ECFs are known to underestimate the actual costs (Sanabra et al.,

281   2014; Miluše Tichavska and Tovar, 2015). The lowest estimate was obtained using NEEDS,

282   with estimated ship costs of 1.1E+02 million € / year at Leixões Port, 7.4E+01 million € / year

283   at Setúbal Port, 6.6E+01 million € / year at Sines Port and 2.5 million € / year at Viana do

284   Castelo Port (Table 4). Although NEEDS has been considered the most recent methodology

285   including values for all European seas (Baltic Sea, Black Sea, Mediterranean Sea and North

286   Sea) and North-East Atlantic region these are not specific to ports. Furthermore, it should be

287   considered that NEEDS was the only approach that did not strictly followed the methodology

288   adopted for the present study (add urban and rural ECFs), which seemed to underestimate the

289   external costs due to in-port shipping emissions.

290   Considering the above limitations, the approach that seems to be the most reliable is the

291   combined use of urban ECFs from BeTa project (specific to ports) with the most updated rural

292   ECFs from CAFE. Thus, from here on results assessment will only refer to the approach BeTa

293   Urban + CAFE SC average + Song (2014). It should be noted that the ECF obtained from Song

294   (2014) was not mentioned because it concerns CO_2 and was similar for the several approaches

295   (it varied only between ports).

296   The damage costs of air pollution produced by ships were found to be in proportion to in-port

297   shipping emissions for each port (Table 4), i.e. they are more pronounced in Sines and Setúbal

298   (around 2.0E+02 million €), followed by Leixões (around 1.8E+02 million €), and Viana do

299   Castelo (around 6.3 million €). Regarding external costs by pollutant, the highest were

300   estimated for SO_2, NO_x and $PM_{2.5}$ with damages of: i) 76, 73 and 46 million € in Sines

301   accounting for 37, 36, and 22% of the total external costs; ii) 77, 70 and 42 million € in Setúbal

302   accounting for 39, 35, and 21% of the total External costs; iii) 69, 63 and 39 million € in Leixões

303   accounting for 39, 36, and 22% of the total external costs; and iv) 2.8, 2.1 and 1.2 million € in

304   Viana do Castelo accounting for 45, 32, and 19% of the total external costs. It should be noted

305   that although the amount of CO_2 emissions was the largest when compared with the other

306   pollutants, and their respective external costs were also significant, its environmental cost was

307   relatively low when compared with the costs of other pollutants (accounting for 3 to 4% of total

308   external costs in each port). These results are consistent with the pattern as reported by Song

309   (2014), that used external costs from various studies, as well as Berechman and Tseng (2012)

310   and Tzannatos Ernestos (2010), that used ECFs from BeTa and CO_2 ECF from Bickel et al.

311   (2006) and Maibach et al. (2007).

312   *4.2 Ports eco-efficiency assessment*

313   The evaluation of ports eco-efficiency was performed based on basic economic data and on

314   environmental and social indicators. Table 5 summarizes the eco-efficiency parameters for the

315   port's performance assessment. According to the results, Sines port was the one showing better

316   results in terms of handling efficiency (less emissions and external costs per cargo and TEUs).

317   Regarding ship calls Viana do Castelo showed the best results (less emissions and costs) which

318   seems to be related with the lower number of calls in this port comparing to others. For Ports

319   of Setúbal and Viana do Castelo it was estimated the highest emissions and costs per every 1

320   000 TEUs handled, since these ports are essentially used for other purposes, receiving

321   containers only sporadically (only 471 TEUs were handled in Viana do Castelo), raising the

322   costs.

323   To allow a concise and complete visual evaluation of the studied ports and to compare them

324   considering environmental, social and economic criteria, the indicators were feature scaled (all

325   compared to the maximum reported value) to bring all values into the range 0 to 1. Figure 2

326   provides the evaluation of eco-efficiency of the four Portuguese ports studied (Leixões, Setúbal,

327   Sines and Viana do Castelo). The area of the radar chart indicates the performance of the port

328   for the different eco-efficiency indicators (larger area corresponds to better performance).

329   Figure 2 shows that Sines port exhibits the best overall performance in terms of economic

330   indicators with the highest number of handled cargo, containers and annual income, only

331   surpassed by Leixões port in the number of calls. Moreover, Sines seems to develop their

332   commercial activities with less impacts from in-port emissions than the other ports, combining

333   the highest number of handled cargo, containers and annual income followed by the lowest

334   emissions and total external cost values. Leixões was the port that registered the second best

335   overall performance followed by Viana do Castelo port and finally Setúbal port. Although

336   Viana do Castelo port has been the port with the lowest economic indicators (due to its size), it

337   was not the less eco-efficient.

338   4.3 Uncertainties and Limitations

339   External costs estimation has several uncertainties and limitations that are widely discussed. In

340   this study the uncertainties are mainly related with the use of a top-down approach based on

341   external factors from major European reports where IPA was used. IPA is recognised as the

342   most reliable tool for environmental impact assessment, however it has per se some

343   uncertainties and limitations. These uncertainties and limitations arise primarily from: i) the

344   source and the reliability of the emission inventories used (details not easily available and

345   outdated); ii) the evaluated scenarios and availability of recent modelling data (according to on

346   BeTa project difficulties arose particularly when modelling ozone and shipping); and iii) data

347   availability on exposure, biophysical impacts and valuation of the impacts (can be limited and

348   difficult to obtain). In this sense, IPA requires a lot of detailed information, which is very

349   difficult to update in a single study that focuses on a specific issue. As a result, outdated

350   information can be transferred from study to study without proper correction or adjustment

351   (from bottom-up to bottom-up studies and bottom-up to top-down studies). To minimize these

352 uncertainties, in this study efforts were made to select the most proper ECFs: i) only ECFs from

353 European studies that considered external costs of shipping emissions were used; ii) ECFs were

354 adjusted according to population (BeTa urban ECFs for $PM_{2.5}$ and SO_2) and population density

355 (NEEDS ECFs for $PM_{2.5}$) of the cities where ports are located; iii) ECFs values were update for

356 2013 (the same year of the emissions inventory and ports related data) considering the

357 Consumer Price Index (CPI) of Portugal from OECD country statistical profiles; iv) for ports'

358 eco-efficiency assessment urban ECFs from BeTa and rural ECFs from CAFE (average results

359 for four sensitivity scenarios) were used, because this seemed to be the most reliable approach

360 to estimate external costs due to shipping emissions; and v) major port data was all obtained

361 from a report performed by Mobility and Transports Portuguese public Institute which made

362 data more homogeneous and comparable.

363 Furture work is needed to improve the outcomes of this study and minimize the range of

364 uncertainties. Improvement could be achieved by conducting an Impact Pathway Approach

365 (IPA) starting from emissions estimation using AIS data to describe ships activities, followed

366 by concentrations calculation based on refined information of pollutant dispersion, health

367 impact assessment with accurate population data and response functions, and valuation of the

368 economic costs using customized cost functions with as much as possible updated and reliable

369 data.

370

371 **5. Conclusions**

372 The most reliable approach to estimate external costs due to shipping emissions was the

373 combined use of the urban external cost factors from BeTa project (specific to ports) with the

374 most updated urban external cost factors from CAFE.

375   Regarding the total external costs, Sines and Setúbal were the ports with the highest estimated

376   ones (2.0E+02 million €), followed by Leixões (1.8E+02 million €), and Viana do Castelo (6.3

377   million €). Regarding external costs by pollutant, the highest were estimated for NO_x, SO_2, and

378   Sines was the port that exhibited the best overall eco-efficiency, followed by Leixões Port,

379   Viana do Castelo Port and Setúbal Port. Although Setúbal Port had better performance than

380   Viana do Castelo regarding economic data, when social and environmental aspects were

381   considered, results showed the opposite, thus demonstrating the importance of doing a more

382   comprehensive analysis using social and environmental indicators, which are not considered in

383   most studies.

384   Efforts were made to make ECFs as localized as possible, however there are uncertainties

385   regarding the use of the proposed methodology. These uncertainties are directly related with

386   the use of a top-down approach and the limitations of the cost factors of the European reports

387   (year of study, source of the emission inventories, evaluated scenarios and availability of recent

388   modelling data). Although it is known that a full bottom-up approach (Impact Pathway

389   Approach) gives a more reliable and accurate estimation of the external costs of emissions, their

390   application was not possible in this study. Despite the above referred, this study provides a

391   reliable estimation of the associated externalities of shipping emissions for Portugal.

392   In the future it is recommend to carry out an Impact Pathway Approach (IPA) starting from

393   emissions estimation using AIS data to describe ships activities, followed by concentrations

394   calculation based on refined information of pollutant dispersion, health impacts assessment

395   (population data and response functions) and valuation of the economic costs (cost functions

396   customized). Moreover, in the future, the findings of this study can be used to support the

397   implementation of port policies for abatement of shipping related in-port emissions. Findings

398   can also support a wider study that can incorporate other sources of pollution from ports (adding

399   land-based emission sources for example) to provide a more detailed evaluation of the eco-

400   efficiency of ports.

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Table 1 – In-port shipping emissions of NOx, SO2, CO2, VOCs and PM2.5 (adapted from Nunes et al. (2017).

Study Ports	In-port ship emissions (t y^{-1})				
	NO_x	SO_2	CO_2	VOCs	$PM_{2.5}$
Leixões	8.1E+03	3.3E+03	1.9E+05	1.0E+02	3.2E+02
Setúbal	9.8E+03	4.2E+03	2.6E+05	1.6E+02	4.3E+02
Sines	9.4E+03	5.0E+03	3.0E+05	1.8E+02	5.2E+02
Viana do Castelo	3.6E+02	1.4E+02	8.1E+03	4.1E+00	1.4E+01

Table 2 – Number of inhabitants, scale factors and external costs calculated for each city of this study (PORDATA, 2017).

City	Number of inhabitants	Scale factor	Urban external costs (€/tonne)	
			SO_2	$PM_{2.5}$
Matosinhos	175 478	1.75	10 500	57 750
Setúbal	121 185	1.21	7 260	39 930
Sines	14 238	1	6 000	33 000
Viana do Castelo	88 725	1	6 000	33 000

Table 3 – Updated external cost factors for 2013 based on consumer price index (CPI) of Portugal from OECD country statistical profiles used in the present study.

Studies	External cost factors (€/tonne)				
	NO_x	SO_2	VOCs	$PM_{2.5}$	CO_2
BeTa Urban (BTU)	5 494	14 070 [a]; 9 728 [b]; 8 040 [c, d]	2 010	77 385 [a]; 53 506 [b]; 44 220 [c, d]	n/a
BeTa rural (BTR)	5 494	4 020	2 010	7 772	n/a
CAFE rural (SC 1)	1 404	3 780	540	23 760	n/a
CAFE rural (SC 2)	2 052	5 832	756	36 720	n/a
CAFE rural (SC 3)	2 376	7 452	1 296	47 520	n/a
CAFE rural (SC 4)	3 456	10 800	1 728	69 120	n/a
NEEDS	2 114	5 346	1 132	212 042 [a]; 53 023 [b, d]; 19 841 [c]	n/a
Song (2014)	n/a	n/a	n/a	n/a	29

[a] Value for Leixões Port; [b] Value for Sétubal Port; [c] Value for Sines Port; [d] Value for Viana do Castelo Port; n/a – not applicable, because the ECFs available on this study were adapted to China and Shangai's reality

Table 4 – Total external costs associated to the in-port shipping emissions at Leixões, Setúbal, Sines and Viana do Castelo during 2013 (in million €).

	BTU[a] + BTR[b] (Portugal) + Song (2014) [c]	BTU + CAFE SC 1[d] + Song (2014)	BTU + CAFE SC 2[e] + Song (2014)	BTU + CAFE SC 3[f] + Song (2014)	BTU + CAFE SC 4[g] + Song (2014)	BTU + CAFE SC average [h]+ Song (2014)	NEEDS + Song (2014)
Leixões	1.8E+02	1.5E+02	1.7E+02	1.8E+02	2.1E+02	1.8E+02	1.1E+02
Setúbal	2.0E+02	1.7E+02	1.9E+02	2.0E+02	2.3E+02	2.0E+02	7.4E+01
Sines	2.0E+02	1.7E+02	1.9E+02	2.1E+02	2.5E+02	2.0E+02	6.6E+01
Viana do Castelo	6.6	5.3	6.0	6.5	7.6	6.3	2.5

[a] BeTa Urban; [b] BeTa rural; [c] For CO_2 costs estimation; [d] BeTa sensitivity scenario 1; [e] BeTa sensitivity scenario 2; [f] BeTa sensitivity scenario 3; [g] BeTa sensitivity scenario 4; [h] Average results from the four sensitivity scenarios
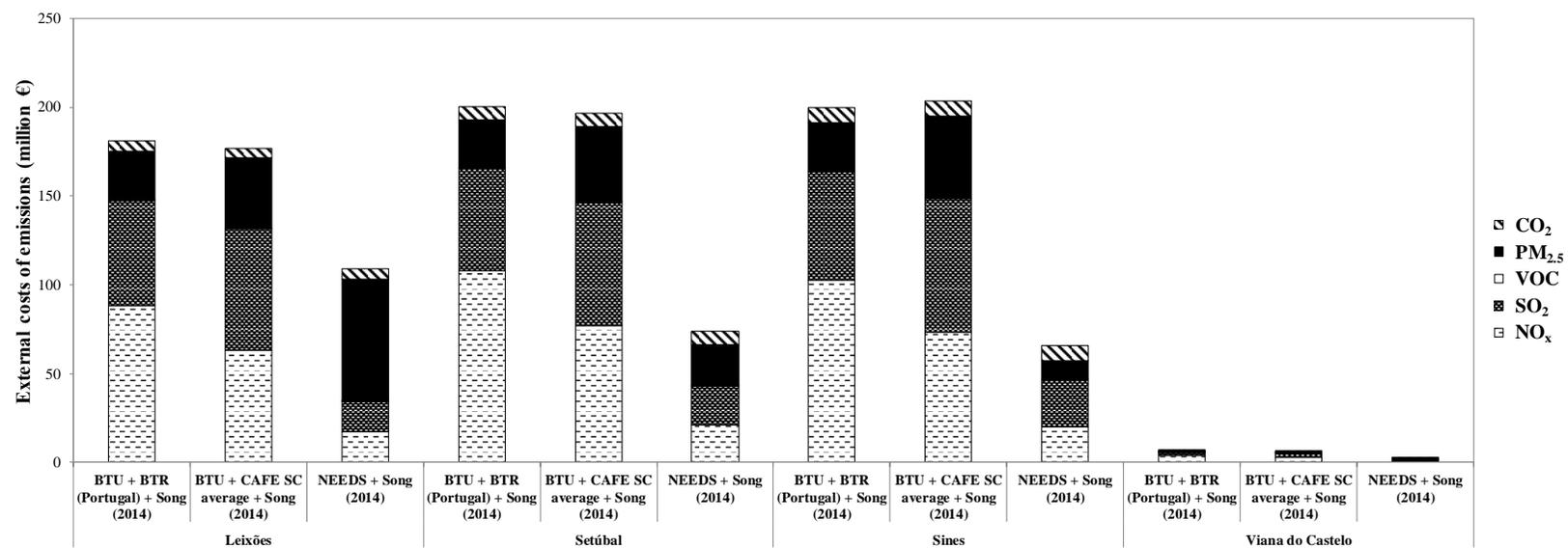
Figure 1: Estimated external costs for the different approaches and by pollutant type for ports of Leixões, Setúbal, Sines and Viana do Castelo.
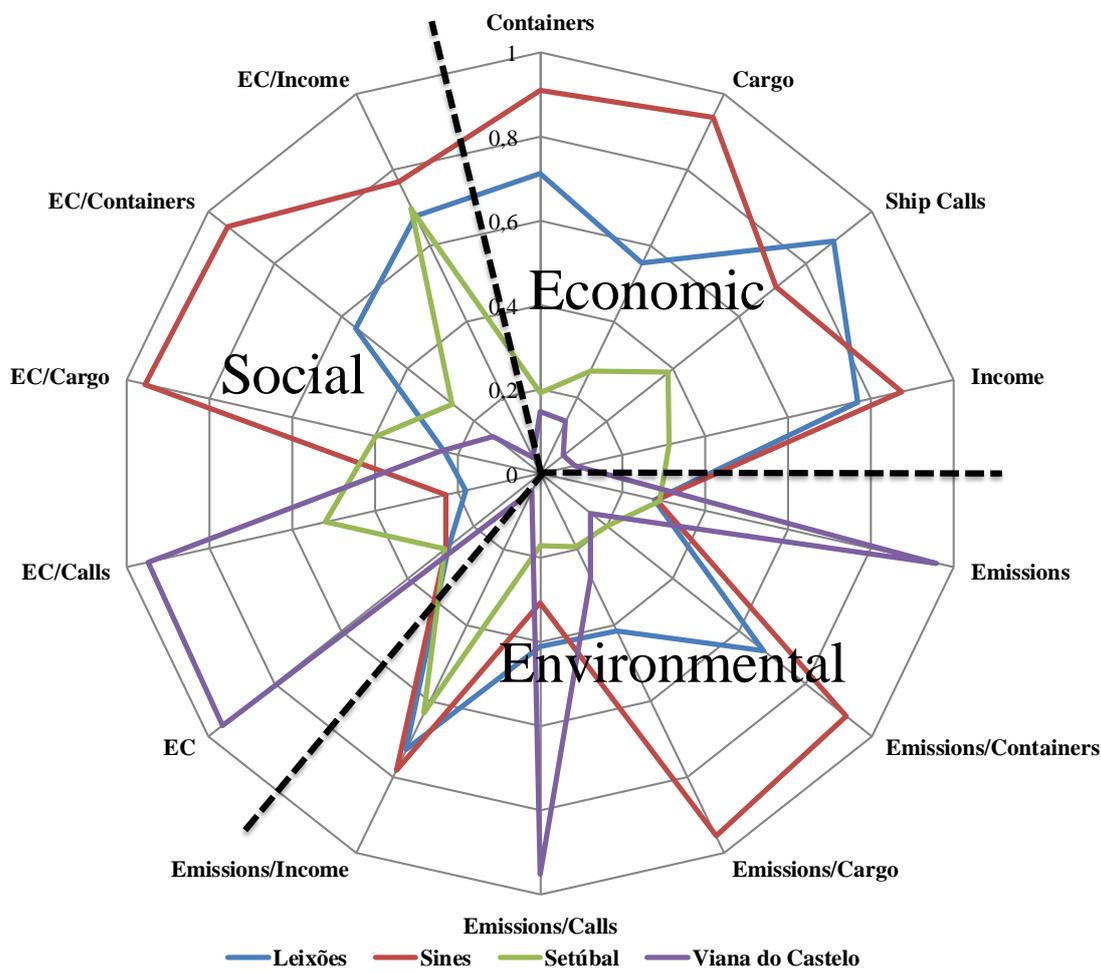
Figure 2: Evaluation of Leixões Port, Setúbal Port, Sines Port and Viana do Castelo Port based on economic, environmental and social criteria regarding in-port ship emissions

Table 5 – Ports eco-efficiency performance parameters

Port	Cargo (tonnes)	Number of Calls	Containers (TEUs)	Income (million €)	Emissions per cargo (ton/1000 ton)	Emissions per ship call (ton/call)	Emissions per tons of TEUS (ton/1000 TEU)	Emissions per income (ton/million €)	External cost per tons of cargo (€/ 1000 ton)	External cost per ship call (€/call)	External cost per tons of TEUS (€/ 1000 TEU)	External cost per income (€/million €)
Leixões	1.7E+07	2580	6.3E+05	10.1	12	79	3.3E+02	2.0E+04	1.0E+04	6.9E+04	2.8E+05	1.8E+07
Setúbal	7.0E+06	1253	7.1E+04	3.4	39	2.2E+02	3.9 E+03	8.1E+04	2.8E+04	1.6E+05	2.8E+06	5.8E+07
Sines	3.7E+07	2010	9.3E+05	12.4	9	1.5E+02	3.3E-01	2.5E+04	5.6E+03	1.0E+05	2.2E+02	1.6E+07
Viana do Castelo	5.0E+05	199	471	-1.5	17	43	1.8E+04	n/a	1.3E+04	3.2E+04	1.3E+07	n/a

n/a – not applicable, because Viana do Castelo Porto had a negative income in 2013