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How the inclusion of life cycle impacts affects transport cost-benefit analysis

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Transport cost-benefit analysis frameworks do not consider the environmental impacts deriving from the life cycle of the transport system's components. This leads to an inaccurate representation of the environmental impacts of transport projects, which can be instead more thoroughly represented by life cycle assessment methods. In the present study, we describe a transport cost-benefit analysis model combined with a life cycle assessment module developed based on life cycle ReCiPe 2016 methodology. The suggested approach makes it possible to include the life cycle impacts on human health, ecosystem and natural resource depletion in the project assessment. We discuss the methodological issues of combining cost-benefit analysis and life cycle assessment in transport appraisals. We illustrate the results from the application of the model to a transport case study related to the construction of a new fixed link across the Roskilde Fjord in Frederikssund (Denmark). The analysis shows that the environmental impacts deriving from the life cycle of the system components notably affect the key indicators of the model output, such as benefit-cost ratio and net present value. The results from the model are then tested through sensitivity analysis related to some of the assumptions made for the study. The study concludes that the inclusion of life cycle impacts in transport cost-benefit frameworks allows taking into account environmental costs and benefits otherwise not accounted for, thereby providing to the decision makers a more exhaustive information about the environmental impacts of the project.

Keywords: *cost-benefit analysis, life cycle assessment, environmental impacts, decision support.*

1. Introduction

The environmental impacts of transport originate from direct, indirect and supply chain processes relevant to the transport system (Chester et al., 2014). The direct processes relate to the primary goal of the transport system, i.e. the mobility of people and goods, and are associated

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with the energy consumption and emissions deriving from vehicles. On the other hand, the indirect and supply chain processes, and their environmental impacts, are related to the production, maintenance and end of life of the transport system components, i.e. vehicles, infrastructure and services, required to achieve the goal of mobility. The transport project evaluation frameworks rooted in Cost-Benefit Analysis (CBA) consider the impacts from the direct processes, primarily vehicle emissions, but do not include the impacts from indirect and supply chain processes.

Both direct and indirect environmental impacts can be assessed in Life Cycle Assessment (LCA). LCA is defined by the ISO 14040 (2006) as the assessment of the environmental impacts of a given product throughout its lifespan, where the word product refers to both tangible goods and services. LCA is used to compare alternative products so that the one with the least environmental impact can be prioritized or to identify the hotspots where appropriate modifications can be made to the system creating the product to reduce the environmental impacts. The assessment starts from the raw material extraction and processing and goes through the manufacturing, distribution, usage, maintenance, recycling and disposal. The LCA framework consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results. The goal and scope definition (ISO 14041, 1998) aims to delineate the study purpose, the functional unit and the boundaries of the system analysed. In the inventory analysis (ISO 14041, 1998), the actual life cycle modelling is implemented using LCA software and the processes instrumental to the production of the system output are quantified in terms of input and output (Wolf et al., 2012). The system input (resources taken from the ecosystem) and output (emissions released to the ecosystem) are expressed per functional unit of the system output. The life cycle impact assessment (ISO 14042, 2000) and the interpretation of the results (ISO 14043, 2000) conclude the procedure. The impact assessment consists in aggregating the different input and output flows in different categories of midpoint environmental impacts, such as acidification, human toxicity, and global warming. Afterwards, the midpoint impacts can be further assessed in terms of endpoint impacts, expressing the final estimated damage to human health, ecosystem, and resource scarcity. Finally, the results are interpreted; this may lead to the decision of redefining some of the previous steps, so starting an iterative process (Wolf et al., 2012).

Transport LCA studies have been implemented to investigate the life cycle impacts of different transport modes, policies and infrastructures. With respect to transport modes, the literature includes for instance LCA studies on rail, e.g. Yue et al. (2015) and Jones et al. (2017), public transport, e.g. Ercan and Tatari (2015), freight transport, e.g. Fries and Hellweg (2014), and comparison among modes, e.g. Chester and Horwath (2012) and Robertson (2017). LCA has been used also to investigate transit development-land use interaction, e.g. Nahlik and Chester (2014), and transport policy options, e.g. Lederer et al. (2016). Overall, these studies show that the indirect impacts quantified through LCA may dominate the potential damages to human health and environment (Chester and Horwath, 2012). The importance of indirect environmental impacts, quantified through LCA, is also proven with respect to transport infrastructure projects, in particular for road infrastructures, e.g. Miliutenko et al. (2014) and O'Born et al. (2016), bridges, e.g. Mara et al. (2013) and Du et al. (2014), and tunnels, e.g. in Schwartzentruber et al. (2015). Some of the studies, such as Miliutenko et al. (2014) and O'Born et al. (2016), include the impacts from the traffic in the LCA of the infrastructure. These studies found that the environmental impacts from the traffic outweigh those from the infrastructures in terms of both greenhouse gas emissions and energy consumption, and suggest that traffic calculation should be included in transport LCA studies (O'Born et al., 2016).

Stripple and Erlandsson (2004) and Potting et al. (2013) suggest that LCA should be seen as an effective tool to be used in combination with existing transport assessment frameworks. In fact, including information obtained from LCA might modify the results of transport project evaluations that focus only on direct environmental impacts (van Wee et al., 2005). Manzo and

Salling (2016) describe a model used to assess transport projects that combine CBA and LCA. By using as case study the construction of a road bridge across the Roskilde Fjord in Frederikssund (Denmark), the study investigates how the results from the CBA change when including a LCA module. The LCA module first quantifies the life cycle impacts of the system components (i.e. bridge, connecting roads and vehicles) related to five selected air pollutant agents. The effects on traffic of the planned infrastructure are simulated using the Danish National Transport Model (NTM) (Rich et al., 2010), while the life cycle inventory analysis is run by means of the software SimaPro 8 (2016). The LCA module then translates the LCA impacts into monetary values using standard unit costs for air pollutant agents from Danish CBA guidelines and, finally, it includes the monetized costs in the CBA model as part of the external costs of the project (i.e. accidents, noise and air pollution). The inclusion of the life cycle impacts in the CBA model gives rise to a noticeable variation in the socio-economic indicators, output of the model, and significantly modifies the relative weight of the different components of the overall project costs. The authors argue that the combined CBA-LCA approach provides decision makers with a more thorough insight into the environmental impacts of the project.

Building upon Manzo and Salling (2016), the present study first describes an improved CBA-LCA transport model by considering all LCA impact categories available in the life cycle ReCiPe 2016 methodology (Huijbregts et al. 2016). This approach allows including the LCA endpoint impacts on humans, ecosystem and natural resources in the CBA, rather than air pollution only. For the monetization of the impacts, the endpoint unit values are retrieved from Weidema (2009). The improved model is then applied to the same case study as in Manzo and Salling (2016). The results from a standard CBA model are compared with those from the CBA model combined with an LCA module. The robustness of the results is further tested through sensitivity analysis. Along with the comparative exercise, the paper discusses the methodological issues related to the integration of CBA and LCA.

The paper is structured as follows. Section 2 describes the case study, the input and assumptions used to run the CBA, and the LCA system referring to the case study. Section 3 presents and discusses some of the most important methodological issues of combining CBA and LCA. The results from the experiment, including those from the sensitivity analysis, are summarised in Section 4. Finally, Section 5 includes conclusions, limits and perspectives regarding the present study.

2. The case study: the Roskilde Fjord bridge project

The case study refers to the Roskilde Fjord bridge project, shown in red in Figure 1. The project is located in the municipality of Frederikssund, in Denmark, and it consists in an elevated road bridge with 22 piers and the related road access infrastructure. The current volume of traffic to and from Frederikssund creates congestion in the existing Roskilde Fjord crossing, the Kronprins Frederik's bridge, and it is expected to increase over time. The new bridge, planned to open to the traffic in January 2020, will have a capacity of 2100 vehicles per hour in both directions and will absorb the majority of the traffic, while the Kronprins Frederik's bridge will be downgraded to a local road and will remain free of charge. The project will be partially financed through user charges.

Figure 1. The Roskilde Fjord bridge project

2.1 CBA inputs and assumptions

The CBA model used for the present study is the UNITE-DSS model (Salling and Leleur, 2015). The UNITE-DSS model is developed based on the Danish CBA guidelines (Danish Ministry of Transport, 2015). The model groups the monetized costs and benefits from the project in three categories: user benefits (free and congested travel time and operating costs per km), government impacts (construction and maintenance costs, revenue from tolls, tax distortion, and scrap value) and externalities (accidents, noise and air pollution). Based on this input, the model produces standard CBA socio-economic indicators, e.g. Net Present Value (NPV) and Benefit Cost Ratio (BCR), as output.

For the present study, the CBA was run based on the following inputs and assumptions. The effects of the planned infrastructure on the traffic and derived measures for the opening year are taken from Manzo and Salling (2016) who use the results from the NTM simulations. Table 1 summarizes the variation in Vehicle kilometres (Vkm) travelled and Travel Time Savings (TTS) following the opening of the infrastructure for the entire Danish road network by vehicle class: cars, vans (light commercial vehicles, 1.5 metric tons) and trucks (heavy commercial vehicles, 16 metric tons). Given the characteristics and location of the new infrastructure, the effects on traffic are in fact assumed to go beyond the municipality of Frederikssund.

As can be seen, (i) cars are expected to travel more (positive Vkm) and save time (positive TTS), (ii) vans are expected to travel less (negative Vkm) and save time (positive TTS), and (iii) trucks are expected to travel more (positive Vkm) and lose time (negative TTS). The differences among modes may be partially explained by the assumption that, with respect to cars and trucks, building the bridge might result in inducing more traffic and an increase in the overall Vkm travelled, with higher travel time for trucks due to longer journeys and speed restrictions. Instead, with respect to vans, the bridge might be an effective shortcut for (local) business freight vans, which would travel shorter distances then saving time, while the number of trips remains unchanged due to fixed schedules. The values in Table 1 are used as input for the UNITE-DSS model to estimate the user benefits deriving from the project.

Table 1. Vkm and TTS from traffic simulation

	Cars	Vans	Trucks
Vkm	+9,472	-50,773	+28,320
TTS	+406	+684	-264

Source: Manzo and Salling (2016)

With respect to the infrastructure, the estimated cost is 2 billion Danish Kroner (DKK) and the yearly maintenance cost is assumed to be 2% of the construction cost per year (Danish Road Directorate, 2010). The opening year is set to 2020, with a 5-year construction period (2015-2020). As regards to the traffic, the NTM simulation is run for the opening year after which the overall network is assumed to undergo an annual increase in demand of 2% for the first 20 years and then to remain constant. The revenue from tolls is estimated to be 26 million DKK for the opening year, based on the number and types of vehicles crossing the bridge, as modelled by the NTM. To monetize the transport related non-market goods, such as value of time, standard values for CBA in Denmark were applied (Transport Economic Unit Prices, 2016).

Following the Danish CBA guidelines, the net taxation factor is set at 32.5% and the tax distortion factor at 20%. With respect to the net taxation factor, calculated as the ratio between the gross domestic product and the gross factor income, all costs (except taxes) must be multiplied by this factor to ensure that they are expressed in market prices. On the other hand, the tax distortion factor is applied to the share of the project costs covered by public funding, and it represents the distortion of economic activities, i.e. extra costs, deriving from an increase in the tax level required to finance the project. The evaluation period for the infrastructure is 50 years. The discount rate is set at 4% for the first 35 years and 3% for the remaining 15 years (Danish Ministry of Transport, 2015). Finally, the externalities are estimated based on the variation in the Vkm travelled and unit prices per km from Transport Economic Unit Prices (2016). The externalities included in the model refer to accidents, noise and air pollution (due to emissions from the vehicles).

2.2 The LCA module

To include the life cycle impacts of the project components in the UNITE-DSS model, first an LCA is run and the endpoint impacts are quantified. Afterwards, the LCA module translates the endpoint impacts into monetary values using unit costs retrieved from the literature. Finally, the LCA module includes the monetized life cycle endpoint impacts in the UNITE-DSS model as part of the externalities of the project. The LCA is run using SimaPro 8 (2016). The four phases of the LCA are specified as follows.

2.2.1 Goal and scope definition

For the present study, the LCA module aims to assess the environmental impacts associated with the life cycle of the new infrastructure. The primary function of the infrastructure is to provide transport access between the west bank and the east bank of Roskilde Fjord. The time period considered for the LCA study needs to be consistent with the one of the CBA assessment. Thus, the functional unit is defined as "Road bridge infrastructure that allows transport access between west bank and the east bank of Roskilde Fjord south of Frederikssund, with the capability of 2100 vehicles/hour for each direction, over a period of 50 years". However, in addition to its primary function, the new infrastructure is expected to influence the transport behaviour on a bigger part of the Danish road network. Thus, a system expansion is performed to deal with the multi-functionality of the infrastructure. As a result, the system boundaries of the study include the life cycle of the new infrastructure (i.e. the bridge and connecting roads) and the change of traffic's behaviour on the Danish road network caused by the new infrastructure. The system boundaries include:

- Construction of the new infrastructure including, among others, the production of construction-ready materials (e.g. gravel, bitumen, reinforcing steel and concrete), land occupation, excavation, emission and waste treatment during the construction process and energy consumption.
- Operation of the new infrastructure including, among others, transport for inspection, the production of materials such as paint and gravel, and electricity. The impact assessment only refers to road and motorway. The information about the operation of the bridge was not complete and therefore is not included into the analysis.
- End-of-Life (EoL) of the new infrastructure. The EoL happens beyond the CBA assessment period of 50 years but it is included in the analysis and credited to the last year of the assessment.
- Traffic variation on the Danish road network due to the construction of the infrastructure. It encompasses operation (which includes emissions) and maintenance for cars, vans and trucks and road maintenance due to Vkm travelled.

2.2.2. Inventory analysis

The inventory database Ecoinvent (Ecoinvent 3.1, 2014) is used to perform the LCA using the software SimaPro 8 (2016). With respect to the infrastructure, the input inventory is run based on standards from the sector combined with the available information from the project description report (Danish Road Directorate, 2010), summarized in Table 2. The life cycle inventory of the bridge includes that of the 22 piers, having a section size 1.5mt*2.1mt.

Table 2. Infrastructure components length and width

	Length*	Width**
Bridge	1.36	26
Motorway	10	26
Road	14.2	20

* Kilometres ** Metres

The environmental impacts from vehicles are calculated as a function of the travelled Vkm and Ton Kilometre (Tkm) for car passengers and commercial vehicles, respectively. Currently, around 70% of the private car fleet in Denmark has petrol engines, around 30% diesel engines and less than 1% are Electric Vehicles (EV) (Statistics Denmark, 2017). However, over time the market share for EV may be expected to increase, whilst that of diesel vehicles is expected to drastically decrease. For the present study, we use a base case that assumes the market shares to remain constant over time and a scenario case that assumes a gradual increase of the EV market share (Section 4.1). With respect to commercial vehicles, we use average loads from EcoInvent of 0.3 and 5.8 tons for vans and trucks respectively, although these values can be considered conservative. Finally, the road maintenance component allows including into the analysis the increases and decreases of road maintenance due to variation in Vkm throughout the overall road network.

As stated in the definition of the functional unit, the system is assessed over a period of 50 years. Therefore, the life span of the roads and that of the bridge are both set at 50 years. However, with respect to the bridge, a longer lifespan is more realistic. Hence, a scenario case is implemented in which the bridge is assumed to have a lifespan of 100 years and the results are compared with those from the base case (Section 4.1). Full results from the system inventory analysis are available upon request.

2.2.3 Life cycle impact assessment and interpretation of the results

The different output flows resulting from the life cycle inventory can be aggregated at midpoint level or endpoint level as described in the introduction. In the current literature on transport LCA there is no uniform approach with respect to which methods to use. Some studies, e.g. O'Born et al. (2016) focus on total Green House Gases (GHG) emissions and energy demand. Others, e.g. Du et al. (2014), use midpoint impacts.

For the present study, we applied the ReCiPe 2016 endpoints, which allows expressing the final estimated damage to human health, ecosystem and resource scarcity in terms of Disability-Adjusted Life Year (DALY), loss of species during a year, hereinafter "Species.yr", and US Dollars (USD), respectively. As compared to midpoints, LCA endpoints are considered to have higher inherent uncertainty, but also to be more valuable in cases where aggregation is needed and to lead to more understandable and easy to communicate results. For more details, we refer to Bare et al. (2000).

Figure 2 graphically shows the endpoint impacts of the studied system (full results are summarised in Annex 1 and Annex 2). As can be seen, the highest impact for the three endpoints comes from the traffic. The overall variation of Vkm travelled has a positive impact on human health, ecosystem and resource scarcity, expressed as negative values in the LCA endpoints. The (negative) impacts deriving from the infrastructure are lower as compared to those from the vehicles, and they are mainly related to the construction phase. Those from the EoL have a positive impact due to the recycling of most of the material used. Overall, these results are consistent with what was already found in the LCA transport literature, e.g. Miliutenko et al. (2014) and O'Born et al. (2016), who calculate that the environmental impacts from the usage of vehicles, although restricted to GHG and energy demand, represent a major source of environmental impacts.

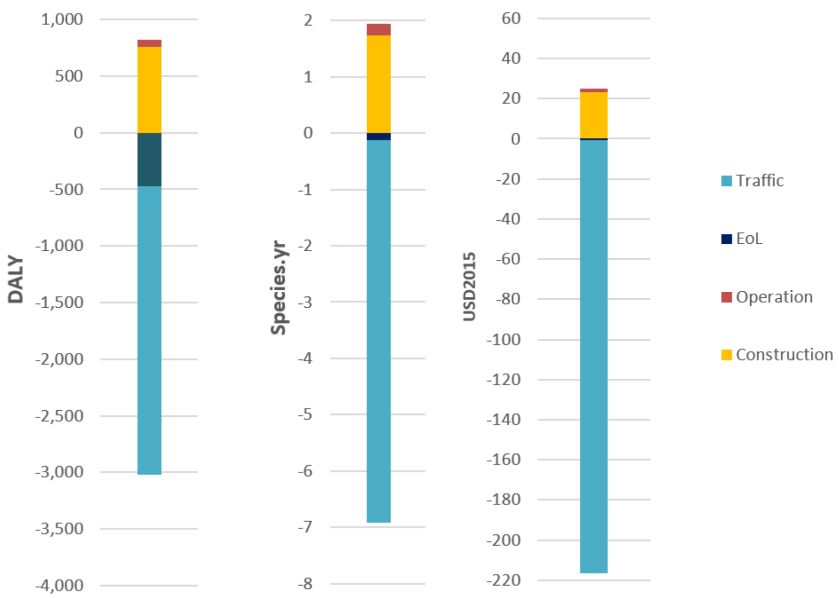

Figure 2. LCA impacts on human health (DALY), environment (Species.yr) and resource scarcity (million USD2015) by system component

3. Methodological issues of combining CBA and LCA

To proceed with the integration of the results from the LCA module into a CBA framework, three main methodological issues need to be considered: the monetization of the LCA impacts, the discounting, and the spatial and temporal resolution of the LCA as compared to that of the CBA.

3.1 Monetization

Monetisation is normally used in CBA to compare non-market social and environmental impacts with costs and benefits already expressed in monetary terms. While accepted in CBA, monetization is not applied extensively in LCA, primarily for two reasons (Pizzol et al., 2015). The first is related to the ethical objections about giving a (monetary) value to non-tradeable goods and values, the second is the concern about the arbitrariness and subjectivity when quantifying such values. Nevertheless, monetization has already been used in LCA studies, such as in Du et al. (2014).

The integrated CBA-LCA approach applied for the present study requires the monetization of the DALY and Species.yr calculated by the LCA (the resource scarcity being already expressed in monetary terms). Pizzol et al. (2015) reviewed five different approaches used in LCA studies to monetize the life-cycle impacts, including: observed preferences, revealed preferences, stated preferences, abatement cost and budget constraint. The first three methods are survey-based methods and they are used to determine the willingness to pay for a good or service in an existing market, a surrogate market or a hypothetical market, respectively. The abatement cost approach instead is used to estimate the cost of the replacement for a change in the availability of a non-market good. Overall, the authors find that these methods have solid scientific foundations and that they are suitable for LCA studies. However, these methods tend to be case, space and time specific, so limiting the possibility of generalizing the results.

With respect instead to the last of the five methods, Pizzol et al. (2015) define the budget constraint approach as a monetary evaluation method where the value of an additional Quality Adjusted Life Year (QALY), i.e. a life year lived at full well–being, is quantified on the basis of the potential annual economic income per capita. The budget constraint approach has two main advantages as compared to the other methods. The first is that the budget constraint unit price is based on registered data and has lower variation as compared to that derived through the survey based methods (Pizzol et al., 2015). In fact, the unit price from the survey based methods is more dependent on individual's evaluation and, therefore, on geographical location, population and context. The second is that whilst other methods often require the combination of separate monetization exercises, the budget constraint approach guarantees internal consistency and transparency of the assumptions made (Weidema, 2009).

For these reasons, the present study applies LCA endpoint unit values from Weidema (2009), which uses a budget constraint approach. Weidema (2009) uses an (estimated) available annual budget per capita to define the maximum monetary value that an average person can afford to pay for a QALY, as well as to keep a hectare/year in its unaffected state, or Biodiversity Adjusted Hectare Year (BAHY). The study suggests a central value of 74,000 Euro2003 for a unit of QALY and 1,400 Euro2003 for a unit of BAHY, where 1 QALY = -1 DALY and 1 BAHY = -1.5E-04 Species.yr[5]. Using these monetary unit values, the LCA endpoints for the present study are first monetized and then translated in DKK2015, as summarized in Table 3. The values are reported before to be credited to specific years and discounted, as discussed in the Section 3.2.

[5] QALY and BAHY measure both a positive state, thus having a positive sign, whilst DALY and Species.yr measure damages, therefore having a negative sign.

Table 3. LCA endpoints (absolute) values

	Infrastructure*			Traffic**				
	Construction	Operation	EoL	Car Diesel	Car Petrol	EV	Trucks	Vans
DALY	511	45	318	0.22	0.24	0.12	0.90	0.56
Species.year	149	19	11	0.09	0.08	0.05	0.34	0.19
Resource	175	10	5	0.20	0.21	0.03	0.77	0.39
Tot	835	74	334	0.50	0.52	0.20	2.02	1.14

* Functional unit 50 years, Million DKK2015 ** DKK2015 per Vkm

3.2 Discounting

In CBA, the future costs and benefits are discounted to a present value to make them comparable to current costs and benefits. In economic studies, the rationale of discounting is primarily based on three reasons: time preference, the variation over time of the capital productivity, and the uncertainty related to the future (e.g. Hellweg et al., 2003). On the contrary, in standard LCA there is no explicit differentiation between impacts occurring in different times (Yuan et al., 2015) as the weight of the environmental impacts is considered constant over time. Nevertheless, some exceptions exist. For instance, when temporal cuts are included in an LCA, an implicit discount rate is applied, equal to zero for the time horizon of the assessment and to infinity afterwards. More in general, though explicit discounting has rarely been applied in LCA, the idea of temporal differentiation of the LCA impacts has been explored and applied in some studies, as reviewed in Yuan et al. (2015).

In the present study, to be consistent with the CBA methodology, the discount rates set for the CBA, as specified at the end of Section 2.1, are also applied to the monetized impacts from the LCA module. To do this, the LCA impacts from the case study need to be assigned to a specific year. The LCA impacts deriving from the construction of the infrastructure are evenly divided and credited to the five construction years, while those deriving from the EoL are assigned to the last year of evaluation. With respect to the operation of the infrastructure and the traffic, the LCA impacts are credited and discounted yearly. As previously said, the LCA impacts from the operation/maintenance of the bridge itself could not be performed, and only their monetary cost are included into the analysis as cost component of the CBA.

3.3 Spatial and temporal resolution

With regard to the definition of the geographical boundaries, some of the impacts considered by the LCA do not affect the geographical location where the project is planned to be implemented. For instance, the extraction of raw materials required to build the bridge can hardly generate any impact directly affecting the geographical area where the project is located. Nevertheless, LCA places equal weight on all the impacts regardless the location. This approach, however, may not reflect transport policy goals (Chester et al., 2014) because the geographical perspective of the LCA definition of sustainability may not coincide with that of standard transport project assessments that have a local, sometimes national, boundary.

The issue related to the site-independency of LCA is acknowledged and discussed in the literature; site-dependent or even site-specific approaches are suggested, e.g. Henryson et al. (2018) and Juergen et al. (2016). For the present study, as already described in Section 2.2, with respect to the infrastructure, we include the LCA impacts irrespective of their geographical location. This approach is chosen for two main reasons. The first is that site-dependent or site-specific LCA inventories were not available. The second is to implement the analysis in a more comprehensive sustainability vision. With respect to the vehicles instead, transport CBA usually only consider emissions from vehicles operation, which directly affect the area where the project is located, ignoring impacts located elsewhere, e.g. from vehicles manufacturing. For the present study, we included LCA impacts deriving from vehicles' operation as in, e.g., Miliutenko et al. (2014) and O'Born et al. (2016). However, we also included the impact deriving from the maintenance of the vehicles and that of the road network, due to the variation in the Vkm travelled.

As regards to the definition of the temporal boundaries instead, the life span of transport infrastructures is usually longer than that of the standard assessment period, which typically does not pass 50 years. As the two need to be harmonized, for the present study we applied to the LCA a temporal cut approach described in Section 3.2. Nevertheless, the harmonization of temporal boundaries is an issue as problematic as that of the definition of the spatial boundaries.

4. Results and discussion

Based on the information and assumptions presented in Section 2 and Section 3, the UNITE-DSS model is run three times: first without the LCA module ("UNITE-DSS"); second with the LCA module including only impacts from the LCA of the infrastructure ("Infrastructure"); and third with the LCA module including impacts referring to both the infrastructure and the traffic ("Infrastructure&Traffic"). Table 4 shows the externalities of the project and the main evaluation criteria from the model output, namely BCR, NPV and Internal Rate of Return (IRR).

As can be seen, by including the infrastructure LCA impacts the external costs for the case study increase in absolute value from -1,192 to -1,528 million DKK (-336 million DKK). Instead, when considering both the infrastructure and the vehicles' life cycle impacts, the external costs decrease from -1,192 to -1,174 (+18 million DKK); this effect is primarily due to the variation in Vkm travelled, as explained in more detail in the following paragraphs. With regard to the BCR, IRR and NPV, their variation due to the inclusion of the LCA impacts is as follows. In the two runs with the LCA module, the BCR changes from 1.63 to 1.59 and 1.68, respectively -2.25% and +3.06% as compared to the model run without the LCA module. The IRR changes from 3.71% to 3.66% and 3.96%, respectively -1.31% and +6.85%, while the NPV changes from 2,569 to 2,419 and 2,772 million DKK, respectively -5.83% and +7.92%.

Table 4. UNITE-DSS-LCA results

	UNITE-DSS	Infrastructure	Infrastructure&Traffic
Externalities*	-1,192	-1,528	-1,174
BCR	1.63	1.59	1.68
IRR	3.71%	3.66%	3.96%
NPV*	2,569	2,419	2,772

*million DKK2015

Overall, including the LCA impacts from the infrastructure reduces the CBA performances of the project, while including the full LCA improves them. The changes in the evaluation criteria following the inclusion of the LCA impacts offer useful information by providing more comprehensive overview about the environmental costs of the project. In fact, the LCA module allows internalizing externalities otherwise overlooked in the standard CBA appraisal. Such information would be crucial whenever a choice between alternative projects in a sustainability-oriented approach has to be made. Similarly, for projects close to the acceptance/rejection threshold, including impacts from the LCA could have a relevant effect in terms of the final decision. Furthermore, it seems worth to notice that the spread around the UNITE-DSS results could have been higher with different assumptions, as some of the values used to run the model are conservative. For instance, the LCA impact from the infrastructure does not include the operation and maintenance of the bridge itself, while the average loads for the commercial vehicles used to run the model are probably lower than in reality, therefore reducing the impact from the traffic component of the model.

Table 5 shows the project externalities by components. Without the LCA module ("UNITE-DSS"), the number of accidents account for around 60% of the total external costs, while the weight of the environmental impact from emissions ("Air pollution–vehicles") for around 40%. Furthermore, the changes in traffic have a small but positive effect on the noise component that remains constant over the three model runs. When including the infrastructure LCA ("Infrastructure"), the LCA component of the planned infrastructure (-336 million DKK) accounts for around 22% of the total external costs. The weight of accidents and air pollution decreases to around 50% and 28%, respectively.

Finally, when including the life cycle impacts from the vehicles ("Infrastructure&Traffic"), which comprise air pollution as well, the environmental impact generated by the vehicles decreases from -439 million DKK to -85 million DKK, shown in Table 5 divided between vehicles operation and maintenance (-46 million DKK), and maintenance of the roads (-39 million DKK). The new infrastructure leads to a distinctive reduction in the vans Vkm and to a smaller increase in that of cars and trucks (Table 1). When considering the LCA impacts from vehicles, the decrease in vans Vkm compensates the negative impacts due to the increase in Vkm for cars and trucks (which, on the other hand, are dominant when considering only the air pollution from the use of the vehicles). These results related to the traffic highlight that including the LCA approach into a standard transport CBA does not always result in adding extra costs to the evaluation process but can instead reveal unaccounted benefits.

Table 5. Project externalities by components (million DKK2015)

	UNITE-DSS	Infrastructure	Infrastructure&Traffic
Accidents	-757	-757	-757
Noise	4.5	4.5	4.5
Air pollution-vehicles	-439	-439	
LCA-Infrastructures		-336	-336
LCA-vehicles*			-46
LCA-vehicles**			-39

*Vehicles operation and maintenance **Road maintenance

4.1 Sensitivity analysis

In transport CBA studies, sensitivity tests are usually run on key input such as traffic forecasts and investment costs. However, these are variables already known to have a major impact on the results from transport project assessments (Asplund and Eliasson, 2016). Instead, for the present study we investigated four scenarios all referring to the assumptions or input related to the LCA module component of the framework.

The first test refers to the life span of the bridge. The life cycle of the bridge is set to 50 years to make it consistent with the temporal length of the CBA. However, the lifespan of the bridge can be more realistically set at 100 years. Hence, a sensitivity test that considers a lifespan for the bridge of 100 years is implemented (Scenario 1) within the assessment period of 50 years, i.e. by doubling the impact from the bridge. With respect to the market shares of the vehicles, the base case relies on the assumption of constant market shares among petrol, diesel and electric vehicles. The Scenario 2 instead assumes that the market shares have a (linear) annual change, so that for the last year of appraisal, i.e. 2070, they are 30% for petrol and 70% for EV.

The sensitivity of the model output is also tested with respect to the unit values we use to monetize the LCA endpoints DALY, Species.yr and resource scarcity. The monetized values of the LCA endpoints have the crucial role of translating the environmental impacts from the LCA module into monetary terms. However, the monetization process implies a degree of subjectivity. Two scenarios are tested, where the unit values used in the model for DALY, Species.yr and resource scarcity are modified by -/+20%, in Scenario 3 and Scenario 4 respectively. Table 6 summarizes the results from the four scenarios as compared to the results from the "Infrastructure&Traffic" shown in Table 4, with respect to externalities, BCR, IRR, and NPV.

Table 6. Sensitivity analysis

	Infrastructure&Traffic	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Externalities*	-1,174	-1,645	-1,153	-1,090	-1,259
BCR	1.68	1.56	1.68	1.69	1.67
IRR	3.96%	3.54%	3.96%	3.99%	3.94%
NPV*	2,772	2,302	2,794	2,819	2,725

*million DKK2015

In relation to Scenario 1, externalities change from -1,174 to -1,645 million DKK (+40.06%), whilst the other indicators show a lower sensitivity, with a variation of around -6.86% for the BCR, and -10.81% for the IRR and -16.97% for the NPV. With regard to Scenario 2, externalities only change of -1.86%, while BCR, IRR and NPV vary between +0.32% and +0.79% (some variations are not shown in the Table 6 due to limited decimals). A higher sensitivity to the variation in the vehicles engine market shares could have been expected, given that the life cycle impacts from vehicles engine differ (Table 3). However, the market share of the EVs becomes dominant only over time (70% in year 2070), when the monetary value of their environmental impact is reduced due to the discounting. With respect to the variation in unit prices, in Scenario 3 and Scenario 4 the externalities vary between -/+7.19% while BCR, IRR and NPV vary of +/-0.69%, +/-0.73% and +/-1.70% respectively.

Overall, the results from the sensitivity tests show that the output of the CBA-LCA model is stable, in the measure that the socio economic indicators stay favourable to the project in all scenarios. However, the definition of the system temporal boundaries (Scenario 1) has a noticeable impact on BCR, IRR and NPV. This should be carefully considered, given that the definition of the system temporal boundaries have some level of subjectivity. The sensitivity of the model output to the vehicles engine market shares (Scenario 2) is instead less relevant, but, as previously discussed, this is mainly due to the discounting factor. Finally, the model shows relatively low sensitivity to unit prices, within the range of values tested.

5. Conclusions and perspectives

The aim of the present study was twofold. Firstly, to build an improved CBA-LCA model using the LCA ReCiPe 2016 methodology. Secondly, to use the model to assess the effects of combining standard CBA and LCA in a transport project appraisal, with reference to the Roskilde Fjord bridge project as case study. The advantage of the CBA-LCA approach is that it enables the inclusion of the costs of the environmental impacts related to the life cycle of the transport system components into standard CBA. As compared to the model used in Manzo and Salling (2016), which assesses only the impacts from five pollutant agents, the ReCiPe 2016 methodology allows including the LCA endpoint impacts on humans, ecosystem and natural resources in the project assessment. This approach produces a more thorough representation of the environmental impacts from the project, given that the LCA endpoints capture more environmental impacts than the air pollutant agents only.

The results from the LCA of the case study show that the environmental impacts from the changes in traffic, modelled by the Danish NTM, are higher (in absolute values) than those from the infrastructure. This result is consistent with the findings from the literature, such as in Miliutenko et al. (2014) and O'Born et al. (2016). When included in the CBA, the LCA impacts from the infrastructure result, as expected, in an increase of the external costs of the project, whilst the LCA impacts from the traffic lead to a decrease of such costs. This is consistent with what found in Manzo and Salling (2016), although a direct comparison of the results is not possible given that the unit values used to monetize the LCA impacts come from different sources.

Sensitivity tests show that the CBA-LCA model output remains in favour of the project in all the four scenarios tested. However, the choice of the system temporal boundaries have a noticeable impact on the indicators output of the CBA. Therefore, the subjectivity inherent their choice has to be acknowledged and investigated, through sensitivity analysis as well as uncertainty analysis.

The results from the present study are project specific and therefore cannot be generalized. Nevertheless, they suggest that by using a CBA-LCA integrated model it is possible to include part of the costs and benefits otherwise neglected by standard CBA in the assessment of a transport project. This capacity of the CBA-LCA integrated approach to address a wider spectrum of negative as well as positive environmental impacts can provide a better-informed support toward sustainable-oriented decision making than stand-alone CBA. On the other hand, an integrated CBA-LCA model would necessarily be based on high number of assumptions, and the results from the sensitivity tests implemented for the present study show that this issue should be considered carefully.

Although numerically straightforward, combining CBA and LCA presents some methodological issues that are primarily related to the monetization of the impacts, the discounting and the definition of the geographical and temporal system boundaries. Monetization of the non-marketable impacts and discounting are issues already known in standard CBA and, to a less extent, LCA. Different approaches can be found in the literature to deal with these issues, as discussed in the present paper. However, the definition of the geographical and temporal system boundaries appears to be a difficult issue to solve.

The present study has some main limitations acknowledged by the authors. Firstly, some assumptions were needed regarding the technical characteristics of the bridge. However, as pointed out also in O'Born et al. (2014), these assumptions might limit the validity of the results with respect to the specific project but do not affect the overall conclusions of the study. Secondly, the information about the LCA impacts deriving from the operation/maintenance of the bridge was missing; hence, it was not included in the system boundaries. Thirdly, several of the model variables have inherent uncertainty, most importantly the estimated LCA endpoints and the monetary unit values used to monetize the LCA endpoint impacts. However, the analysis of this uncertainty, and its effect on the CBA-LCA model output, has not been conducted. Therefore, the results from the present study refer only to the point estimates of the variable mean values.

Being aware of the acknowledged and overlooked limitations, the present paper describes and tests a methodology that effectively includes the indirect environmental impacts represented by the life cycle impacts of the project system components in a transport CBA. This approach may prove useful in providing a better and more informed decision-support for the assessment of the environmental sustainability of transport projects.

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Appendix A: Infrastructure impact assessment

		Construction			Operation		EoL		
		Bridge	Motorway	Road	Motorway	Road	Bridge	Motorway	Road
Global warming, Human health	DALY	1.53E+02	3.57E+01	4.55E+01	1.88E+01	1.48E+01	-2.33E+01	1.18E+00	1.51E+00
Global warming, Terrestrial ecosystem	species.yr	4.63E-01	1.08E-01	1.37E-01	5.67E-02	4.45E-02	-7.04E-02	3.57E-03	4.55E-03
Global warming, Aquatic ecosystems	species.yr	1.26E-05	2.94E-06	3.75E-06	1.55E-06	1.22E-06	-1.92E-06	9.75E-08	1.24E-07
Stratospheric ozone depletion	DALY	2.06E-02	1.49E-02	1.89E-02	8.32E-03	6.53E-03	-5.49E-03	3.98E-04	5.07E-04
Ionizing radiation	DALY	5.29E-02	2.80E-02	3.57E-02	3.80E-02	2.98E-02	-6.51E-02	-6.51E-03	-8.29E-03
Ozone formation	DALY	3.72E-01	2.54E-01	3.24E-01	3.12E-02	2.45E-02	-1.71E-02	1.84E-02	2.34E-02
Fine particulate matter	DALY	1.79E+02	3.56E+01	4.54E+01	1.14E+01	8.93E+00	-2.55E+01	5.32E+00	6.78E+00
Ozone formation, ecosystems	species.yr	5.57E-02	3.92E-02	4.99E-02	4.67E-03	3.66E-03	-2.57E-03	2.64E-03	3.36E-03
Terrestrial acidification	species.yr	1.16E-01	3.95E-02	5.03E-02	1.25E-02	9.84E-03	-2.03E-02	1.17E-03	1.49E-03
Freshwater eutrophication	species.yr	4.95E-02	4.11E-03	5.24E-03	4.70E-03	3.69E-03	-1.28E-02	-4.25E-04	-5.41E-04
Terrestrial ecotoxicity	species.yr	7.38E-03	1.36E-03	1.73E-03	5.99E-04	4.70E-04	-6.38E-03	3.89E-05	4.95E-05
Freshwater ecotoxicity	species.yr	5.42E-03	4.29E-04	5.46E-04	4.47E-04	3.51E-04	-3.32E-03	-9.66E-05	-1.23E-04
Marine ecotoxicity	species.yr	1.16E-03	9.55E-05	1.22E-04	9.20E-05	7.22E-05	-7.24E-04	-2.02E-05	-2.57E-05
Human carcinogenic toxicity	DALY	1.78E+02	6.90E+00	8.79E+00	2.29E+00	1.79E+00	-3.96E+02	-8.82E+00	-1.12E+01
Human non-carcinogenic toxicity	DALY	5.03E+01	3.83E+00	4.88E+00	3.26E+00	2.56E+00	-1.66E+01	-5.94E-01	-7.56E-01
Land use	species.yr	5.01E-02	2.20E-01	2.80E-01	3.13E-02	2.46E-02	-1.14E-02	-7.62E-04	-9.70E-04
Mineral resource scarcity	USD2013	1.30E+06	4.53E+04	5.78E+04	1.00E+04	7.88E+03	-3.76E+04	-4.43E+03	-5.64E+03
Fossil resource scarcity	USD2013	7.86E+06	9.91E+06	1.26E+07	1.05E+06	8.27E+05	-1.48E+06	2.82E+05	3.59E+05
Water consumption, Human health	DALY	3.87E+00	1.44E+00	1.83E+00	1.63E+00	1.28E+00	-1.36E+00	-3.33E-01	-4.24E-01
Water consumption, Terrestrial ecosystem	species.yr	2.35E-02	8.74E-03	1.11E-02	9.92E-03	7.79E-03	-8.28E-03	-2.03E-03	-2.58E-03
Water consumption, Aquatic ecosystems	species.yr	1.05E-06	3.91E-07	4.98E-07	4.44E-07	3.48E-07	-3.70E-07	-9.06E-08	-1.15E-07

Annex B: Traffic impact assessment

		Traffic				
		Cars_Diesel	Cars_EV	Cars_Petrol	Lorries	Vans
Global warming, Human health	DALY	2.18E-07	8.39E-08	2.36E-07	1.46E-07	1.65E-06
Global warming, Terrestrial ecosystem	species.yr	6.58E-10	2.53E-10	7.11E-10	4.39E-10	4.97E-09
Global warming, Aquatic ecosystems	species.yr	1.80E-14	6.91E-15	1.94E-14	1.20E-14	1.36E-13
Stratospheric ozone depletion	DALY	5.05E-11	3.72E-11	7.90E-11	6.27E-11	5.53E-10
Ionizing radiation	DALY	4.76E-11	1.67E-10	5.06E-11	3.68E-11	4.41E-10
Ozone formation	DALY	8.09E-10	2.28E-10	2.48E-10	4.53E-10	7.27E-09
Fine particulate matter	DALY	8.36E-08	5.73E-08	9.45E-08	7.01E-08	1.13E-06
Ozone formation, ecosystems	species.yr	1.17E-10	4.01E-11	3.87E-11	6.59E-11	1.06E-09
Terrestrial acidification	species.yr	1.29E-10	5.72E-11	9.41E-11	8.00E-11	1.15E-09
Freshwater eutrophication	species.yr	6.11E-12	2.09E-11	6.70E-12	3.98E-12	9.36E-11
Terrestrial ecotoxicity	species.yr	1.37E-11	5.54E-12	1.30E-11	3.03E-11	8.33E-11
Freshwater ecotoxicity	species.yr	1.35E-12	2.07E-12	1.30E-12	6.71E-13	5.89E-12
Marine ecotoxicity	species.yr	3.25E-13	4.34E-13	3.14E-13	2.41E-13	1.55E-12
Human carcinogenic toxicity	DALY	6.36E-09	1.18E-08	5.96E-09	4.51E-09	8.51E-08
Human non-carcinogenic toxicity	DALY	1.08E-08	1.67E-08	1.06E-08	8.71E-09	6.00E-08
Land use	species.yr	5.80E-11	1.57E-10	5.41E-11	6.18E-11	4.47E-10
Mineral resource scarcity	USD2013	4.03E-05	4.46E-05	4.25E-05	2.94E-05	2.68E-04
Fossil resource scarcity	USD2013	3.58E-02	6.02E-03	3.74E-02	2.42E-02	2.53E-01
Water consumption, Human health	DALY	1.43E-09	7.11E-09	1.48E-09	1.01E-09	1.21E-08
Water consumption, Terrestrial ecosystem	species.yr	8.67E-12	4.32E-11	8.99E-12	6.12E-12	7.39E-11
Water consumption, Aquatic ecosystems	species.yr	3.88E-16	1.93E-15	4.02E-16	2.74E-16	3.30E-15