ROADWAYS AND INFRASTRUCTURE

Freight transport in the context of industrial ecology and sustainability: evaluation of uni- and multi-modality scenarios via life cycle assessment

Carlo Ingrao[1] · Flavio Scrucca[2] · Agata Matarazzo[1] · Claudia Arcidiacono[3] · Anastasia Zabaniotou[4]

Abstract

Purpose This study aims at comparing, from an environmental point of view, four different scenarios of freight transport at the Italian level, on an equal base of route between supplier and customer. The first scenario included freight movements by truck and mainly ship, the second included track and mainly train, the third was the three-modal based scenario, whilst the fourth scenario was the only uni-modal, based only upon truck movement.

The study was conducted to find the environmentally sustainable solution, or at least a sustainable trade-off, as well as the most environmentally burdening issues, associated with the geographic dimension of transport in Italy, towards sustainability.

Methods Using uni- and multi-modal freight movements by truck, rail and ship, a life cycle assessment (LCA) was developed to estimate the related environmental burdens both at the midpoint and at the endpoint levels from the consumption of primary energy and natural resources along with the emissions of greenhouse gases (GHGs) and of other pollutants. Primary data were compiled as part of the inventory analysis and consisted in the transport flows associated with the system investigated: those were calculated from the distance travelled and the goods load transported. Primary data were then combined with secondary data that were modelled with the transport life cycle modules contained in Ecoinvent: from those modules, the fuel consumption amounts associated transport flows were extrapolated, and used for the assessment.

Results Results showed that the environmental impact of the multi-modal scenarios is lower compared with the uni-modal scenario. The best performing option was found to be the third scenario providing use of all the three freight means, namely ship, train and truck. However, this scenario is not being practiced for several reasons, mainly due to control and monitoring difficulties of each step and higher operational costs. The first and second scenarios showed a quite comparable environmental behaviour and so are to be considered as viable options.

Conclusions Apart from highlighting the most environmentally viable transport options, the study contributed to finding the indicators of environmental impact and damage that best describe the system investigated and are recommended by this author team to be accounted for in future assessments in the transport sector. Finally, although site-specific, the results of this study may be useful to logistics companies, policy and decision makers of other regions and countries towards identifying and promoting environmentally optimal freight transport solutions, contributing to sustainability of the transport sector.

Keywords Industrial ecology · Transportation · Sustainability · Life cycle assessment · Fuel consumption · Greenhouse gas emissions

---

Communicated by Marzia Traverso

✉ Claudia Arcidiacono
claudia.arcidiacono@unict.it; carcidi@unict.it

1 Department of Economics and Business, University of Catania, Corso Italia, 55 - 95129 Catania, Italy

2 Department of Sustainability, ENEA - Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Lungotevere Thaon Di Revel, 76 – 00196 Rome, Italy

3 Department of Agriculture, Food and Environment (Di3A), University of Catania, Via S. Sofia, 100 - 95123 Catania, Italy

4 Biomass Group, Department of Chemical Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

1 Introduction

Industrial ecology (IE) is fundamentally based upon the following: the interrelationships between components and elements characterising both the industrial and the natural systems; and the concept of "industrial symbiosis", according to which firms are considered interlinked systems of a productive network (Chiu and Yong, 2004; Desrochers, 2004; Ardente et al., 2010).

IE is a science that studies the interaction between society (to be intended as a productive entity) and the environment, and several of the relevant connected issues. Chief amongst them are the exploitation of energy and material resources, and the emission of pollutants in air, water and soil in the supply chains (SCs) of products (Lifset and Graedel, 2002; Udo de Haes, 2002). In this regard, SCs can be considered as in the following steps: production of raw materials, fuels and energy from extraction of primary energy and natural resources; manufacturing and distribution of the given product, followed by its use (if significantly burdening in environmental terms) and its possibly recovery-oriented end-of-life (Andersen, 2002). In the light of this, it is understood that the approach is to include all the life cycle stages of the products and their environmental demands throughout the entire SC. In doing so, transport should never be neglected, as it would mean running the risk of omitting important environmental impacts. This could be problematic when transport is such to be a relevant source of environmental impacts within the SC investigated (Andersen, 2002).

Transportation systems are infrastructures and services that characterise the built environment, and so are planned and designed in ways to be available on consumers' demand, reliable for operation, robust to attacks, and scalable to support and meet changes in needs and population demographics (Sarwat et al., 2018; Ingrao et al., 2018). Therefore, it can be asserted that, as one element of built environments, transports (including the freight ones) play multiple key roles in the society and are the result of numerous socio-economic factors and processes, that are central to—and determine the way to—proceed towards sustainable development (Forsberg and von Malmborg, 2004; Ingrao et al., 2018).

Despite of such benefits, the transport sector is responsible for one major share of fossil energy-related greenhouse gas (GHG) emissions worldwide, and so can be considered as one substantial contributor to human-induced primary-energy resource depletion and climate change (Tang et al., 2019; Pizzol, 2019). The transport sector represents around a quarter of the GHG emissions of the European Union (Pizzol, 2019). In 2017, those emissions were due to road transport for 71.7%, to aviation for 13.9%

and to navigation for 13.3%. Rail transports contributed the lowest share which was around 0.5%, along with other transportation means that accounted for the remaining 0.6% (EEA, 2019).

Freight transport via road was highlighted by Pizzol (2019) to be a major emission source, with an average contribution of 6% to the total emissions at the European level. Reducing GHG emissions from the global transport sector is, therefore, essential to slow the worsening effects of climate change (Taptich et al., 2015). This can be achieved by making strategies and adopting solutions, with the final aim of complying with the 80% GHG emission reduction that has been targeted by the Paris agreement to be achieved by 2050 (Pizzol, 2019). Actually, there is no consensus on affirming that rural areas cause less emissions on a per-capita level than urban and semi-urban areas, yet rather lifestyles and the availability of spatial forms and public transports are crucial in the generation of those emissions (Kamal-Chaoui and Alexis, 2009; Heinonen and Junnila, 2011; Ambarwati et al., 2017).

The assessment of strategies that reduce emissions through technology, fuel and behavioural changes is particularly significant. Taptich et al. (2015) documented that adoption of new, innovative technologies can largely contribute to reducing the intensity of GHG emissions of both passenger and freight transport, by 2050. Similarly, Patella et al. (2019) showed that the penetration of new technologies in transportation, such as the use of fully electric autonomous vehicles, can lead to an improvement in the network performances and also to a significant reduction (about 60%) of the environmental impact at the mobility system level. Amongst the available technologies, Pizzol (2019) acknowledges the development and utilisation of more energy-efficient and net zero-emission engines; the reduction and the optimisation of transport distances, also through multi-modal transport solutions; and the shift from high to low emission vehicles, like from truck to train and/or ship.

Multi-modality indicates a subsequence of, at least, two different modes through which transport of goods is carried out (Steadieseifi et al., 2014). In this regard, in line with Pizzol (2019), it is interesting to mention that Kreutzberger et al. (2003) documented multi-modal freight transport to have, overall, lesser GHG emissions and better environmental performances than the uni-modal one, generally operated by truck. Multi-modal transportation has been suggested, indeed, as an appropriate strategy for decarbonisation of the freight transport sector (Kaack et al., 2018), thereby complying with the strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050 promoted by the European Commission (EU, 2018).

Tools like life cycle assessment (LCA) can be valid to find the most sustainable of the solutions indicated by Pizzol (2019) or, at least, the most viable trade-offs at the

environmental, economic and social level (Traverso et al., 2012). LCA is an important tool for both planning and implementation IE-based systems, as it enables to assess IE strategies and to find the most suitable ones in an integrated, holistic approach to sustainability (Andersen, 2002; Ardente et al., 2010). The literature has, indeed, confirmed its importance as a tool to support decisional processes in contexts ranging from product development to policy making (Zamagni et al., 2012; Asdrubali et al., 2015).

Application of LCA in the transport sector is becoming increasingly widespread, and studies developed thus far have often referred the obtained results to a measure of the transport flow, generally expressed as a particular weight being moved over a particular distance (i.e. t km). However, there is a small gap in the literature, which is because those studies often lack in analysing the effects of uni- and multimodal trips, or the way trips spanning through long distances should be addressed, in order to provide support to making micro- and macrolevel decisions (Nahlik et al., 2015). This study may contribute to filling that gap, as it was conceived to explore relevant environmental issues associated with different transport systems providing a combination of different intermediate routes (i.e. road, rail and water) under uni- and multi-modality conditions. This is in line with Nahlik et al. (2015) recommending to understand trip impacts, because it is not always possible for reasons owing to market, sender and recipient locations, or infrastructure conditions, to shift transport of goods from one mode to another, though it is important for the sake of emission reduction. In addition to this, 100% replacement of one mode with another one is often difficult because, generally for optimisation of efficiency in goods delivery, transport is operated under multimodality conditions (Nahlik et al., 2015). For example, in a long distance transport, there can be a series of intermediate routes, with the core one(s) being generally performed by train, ship or aircraft, and those at the extremes being run by truck (i.e., from the sender to the departure port/station, and from the arrival port/station to the recipient).

In this context, efforts are required to improve the environmental issues associated with the movement of goods from one place to another, especially when long distances need to be travelled. To this end, the life cycle thinking (LCT) approach can play a vital role, as it enables identifying the processes, the materials, the energy and the fuels, as well as the emission and waste streams to be considered, already in the phases of planning and design, for the sustainability of transport systems (Nahlik et al., 2015). Identification of viable solutions for the greening of the freight transport sector contributes to implementing greenlogistics systems, that is, a set of SC management practices and strategies that reduce the ecological and energy footprints of goods distribution. This can generate, in turn, a positive change in the environmental performance of

suppliers and customers (Lee and Klassen, 2008; Seroka-Stolka and Ociepa-Kubicka, 2019).

LCA substantiates the LCT approach, and its application to the goods movement field is particularly significant, considering the expansion of the sector and the subsequently generated environmental and economic burdens.

Therefore, sustainable solutions for distribution of material commodities need to be found and pursued by taking into account the transport geography of logistics and freight distribution with the fundamental question to reside not only in the nature, origins and destinations of freight movements but also in the way freights move. This study wants to contribute this specific research field and, indeed, was conducted to find the environmentally sustainable solution (whether there is one), or at least a sustainable trade-off, as well as the most environmentally burdening issues associated with the geographic dimension of transport in Italy. For this purpose, LCA was applied in this study, because it is acknowledged today as one valid tool for conducting environmental evaluations in a wide range of sectors, including the transport one (Duan et al., 2015). GHG reduction policy in Europe is important, and increasing interest in using LCA to estimate indirect and supply chain effects raises issues of the geography that can affect change in processes in complex infrastructure systems. Through a comparative LCA of the environmental issues associated with a set of transport systems providing a combination of different intermediate routes (i.e. road, rail and water) with an uni- and multi-modal approach, this study takes the case of the freight transport from South to North in Italy (from Catania to Milan), through the ports of Genoa and Naples. The study was conducted in collaboration with an Italian logistics firm involved in the transport of unperishable goods. Although site-specific, the results from this study may be useful to companies working in the logistics sector and to policy and decision makers of other territories and countries, towards identifying and promoting environmentally optimal freight transport solutions contributing, in turn, to boosting sustainability of transports in an IE context.

2 Materials and methods

The LCA approach was developed according to the specific International Standards 14040-44: 2006 (ISO, 2006a, b), to highlight environmental hotspots of logistics activities.

Therefore, the study was articulated as follows: goal and scope definition shaping the methodology, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation. Each of those phases was discussed in the following of the text.

2.1 Goal and scope definition

The study was conceived with the aim of environmentally comparing four different freight-transport scenarios, that provide a combination of different intermediate routes (i.e. road, rail and water) from an uni- and multi-modal logistics perspective, on an equal base of supplier and customer locations. Following Pizzol (2019), issues related to route costs and time saving, which are as important as the environmental ones in making decisions upon the route to be preferred, were considered beyond the scope of this study.

For the assessment, four freight-transport scenarios were identified and explored with the support of the aforementioned logistics company. As shown in Fig. 1, they refer to the route Catania-Milan that was chosen as a case study in agreement with the company managers, as it is highly representative of the firm activity and, mostly, is generally operated with the use of different transport means, so making it well suited for such an assessment. Additionally, 25-t goods was chosen by the authors as the

object of the transport service because, according to reliable information provided by the company managers, it is the most frequently transported amount of goods for such a route. They are transported in one trip by means of a shipping container with an 80–90% filling rate, so never exceeding the weight limit for the truck utilised.

For greater understanding of the study conducted, it is clarified here that the first scenario is based upon a double-modal option, composed by road transport from the warehouse to the port of Catania and from the port of Genoa to the destination in Milan. In this scenario, the core, intermediate route is travelled by ship, from the port of Catania to the port of Genoa, following the shipping routes with a stopover at the port of Naples.

The second scenario is also based on a double-modal option, providing road transport from the warehouse to the train station of Catania and from that of Segrate to the final destination in Milan, whilst the core intermediate route is operated by train.

Fig. 1 The four scenarios investigated and the transport systems implied are depicted using different colours: road (blue), rail (red) and water (green)
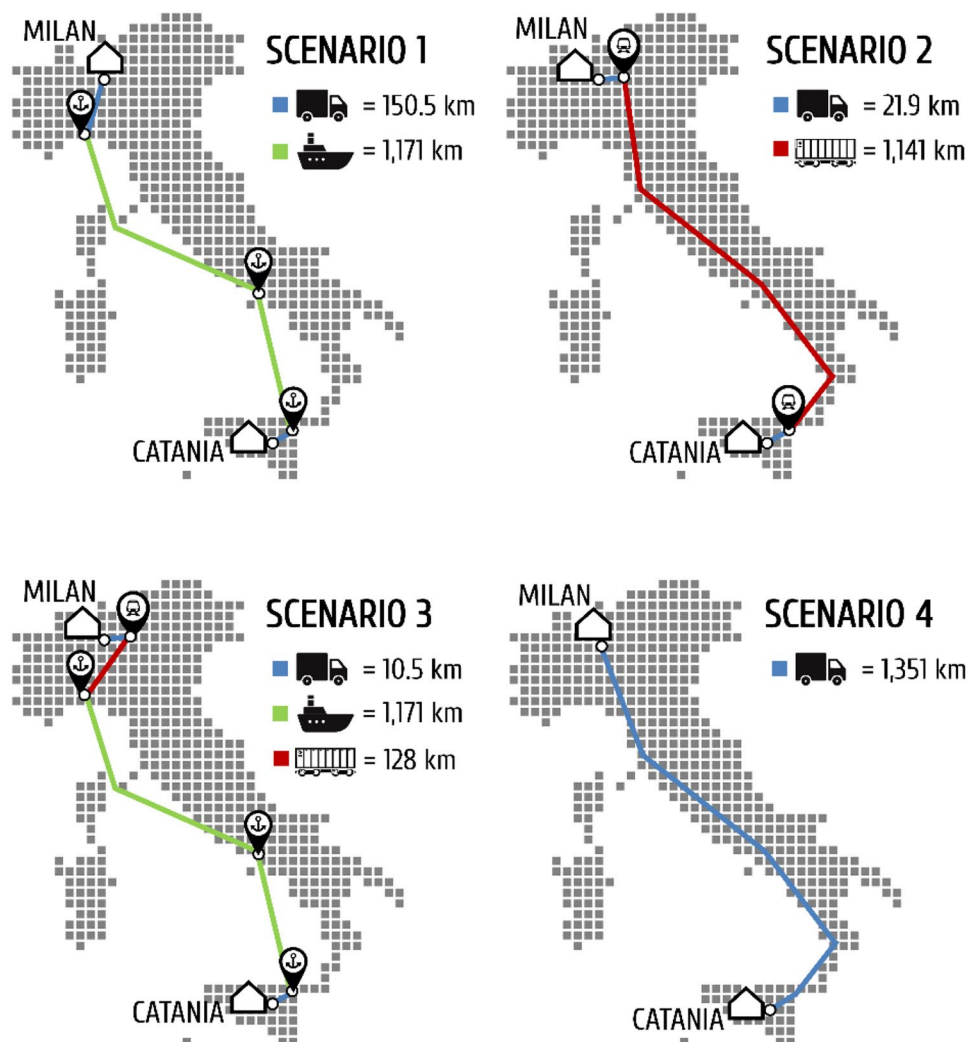
The third scenario represents the three-modal scenario as it was designed to contain all transport means considered in this study. It has a lot in common with the first one, with the only difference that the goods load from the port of Genoa is transported by train to the train station of Segrate (close to Milan) and then by truck to the final destination.

Finally, the fourth transport scenario is the only uni-modal one, as it is entirely operated by truck travelling from sender to recipient.

By summing up the travelled distances for each interme-diate route, it was found that the first, the third and the fourth scenarios are characterised by comparable distance values, namely 1321.5 km, 1309.5 km, and 1351 km, respectively. In contrast, a reduced distance to be travelled was found in the second scenario and was equal to around 1160 km. Fig. 2 shows how those distance values are distributed on a percentage scale and what the transport flow values are, in each scenario considered. In this regard, it is clarified that scenario 4 is not appearing in Fig. 2 as the related transport is 100% by road, and so there was no distribution worth being highlighted.

Attention was paid upon the distribution sector, because it is globally accepted to be a large contributor to the environ-mental and socio-economic burdens and impacts associated with life cycles of products and services, and so it can nega-tively influence the related sustainability rates.

As a part of this phase, the functional unit (FU) and the system boundaries were defined, to represent the investi-gated process and be consistent with the aim of the study. It represents the unit of the product and provides a reference trough which inputs are linked to outputs, and both are to the resulting impact and damage indicators (Arzoumanidis et al., 2013; Robertson, 2013). In this case, the FU was 1 p, which corresponds to the transport-flow mix shown in Fig. 2 that is associated with the transport of 25 t travelling from Catania to Milan under uni- and/or multi-modality condi-tions. With regard to the system boundaries, they define the unit operations that need to be considered when assessing the life cycle of a product (Arzoumanidis et al., 2013), for the reliability of the system model created and of the results obtained from the analysis of inventories and environmental impacts/damages.

The system boundaries were defined in this study based upon organisational, managerial and technologi-cal issues as featuring the supporting firm, according to Clasadonte et al. (2013). This made it possible for the authors to understand all the processes and stages of the transport system investigated and the way the input and output inventories are interlinked, thereby favouring

Fig. 2 The figure shows the transport options in each scenario considered. Values are given as percentages com-pared with the overall distance travelled and as transport flows associated with the goods load (25 t) taken as reference and representing the functional unit of the study
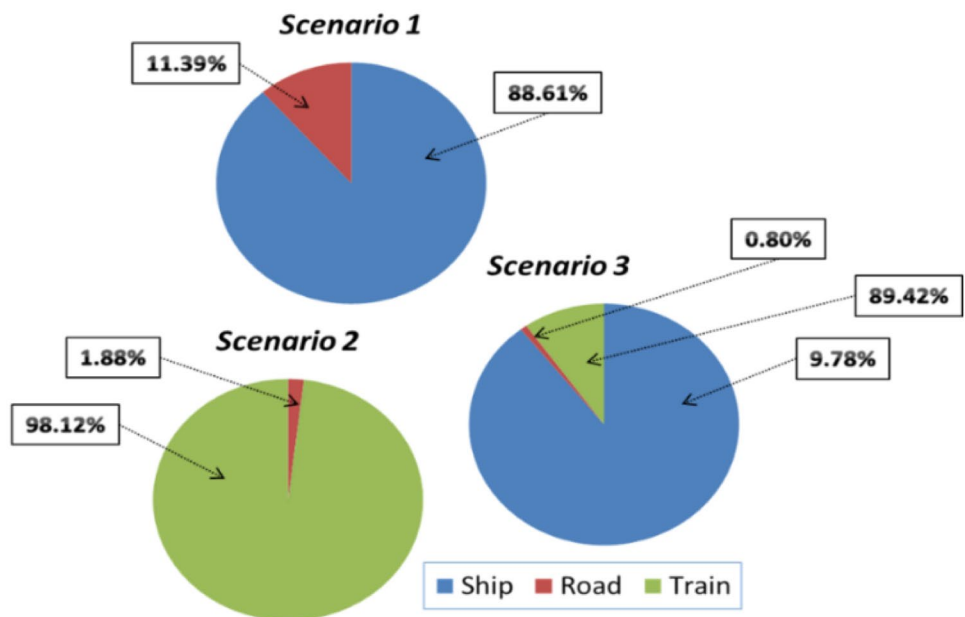
SCENARIO	FUNCTIONAL UNIT (FU)	TRANSPORT SYSTEM		
		Road	Rail	Water
		tkm/FU		
1		3762.5	---	29275
2		547.5	28525	---
3	1p	262.5	3200	29275
4		33775	---	---

the correctness and reliability of the environmental assessment.

Following Ingrao et al. (2019), the FU and the system boundaries were defined to be consistent with the aim of the study, best represent the system investigated, make the study reproducible, contribute to delivering reliable results, and enable comparisons with other similar systems. In this case, the system boundaries were defined in line with Nahlik et al. (2015) and Pizzol (2019), and so they included the following steps:

- Manufacturing of the transport means utilised from raw material production and acquisition
- Maintenance of the means, and fuel consumption and related emissions in their operating phase
- End of life of the means
- Auxiliary services, infrastructures and equipment, with a life cycle approach

Furthermore, it should be noted that the intermediate steps of loading and unloading the transported goods were excluded, because those phases were considered to be far less environmentally burdening compared with the entire transport activity. This mainly owns to the long service life of the equipment utilised and the huge number of those steps carried out over the course of that life, also for goods other than those considered in this study. In addition to this, that equipment generally belongs to port/station handling local authorities, that is, it was out of the control of the logistics company in question and primary data collection was quite difficult to be carried out.

Finally, to be excluded was also the intermediate ferry step to move both the truck in scenario 4 and the freight train in scenario 2 through the Strait of Messina. This was done because of:

- The extreme difficulty of collecting site-specific data on fuel consumption; and
- The lack—to these authors' knowledge—of modules in the Ecoinvent v 3.5 database (Ecoinvent, 2018), which are suitable to represent the life cycle of the ferry involved.

Therefore, the related route was considered as pertaining to the next core one and so was assumed to be entirely operated by truck or train, depending from the case. However, according to this author team, the resulting uncertainty can be considered negligible, because so is the length of the route in question (around 10 km), compared with the overall distance associated with the involved scenarios.

2.2 Life cycle inventory

This phase plays a key role in any LCA and related studies, as it is about compilation, qualification and quantification of input and output streams as connected with a given product or service. Specifically, the input streams consisted in the transport flows calculated as discussed in the following of the text, whilst the output streams were represented by material emissions in air, water and soil and by exploitation of primary-energy resources. The transport flows represent, therefore, the primary data used for the assessment. Such data were combined with secondary data extrapolated from databases of acknowledged scientific value and relevance, like Ecoinvent v.3.5 (Ecoinvent, 2018), as available in the SimaPro 9.0 (Prè, 2019), that was used for this study development. The aforementioned flows were calculated from route lengths within the scenarios considered, with reference to a 25t transported amount (FU of the study, that was labelled as '1p'): values are those already reported in Fig. 2.

Secondary data were represented by the transport life cycle modules that are contained in Ecoinvent and are referred to 1t km transport flow. To make the study easy to follow and reproduce, those modules were reported below, with the related dataset description as of Ecoinvent v.3.5 in line with the defined system boundaries:

- Transport, freight, lorry 16–32 metric ton, EURO5 {RER}: Included processes are the followings: operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.
- Transport, freight train {IT}: The following steps were considered: production, maintenance, operation, and disposal of the train; and construction and maintenance and disposal of railway tracks
- Transport, freight, sea, transoceanic ship {GLO}: The module calls the modules addressing: operation of vessel; production of vessel; construction and land use of port; operation, maintenance and disposal of port.

Each of those modules was chosen in close collaboration with the firm stakeholders in a way to be representative of the real practice, so contributing to the final reliability and usability of this assessment and of the obtained results.

Finally, Table 1 shows values of the fuel consumption associated with the transport means operation, based upon the above modules, along with the titles of the fuel production modules contained in the version of Ecoinvent used for the system modelling.

Values in Table 1 were calculated extrapolating the following factors from those Ecoinvent modules, and then by multiplying those factors by the FU-related transport flows shown in Fig. 2 for each explored scenario:

Table 1 Consumption of energy sources in each scenario investigated considering the means utilised (values are referred to the transport flows shown in Fig. 1).

Energy source consumed	Transport mean	Unit of measure	Scenario				Ecoinvent module description
			1	2	3	4	
Low-sulphur diesel	Truck	kg	141.47	20.59	9.87	1269.94	Diesel, low-sulphur {RER}| market group for	APOS, U
Heavy fuel oil	Freight ship	kg	61.77	---	61.77	---	Heavy fuel oil {RoW}| petroleum refinery operation	APOS, U
High-voltage electricity	Freight train	kWh	---	1362.86	152.89	---	Electricity, high voltage {IT}| market for	APOS, U
Diesel		kg		31.09	3.49		Diesel {Europe without Switzerland}| market for	APOS, U

- Low-sulphur diesel: 0.0376 kg/t km
- Heavy fuel oil: 0.0021 kg/t km
- High-voltage electricity: 0.048 kWh/t km
- Diesel: 0.0011 kg/t km

Finally, from Table 1, there is evidence that the peak in low-sulphur diesel consumption was recorded in scenario 4, as road transport is the only mode considered. Far less but, however, significantly demanding was found to be scenario 1, because road transport is limited just to the extreme part of the routes, as already clarified.

Heavy fuel oil is equally consumed in scenarios 1 and 3 because for both of them the core part of the route is operated by freight ship, with an equal distance travelled, namely 1171 km; differences between the two scenarios stay in the transport mode adopted at the up- and down-stream step of the core route: entirely by truck in scenario 1; and a combination of train and truck in scenario 3.

Finally, train is utilised in both scenarios 2 and 3, with core and marginal function, respectively, which explains why consumption of electricity and diesel in scenario 2 is way bigger than in scenario.

2.3 Life cycle impact assessment

De Benedetto and Klemes (2009) indicate this phase as to be developed by aggregating the material and energy output inventories in a limited set of impact categories (ICs), also known as 'midpoint categories'. Such was done here in this study, by using the classification/characterisation scheme of Impact 2002+ (Jolliet et al., 2003). This method was used for the assessment because the authors of this paper found it to be valid for the assessment and the highlight of the environmental burdens best representing the system investigated both at the midpoint and endpoint level. In the midpoint approach, LCIA results were expressed by means of equivalent indicators, such as the following: kgCO$_2$eq for 'Global warming', MJ primary for 'Non-renewable energy', and kgPM$_{2.5}$ eq for 'Respiratory inorganics'.

Thereafter, the ICs were grouped into damage categories (DCs), with the aim of describing the environmental compartments being damaged by the product in its life cycle. The classification scheme used for this phase development is the one provided by Impact 2002 + and duly described by Jolliet et al. (2003).

Therefore, the phases of 'normalisation' and 'weighing' were included in the assessment, as part of the endpoint approach, thereby expressing results in the forms of 'weighing points' or 'damage points' or 'eco-points' or, more simply, 'points'. Therefore, the end-point approach was used in this paper to represent quantitatively the environmental damage associated not only with the transport system investigated but, also, with the related output streams. This made it possible: to create a point-based scale of the overall environmental profiles exhibited by the various transport systems investigated; and to identify the most environmentally burdening of the aforementioned streams.

3 Results and discussion

This section is dedicated to presenting and discussing results obtained by performing the LCIA phase in SimaPro (v. 9.0) using the Impact 2002+ method (Jolliet et al., 2003). They showed that the best transport option is the third one, with a damage point value equal to 0.234 pt, and that comparable values are in the first and in the second scenario around of 0.40 pt (see Fig. 3).

Despite its environmental sound, the third scenario is rarely operated by this study supporting company, mainly owing to the greater variety of means utilised generating, in turn, an increase in the number of intermediate steps for loading and unloading of the transported goods. All of this makes this scenario difficult to be controlled in each step of the way, and higher cost demanding compared with the others.

In contrast, scenarios 1 and 2 are the most pursued ones on average by the company and, in light of the results
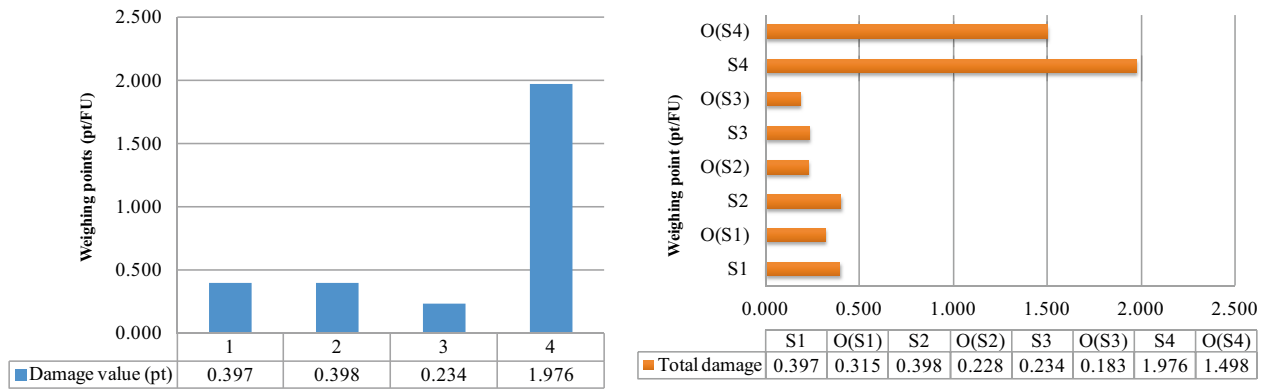
	S1	O(S1)	S2	O(S2)	S3	O(S3)	S4	O(S4)
Damage value (pt)	0.397		0.398		0.234		1.976	
Total damage	0.397	0.315	0.398	0.228	0.234	0.183	1.976	1.498

Fig. 3 Results from comparison of the four transport systems investigated. On the left, the total damage scale was depicted, and both the most and the less burdening of the four scenarios investigated were highlighted along with those in between whilst, on the right, the com- parative assessment was extended to the contribution exhibited by the transport-means operating phase (labelled as O(Si)) in each life cycle scenario

obtained, they can be considered as valid trade-offs in terms of feasibility and sustainability of the transport ser- vice performed. Such a finding would meet Pizzol (2019) on freight transport in container ships and trains, over long distances, allowing to lower carbon emissions compared with air or road modes.

In addition to this, the worst scenario was detected to be the fourth one, with a damage value that has been quanti- fied in almost 2.0 pts, so being hugely higher than the previous three and, at the same time, confirming the envi- ronmental unsound of long distance transport solutions that are entirely based upon road means. This is again in line with Pizzol (2019) stating that road freight-transport is a major-source of emissions and environmental burdens, mainly because heavy-duty vehicles are responsible for 6% of the total emissions of the European Union.

Apart from the total damages associated with the inves- tigated transport systems, Fig. 3 shows the contribution played by the operating phase. It can be asserted that the largest share of those damages is due to operation of the means utilised, i.e. O(S$_i$) with i = 1 to 4, with percentage values depending upon the mix of means utilised and the related transport flows in each of the four scenarios con- sidered. Transport means operation is, indeed, at the centre of global environmental policies pushing for improvement of the means engines, to contribute to reducing consump- tion of fuels and resulting emissions of GHGs and other pollutants.

In this study, comparable operation incidence percentages were recorded in scenarios 1, 3, and 4 with values equal to 79.33%, 78.23% and 75.85%, respectively, while in sce- nario 2, a quite lower value (57.35%) was observed. Such leads to deducing that, based upon the way that mix has been designed (i.e. type of mean and related travelled distance), the ensemble of life cycle phases other than the operational one was environmentally heavier in scenarios 2 than in the others.

The assessment was extended to the damage categories, by reporting results per each scenario investigated. In par- ticular, damages assessment values were shown in Fig. 4, along with the weighing results expressed on a percentage scale based upon the total damage values depicted in Fig. 3.

From Fig. 4, there is evidence that 'Human health', 'Cli- mate change', and 'Resources' are the most affected damage categories covering a total of 85–95%, and so can be consid- ered as the most representative of the environmental profiles of the transport systems investigated, at the end-point level. In addition to this, scenario 4 was found to be the worst one because of the biggest environmental damage exhibited per each of the four damage categories considered.

The end-weighing assessment regarded also the most environmentally burdening material emissions (in air, and soil) for 'Climate Change', 'Human Health' and 'Ecosys- tem Quality' and the primary-energy and natural resources exploited affecting the damage category 'Resources' (Table 2). All of them were extrapolated from the output inventory pack of each transport scenario, because they are the output streams most largely contributing to the damage value associated with the related damage category, and so were considered by this author team as highly representative of those scenarios. Their incidence is indeed in the range of 96–99% for 'Resources', 97–98% for 'Climate Change', 87.5–96% for 'Human Health' and 84–96% for 'Ecosystem Quality'. In this damage category, the range is wider com- pared with the others because higher is the number of dam- aging substances and more distributed is its total damage, with many slightly or negligibly contributing environmen- tal aspects. Some of those were, however, extrapolated and reported in the table because, although far less environmen- tally damaging compared with others like the emission of
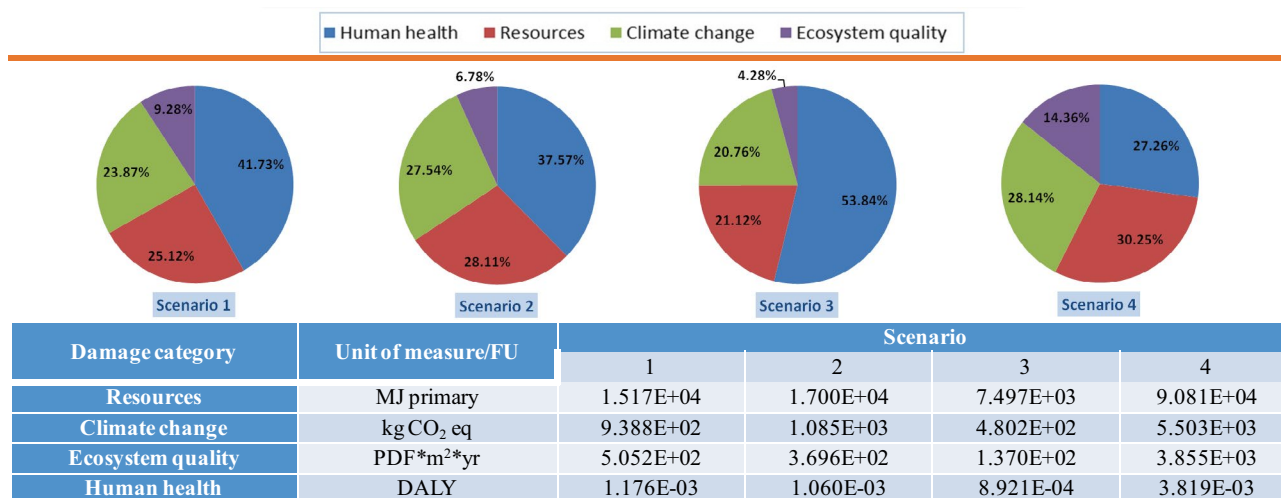
Damage category	Unit of measure/FU	Scenario			
		1	2	3	4
Resources	MJ primary	1.517E+04	1.700E+04	7.497E+03	9.081E+04
Climate change	kg CO_2 eq	9.388E+02	1.085E+03	4.802E+02	5.503E+03
Ecosystem quality	PDF*m^2*yr	5.052E+02	3.696E+02	1.370E+02	3.855E+03
Human health	DALY	1.176E-03	1.060E-03	8.921E-04	3.819E-03

Fig.4 Results per damage category are reported in this figure per each explored scenario. In particular, the upper part shows percentages obtained by referring the damage suffered by each damage category to the total damage associated with the given scenario (as shown in Fig. 3), whilst the table-containing part of the figure shows results from the damages assessment step

zinc and aluminium to the soil due to truck tyre abrasion, they were considered as strictly connected with—and so representative of—the system investigated. This is the case of some metal emissions in air, and of the occupation of the traffic areas invested for road and rail networks, which generate problems associated with land occupation and, possibly, landscape alteration: these and closely related issues should not be neglected when planning and designing transport infrastructures. Actually, the latter produce changes of different nature, from physical–chemical (e.g. soil density, temperature, soil water content, light levels, dust, surface waters, patterns of runoff and sedimentation) to ecological effects on biotic integrity in both terrestrial and aquatic ecosystems (Trombulak and Frissell, 2000). In LCA, land use is included in a unit process, as an intervention or as an ensemble of impact indicators. As for the latter, failing to include some aspects of land use, it is recognised that there is a need to develop indicators to fulfil requirements of more holistic, sustainable use of land (Mattila et al., 2011). In this direction, development of such indicators within environmental frameworks, like the DPSIR (Driving Forces-Pressure-State-Impact-Response) model (Vidal and López-Mesa, 2006; Arcidiacono and Porto, 2010), and the use of geospatial information (Geyer et al., 2010; Arcidiacono and Porto, 2010, 2012; Ambarwati et al., 2017) are recognised as highly valuable. In this regard, inventory modelling would be highly enhanced if LCA was coupled with Geographic information systems (GIS), since LCA does not conventionally utilise geospatial information.

Each of the substances reported in Table 2 was addressed in terms of output-inventory amount, and both characterisation and damages assessment value, in each of the scenarios

investigated: values were extrapolated from the LCIA conducted in SimaPro using Impact 2002+, and were reported in Table 3.

From the Table 3, it can be asserted that emission of fossil carbon dioxide is most largely resultant from the combustion of the fuel consumed in the transport activity, with the peak value in scenario 4 due to the use of a truck for the entire route. Same can be said for the primary-energy resource exploitation, where the 100% road transport scenario exhibits the biggest contribution for all the resources considered, mainly due to the operating step in the life cycle of the mean. Other relevant emissions were detected to be those of nitrogen oxides, sulphur dioxide and particulates with road transport contributing most of them, and with a more or less high gap with respect to the other scenarios.

As already mentioned, emissions affecting 'Ecosystem Quality' are mainly related to the abrasion of the lorry tyres during transport: such explains why the biggest values were recorded in the fourth scenario. In addition to this, for what concerns occupation of traffic area for transport network, it is clear that the highest values were recorded where the related transport mode is predominant: scenario 4 for the road network; and scenario 2 for the rail one.

Finally, based upon results shown in Fig. 3, it is worth highlighting that the largest contribution to those environmental issues (Table 3) should be attributed to the operating step of the life cycle of the transport system considered, with reference to 25t transported commodities.

Finally, the impact categories that resulted from the detailed analysis of the output streams associated with the four scenarios explored (Table 3) can be considered as the most representative of the environmental profiles of

Table 2 Results from the weighing step as related to the most environmentally damaging emitted substances and resources consumed, compared with the total damages associated with the related affected damage categories

Emitted substance	Emission compartment	Scenario			
		1	2	3	4
		Weighing points (pt/FU)			
Climate change					
Carbon dioxide, fossil	Air	9.30E−02	1.05E−01	4.73E−02	5.45E−01
Others		1.80E−03	4.21E−03	1.15E−03	1.06E−02
Human health					
Nitrogen oxides	Air	7.71E−02	5.11E−02	6.03E−02	2.13E−01
Sulphur dioxide		3.70E−02	2.25E−02	3.33E−02	5.88E−02
Particulates, with grain size < 2.5 μm		4.22E−02	5.70E−02	2.70E−02	2.05E−01
Others	Air/water/soil	9.45E−03	1.89E−02	5.08E−03	6.15E−02
Ecosystem quality					
Zinc	Soil	1.78E−02	4.97E−03	1.69E−03	1.58E−01
Aluminium		4.85E−03	6.45E−03	2.61E−03	2.81E−02
Nitrogen oxides	Air	2.56E−03	1.70E−03	2.00E−03	7.07E−03
Copper		4.33E−03	1.41E−03	4.38E−04	3.84E−02
Aluminium	Air	8.73E−04	4.00E−03	7.75E−04	5.18E−03
Zinc		1.92E−03	1.25E−03	3.17E−04	1.66E−02
Nickel		6.17E−04	2.64E−04	5.75E−04	6.82E−04
Copper	Soil	6.35E−04	8.10E−04	1.69E−04	5.28E−03
Occupation, traffic area, road network	Soil-resource exploitation	1.65E−03	4.32E−04	1.72E−04	1.45E−02
Occupation, traffic area, rail network		4.45E−06	1.29E−03	1.46E−04	2.70E−05
Others	Air/water/soil/resources	1.68E−03	4.40E−03	1.11E−03	1.02E−02
Resources					
Crude oil	Resources	8.44E−02	3.42E−02	3.29E−02	5.24E−01
Natural gas		5.75E−03	3.08E−02	5.88E−03	3.15E−02
Uranium		2.45E−03	1.46E−02	3.10E−03	9.36E−03
Hard coal		5.89E−03	2.84E−02	6.21E−03	2.72E−02
Others		1.33E−03	3.92E−03	1.23E−03	5.19E−03

Climate change: 0.0948 pt/FU (S1), 0.109 pt/FU (S2), 0.0485 pt/FU (S3) and 0.555 pt/FU (S4). Human health: 0.166 pt/FU (S1), 0.150 pt/FU (S2), 0.126 pt/FU (S3) and 0.539 pt/FU (S4). Ecosystem quality: 0.037 pt/FU (S1), 0.027 pt/FU (S2), 0.010 pt/FU (S3) and 0.284 pt/FU (S4). Resources: 0.100 pt/FU (S1), 0.112 pt/FU (S2), 0.049 pt/FU (S3) and 0.598 pt/FU (S4)

the transport systems investigated. They were detailed in Fig. 5 in terms of total characterisation value and weighing point. However, amongst those, the most environmentally important are the 'Non-renewable energy', 'Global warming', 'Respiratory inorganics' and 'Terrestrial ecotoxicity'. So, these represent the target impact indicators which are prior to be considered when planning new transport systems or when making improvements in the already existing ones. 'Land occupation' is amongst the less alarming ones but, according to this author team, the issue connected with investing lands for establishment of road and rail networks and related infrastructures is, however, important to be addressed. This is, specially, when looking at large-scale goods market and distribution systems where the damage due to the occupation of the involved lands on the quality of landscape and the ecosystems can be drastically amplified.

Finally, results confirm the largest contribution coming from scenario 4 and the lowest exhibited by scenario 3, for all impact categories considered, whilst scenarios 1 and 2 are confirmed as fully environmentally feasible.

4 Conclusions

One of the key aspects of IE is that of favouring the transition towards more energy efficient and sustainable industrial systems, which can be achieved also through improvements in the transport sector. As a matter of fact, any environmental assessment which is conducted at the SC level with an IE approach should never omit taking into account all transports involved in raw-material acquisition and in the delivery of intermediate and finished products. This is because the

Table 3 Substances and resources from Table 2 were classified based upon the amounts obtained from the output inventory analysis, and the values of characterisation and damages assessments. All of them were referred to the FU of the study (1p)

Material emission/ consumption item	Output inventory Amount				Unit of measure	Characterisation Value				Unit of measure, equivalent	Impact category	Damage assessment Value				Unit of measure
	S1	S2	S3	S4		S1	S2	S3	S4			S1	S2	S3	S4	
Air																
Aluminium	11.658	53.481	10.359	69.209	g	0.0057	0.0260	0.0050	0.0336	kg C_2H_3Cl	Non-carcinogens	1.59E−08	7.28E−08	1.41E−08	9.42E−08	DALY
						5.75E+03	2.64E+04	5.11E+03	3.41E+04	kg TEG water	Aquatic ecotoxicity	11.952	54.833	10.621	70.958	PDF m^2 year
						1.47E+03	6.76E+03	1.31E+03	8.75E+03	kg TEG soil	Terrestrial ecotoxicity					
Carbon dioxide, fossil	920.97	1043.36	468.81	5398.20	kg	920.98	1043.36	468.81	5398.20	kg CO_2	Global warming	920.97	1043.36	468.81	5398.20	kg CO_2 eq
Copper	6.241	2.035	0.631	55.361	g	0.0127	0.0042	0.0013	0.1130	kg C_2H_3Cl	Non-carcinogens	3.57E−08	1.16E−08	3.61E−09	3.17E−07	DALY
						1.84E+04	5.98E+03	1.86E+03	1.63E+05	kg TEG water	Aquatic ecotoxicity	59.349	19.355	6.003	526.497	PDF m^2 year
						7.39E+03	2.41E+03	7.47E+02	6.55E+04	kg TEG soil	Terrestrial ecotoxicity					
Nickel	1.895	0.812	1.765	2.096	g	0.0168	0.0072	0.0157	0.0186	kg C_2H_3Cl	Non-carcinogens	4.71E−08	2.02E−08	4.38E−08	5.21E−08	DALY
						3.39E+02	1.45E+02	3.15E+02	3.75E+02	kg TEG water	Aquatic ecotoxicity	8.452	3.621	7.872	9.349	PDF m^2 year
						1.07E+03	4.57E+02	9.93E+02	1.18E+03	kg TEG soil	Terrestrial ecotoxicity					
Nitrogen oxides	6.137	4.069	4.803	16.980	kg	0.78	0.52	0.61	2.16	kg $PM_{2.5}$	Respiratory inorganics	0.000547	0.000363	0.000428	0.001513	DALY
						33.68	22.33	26.36	93.19	kg SO_2	Terrestrial acid/nutr	35.029	23.226	27.415	96.915	PDF m^2 year
Particulates, with grain size < 2.5 micron	0.428	0.578	0.274	2.076	kg	0.43	0.58	0.27	2.08	kg $PM_{2.5}$	Respiratory inorganics	0,0003	0,000404	0,000192	0,001453	DALY

Table 3 (continued)

Material emission/consumption item	Output inventory Amount				Unit of measure	Characterisation Value				Unit of measure, equivalent	Impact category	Damage assessment Value				Unit of measure
	S1	S2	S3	S4		S1	S2	S3	S4			S1	S2	S3	S4	
Sulphur dioxide	4.807	2.923	4.330	7.638	kg	0.37	0.23	0.34	0.60	kg $PM_{2.5}$	Respiratory inorganics	0.000262	0.00016	0.000236	0.000417	DALY
						4.81	2.92	4.33	7.64	kg SO_2	Terrestrial acidi/nutr	5.000	3.040	4.503	7.943	PDF m^2 year
Zinc	3.287	2.130	0.542	28.302	g	0.3049	0.1975	0.0502	2.6249	kg C_2H_3Cl	Non-carcinogens	8.54E–07	5.53E–07	1.41E–07	7.35E–06	DALY
						6.70E+02	4.34E+02	1.10E+02	5.77E+03	kg TEG water	Aquatic ecotoxicity	26.337	17.064	4.339	226.772	PDF m^2 year
						3.33E+03	2.15E+03	5.48E+02	2.86E+04	kg TEG soil	Terrestrial ecotoxicity					
Soil																
Aluminium	10.769	14.306	5.796	62.388	g	0.0406	0.0651	0.0230	0.2357	kg C_2H_3Cl	Non-carcinogens	1.14E–07	1.82E–07	6.45E–08	6.60E–07	DALY
						3.77E+04	5.00E+04	2.03E+04	2.18E+05	kg TEG water	Aquatic ecotoxicity	66.484	88.320	35.780	385.149	PDF m^2 year
						8.17E+03	1.08E+04	4.39E+03	4.73E+04	kg TEG soil	Terrestrial ecotoxicity					
Copper	155.932	198.938	41.474	1297.121	mg	0.0028	0.0090	0.0014	0.0232	kg C_2H_3Cl	Non-carcinogens	7.95E–09	2.53E–08	3.95E–09	6.49E–08	DALY
						3.19E+03	4.07E+03	8.48E+02	2.65E+04	kg TEG water	Aquatic ecotoxicity	8.701	11.101	2.314	72.381	PDF m^2 year
						1.08E+03	1.38E+03	2.87E+02	8.98E+03	kg TEG soil	Terrestrial ecotoxicity					
Zinc	5.192	1.455	0.493	46.109	g	3.905	1.515	0.429	34.580	kg C_2H_3Cl	Non-carcinogens	1.09E–05	4.24E–06	1.20E–06	9.68E–05	DALY
						7.25E+03	2.03E+03	6.89E+02	6.44E+04	kg TEG water	Aquatic ecotoxicity	243.197	68.136	23.114	2159,658	PDF m^2 year
						3.07E+04	8.60E+03	2.92E+03	2.73E+05	kg TEG soil	Terrestrial ecotoxicity					

Primary-energy and natural sources

Table 3 (continued)

Material emission/consumption item	Output inventory				Unit of measure	Characterisation				Unit of measure, equivalent	Impact category	Damage assessment				Unit of measure
	Amount					Value						Value				
	S1	S2	S3	S4		S1	S2	S3	S4			S1	S2	S3	S4	
Crude oil	279.979	113.431	109.257	1739.732	kg	1.28E+04	5.20E+03	5.00E+03	7.97E+04	MJ primary	Non-renewable energy	1.28E+04	5.20E+03	5.00E+03	7.97E+04	MJ primary
Hard coal	46.857	225.591	49.374	216.140	kg	8.95E+02	4.31E+03	9.43E+02	4.13E+03			8.95E+02	4.31E+03	9.43E+02	4.13E+03	
Natural gas	22.798	122.229	23.317	125.121	m^3	8.73E+02	4.68E+03	8.93E+02	4.79E+03			8.73E+02	4.68E+03	8.93E+02	4.79E+03	
Uranium	0.664	3.961	0.841	2.540	g	3.72E+02	2.22E+03	4.71E+02	1.42E+03			3.72E+02	2.22E+03	4.71E+02	1.42E+03	
Occupation, traffic area, road network	26.893	7.053	2.810	235.896	m^{2}a	20.725	5.435	2.166	181.792	m^{2}org. arable	Land occupation	22.590	5.924	2.361	198.153	PDF m^2 year
Occupation, traffic area, rail network	0.072	21.048	2.387	0.440		0.056	16.220	1.840	0.339			0.061	17.680	2.005	0.370	

level of sustainability of the transport system considered, as resulting from the combined effect of the distance travelled and the type and energy efficiency of the means utilised, is reflected upon the sustainability of the material commodity delivered.

This study investigated and compared four different scenarios of the freight transport sector under uni- and multimodality conditions, on an equal base of route between supplier and customer for the case of Italy. The environmental benefits of the multi-modal scenarios over the uni-modal were highlighted in this study, in line with the related literature. The best performing option is represented by the multimodal scenario where all the three freight means, namely ship, train and truck, were provided. However, this is not practicable for several reasons mainly related to problems in properly controlling and monitoring each step of the way, as well as to the increase in operational costs. This is why companies like the one which supported this study development generally opt for alternatives that are based upon using two transport modes, like done in scenarios 1 and 2 that showed indeed a quite comparable environmental behaviour and are considered as absolutely viable options.
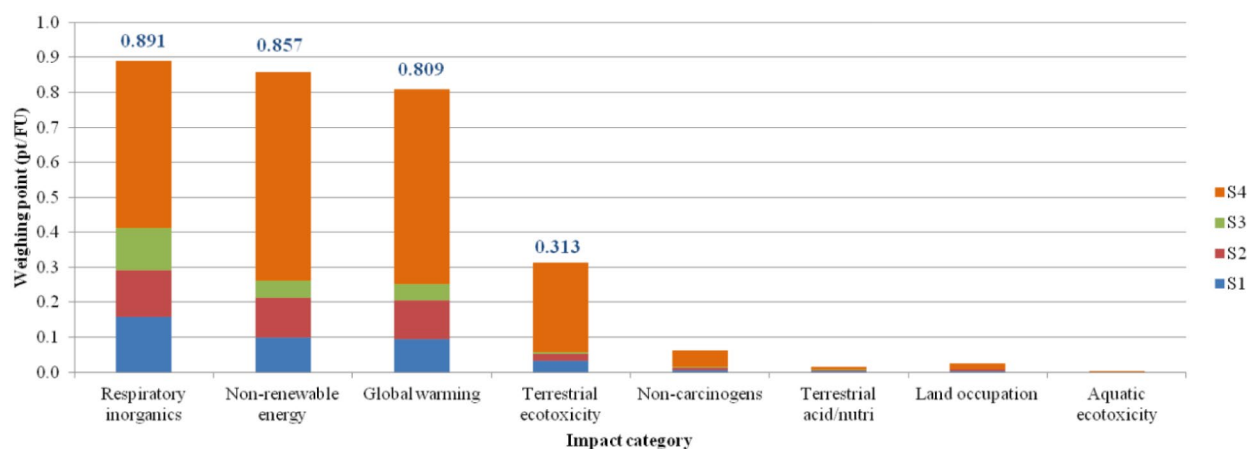
Estimation of the most environmentally damaging emitted pollutants and resources consumed was performed in this study. Fundamentally, they were documented as falling within four major impact categories, which are 'Non-renewable energy', 'Global warming', 'Respiratory inorganics', and 'Terrestrial ecotoxicity' and belong, in turn, to the following damage categories: 'Resources', 'Climate change, 'Human health' and 'Ecosystem quality'. These can be read as the indicators of environmental impact and damage that best describe the system investigated and are recommended by this author team to be accounted for in future assessments in the transport sector.

The incidence on those damage categories was found to be in the range of 96–99% for 'Resources', 97–98% for 'Climate change', 87.5–96% for 'Human health' and 84–96% for 'Ecosystem quality'.

Emission of fossil carbon dioxide deriving from the combustion of the fossil fuel consumed in the transport activity, and other relevant emissions such nitrogen oxides, sulphur dioxide and particulates, as well as primary-energy resource exploitation were documented to be higher in the uni-modal scenario than in the multi-modal scenarios, due to the use of a truck for the entire route.

Impact on 'Land occupation' for establishment of road and rail networks and related infrastructures was also explored because, although far less alarming than the other categories, it is however representative of such transport systems and so is desirable to be accounted in the assessment.

Although site-specific, the results from this study may be of support to logistics companies as well as to policy and decision makers to identify and promote environmentally

Fig. 5 Representative midpoint indicators (impact categories) for all transport scenarios investigated (Weighing point were reported just for the four most significant ones)

Impact category	Unit of measure, equivalent	Scenario			
		1	2	3	4
Aquatic ecotoxicity	kg TEG water	8.51E+04	1.05E+05	3.43E+04	5.93E+05
Global warming	kg CO_2	938.792	1084.994	480.219	5503.228
Non-carcinogens	kg C_2H_3Cl	15.563	19.141	5.749	113.434
Non-renewable energy	MJ primary	1.52E+04	1.69E+04	7.49E+03	9.07E+04
Respiratory inorganics	kg $PM_{2.5}$	1.589	1.361	1.231	4.843
Terrestrial acid/nutri	kg SO_2	39.139	29.866	31.725	102.084
Terrestrial ecotoxicity	kg TEG soil	5.43E+04	3.47E+04	1.17E+04	4.41E+05
Land occupation	PDF*m^2*yr	28.198	53.863	9.235	237.145

optimal freight transport solutions, so contributing to enhancing sustainability of the transport sector in a sustainable IE context.

Furthermore, in line with the specialised literature currently available in the field, through this study the endpoint approach was documented as useful when assessing improvements or conducting comparative analyses of different systems, because it enables global evaluation and rating of those systems on the same scale of damage points.

Finally, it should be observed that the study was focussed upon the environmental aspects connected with freight transport, but the authors understand the importance of additional, relevant issues like the economic one to be assessed. For reasons of giving due importance to both of these sustainability spheres, the authors will devote an entire paper to the economic assessment, with the final aim of checking whether economic results are in line with the environmental ones obtained in this study, or whether there is contradictory and whether further trade-offs need to be found subsequently. In addition to this, further studies could be developed by the authors to deepen issues related to collection of additional inventory data coming from elaboration of geospatial information about land use through GIS tools, so further contributing to the modelling step.

Author contributions Carlo Ingrao: Study conceptualisation; life cycle assessment setting and development; data curation; original draft writing; supervision. Flavio Scrucca: life cycle impact assessment; software; original draft writing. Agata Matarazzo: data curation. Claudia Arcidiacono: original draft writing; reviewing and editing. Anastasia Zabaniotou: reviewing and editing.

References

Ambarwati L, Verhaeghe R, Arem BV, Pel AJ (2017) Assessment of transport performance index for urban transport development strategies — incorporating residents' preferences. Environ Impact Assess Rev 63:107–115

Andersen O (2002) Transport of fish from Norway: energy analysis using industrial ecology as the framework. J Clean Prod 10:581–588

Arcidiacono C, Porto SMC (2010) A model to manage crop-shelter spatial development by multi-temporal coverage analysis and spatial indicators. Biosyst Eng 107(2):107–122

Arcidiacono C, Porto SMC (2012) A set of landscape indicators to describe environmental impacts of crop-shelter coverage. Acta Hortic 937:1011–1018

Ardente F, Cellura M, Brano VL, Mistretta M (2010) Life cycle assessment-driven selection of industrial ecology strategies. Integr Environ Assess Manag 6(1):52–60

Arzoumanidis I, Petti L, Raggi A, Zamagni A (2013) Life cycle assessment for the agri-food sector. In: Salomone R, Clasadonte MT, Proto M, Raggi A (eds) Product-oriented Environmental Management Systems (POEMS). Springer Science+Business Media, Dordrecht, The Netherlands, pp 105–122

Asdrubali F, Baldinelli G, Scrucca F (2015) Comparative life cycle assessment of an innovative CSP air-cooled system and conventional condensers. Int J Life Cycle Assess 20:1076–1088

Chiu ASF, Yong G (2004) On the industrial ecology potential in Asian developing countries. J Clean Prod 12:1037–1045

Clasadonte MT, Lo Giudice A, Matarazzo A (2013) Guidelines for environmental labels in the agri-food SMEs. In: Salomone R, Clasadonte MT, Proto M, Raggi A (eds) Product-oriented Environmental Management Systems (POEMS). Springer Science+Business Media, Dordrecht, The Netherlands, pp 203–243

De Benedetto L, Klemeš J (2009) The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process. J Clean Prod 17(10):900–906

Desrochers P (2004) Industrial symbiosis: The case for market coordination. J Clean Prod 12:1099–1110

Duan H, Hu M, Zhang Y, Wang J, Jiang W, Huang Q, Li J (2015) Quantification of carbon emissions of the transport service sector in China by using streamlined life cycle assessment. J Clean Prod 95:109–116

Ecoinvent (2018) The Swiss Centre for Life Cycle Inventories. Ecoinvent v3.5

European Commission (EU) (2018) Communication from the commission to the European parliament, the European council, the council, the European economic and social committee, the committee of the regions and the European investment bank - A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM 2018:773

European Environmental Agency (EEA) (2019) Greenhouse gas emissions from transport in Europe. Available: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12 (Accessed: September 28, 2020)

Forsberg A, von Malmborg F (2004) Tools for environmental assessment of the build environment. Build Environ 39:223–228

Geyer R, Stoms DM, Lindner JP, Davis FW, Wittstock B (2010) Coupling GIS and LCA for biodiversity assessments of land use. Int J Life Cycle Assess 15(5):454–467

Heinonen J, Junnila S (2011) A carbon consumption comparison of rural and urban lifestyle. Sustainability 3(8):1234–1249

Ingrao C, Messineo A, Riccardo B, Yigitcanlar T, Ioppolo G (2018) How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance. J Clean Prod 201:556–569

Ingrao C, Selvaggi R, Valenti F, Matarazzo A, Pecorino B, Arcidiacono C (2019) Life cycle assessment of expanded clay granule production using different fuels. Resour Conserv Recy 141:398–409

ISO (International Organization for Standardization) (2006a) 14040-Environmental Management - Life Cycle Assessment e Principles and Framework

ISO (International Organization for Standardization) (2006b) 14044-Environmental Management - Life Cycle Assessment - Requirements and Guidelines

Jolliet O, Manuele M, Raphael C, Sébastian H, Jérome P, Gerald R, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8(6):324–330

Kaack LH, Vaishnav P, Morgan MG, Azevedo IL, Rai S (2018) Decarbonizing intraregional freight systems with a focus on modal shift. Environ Res Lett 13(8):083001

Kamal-Chaoui L, Alexis R (eds.) (2009) Competitive Cities and Climate Change, OECD Regional Development Working Papers N° 2, 2009, OECD publishing, © OECD

Kreutzberger E, Macharis C, Vereecken L, Woxenius J (2003) Is intermodal freight transport more environmentally friendly than all-road freight transport? A review. NECTAR Conference No 7

Lee S-Y, Klassen RD (2008) Drivers and enablers that foster environmental management capabilities in small- and medium-sized suppliers in supply chains. Prod Oper Manag 17(6):573–586

Lifset R, Graedel TE (2002) Industrial ecology: goals and definitions. In: Ayres RU, Ayres LW (eds) A Handbook of Industrial Ecology, 1st edn. Edward Elgar Publishing Ltd., Cheltenham, pp 3–15

Mattila T, Helin T, Antikainen R, Soimakallio S, Pingoud K, Wessman H (2011) Land use in life cycle assessment, THE FINNISH ENVIRONMENT INSTITUTE 24 | Helsinki ISBN 978–952–11–3926–0 (available at: https://core.ac.uk/download/pdf/14925706.pdf. Accessed on 18 November 2019)

Nahlik MJ, Kaehr AT, Chester MV, Horvath A, Taptich MN (2015) Goods movement life cycle assessment for greenhouse gas reduction goals. J Ind Ecol 20(2):317–328

Patella SM, Scrucca F, Asdrubali F, Carrese S (2019) Carbon Footprint of autonomous vehicles at the urban mobility system level: A traffic simulation-based approach. Transportation Research Part D: Transport and Environment 74:189–200

Pizzol M (2019) Deterministic and stochastic carbon footprint of intermodal ferry and truck freight transport across Scandinavian routes. J Clean Prod 224:626–636

Prè (2019) LCA software and database manual. Prè Consultants BV, Amersfoort, The Netherlands

Robertson GL (2013) Food packaging – principles and practice, 3rd edn. Taylor & Francis Group LLC, Boca Raton, FL, USA

Sarwat AI, Sundararajan A, Parvez I, Moghaddami M, Moghadasi A (2018) Toward a smart city of interdependent critical infrastructure networks. In: Amini MH, Boroojeni KG, Iyengar SS, Pardalos PM, Blaabjerg F, Madni AM (eds) Sustainable Interdependent Networks - from Theory to Application, Studies in Systems, Decision and Control 145. Springer International Publishing, Cham, pp 21–45

Seroka-Stolka O, Ociepa-Kubicka A (2019) Green logistics and circular economy. Transp Res Proc 39:471–479

Steadieseifi M, Dellaert NP, Nuijten W, Van Woensel T, Raoufi R (2014) Multimodal freight transportation planning: a literature review. Eur J Oper Res 233(1):1–15

Tang B-J, Li X-Y, Yu B, Wei Y-M (2019) Sustainable development pathway for intercity passenger transport: a case study of China. Appl Energy 254:113632

Taptich MN, Horvath A, Chester MV (2015) Worldwide greenhouse gas reduction potentials in transportation by 2050. J Ind Ecol 20(2):329–340

Traverso M, Finkbeiner M, Jørgensen A, Schneider L (2012) Life cycle sustainability dashboard. J Ind Ecol 16(5):680–688

Trombulak SC, Frissell CA (2000) Review of ecological effects of roads on terrestrial and aquatic communities. Conserv Biol 14(1):18–30

Udo de Haes HA (2002) Industrial ecology and life cycle assessment. In: Ayres RU, Ayres LW (eds) A Handbook of Industrial Ecology. Edward Elgar, Cheltenham, pp 138–148

Vidal R, López-Mesa, B (2006) Impact indicators in transport infrastructures: a new market for engineering design researchers. International Design Conference - Design 2006 Dubrovnik - Croatia, May 15 - 18, 2006

Zamagni A, Masoni P, Buttol, P, Raggi A, Buonamici R (2012) Finding Life Cycle Assessment Research Direction with the Aid of Meta-Analysis. J Ind Ecol 16(SUPPL.1):S39–S52