Evaluation of COLDTAINER's economic and environmental benefits

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Introduction

Sustainability has recently taken on a dramatic general relevance due to the clear effects of Global Warming. Sustainability is a priority theme in new European strategies such as the Road Map 2050, the Next Generation EU, and at a national level the recent Integrated National Plan for Energy and Climate for the years 2021 - 2030 (PNIEC) and the National Recovery Plan and Resilience (PNRR).

Since 2022, sustainability has taken on a new technical, economic, and social relevance given the challenges introduced by the Sustainable Development Goals (SDGs), the COVID-19 pandemic and the war on the energy sector, i.e., the difficulty in procuring methane gas and the considerable increase in the costs of energy vectors [1, 2]

Refrigeration systems play a key role in temperature-controlled transportation of perishable products, such as fresh and frozen foods and pharmaceuticals. Refrigerated transport is critical not only in terms of maintaining the temperature integrity of the products but also in terms of the environmental impact in terms of energy consumption and greenhouse gas and particulate emissions. Temperature-controlled transportation exhausts more emissions than ambient temperature transport because of the extra fuel requirements for cooling and because of leakage of refrigerant.

A recent report by the International Energy Association [3, 4] highlighted that the transport sector represents approximately 26% of total energy consumption, consumption increased by approximately 4% in 2022, continuing to rise towards pre-Covid levels. Furthermore, electricity demand from road transport was almost 60% higher in 2022 than in 2019. Related CO_2 emissions from transport also continued to grow in 2022, returning almost to 2019 levels: in 2022, global CO_2 emissions from the transport sector grew by more than 250 Mt CO_2 to almost 8 Gt CO_2, 3% more than in 2021: a level 71% higher than what was seen in 1990. The highest absolute increase was in road transport (although in relative terms bunkers increased the most). Overall, the share of road transport emissions points to about 73%. Current transportation systems are far from being efficient and this issue is more severe in temperature-controlled transportation systems for which additional energy is needed to regulate temperature and ensure quality, product safety, and shelf-life [5,6]. Greenhouse gas emissions from conventional diesel engine vapor compression refrigeration systems can reach about 40% of the total vehicle's emissions [7]. Even though the efficiency of refrigerated equipment is constantly progressing, the refrigeration demand is expected to grow in the coming years because of an increasing demand of goods and of higher requirements imposed by quality, hygiene, and safety standards. For instance, a 60% increase in food demand is expected by 2050 [8]. At the same time, the recent climate change increases the likelihood of more extreme temperatures and unpredictable weather events, which affects the production process of perishable products and requires more refrigeration.

EU and UK legislation covers temperature control requirements during the storage and transport of perishable foods. These regulations were revised in early 2006 and regulation EC No. 852/ 2004 on the Hygiene of Foodstuffs requires manufacturers to have suitable temperature-controlled handling and storage facilities that can maintain food at appropriate temperatures and enable these temperatures to be monitored controlled and recorded. The transport of perishable food products, other than fruit and vegetables, and the equipment used for the carriage of these products is governed by an agreement drawn by The Inland Transport Committee of the United Nations Economic Committee for Europe in 1970–1971. The agreement is known as the Agreement on Transportation of Perishable foodstuff (ATP), which aims to facilitate international traffic by setting common internationally recognised standards for temperature-controlled transport vehicles such as road vehicles, railway wagons, and sea containers. The ATP certificate ensures that the insulated body and the refrigeration unit have been tested by a third party and that the two have been appropriately matched. An ATP-certified vehicle or body could carry a single certificate that covers both the insulated body and the refrigeration unit. However, refrigerated transport is not subject to energy efficiency requirements. The equipment used to transport refrigerated goods internationally would be particularly complex to regulate due to the lack of clarity of ownership and their operation across EU borders [9].

The most common drive systems for refrigerated transport vapor compression systems are vehicle alternator units (commonly used in small delivery vans), direct belt drives, auxiliary alternator units, and auxiliary diesel units (used in the vast majority of medium to large vehicles). The performance and power requirements of transport refrigeration systems are normally assessed at full load. However, these systems operate over a wide range of loads. To match the varying load, the refrigeration system is either switched on and off, or its capacity is modulated to maintain the set temperature with a consequent reduction in efficiency. This is particularly relevant for multi-drop deliveries since they are characterized by multiple doors opening which result in increased variability of the inside temperature due to the air infiltration.

Moreover, the performance of insulation materials deteriorates with time due to the inherent foam characteristics. Recent data show a typical loss of insulation value of between 3% and 5% per year which can lead to a considerable rise in the thermal conductivity after a few years resulting in increased energy consumption and CO_2 emissions [7]. Reducing the overall environmental impact of refrigerated road transport systems, which highly contributes towards global warming and climate change, and developing sustainable designs are imperative for the cold chain industry. Decarbonization of road transport vehicles is associated with some challenges, one of which is refrigerant leakage. Leakage of refrigerant gases from these systems impacts the environment in two ways [10]: a direct effect due to the global warming potential of the leaked gas, and an indirect effect due to the decreased efficiency of the refrigeration system (due to the loss of charge) which leads to increased energy consumption. Annual leak rate can be an average of 11% and, in some cases, up to 30% [11]. Refrigerant leakage can also have a significant financial impact on the user depending on how quickly the leak is found and repaired.

Portable refrigerated units (PRU) represent a novel solution that can be used by logistic companies to offer their customers a refrigerated transport service for small and medium volumes (e.g., Less than truckload transport) of perishable goods on board their standard vehicles, without the need for investment in special vehicles and infrastructures. The use of this solution can lead to relevant economic and environmental benefits concerning the traditional refrigerated transport which is usually belt-driven from the vehicle engine with diesel as the fuel source.

Research objectives

The objective of this study consists of the economic and environmental comparison of two logistic systems for refrigerated transport services for small and medium volumes. The comparison involves (1) a traditional refrigerated transport, which consists of a vehicle aftermarket equipped with a refrigeration system belt-driven from the vehicle engine with diesel as the fuel source, and (2) a novel solution characterized using portable refrigerated units.

In the following, the relevant elements related to traditional and novel refrigeration systems are presented. Then, a description of the methodology and models used for the economic and environmental comparison is defined, detailing configuration parameters and performance. Finally, the results of the comparison are presented for the considered scenarios.

Portable Refrigerated Units

Description and features of Portable Refrigerated Units

Portable refrigerated units are made of polyethylene for food use with a rotational molding technology, which allows to obtain unique impact-resistant cable bodies. Such containers can be easily sanitized in compliance with regulation No. 852/2004 of the European Parliament (HACCP). The thermal insulation is made of expanded polyurethane, with thickness ranging from 65 to 130 mm. Furthermore, the larger models are tested under ATP regulations and have a technical dispersion coefficient "K" less than 0.40 Wm^2/K.

The refrigeration units use Secop hermetic compressors (12-24Vdc), developed specifically for use on vehicles and therefore with low absorption and can function perfectly even in the presence of vibrations and angles up to 30°C. Coolant gas is R134a, non-flammable, and compatible with environmental regulations, for + 4 °C solutions while R404a is for – 20 °C solutions.

Transport and storage of Portable Refrigerated Units

The use of active refrigerated containers simplifies different phases of the cold chain with an obvious reduction in direct and indirect costs, a significant improvement in delivery time, and a reduction in the risk of food contamination and breaks in the chain itself. This entails environmental benefits in terms of reducing energy consumption and CO2 emissions. This technology simplifies the transport and storage of refrigerated goods.

From the storage point of view, containers can be placed in non-refrigerated traditional warehouses and used as a local refrigerated space by connecting them to the power supply. This allows you to not make specific refrigerated warehouses while avoiding investments. From the transport point of view, these containers can therefore be loaded directly with a forklift truck on an un-refrigerated truck (powered by 12V/24V batteries of the vehicle) for direct delivery to their destination. This system therefore eliminates the need for specialized refrigerated vehicles.

PRUs also enable the joint delivery and storage of refrigerated and non-refrigerated goods, since they allow to set different temperatures to each unit avoiding the deterioration of products. In the food supply chain where the temperature, relative humidity, hygienic conditions and possibly even air composition must be strictly controlled and monitored to accelerate or slow down the product aging process (controlled atmospheres). PRUs allow also to avoid the partitioning of the warehouse into smaller cells for the preservation of goods with similar characteristics.

Methodology

To compare the traditional refrigerated transportation and the solution based on the use of portable refrigerated units, two models have been proposed: one for the environmental impact evaluation, and the other for the economic assessment. Specifically, for the economic evaluation, the *Total Cost of Ownership* (TCO) is used, which allows to calculate the total cost made up of all the costs of the use cycle, from purchase to installation, operation, and maintenance. The environmental assessment is based on the calculation of the *carbon footprint* that quantifies the CO_2 emissions linked to the life cycle. The first subsection proposes the formulation of the models used for the environmental and economic assessments. Then, the second subsection defines the problem and the methodology applied for the case study.

Models formulation

Economic analysis

The main parameters related to the transport activities employed for the economic analysis are the following:

- Delivery schedules (i.e., distance covered, time limit, mean seed, etc.)
- Transport vehicles features
  - Tare
  - Fuel consumption coefficient for both motive and refrigeration functions, different for any vehicle type
  - Cargo capacity (weight), different for any vehicle type
  - Refrigerant charge and related leakage
- Fuel and refrigerant unit cost
- Units features (i.e., volume and tare)
- Cargo capacity as number of units, different for any vehicle types, and it depends on type of units considered.

The two scenarios (i.e., traditional refrigerated transport and Coldtainer solutions) are compared based on the TCO, which defines the overall cost of owning and using the specific vehicle for the refrigerated transportation (1). Specifically, from the time of purchase, through its operation and maintenance to the time it leaves the possession of the owner. The relevant costs investigated are the purchasing cost given by the investment cost in the vehicle and in the refrigeration system, I_0, the annual operation costs dealing with the fuel and refrigerant consumptions and the quality depletion, O_i, and the annual cost for the maintenance interventions on the refrigeration system, M_i. To make the results comparable the same period of time, N, should be considered, hence we introduced also the residual value of the vehicle and refrigeration system, RV_N. It has been assumed a straight-line depreciation of the equipment.

$$TCO = I_0 + \frac{\sum_{i=1}^{N}(O_i + M_i + RV_N)}{(1+\rho)^i} \tag{1}$$

$$I_0(€) = \begin{cases} pc^{trailer} + pc^{trad} & Trad \\ pc^{trailer} + pc^{PRU}n^{PRU} & PRU \end{cases} \tag{2}$$

$$O_i\left(\frac{€}{year}\right) = \begin{cases} \left(\frac{D^T}{fc}e + C^{\,trad}\,LR^{trad}\,V\,rc + p\left(1 - e^{-k\cdot T^T}\right)W^F n^{SKU}\right)n_{trip} & Trad \\ \left(\frac{D^T}{fc}e + C^{PRU}\,LR^{PRU}\,n^{PRU}\,rc\right)n_{trip} & PRU \end{cases} \tag{3}$$

$$M_i = mc \cdot n^M \tag{4}$$

$$RV_N = \begin{cases} \frac{pc^{trailer}}{N_{trailer}}(N_{trailer} - N) + \frac{pc^{trad}}{N_{trad}}(N_{trad} - N) & Trad \\ \frac{pc^{trailer}}{N_{trailer}}(N_{trailer} - N) + \frac{pc^{PRU}}{N_{PRU}}(N_{PRU} - N) & PRU \end{cases} \tag{5}$$

where $n_{trip} = ruondup\left\{\frac{D}{W^F \cdot n^{SKU}}\right\}$ for the traditional refrigerated transportation, while $n_{trip} = ruondup\left\{\frac{D}{W^F \cdot n^{PRU}}\right\}$ for the transport with PRU solution.

Environmental analysis

The proposed environmental analysis is focused on the carbon footprint of the two solutions. Emissions are mainly directly generated from the refrigerant consumption due leakages - (6) and (8), and indirectly from the engine fuel consumption - (7) and (9).

$$E_{ref}\left(kg_{CO_2eq}/trip\right) = C^{trad} \cdot LR^{trad,x} \cdot V \cdot en_{CO_2}^{ref} \tag{6}$$

Traditional solution

$$E_{fuel}\left(kg_{CO_2eq}/trip\right) = \frac{D^T}{fc^{trad,x}} \cdot en_{CO_2}^{diesel} \tag{7}$$

PRU solution

$$E_{ref}\left(kg_{CO_2eq}/trip\right) = C^{PRU} \cdot LR^{PRU,x} \cdot n^{PRU} \cdot en_{CO_2}^{ref} \tag{8}$$

$$E_{fuel}\left(kg_{CO_2eq}/trip\right) = \frac{D^T}{fc^{PRU,x}} \cdot en_{CO_2}^{diesel} \tag{9}$$

where x defines the type of product considered and consequently the refrigeration requirements (i.e., chilled or frozen). Hence, the annual total emissions are given by the sum of the two contributions times the number of trips needed to satisfy the yearly demand, n_{trip}.

Problem definition

The case study performed focuses on the food distribution, in which refrigerated shipments are used to supply stores, community and for home deliveries. In this kind of shipments, cargo capacity of transport vehicles is usually much higher than required, hence, it is difficult to increase the economic and environmental performance. In multi-drop delivery schedules, there are many different points of shipments with limited goods quantities to be delivered, which means several and frequent door openings.

Two refrigeration systems (i.e., one traditional and one based on portable refrigerated unit - COLDTAINER), two food products (one chilled and one frozen), and two delivery schedules (long delivery, and multi-drop delivery) are investigated for assessment purposes. In Table 1, the route protocol for carrying out the tests is presented. While in Figure 1, the alternative refrigerated solutions are depicted.

Table 1. Route protocol for the test carried out

	Long distance	**Multi-drop**
Distance (km)	100	50
Duration (h)	2.5	2.5
Speed	avg. 50 km/h max 80 km/h	avg. 25km/h max 50 km/h
# openings	2	10

Unloading activity	1 complete at the end of the trip	1 min at every opening
Initial condition	Emptied vehicle and shut down for 12 hours. Products set at the transportation temperature	

FIAT Doblò	**COLDTAINER**	**Traditional refrigeration system**
Chilled		
Frozen		

Figure 1. Transportation modes for the different scenarios

The vehicle used for the tests is a FIAT Doblò, which can transport one SKU or PRU per trip. More information of the vehicles used for the tests are provided in Table 2. For both the refrigeration systems, the refrigerant R134a is used for the chilled product (i.e., + 4 °C), while the refrigerant R404a for the frozen product (i.e., - 20 °C).

Table 2. Information of the vehicles used in the tests

Refrigeration system	-	**Traditional +4°C**	**Traditional -20°C**
Fuel	Diesel	Diesel	Diesel
Engine size [cm^3]	1248.00	1598.00	1598.00
Identification No.	199A3000	198A3000	198A3000
Environmental class	2003/76/CE-B	195/2013	195/2013

In the PRU solution, the version F0720 of the Coldtainer has been loaded: NDN model for the transport of refrigerated products, and FDN model for the transport of frozen products. The main features of the alternative solutions are depicted in Table 3.

Table 3. Features and characteristics of the transport solutions

	Chilled (+ 4 °C)	**Frozen (- 20 °C)**
Load compartment volume (m3)	3.4	3.4
Gross weight (ton)	1.27	1.27
Gross weight with Coldtainer (ton)	1.414	1.42
Gross weight with traditional refrigeration system (ton)	1.71	1.840
Payload traditional solution (kg)	390	435
Payload Coldtainer solution (kg)	531	525
Traditional refrigeration system price (€)	11,000	12,000
Coldtainer price PRU (€)	4,000	4,900
Vehicle price (€)	19,000	19,000
Annual leakage in the traditional refrigeration system	10%	12%
Annual leakage in the Coldtainer	-	-
Unit refrigerant charge for PRU (kg/PRU)	0.135	0.304
Unit refrigerant charge for traditional (kg/m3)	0.324	0.421

In the case of Coldtainer, there are no refrigerant leaks as hermetic systems are used with welded metal pipes without junctions.

A long distance and a multi-drop transportation have been considered in the comparison between the refrigeration alternatives. Long distance transport refers to the use of refrigerated vehicles with transit times of no less than one working day. The vehicle is loaded with foodstuffs and delivered to a single customer; hence less than two door openings are expected during the voyage. On the contrary, in short-distance multi-drop refrigerated vans or small trucks products are delivered to different points (e.g., different customers). Hence, these transports are characterized by multiple door openings, short times for product temperature recovery, and generally shared cooling capacity between two or more compartments in a single vehicle (e.g., freezer and chiller compartments within the same truck).

The fuel consumption is a function of many factors, such as the speed, the amount of stops and restarts, the type of refrigeration system, and the temperature set inside the vehicle. Hence, the average amount of km traveled per liter of fuel has been measured on the field and is defined in Table 4.

Table 4. Average fuel consumption measures for long-distance (LD) and Multi-drop (M-D) routes

Average fuel consumption (km/l)	**Doblò Chilled**		**Doblò Frozen**	
	LD	M-D	LD	M-D
Traditional scenario	12.9	8.5	12.59	8.49
Coldtainer scenario	19.23	12.38	18.87	12.2

Coldtainer PRU faces lower aging, resulting in a higher lifetime and requires less maintenance, with an annual cost almost negligible assumed as 5% of the purchasing cost. While, in the traditional refrigerated system an annual intervention of maintenance is needed to maintain acceptable performance. In this case study, we assumed an annual maintenance cost for the traditional refrigeration system equals about 15% of its purchasing price. Moreover, the traditional solution limits the lifetime of both the refrigeration system and the vehicle to 12 years due to the validity of the ATP. In the case of the Coldtainer, the vehicle can also be used in the following years.

Furthermore, while conducting the tests, the temperature inside the refrigerated volume has been monitored using sensors in order to observe the variability of the same. For instance, Figure 2 shows the sensors installed to measure the temperature in different points inside the Coldtainer.

Figure 2. Temperature sensors in different points inside the Coldtainer

Results

Hypothesis and limitations

In the following, the parameters used to compare the overall costs and emissions of the traditional solution with Coldtainer are assumed as follows:

- Fuel unit cost: 1.911 €/l
- Refrigerant R134a unit cost: 27 $/kg
- Refrigerant R404a unit cost: 45 $/kg
- Demand for refrigerated goods: 100 ton/year
- Weight of food delivered in each trip: 250 kg
- Discount rate: 4%/year
- Product value: 4 €/kg
- Length of the analyses: 6 years

To perform the analyses, some simplifications have taken place which represents some limitations of the present study. For instance, the delivery schedules have been travelled at the same time to face the same external conditions (e.g., traffic, ambient temperatures). However, to do this, two vehicles have been used with different engine size, aging, payload, and driver which can affect the effective consumptions. Moreover, there is not a direct measure of the fuel consumption. Hence, it is defined only through an accurate estimation by evaluating the amount of fuel charged to fill the tank before and after the delivery schedule.

Economic analysis

In Table 5 and Figure 3, it is shown that the use of Coldtainer, as compared to the traditional solution, allows a cost saving in the six years of the analysis of about 15% in each delivery schedule (i.e., long distance, and multi-drop delivery) for both the product categories (i.e., chilled, and frozen)): i.e., about 20 k€ for the multi-drop delivery and 23 k€ for the long-distance delivery. This relevant saving is mainly due to the lower initial expenditure needed to install the refrigerated solution, the reduction of fuel and refrigerant consumption, the negligible maintenance required, and the better preservation of the product quality. Furthermore, the vehicle has a higher residual value since it is not equipped with an irreversible refrigeration system and hence has a longer lifetime (about 70% against 50% of the vehicles equipped with the traditional refrigeration system).

Table 5. Economic results for different delivery schedules, product categories, and refrigeration system

Cumulative Discounted Cash Flow	Chilled		Frozen	
	M-D	LD	M-D	LD
Traditional solution	-€ 47,964	-€ 55,455	-€ 49,145	-€ 57,374
Coldtainer solution	-€ 28,140	-€ 32,794	-€ 29,159	-€ 33,972
	-41.3%	-40.9%	-40.7%	-40.9%

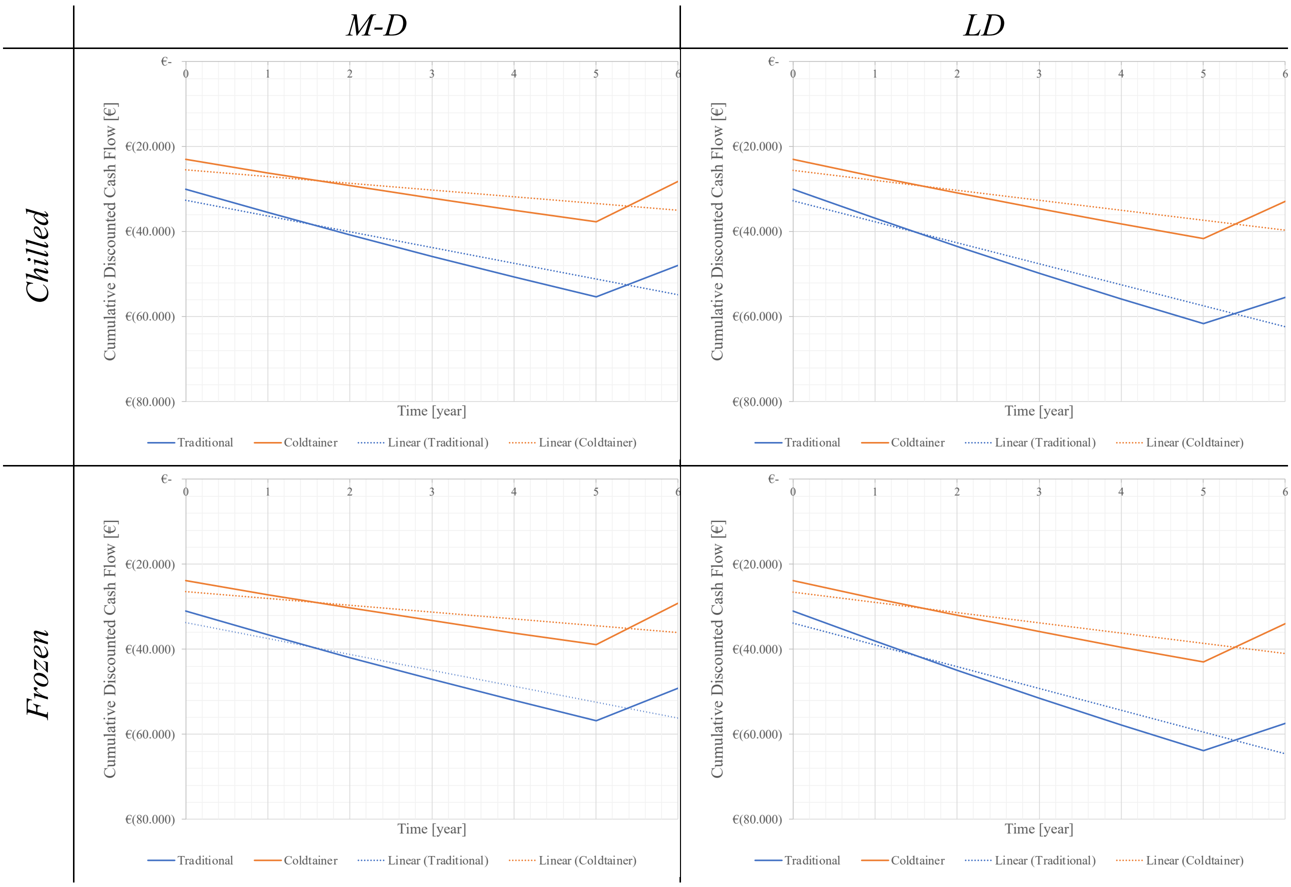
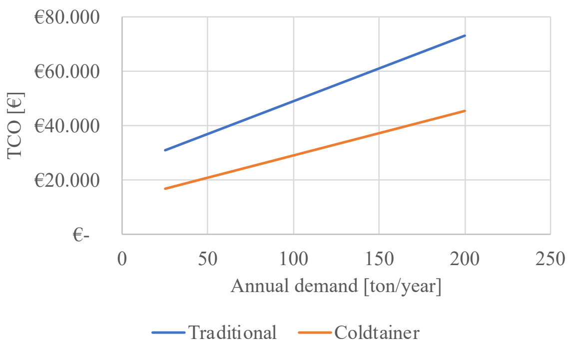
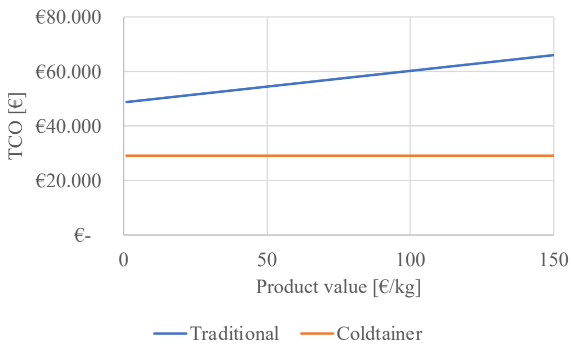


Figure 3. Cumulative discounted cash flow for the different scenarios

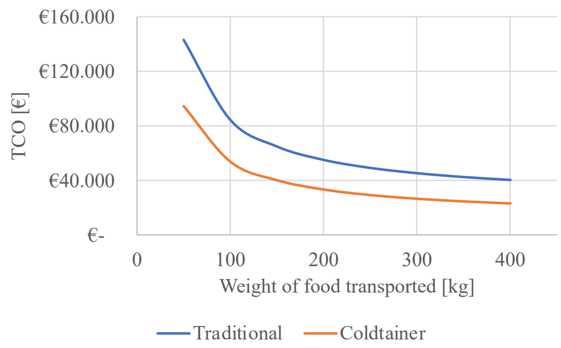
Since the results are strictly dependent on the parameters used, some sensitivity analyses have been performed for the scenario with frozen products and a multi-drop delivery schedule. Specifically,



(a)

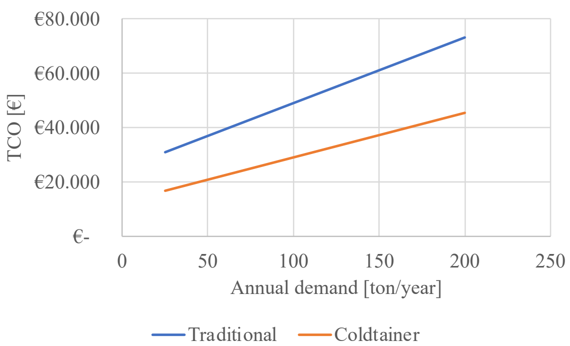


(b)

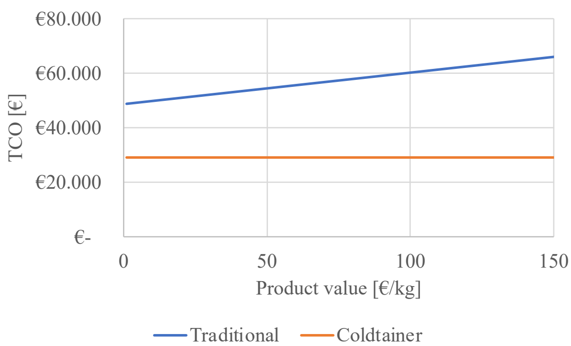


(c)

Figure 4a shows the trend of the TCO for different annual demands of the goods,



(a)



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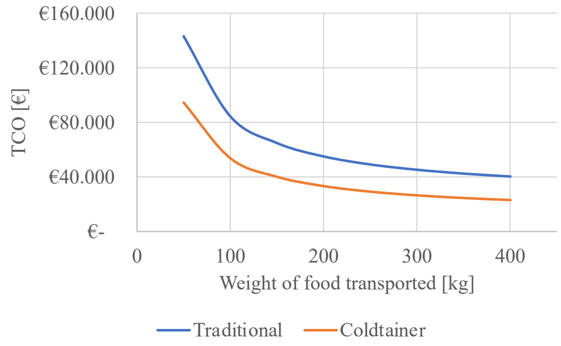
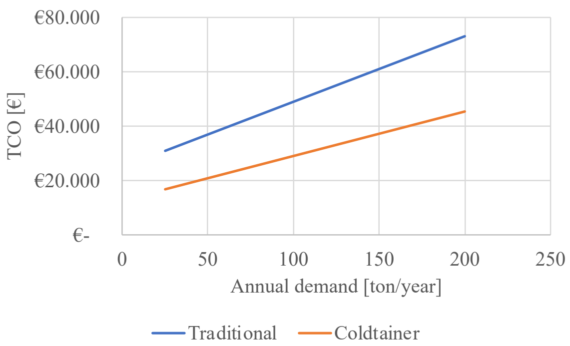


(c)

Figure 4b for different values of the delivered product, and



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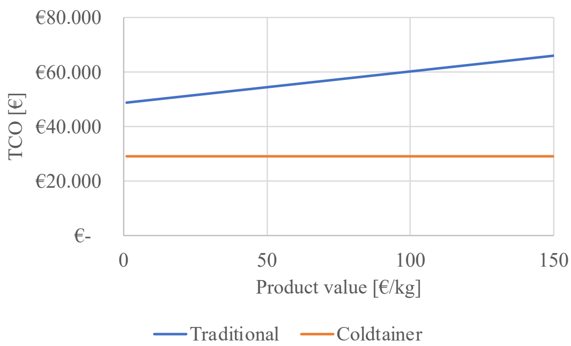

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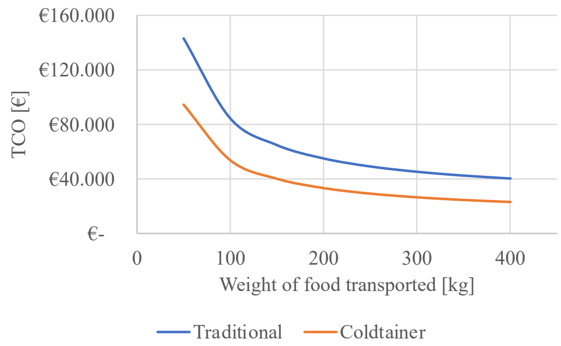
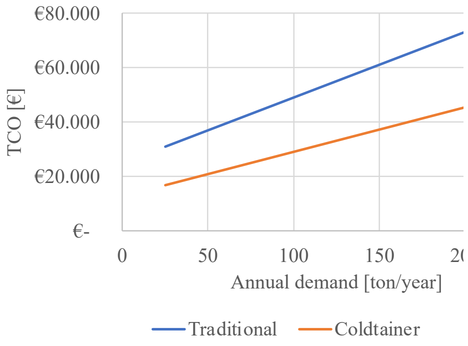
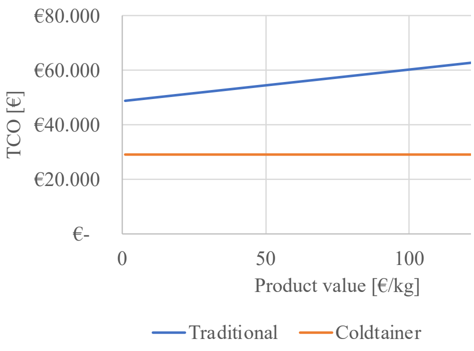


(c)

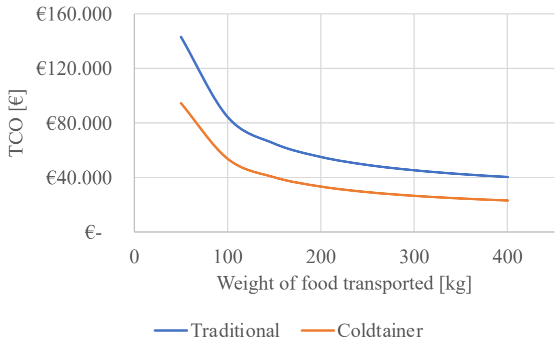
Figure 4c for different quantities of transported goods in each trip. As can be observed, lower annual demand, higher product value, and higher quantities transported each trip result in higher convenience of the Coldtainer solution over traditional refrigerated transportation.


€80.000
€60.000
€40.000
€20.000
€-
TCO [€]
0
50
100
150
Annual demand [ton/year]
Traditional
Coldtainer

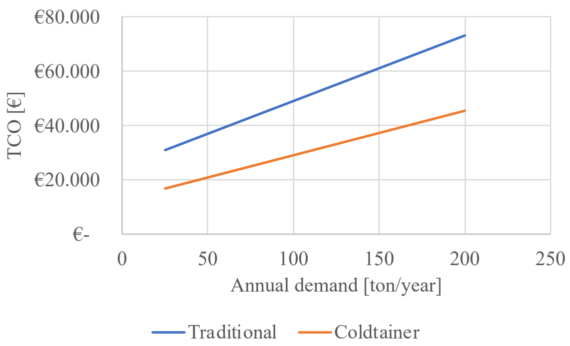
(a)


€80.000
€60.000
€40.000
€20.000
€-
TCO [€]
0
50
100
Product value [€/kg]
Traditional
Coldtainer

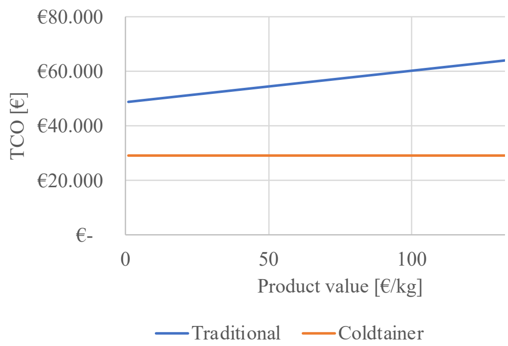
(b)


€160.000
€120.000
€80.000
€40.000
€-
TCO [€]
0
100
200
300
400
Weight of food transported [kg]
Traditional
Coldtainer

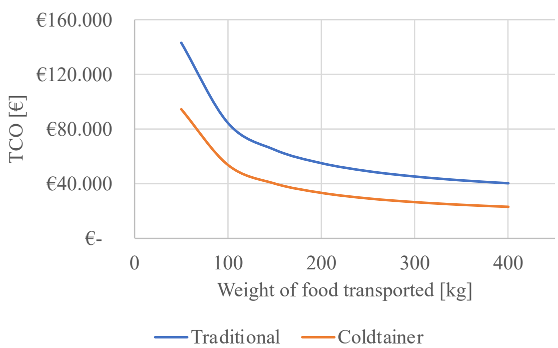
(c)


€80.000
€60.000
€40.000
€20.000
€-
TCO [€]
0
50
100
150
200
250
Annual demand [ton/year]
Traditional
Coldtainer

(a)


€80.000
€60.000
€40.000
€20.000
€-
TCO [€]
0
50
100
Product value [€/kg]
Traditional
Coldtainer

(b)


€160.000
€120.000
€80.000
€40.000
€-
TCO [€]
0
100
200
300
400
Weight of food transported [kg]
Traditional
Coldtainer

(c)

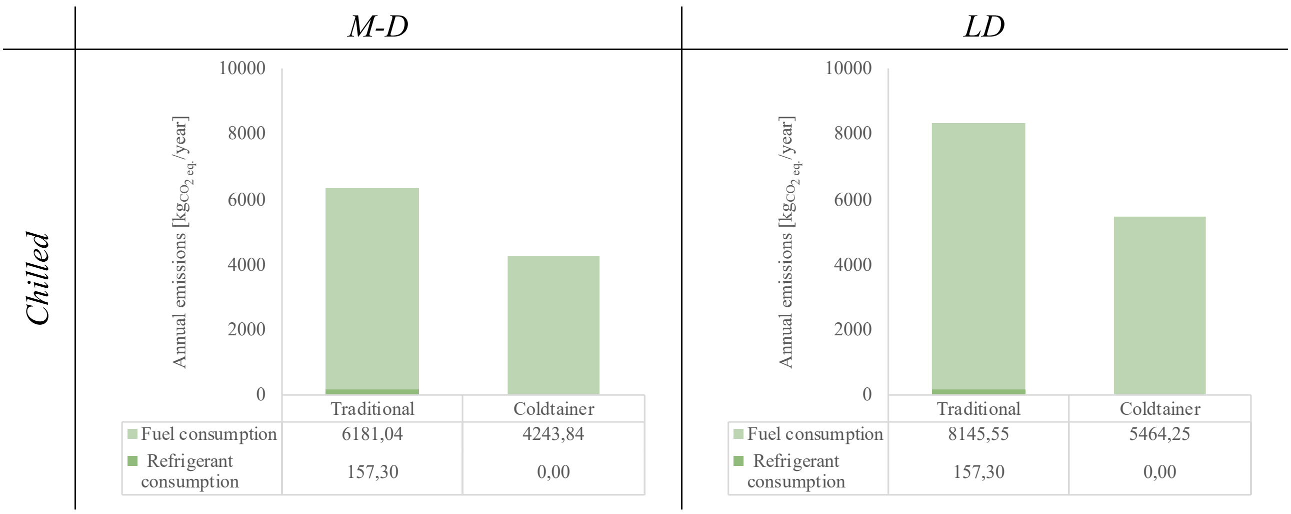
Figure 4. Sensitivity analyses on the TCO by varying: (a) the annual demand of the goods, (b) the values of the delivered product, and (c) the quantity shipped in each trip.

Environmental analysis

Considering CO_2 emissions, the Coldtainer solution achieves savings in the range of 33 - 38% depending on the product category and the delivery scheduling, corresponding to about 2.1 and 3.5 ton/year. As evidenced in Table 6 and Figure 5, the Coldtainer solution considerably limits the refrigerants leakages, which are characterized by a very high emission factor. The lower emissions of the Coldtainer solution are also due to the lower gross weight of the vehicle which means lower fuel consumption. It can also be observed that the delivery of frozen product is responsible to higher emissions related to the refrigerant leakages due to the higher emission factor of the R404a than the R134a.

Table 6. Annual CO_2 emissions for different delivery schedule, product category and refrigeration system

Annual CO_2 emissions	Chilled		Frozen	
	M-D	LD	M-D	LD
Traditional solution	6338.34	8302.85	6861.33	9019.13
Coldtainer solution	4243.84	5464.25	4306.46	5568.50
	-33%	-34%	-37%	-38%



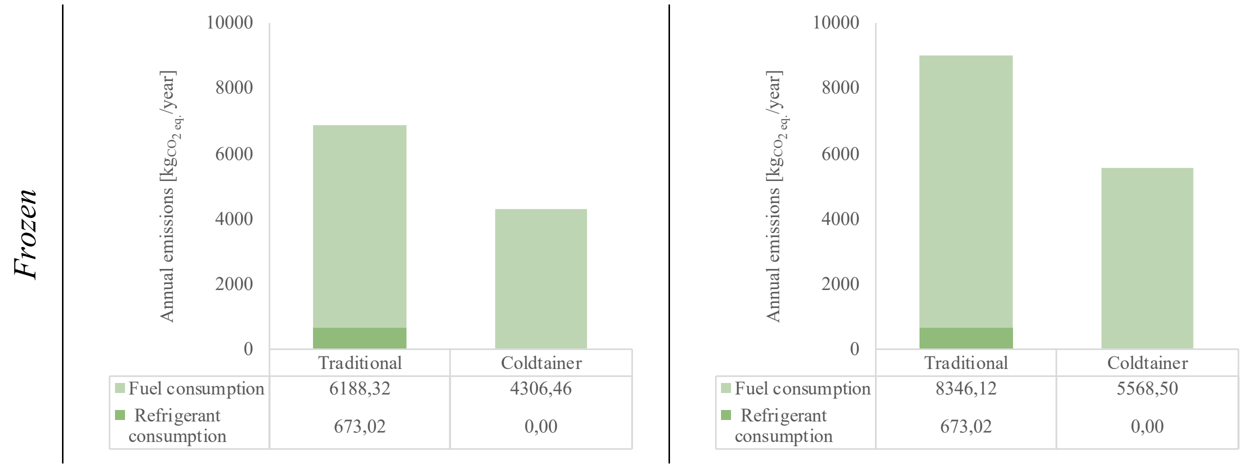
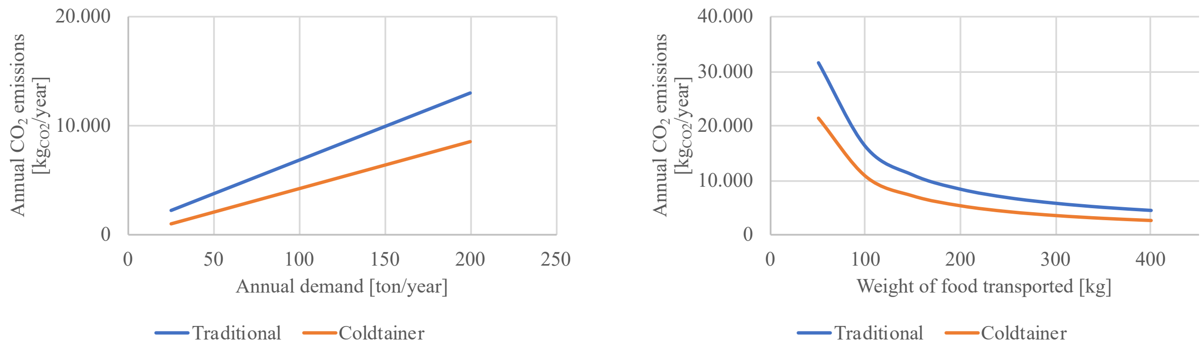


Figure 5. Annual CO_2 emissions for the different scenarios

From the sensitivity analyses it is possible to observe that lower annual demand, and higher quantities transported each trip result in higher convenience of the Coldtainer solution over the traditional refrigerated transportation from an environmental point of view (Figure 6).



(a) (b)

Figure 6. Sensitivity analyses on the annual CO_2 emissions by varying: (a) the annual demand of the goods, and (b) the quantity shipped in each trip.

Temperature behaviour

The test of the chilled product was performed the 12th of July, with the following time scheduling:

- 9.30 am to 1pm: long distance delivery,
- 1pm to 2pm: lunch break, and
- 2pm to 18pm: multi-drop delivery.

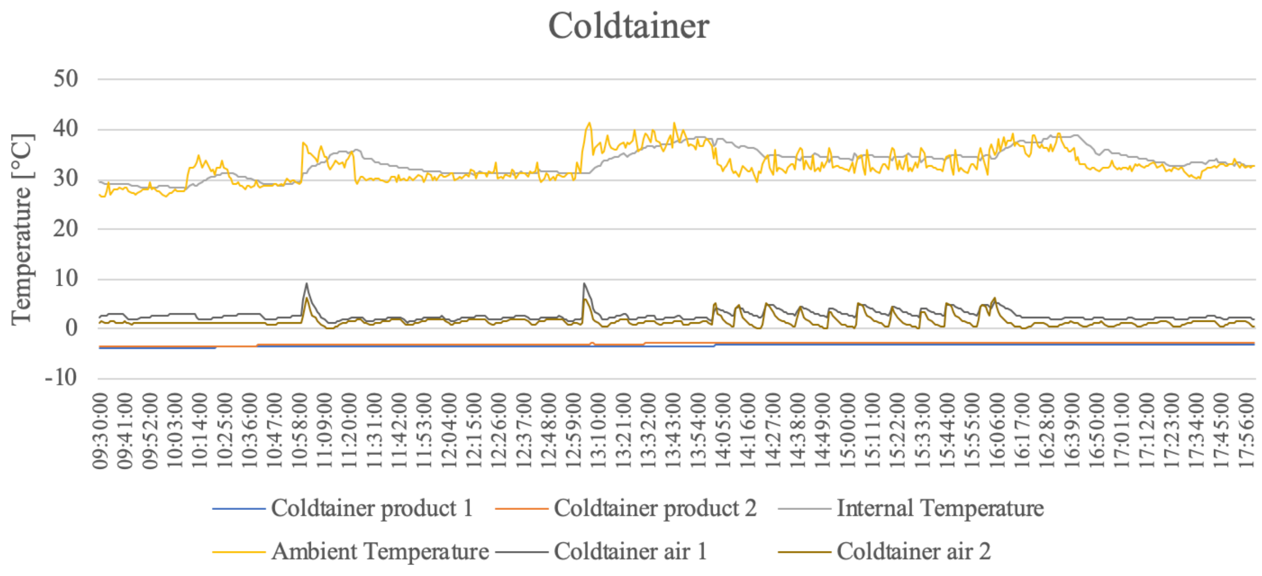


Figure 7. Sensors' measures of the temperatures inside the Coldtainer and of the chilled product (Coldtainer scenario)

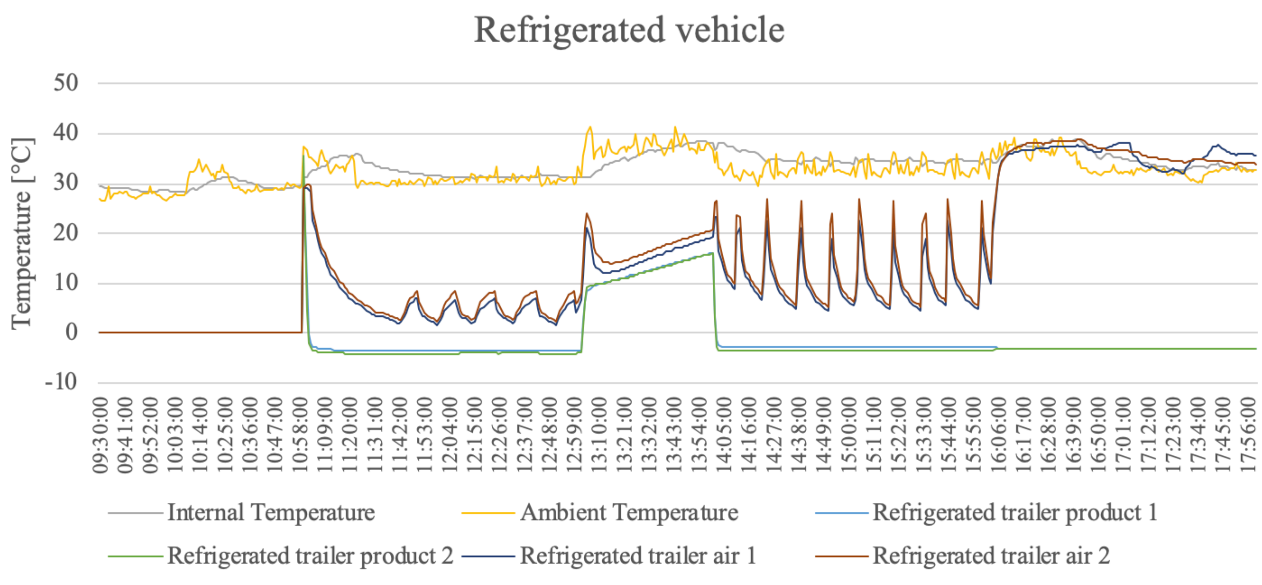


Figure 8. Sensors' measures of the temperatures inside the refrigerated vehicle and of the chilled product (Traditional refrigeration system)

The test of the frozen product was performed the 5th of September, with the following time scheduling:

- 10.10 am to 12.10pm: long distance delivery,

- 12.10pm to 2.10pm: lunch break, and
- 2.10pm to 5.10 pm: multi-drop delivery.

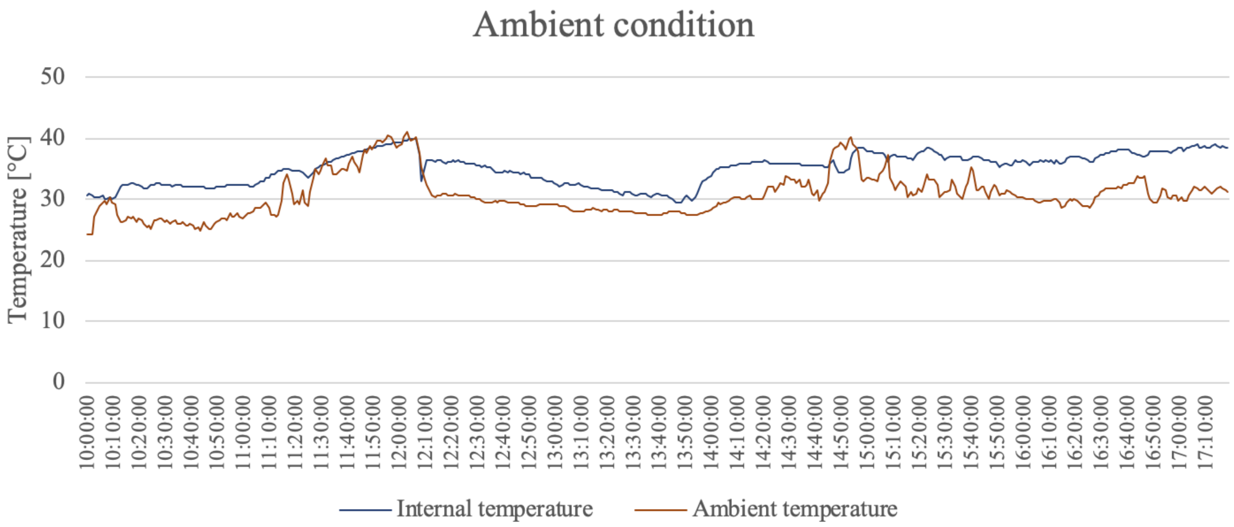


Figure 9. Internal and ambient temperatures related to the test for the frozen product

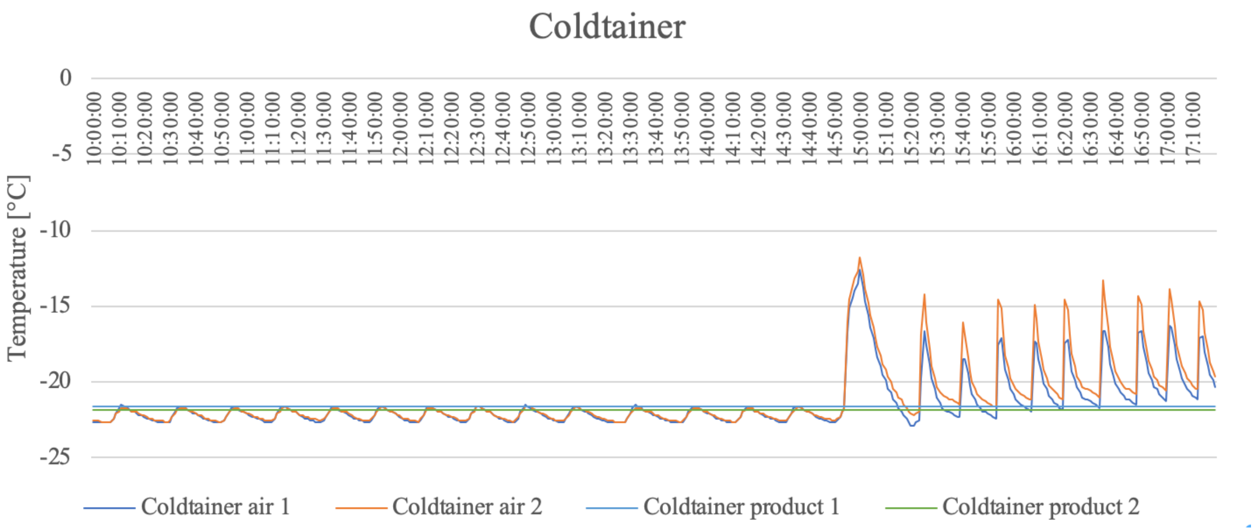


Figure 10. Sensors' measures of the temperatures inside the Coldtainer and of the frozen product (Coldtainer scenario)

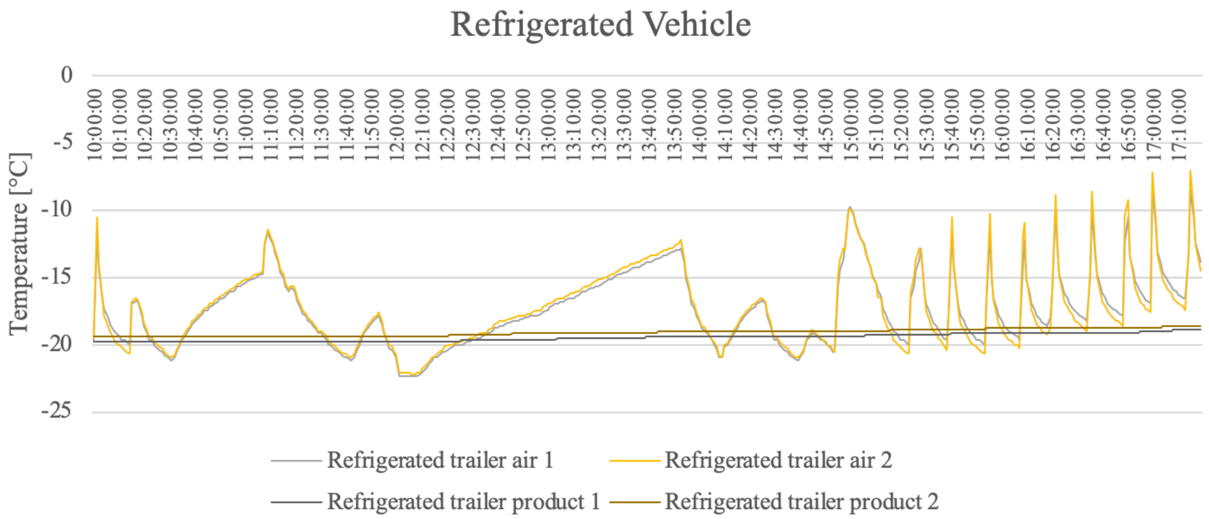


Figure 11. Sensors' measures of the temperatures inside the refrigerated vehicle and of the frozen product (Traditional refrigeration system)

The different preservation of the temperatures is evident for both the product categories (i.e., chilled, and frozen). In particular, the air temperature is subject to huge variability in the case of the traditional refrigeration system (i.e., from 0 to 30 °C in the chilled scenario, Figure 8, and from -22 to -7 °C in the frozen scenario, Figure 11). On the contrary, the Coldtainer solution keeps more stable temperatures (from 0 to 10°C in the chilled scenario, Figure 7, and from -22 to -15 °C in the frozen scenario, Figure 10). Furthermore, the product temperature is subject to lower variations in the refrigerated vehicle while not affected at all in the presence of a Coldtainer. It is interesting also to observe the increase in the product temperature during the lunch break. If the engine of the vehicle is off, the traditional refrigeration system does not work while the Coldtainer PRU continues to refrigerate the products. This behavior assures a better quality and preservation of the product in the Coldtainer scenario.

Conclusions

In conclusion, considering the scenarios defined, the logistics solutions that use Coldtainer for refrigerated transport led to a reduction of about 41% of the total cost of ownership and at the same time a reduction of about 38% of annual CO_2 emissions. These relevant savings occur for both the delivery schedules (i.e., long distance, and multi-drop) and for both the product categories (i.e., chilled, and frozen). The Coldtainer solution leads to the following benefits:

- Lower initial investments
- Reduced operational costs
- Negligible maintenance costs
- A higher residual value of the vehicle since no irreversible interventions are required
- A lower gross weight which means higher payload, lower fuel consumption, and lower CO_2 emissions
- Lower refrigerant leakage
- Better preservation of the product quality
- No loss of guarantee in the case of traditional outfitting
- No downtime for maintenance

Nomenclatures

C	unit refrigerant charge [kg/m^3 or kg/PRU]
D	yearly demand for product [kg]
D^T	reference distance covered by a refrigerated transport vehicle [km/trip]
$en_{CO_2}^{diesel}$	diesel fuel emission factor [kg$_{CO2eq}$/lt]
$en_{CO_2}^{ref}$	refrigerant emission factor [kg$_{CO2eq}$/kg]
e	unit fuel cost [€/lt]
fc	fuel consumption for motive purpose [km/lt]
k	quality depletion coefficient [h^{-1}]
LR	leakage of refrigerant [%/trip]
mc	cost for the maintenance intervention [€/intervention]
N	time period considered for the analyses [years]
$N_{trailer}$	lifetime of the vehicle [years]
N_{trad}	lifetime of the traditional refrigerated system [years]
N_{PRU}	lifetime of the PRU unit [years]
$n^{M,trad}$	amount of maintenance intervention for the refrigeration system [year^{-1}]
n^{PRU}	number of PRU units per trip
n^{SKU}	number of SKU per trip
n_{trip}	number of trips to satisfy the yearly demand [trip/year]
p	value of the product [€/kg]
$pc^{trailer}$	purchase cost of the vehicle [€]
pc^{trad}	purchase cost of the refrigeration system in the traditional scenario [€]
pc^{PRU}	purchase cost for each PRU unit [€]
ρ	discount rate [%/year]
rc	unit refrigerant cost [€/kg]
T^T	reference transport activity time requiring refrigeration per trip [h/trip]
V	inside volume of the vehicle [m^3]
W^F	weight of food related to each SKU or PRU unit [kg]

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