Multi criteria decision analysis for improving cold chain sustainability

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Abstract: Cold chains are responsible of significant energy requirements at each stage of the chain (i.e., refrigerated transport, processing, and storage) with large potentials for savings. An accurate refrigeration is required for the optimal preservation of perishable goods. A critical aspect is represented by the trade-off between the energy required for refrigeration and quality issues. The present study aims to assess the improvement that can be reached in terms of sustainability of cold chains, while varying the temperature set for the raw material, the finished product, and the lot size (which impacts the storage time). Since sustainability can be achieved while optimizing different aspects, a multi criteria decision analysis (MCDA) is implemented. The MCDA is a well-recognized approach for solving complex issues and supporting the decision-making process, which allows selecting the most optimal choice determined primarily by a weighted set of criteria. The TOPSIS approach has been selected since it is recognized as a comprehensive method that gives a complete ranking of alternatives and avoids complex evaluation of each criterion in the selection process and the need for a large quantity of information in assessing these criterions. The MCDA analysis is based on the results coming from two supply chain models developed during the H2020 - ICCEE project: i.e., the energy impact model which assess the energy flow and the quality losses, and the life cycle assessment model, which evaluates the environmental performance. In particular, the criteria used for the evaluation of the different scenarios are the specific energy consumption, the quality losses along the cold chain, the global warming potential, the cumulative energy demand, and the water scarcity. From the insights of the case studies, it is evident how the MCDA analysis is relevant for cold chains due to the double effect of refrigeration: i.e., increased quality at the cost of increased energy consumption. The proposed TOPSIS method can, thus, be useful for prioritizing energy efficiency measures.

Keywords: cold chain, MCDA, sustainability

1.Introduction

Food refrigeration has a significant impact on the environment. While significant progress has been made (Marchi et al., 2019), e.g., through technological and managerial improvements and maintenance practices, emissions are still relevant and are mainly related to the generation of energy from fossil fuels plants (Coulomb, 2008; James and James, 2010). Energy use is mainly due to the refrigeration required to slow down deterioration of chilled and frozen products. Hence, the consumption is related to the temperature set during logistic activities (i.e., storage and transport), the time requiring refrigeration, and the behavior of operators and users. Furthermore, energy and other resources consumed for processing, transporting and storing foods that deteriorates along the cold chain are lost (Zanoni and Marchi, 2021).

To slow deterioration and to deliver safe and high-quality products to consumers, logistic activities from farm-to-fork should occur within a specified time in a chilled or frozen state. Cold chains consist of environmentally controlled logistics chains aiming at preserving the quality of perishable goods, connecting processing, storage, and distribution activities. The design of the chain, the specific foodstuff and the target market affect the total time spent along the refrigerated food chain (Gogou et al., 2015; Mack et al., 2014), from a few hours to some months or up to some years. Distribution centers and transport activities represent critical points in cold chain management. The formers allow sorting, combining, and scheduling shipments to better match retailers' demand, food arrival time, and quality requirements. Meanwhile, transport equipment must reliably operate in more severe environments and lower efficiency than stationary refrigeration (Tassou et al., 2009): i.e., an extensive range of operating settings and restrictions due to the available load and space.

The storage temperature through the cold chain may be different: i.e., regulations provide only a maximum temperature of storage for products. Hence, the synchronization of the different actors of the chain is desirable to avoid temperature abuses. Furthermore, the delivered lot size determines the replenishment timing, and it is affected by the temperature fixed to preserve the food at the quality level required by the retailers. The higher the temperature, the shorter the replenishment cycle. Hence, given the time-temperature relationship, the players of the supply chain must jointly optimize the operation management to increase the efficiency and service level offered to the final customer. The implementation of a holistic approach, shifting from the single company perspective to the chain assessment, leads to increased opportunities for improving energy efficiency and to reduced perceived barriers (Marchi and Zanoni, 2017).

Cold chain has recently caught the interest also of researchers in operations and logistics management. For instance, Meneghetti and Monti (2015) investigated the optimal design of refrigerated automated storage and retrieval systems in relation to cold chain settings, also with renewable energy adoption (Meneghetti et al., 2018). Marchi et al. (2020) studied the impact of storage filling level on the energy consumption of refrigerated warehouses and, subsequently, on inventory management. Later on, Meneghetti and Ceschia (2019) introduced the refrigerated routing problem to model multi-drop deliveries of food to supermarkets, linking refrigeration requirements to delivery characteristics and climate conditions. Behavioral and organizational aspects are important for decision making about energy efficiency, specifically while considering the whole cold chain. Neusel et al. (2020) investigates both aspects more in-depth along the cold supply chain of the food sector, thereby moving from the single company perspective to a full supply chain assessment.

The aim of this paper is to investigate how the main levers affecting the time-temperature relationship (i.e., lot size and temperatures) impact on the cold chain sustainability through a multi criteria decision analysis. This study has been conducted during the EU-funded H2020 project: "Improving cold chain energy efficiency" (ICCEE).

2. ICCEE project

The overall aim of the ICCEE project is to reduce energy consumption and greenhouse gas emissions from the European food cold storage sector through capacity building activities in order to reduce the current lack of awareness and know-how of different stakeholders for supporting the implementation of energy-efficient measures in line with European policy (Zanoni et al., 2020). The project support cold store and transport operators (mainly from SMEs) overcome reservations to the uptake of energy efficient practices. Through a combination of supporting tools, knowledge-based information packages and education programmes, the project aims to help cold chain operators make informed decisions on equipment and identify cost-efficient options for their businesses. The project outcomes aim also to offer policy makers a solid foundation for sector-specific policy. Hence, the specific objectives of ICCEE are to implement and apply analytical energy efficiency tool to support and facilitate the decision- making processes of the SMEs in assessing the current energy and environmental performance of their cold chain, to identify the energy saving potential of companies, and to create a capacity building programme and a community dedicated to support the change in the energy culture of organizations through direct training and the development of an e-module.

The ICCEE toolbox consists of six tools:

1. *Cold supply chain tool*, which deals with the energy requirement in storage and transport activities along the cold chain and evaluate the impact of storage time and temperature on the food quality and the energy consumption (ICCEE, 2020a).
2. *Life cycle assessment tool*, which deals with the life cycle analysis of cold supply chains. It allows users to perform ana analysis of the environmental performance of the whole cold chain (ICCEE, 2020b).
3. *Multi criteria analysis tool*, which consists in a multi criteria assessment approach across various criteria related to energy consumption, food quality and environmental impacts and shows the impact of changes in particular input criteria.
4. *Life cycle costing tool*, which deals with the life cycle costs of energy efficiency measures. It allows users to analyze these measures from a conventional economic perspective, but also offers the possibility to review the impact from a social perspective (ICCEE, 2020b).
5. *Benchmarking non-energy benefits* (NEBs), which deals with the perception of non-energy benefits in individual companies and in the whole cold chain. It allows users to compare their perception of NEBs with the perception within a peer group of other companies in the cold chains (ICCEE, 2020c).
6. *Non-energy benefit evaluator*, which serves as approach to discover the topic of NEBs in an exemplary manner.

ICCEE is coordinated by the University of Brescia with 12 partners: IEECP, FIRE (Federazione Italiana per l'uso razionale dell'energia), Adelphi Research Gemeinnützige, ATEE (Association Technique Energie Environnement), Fraunhofer, Riga Technical University, ESCAN, SPES GEIE, ECSLA, Chamber of Korinthia, University of Stuttgart, and Romalimenta.

3. Multi criteria decision analysis

Multi Criteria Analysis (MCA) is used to identify compromises for resolving decision-related problems and to further support the decision maker towards a systematic decision-making process. The main advantage of the MCA method is to allow to find the best solution as compromise among a set of potential alternatives (Ishizaka and Nemery, 2013). This approach is particularly relevant for the cold chain since it allows to find the best solution while taking care of the existing trade-off between energy consumption for refrigeration purpose and the related environmental impacts, and the quality losses. The choice of the criteria categories is crucial for quantitative evaluation and only impacts on related criteria should be considered. To avoid elicitation issues within the definition indifference, preference and/or thresholds, as it is for the case of PROMETHEE and ELECTRE methods (Karagiannidis and Perkoulidis, 2009), it can be used the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

3.1 The TOPSIS method

The TOPSIS method is based on a defined weighted, normalized, and multi-objective criteria matrix from which the best solution is primarily determined by the definition of an ideal and an anti-ideal option. The basics of TOPSIS is lying on giving such solution as the one which shows the shortest distance to the ideal solution and the furthest distance from the anti-ideal solution (Dong et al., 2014). The application of such approach allows to easily combine identified criteria into a single-score measure.

This method is recognized for having minimal number of inputs from the user, while at the same time providing easy to understand outputs. Moreover, the final output is rather simple to be understood.

The aim of this method is to aid in multiple-attribute decision-making by ranking alternatives in accordance with how they match up with the ideal solution (Tzeng and Huang, 2011).

Similarly, as other MCA methods, TOPSIS has a subjective parameter in form of assignment of weights to each selected criterion (Ishizaka and Nemery, 2013). Five computation steps are distinguished in TOPSIS (Beuthe and Scannella, 2001): 1) gathering of the performances of the alternatives on the different criteria in terms of quantitative value, 2) normalization of the quantitative performances for each alternatives within the decision matrix, 3) weighting of the normalized performances for each alternatives (i.e. definition of a weighted normalized decision matrix), 4) the weighted scores are compared to an ideal and anti-ideal solution alternative, 5) calculation of the distances to the ideal and anti-ideal solutions for each alternative, 6) calculation of the relatively closeness to the ideal and anti-ideal solution to determine the best alternative.

3.2 Evaluating criteria

The criteria used for the evaluation of the different scenarios are linked to the energy consumption, the quality losses, and the environmental impact. In particular, the following criteria are considered:

- Total specific energy consumption (SEC), kWh per kg of chilled or frozen product, which is constituted by two contributions: the energy consumption for refrigerating the product, and the energy wasted due to quality losses evaluated in the supply chain energy impact analysis model
- Quality losses, %, along the overall supply chain evaluated in the supply chain energy impact analysis model
- Global warming potential (GWP), kg_{CO2eq} per kg of chilled or frozen product. This evaluation is proposed in the streamlined LCA model proposed in the tool. The determination of the Global Warming Potential (GWP) is based on the "2013 method" developed by the Intergovernmental Panel on Climate Change (IPCC). It delivers results for a timeframe of 100 years and expresses the impact in terms of kg of carbon dioxide equivalents.
- Cumulative energy demand (CED), MJ per kg of chilled of frozen product, which represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials evaluated in the LCA model.
- Water scarcity, m^3_{eq} per kg of chilled of frozen product. The water scarcity method is developed according to the AWARE method (Availalble WAter Remaining) recommended by the international working group on water use assessment and footprinting (WULCA) for LCA analyses. AWARE represents the relative AWARE per area in a watershed after the demand of humans and aquatic ecosystems has been met. It assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived which includes impacts associated with water use and availability. Such approach is implemented in the LCA model.

The user should provide a weight defining the relevance of each criterion to select the best scenario. In accordance with his priority and to the relevance given to the different criteria, each user can define its own weights in percentage (with the constraint that the sum of the weights should be equal to 1).

3.3 TOPSIS in ICCEE

As previously said, ICCEE focus is on logistic activities requiring refrigeration to slow down deterioration of chilled and frozen products. Supply chain is the series of processes involved in the production and supply of goods, from when raw materials are firstly made until final goods are bought or used (i.e., "from farm to fork"). Hence, the general cold chain considered in the tools consists of seven stages: i.e., storage at the raw material supplier, transportation from the supplier to the producer, storage at the producer (both of raw material and finished product), transportation of finished product from the producer to the distribution center, storage at the distribution center, transportation from the distribution center to the retailer, and storage at the retailer (both in the backroom and in the display area). These stages can be omitted, or additional stages can be introduced in accordance with the specific cold chain considered.

For the specific purposes of the optimization tool to be developed within the frame of ICCEE project TOPSIS (the Technique for Order of Preference by Similarity to Ideal Solution) was selected as MCA tool. This mostly because this method gives a complete ranking of alternatives and allows to avoid complex evaluation of each criterion in selection process and the need for large quantity of information in assessment of these criterions.

The TOPSIS has been applied, using a distributive normalization, to three different levers (i.e., lot size, storage temperature of the raw material and storage temperature of the finished product). Firstly, the same storage temperature has been set at each warehouse storing the considered product (i.e., raw material or finished product), and the optimal storage time (i.e., without any idle time) has been considered at each stage of the cold chain. Since the three levers are independent the sequence of application of the TOPSIS method is not relevant.

In ICCEE tool, the TOPSIS is firstly applied to the actual scenario (namely, 'AS-IS scenario') with optimal storage time by varying the lot size from -90% to the upper limit defined by the lot that saturates the display area at the retailer, with a step of 10%. The saturation of the display area is calculated with the ratio between the lot size and the maximum quantity of products that can be stored in the display area (i.e., the display area size times the space occupation of the finished product).

The best scenario resulting from the TOPSIS on the lot size is then used to perturbate the temperature set for both the raw materials and the finished product. The two temperatures are independent variables, hence, there is not a preferred sequence to perform the TOPSIS analyses.

Firstly, it is set the same temperature for the raw material warehouses at each actor, from supplier to producer (defined as T_{RM}), and the same temperature for the finished product warehouses at each actor, from producer to retailer (defined as T_{FP}). A scenario is generated for each temperature in the admissible temperature range for the specific product deriving from specific regulations, with a step that can be selected by the user. Then the steps of the TOPSIS algorithm previously introduced are carried out for selecting the best temperature for the products. Starting from the raw material and then applying the perturbation of T_{FP} to the best solution found.

4. Case studies

In this section, a case study of the meat cold chain (i.e., beef meat production) is presented to show the potential of the MCA tool developed in the ICCEE project. The supplier of raw material for the specific case study is intended as the slaughterhouse since previous step does not require refrigeration.

The input data required by the tools are mainly focused on the energy and resource consumptions related to the logistic, and on the storage and transportation activities. These data are obtained directly from interviews to companies conducted during the ICCEE project. Specifically, the interviews were conducted to SMEs of the sector since they represent the highest potential for reducing the energy consumption, but also to large companies of the sector since they represent the actors that can easily coordinate and guide other SMEs partners in improving the energy performance of the cold chain. The core business of both the groups of companies (i.e., SMEs, and large) deals with the logistic activities along the cold chain: i.e., storage and transport at different stage for both raw materials and finished products.

The AS-IS scenario considers a starting lot size of 1 ton, the temperature of raw material is set at 7°C, while the finished products at 0°C. The weight considered for the MCA are: 50% for the total SEC, 30% for the quality losses, 10% for the GWP, and 5% for the CED and water scarcity. Aiming to obtain the best scenario, the effects of the lot size are considered varying in both the energy impact model and in the LCA model the dimension of the lot that arrives to the retailer and, accordingly, the average inventory level at each stage. The final ranking of the application of the TOPSIS shows that the best scenario is obtained with a reduction of the lot size of 60% (i.e., 400 kg). This solution allows to almost halve the LCA indicator at the cost of an increase of 12% of the total SEC. In fact, while the quality losses value is constant because the storage conditions are not changed, the SEC value seems to decrease with the increment of the lot size. On the other side, GWP, CED and water scarcity decrease considerably with the decreasing of the lot size.

The analysis continues with the application of the TOPSIS algorithm to the storage temperature of both raw materials and finite products. In this way, the obtained result will be the best solution considering the lot size and the storage temperature along the cold chain. For this step, the research of the optimum is conducted changing the temperature in the cold supply chain tool and in the LCA tool. However, since it is not possible to set a temperature in the LCA tool, a temperature-electricity consumptions relationship has been developed. In fact, through the analysis of the surveys' data it has been pointed out the relation between energy consumptions and the temperature set in the warehouses. Specifically, the equation fitting the data is the following:

$$\beta = \left(\frac{T}{T_0}\right)^{(T-T_{ext})} \quad (1)$$

where T_0 is the temperature set in the AS-IS scenario, T_{ext} is the average external temperature during the hottest season and T is the new set temperature for the TOPSIS analysis. In addition, another hypothesis that has been assumed is that the electricity consumptions consist of a fixed part and a part which varies with the temperature (i.e., 40% of the fixed part and 60% of the temperature-dependent part). In this way, the energy consumptions can be derived as follows:

$$ElectrCons(T) = (0{,}6\beta + 0{,}4)ElectrCons(T_0) \quad (2)$$

From the application of the TOPSIS to the temperatures, it results that the optimal temperature for the raw material is 4°C, while 2°C for the finished product. the lower the temperature is and the better the quality losses value will be. On the other hand, the effects of the change in temperatures seem to influence in a minimal way the other indicators. Specifically, in Table 1 the impact of the optimal temperature on the indicators is shown.

Table 1: Impact of changing the temperature for raw material and finished products on the KPI

KPI	T_{RM} (4°C)	T_{FP} (2°C)
Total SEC	-0.01%	0%
Quality losses	-84%	+31%
GWP	0%	-1%
CED	+3%	-6%
Water scarcity	0%	-1%

To conclude, the TOPSIS algorithm shows that, to obtain the best combination of the chosen performances for this meat supply chain, the lot size should be reduced of the 60%, the raw materials should be stored at 4°C and the storage temperature of the finite products should be increased of 2°C. Therefore, while the SEC value and the quality losses remain constant, the CED value decreases of 1.4%.

The obtained results are referred to a specific case of study and to the defined weighing factors used to classify the performances. Other chains may result in different best scenarios.

It is also interesting to consider the comparison of the results obtained from the cold chains of two different families of products. For this reason, a dairy product cold chain has also been analyzed. In the same way as the meat cold chain previously described, the AS-IS scenario is based on a starting lot size of 1 ton of finished product. The raw materials are stored at 7°C, while the storage temperature of the finite products is 2°C. Since the focus of the defined TOPSIS analysis is on SEC and quality losses (jointly covering 80% of the total weight), to reduce these performances, the method suggests that the lot size should be reduced to 600 kg (-40%). At the same time, the raw materials should be stored at 2°C, while the storage temperature of the finite products should be set at 0°C. In this way, the SEC value is decreased from 2,53 to 2,49 kWh/kg (- 1.58%), the quality losses are reduced of the 1.77%, while GWP, CED and water scarcity are incremented of 1%, 3% and 2% respectively.

In Figure 1, the results obtained with the application of the TOPSIS method to other cold chains for different products are reported.

Since each presented supply chain in this table represents a particular scenario with specific features, it is not possible to define an average value that is able to describe the general result for a family of product. However, it is possible to identify a sort of a trend. Particularly, it seems that for most of the dairy product’s cold chains, the lot size should be decrease to around 600kg and the temperatures can be decreased of about 2°C for both raw materials and finite products. Similarly, the results of the application of the TOPSIS method to the meat supply chain suggest that the lot size should be decreased of the 60% (i.e., ≈ 400kg) while the temperatures should be decreased for the raw materials (i.e., ΔT=-2°C) and increased for the finite products (i.e., ΔT=+1°C). In this way, the improvement in the management of the chain for dairy products is enlightened by an average decrement of the SEC value, quality losses, GWP, CED and water scarcity of 1.28%, 5.61%, 21.7%, 14.14% and 13.97%, respectively. On the other side, the meat cold chain is subjected by an average increment of the SEC value of 14%, while quality losses, GWP, CED and water scarcity values are decreased of 0.001%, 51%, 41% and 52% respectively.

For the fish cold chains, it is suggested to reduce the lot size at around 245kg and to set the storage temperatures at -2°C for the raw materials and at -15°C for the finite products. A different scenario is presented for the beverages cold chain, and it seems to be highly variable. In fact, the lot size can be varied to a final size of around 2500kg or 3500kg, while the suggested storage temperatures are set at 3°C. For instance, if the weighting factors are all set at 20%, the result obtained for the first analyzed chain is a lot size of 200kg, a raw material storage temperature of 5°C and a finite product storage temperature of 3°C. In this way, both the SEC value and the quality losses are increased respect to the previous best scenario, but a better result is obtained for GWP, CED and water scarcity (they are all further decremented of around 5%).

					TOPSIS		
	Product	Lot size [kg]	RM Temp. [°C]	FP Temp. [°C]	Lot size [kg]	RM Temp. [°C]	FP Temp. [°C]
1	Dairy	1000	7	2	1100	4	0
2	Dairy	1000	7	2	600	2	0
3	Dairy	1000	4	2	600	1	-1
4	Dairy	1000	2	4	500	0	0
5	Dairy	1000	2	2	700	0	0
6	Dairy	1000	2	2	700	0	0
1	Meat	1000	7	0	400	4	2
2	Meat	1000	7	0	400	4	1
3	Meat	800	7	0	320	5	2
4	Meat	400	7	0	400	5	1
5	Meat	400	7	0	480	4	-1
6	Meat	1000	7	0	400	4	-1
7	Meat	1000	7	0	400	4	-1
8	Meat	800	7	0	320	6	-1
9	Fruit and Vegetables	1800	4	4	1080	3	1
10	Fruit and Vegetables	1600	4	4	960	2	0
11	Fish	350	0	-18	245	-2	-15
12	Fish	350	0	-18	245	-2	-15
13	Beverage	5000	3	3	3500	3	3
14	Beverage	4000	3	3	2400	3	2

Figure 1: TOPSIS results for different cold chains

The MCDA analysis performed through the TOPSIS approach proposed has several practical implications. Firstly, it increases the awareness of stakeholders on the sustainability of cold chains and on the impacts of different measures on the main KPI. Secondly, it provides a systemic approach for prioritizing these measures for the specific cold chain considered. Finally, it supports closing the implementation gap of energy efficiency measures since it allows to weight different impacts and the multiple benefits introduced.

Based on the results presented the use of the proposed tool could be useful for SMEs as well as energy planners involved in the cold chain of chilled or frozen products. They could have a simple and straightforward tool to sort and rank potential energy efficiency measures implementable towards the entire cold chain. This provides an opportunity to focus on the optimal solutions in turn providing saving in time and costs.

5. Conclusion

The present report provides information about the TOPSIS method which has been used to perform the multi-criteria analysis (MCA). Firstly, the different general steps that should be followed have been defined and equations provided. In particular, the distributive normalization has been selected in the present project.

Then, the levers on which the TOPSIS has been performed and the different KPIs used for the evaluations are introduced:

- Levers: lot size, storage temperature of the raw material, storage temperature of the finished product
- KPIs: total specific energy consumption, quality losses, global warming potential, cumulative energy demand, water scarcity

Each TOPSIS performed in the ICCEE tool is presented.

Finally, two examples of the application to specific cold chains are presented to show insights on the results.

From the insights, it is evident that the TOPSIS method does not aim to decrement the SEC value or a single KPI, but it operates to obtain the optimum scenario for the cold chain itself, under the given conditions and weights. In addition, changing the weighting factors or the AS-IS scenario can lead to different results and a different optimization. Hence, a possible extension of the study deals with performing a more detailed sensitivity analysis on the weights.

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