Environmental and Climate Technologies
2022, vol. 26, no. 1, pp. 428–440
https://doi.org/10.2478/rtuect-2022-0033
https://content.sciendo.com

The ICCEE Toolbox. A Holistic Instrument Supporting Energy Efficiency of Cold Food and Beverage Supply Chains

Fabian DIAZ[1*], Francesco ROMAGNOLI[2], Lisa NEUSEL[3], Simon HIRZEL[4], Jasmin PAULUS[5], Beatrice MARCHI[6], Simone ZANONI[7]

[1,2]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia*

[3,4]*Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139 Karlsruhe, Germany*

[5]*Adelphi Research Gemeinnützige GmbH, Alt-Moabit 91, 10559 Berlin, Germany*

[6]*Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze, 38 25123, Brescia, Italy*

[7]*Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Via Branze, 43 25123, Brescia, Italy*

***Abstract* – Cold supply chains of food and beverage sectors represent one of the main drivers of the EU total final energy consumption. Within this context, food quality losses, changes in temperature regimes, energy use, environmental burdens, and the economic viability of energy efficiency measures are essential aspects to consider for improving cold supply chains' overall sustainability. This paper presents a dedicated toolbox, developed within the Horizon 2020 project ICCEE, for supporting decision-making and actors to assess energy efficiency path within a specific type of food cold-supply (i.e., meat, fish, milk and cheese products, fruits, and vegetables). More in specific the toolbox offers support for decision-makers to understand and minimize the specific energy consumption, to decrease the overall environmental impact even including non-energy benefit evaluation many times underestimated. The six separated tools merged within a unique toolbox consider different methodological approaches such as: assessment of the whole energy requirements in stock and flows considering the storage impact, the logistics and quality losses over time, implementation of Life Cycle Assessment and Life Cycle costs within the environmental and financial assessment of energy efficiency measures, based on a benchmarking approach. Finally, a specific approach implementing Multi Criteria Analysis was developed on selected key performance indicators such as specific and cumulated energy consumptions, quality losses and environmental burdens (i.e., global warming potential and water scarcity). The latest version of the ICCEE toolbox is available as free downloadable package on the ICCEE website.**

***Keywords* – Cold supply chain; energy efficiency; LCA; multi criteria analysis; non-energy benefits**

[*] Corresponding author.
E-mail address: fabian-andres.diaz-sanchez@rtu.lv

©2022 Author(s). This is an open access article licensed under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0).

1. INTRODUCTION

Worldwide food production accounts for 80 % of deforestation worldwide, and it is responsible for 29 % of Greenhouse Gases (GHG) emissions and almost 70 % of freshwater use [1], [2]. The influence of Food Supply Chains (FSC) extends beyond environmental and economic issues, delivering impacts on social topics such as health and safety, wages, working hours, child work, gender equality, animal well-being, food safety, and traceability among others [2]–[4].

It has been estimated by the Food and Agriculture Organization (FAO), that 14–16 % of food in the world is lost in the supply chain before reaching the retail point [5]. If the full life cycle of food products is analysed, the third part of food produced is usually accepted as an actual value for Food Waste (FW), however, this number is merely a general estimation [5].

According to the FAO, FW can be defined as 'the food that is appropriate for human consumption but it is discarded either before or after spoils, as a result from the negligence or a conscious decision to throw it away' [6], [7]. In the specific case of the European Union (EU), it was appraised that in 2011, the amount of food produced was 865 kg/person, and the total amount of FW corresponded to 20 % for the same year [5], [7].

A supply chain can be conceptualized as the interaction among several organizations involved in the flow of products and services to their end customers [8]. The FSC comprises all units dedicated to manufacturing or harvesting products from the basic raw materials obtained from primary activities to deliver final food products to the consumer [9], [10]. The main activities of the agri-food supply chain involve raw material supply, manufacturing and postharvest, storage, distribution, and services [11]. Another definition for FSC is that the '*food supply chain is composed of raw material supply of agricultural products, farming, and breeding of agricultural products, processing of agricultural products, and the production, distribution, retail, and catering of food*' [12], [13]. FSCs are unique, as they deal with the intrinsic issues of perishability, product deterioration, and organic wastes [14], [15].

The sectors contributing the most to the FW stream are the household with 53 %, followed by processing with 19 % [7]; the most significant plans, policies, and measures towards reducing FW in the EU, are addressed to as in the European Union Waste Framework Directive 2008/98. However, there is still the need to tackle FW in FSC, to ensure food quality, and decrease energy consumption estimated at 25 % of the EU-27 total final energy consumption [16]. Moreover, 30 % of potential savings in refrigeration and cooling activities has been estimated for the food sector [17].

The potential risks of hazards compromising the product's safety in the FSC could arise at any stage, undermining the whole supply chain [13]. Society, and various international organizations, like the FAO, the World Food Program (WFP), and the United Nations Environmental Program (UNEP), defined roadmaps to raise awareness among the public towards food safety looking to reduce food losses and reaching the 'zero loss or waste food' in the Zero Hunger Challenge [18], [19].

FW has become a key topic in developed societies due to the increasing environmental and social interest. Accordingly, food loss is the removal of any food and its inedible parts from the supply chain at any stage for whatever use, no matter if it is for recovery or disposal.

The causes for food losses, at least in Europe, are well known, despite not always being easy to track as they involve all actors in the FSC [20]. Among the more important causes, it is worth highlighting quality losses, reached expiration dates, damages during a particular stage, and food discarded due to a batch's sample not meeting the stipulated quality standard [21], [22]. Fortunately, some conditions for recovering FW to use in human consumption are nowadays also known. However, the lack of data is an obstacle to estimating the amount and the quality conditions of food losses for most food typologies [23].

Nowadays, a large share of FSCs occurs in a low-temperature regime (i.e. chilled or frozen product) to extend the perishability time. Following the definition found in the Dictionary of Refrigeration [24], a Cold Supply Chain (CSC) could be defined as the representation of a '*series of actions and equipment applied to maintain a product within a specified low-temperature range from harvest/production to consumption*'. A cold chain includes, but is not limited to, chilled and frozen foods and the subsequent refrigeration, the refrigeration of food after harvesting, transportation, storage, retail distribution, and home storage, aiming to maintain the quality, safety and to extend the shelf life for consumers [25]. The cold chain is vital for reducing FW and ensuring food safety, which influences the environment, water, and land resources [26], [27]. The equipment and facilities in the cold chain may include precooling and freezing facilities, cold storage warehouses, refrigerated trucks, freezers, display cabinets, and home refrigerators, which involve many new technologies and recent developments [12], [27]. Although food cold chain ensures food safety and prolong shelf life, frozen food's quantity is responsible for important energy and refrigerants consumption than a non-refrigerated FSC [28]. Thus, CSC must be adequately addressed to evaluate their real sustainability performance.

The environmental concerns caused by the activities related to CSCs can be divided into direct and indirect impacts. Direct impacts come from resources and emissions consumed and caused by activities within the supply chain's system boundaries. Resource extraction and use are linked to the use and transportation of raw materials, energy use, and other intermediate products necessary for carrying the actions within the involved processes.

The indirect impacts from food produced and not eaten (food losses) in carbon footprint terms are estimated at around 3.3 Gt CO_2 eq. This positions the FW issue as the source number three of carbon emissions after the USA and China if compared with direct country emissions [7], [12]. Hence, CSCs are vital to reduce food losses, yet they come with an environmental toll that must be assessed and addressed properly by improving the overall efficiency of their operations.

2. Rationale for Easy-to-Use Cold Supply Chain Assessment Tools

Recently, the concept of sustainability in the CSC has gained importance proposing a holistic view of the FSC system and its sustainability and aiming to optimize the benefits and results [29]. However, sustainability in the FSC and measuring its performance is difficult as not only the economic dimension must be considered should be the key assessment parameters. Despite the difficulties to be quantified, environmental and social issues must be brought into the assessment as the FSC involves multiple actors [30]. These actors and supply chain partners are required to work together to attain more sustainable outputs and increase the progress rate [31]. This can be achieved in the industrial sector, by reducing the energy consumption to cope with the challenges of meeting consumer expectations, national and international policies and regulations, and resource limitation [4]. Several studies highlight the lack of sustainability and energy efficiency assessment in the FSC under a holistic view [1], [32]. And although the topic has been addressed, it has been predominantly done from the FSC single actors' perspective, creating only a fragmented assessment [1].

One interesting and recent study attempted to evaluate the enablers for effective adoption of sustainability concepts in the FSC using different research methodologies for an Indian

FSC case study [33]. Still, the quantitative evaluation of environmental impacts for sustainability assessments of FSC remains mainly unmapped.

FSCs and CSCs are inherently complex due to their numerous actors, stages and products. Understanding the energy and environmental performance of such chains becomes challenging and data intensive. This makes it particularly difficult for companies who seek to understand the relevance of particular chains, especially when they are small or medium-sized and only have limited resources and absorptive capacities. This calls for tools that can be readily applied to evaluate financial and environmental potentials for improvement within CSCs.

A major example has been developed in the FRISBEE project [34]. Its tool allows assessing the quality of food products, the energy consumption of different supply chains, and CO_2 emissions [34]. While the FRISBEE tool is quite robust for evaluating food quality changes across the CSC, it is limited to modelling steady in time scenarios. Furthermore, it does not allow for comparisons between the current state and future EEM implementations. Thus, a limitation in the environmental assessment appears, as generally, the global warming potential is the only category considered within existing tools, and it is not clear if a holistic approach has been used considering the whole life cycle of the food product evaluated.

A set of tools and methods is gathered and presented in [29], where topicality is aggregated. The main covered issues regarding agriculture supply chains presented are risk management, governance, cold chain management, globalization, information and communication technologies, logistics, short supply chains, and sustainability. However, each of these issues is approached individually by different methodologies.

The necessity for a tool that incorporates a holistic perspective arises to fulfil several objectives: to facilitate the understanding of energy-efficiency measures within CSC of the food and beverage sector, in particular for small and medium-sized companies, to take a holistic perspective on the entire CSC instead of looking at individual companies, only, and to facilitate decisions on investments in energy-efficient technologies.

3. CONCEPT AND IMPLEMENTATION OF THE ICCEE TOOLBOX

The suggested toolbox aims to introduce a set of analytical decision support tools. These shall allow easy-to-use but still customized analyses on the energy and sustainability performance of CSCs. As the food industry includes many different products, they are subjected to different production processes and logistic activities in terms of required operations and energy consumption. For this reason, simplifications are needed. These concern the representation of CSC which, as presented in Fig. 1, can be both regional and global. Breaking down the structure into individual stages is the main advantage and mission of the developed toolbox. It thus allows identifying the potential impacts in diverse stages and activities in the CSC. At the same time, the toolbox remains simple and practical while answering the needs of several stakeholders, ensuring accessibility and an easy-to-use interface.

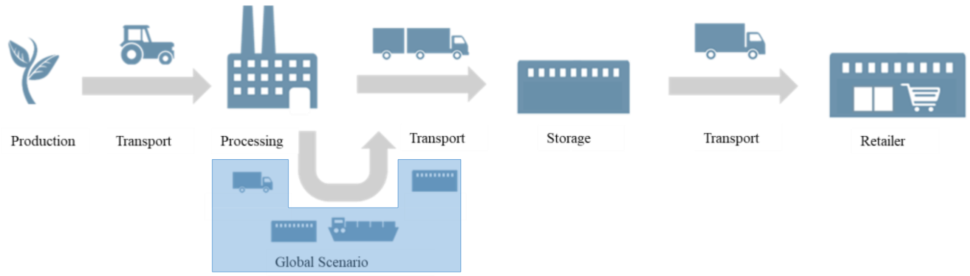

Fig. 1. The cold supply chain of food and beverage.

The toolbox consists of several tools covering different aspects related to the sustainability and energy efficiency of CSCs (Fig. 2). They encompass seven spreadsheets with a common-looking interface to increase the awareness among managers and actors within the CSC of energy efficiency measures from a holistic perspective instead of a conventional single actor perspective.

The whole toolbox is developed to allow the individual evaluation of cost-benefit and impact analysis on the implementation of Energy Efficiency Measures (EEM) in the CSC. As an added value, the toolbox can facilitate the identification of energy hotspots (i.e., processes, auxiliary services) within the whole CSC. The toolbox prioritizes the evaluation of energy savings and their benefits in different areas in independent and stand-alone versions to lessen data safety and incompatible software issues.

Ultimately, it can be said that this toolbox supports the assessment of energy flows, benchmarking, and life cycle impacts. The tools can be explored in detail on the project website [35].

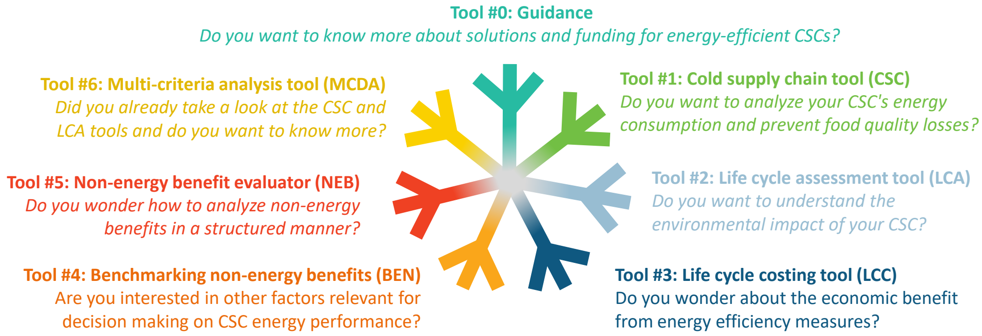

Fig. 2. Structure of the ICCEE toolbox.

Each of the tools can be used as a standalone one, to recognize a specific aspect on the CSC, or all the tools together, to obtain an overall final score that enables identifying a potential best scenario using multi-criteria analysis. A comprehensive description of each one of the toolbox components is presented in the following sub-sections.

3.1. Tool 0: Guidance

The guidance tool provides an introductory orientation on the toolbox itself, best practice examples, and funding opportunities. Next to a brief description of each tool includes the collection of best practice examples (so-called factsheets) for energy efficiency measures tailored to the CSC. The EEMs relevant for CSCs have been grouped into ten categories: auxiliary technologies, buildings, employees, energy generation and recovery, industrial symbiosis, maintenance, management, monitoring and control, refrigeration system, and transport. Furthermore, the tool also provides an overview of national support schemes concerning energy efficiency in the CSC, including eligibility information and links to further information. Thus, the guidance tool serves as a repository of technical and funding information on energy efficiency within CSCs.

3.2. Tool 1: Cold Supply Chain Tool (CSC)

Chilled and frozen foods have a short shelf life and high sensitivity to the surrounding environment (i.e., temperature, humidity, and light intensity). For these reasons, they must be distributed within a specified time and require special equipment and facilities (e.g., refrigeration and dehumidification systems) from farm-to-fork to slow deterioration and to deliver safe and high-quality products to consumers. These requirements establish a trade-off between energy consumption and quality losses. The CSC tool deals with assessing the energy requirement in storage and transport activities along cold supply chains and the impact of storage time and temperature on food quality and energy consumption.

This model aims to support decision-makers in understanding and minimizing the overall specific energy consumption along cold supply chains, including quality losses. For this purpose, it allows to analyse:

1. Energy requirement in storage activities;
2. Energy requirements in transport activities;
3. Time-temperature effects on the food quality and consequent energy consumption.

The target group refers to supply chain managers and environmental managers of companies.

The supply chain proposed in the tool consists of up to seven stages from the raw material supplier to the retailer and includes a set of predefined products. In case the supply chain under analysis looks different, it is possible to omit or aggregate input of some stages to match the specific chain. The input required deals with the logistic activities of the stages with temperature control requirements. Specifically, three different macro-categories of input data can be distinguished:

- General inputs; in terms of annual demand rate of the final product, space occupation of the raw material and the final product, amount of raw material for producing a unit of the final product, and the product family of both raw material and final product;
- Storage data required for each warehouse in the chain; in terms of the average value of ambient temperature in the hottest season, inside reference temperature during the storage activities, annual consumption for refrigeration purpose for each energy carrier, storage size, production rate (if any), average warehouse utilization and average storage time at the warehouse;
- Transport data: in terms of fuel type, an average distance for a roundtrip, average travel time requiring refrigeration, distance travelled per unit of fuel, electrical power of refrigeration equipment (if any), a payload which defines the maximum amount of product transportable per trip, average amount of product transported, average value of ambient temperature in the hottest season, and inside reference temperature during the transport activities.

This tool provides some unique features like:

- Evaluation of the CSC's energy performance with a holistic and life cycle approach;

- Contribution analysis of each actor in terms of quality losses and energy consumption;
- Considerations of a trade-off between time-quality-energy for the overall cold chain, analysis of the influence of different temperature levels;
- Considerations of distribution, transportation and storage policies, and the assessment of the EEMs impacts and consequent prioritization.

3.3. Tool 2: Life Cycle Assessment Tool (LCA)

The LCA tool deals with the life cycle analysis of CSCs. This tool integrates inventory data from existing LCA databases to assess the environmental performance in three different areas of concern. The tool is designed to help practitioners or interested cold chain actors to quickly identify the environmental impact of cold supply chains in terms of Global Warming Potential (GWP), Cumulative Energy Demand (CED), and water scarcity based on the AWARE method (Available Water Remaining).

The model is based on the following data and methods: the determination of the GWP, based on the '2013 method' developed by the Intergovernmental Panel on Climate Change (IPCC) [30]. It delivers results for a timeframe of 100 years and expresses the impact in terms of kg of carbon dioxide equivalents. The determination of the CED is based on the method published by the environmental data system '*ecoinvent version 2.0*' [36] and expanded for raw materials available in the life cycle database '*SimaPro 9*' [37]. The AWARE method is used according to the recommendation of the international working group on water use assessment and foot printing (WULCA) [31]. It assesses the potential of water deprivation to either humans or ecosystems, based on the assumption that the less water remaining available per area, the more likely another user is deprived.

The main novelty of this tool relies on the quick assessment of environmental impacts while creating different scenarios for cold chains within most countries of the EU-27. Furthermore, the LCA methodology proposed by ISO 10040 and 14044 is simplified in this tool so the user can create their product system, by altering system boundaries to evaluate from a cradle-to-grave to a gate-to-gate system, including process taking place upstream and downstream from a single actor stage.

The LCA tool allows the user to select available raw material products from the tool database. Moreover, it also permits to consider if regional or global cold chains are to be modelled, automatically expanding the boundaries by inserting the proper stages necessary for evaluating a globalized supply chain. The unique tool features are:

- Evaluation of the environmental impacts (and benefits) of potential energy efficiency measures within CSCs, based on the LCA methodology following the ISO Standard 14044:2006;
- Exploration of the interdependency among technological and ecological systems;
- Streamlined, yet consistent, exploration of the overall environmental impact over possible cold chains of chilled and frozen products;
- Evaluation of all environmental contributions associated with transportation (with or without refrigerant – cooling system unit), the energy mix, and the waste management within each stage of the cold chain meeting the needs to have a holistic approach of all the main key actors in the whole chain of a product's life cycle;
- Possibility to include a feedstock product before entering in the cold chain (e.g., fresh fish) as a backstream process;
- Quantitative results in terms of the three environmental categories selected (i.e. Cumulated Energy Demand – CED, Global Warming Potential – GWP, Water footprint by AWARE approach).

In definitive, this tool allows stakeholders to quickly assess potential CSC's environmental impact without requiring deep knowledge in the LCA methodology.

3.4. Tool 3: Life Cycle Costing Tool (LCC)

The life cycle costs (LCC) methodology traces all relevant costs associated with a product for its entire life cycle. Three main types of LCC approaches are usually evaluated: conventional, environmental, and societal types [32].

A conventional LCC (C-LCC) is a pure economic evaluation and a quasi-dynamic method [32]. Generally, it includes (conventional) costs associated with a product that are borne directly by a given actor. This type of LCC is usually presented from the perspective of the producer or consumer alone. In this approach, external costs, that are not immediately tangible, are often neglected. Additionally, C-LCC does not always consider the complete life cycle; for example, end-of-life (EoL) operations are not included in any case. C-LCC is, to a large extent, the historic and current practice in many governments and firms.

The environmental LCC (E-LCC) uses the system boundaries and functional units equivalent to those of an LCA and is based on the same product system model, addressing the analysis to the complete life cycle. In this sense, the two analyses (i.e. LCA and E-LCC) are complementary in the fact that all costs are included as directly borne throughout the chain, including the already internalized cost of external effects. It assesses the cost that occurred during the Life Cycle in its LCA-related approach.

Societal LCC (S-LCC), as developed for cost-benefit analysis (CBA), uses an expanded macroeconomic system and includes a larger set of costs. These correspond to those that will be or could be, relevant in the long term for all stakeholders directly affected and for all indirectly affected through externalities (direct and indirect cost covered by society). In addition, S-LCC includes, but not necessarily, the monetized environmental effects of the investigated product as may be based on a complementary LCA.

This tool aims to deal with the life cycle costs of energy efficiency measures, allowing users to analyse these measures from a conventional economic perspective offering the possibility to review the impact from a social outlook. Furthermore, the tool offers unique features considering a holistic approach for CSCs in terms of an economic perspective, the evaluation of the economic feasibility of an energy efficiency measure for a specific actor of the CSC, the monetarization of the environmental benefits of energy efficiency solutions for any actor included in the cold chain, as well as the evaluation of the LCC under the aforementioned different approaches.

3.5. Tool 4: Benchmarking On-Energy Benefits (BEN)

In addition to evident energy and CO_2 savings, EEMs can also entail non-energy benefits (NEBs). NEBs can be described as improvements due to energy-efficient technologies that yield ‘additional enhancements to the production processes’ [33]. Such enhancements include improvements in areas such as waste generation, emissions, operation and maintenance, production, and working environment. Prior investigations from the European context suggest that three out of four companies in the CSCs of the food sector see benefits besides lower energy bills when thinking about EEMs [38].

Against this background, this tool aims to help create awareness and understanding of the role of NEBs within companies of the CSC. For this purpose, it allows, firstly, to reflect on non-energy benefits in a structured manner and secondly, to compare this reflection with views by other companies active in CSCs. These views are based on survey results that were explicitly collected to provide an overview of energy efficiency and non-energy benefits in cold supply chains.

Another key feature of the benchmarking is to compare the energy efficiency awareness of the individual company with that of the CSC to underline the particularities of CSCs. In addition, the users can compare their view with a peer group of similar company size. According to the survey, which serves as benchmarking basis, most companies at least sometimes consider energy efficiency in decision-making – both about their company and their cold supply chain. Concerning NEBs, the survey showed that most individual companies associate positive effects besides reducing energy demand and CO_2 emissions with EEMs. However, the general awareness of NEBs along the entire cold chain seemed to be lower in comparison.

To conclude, the benchmarking tool serves as an entry point to initiate a deeper reflection on the role of energy efficiency and non-energy benefits in the cold supply chain. Non-energy benefit evaluator (NEB).

It has been pointed out in the literature that NEBs can have a significant impact on the value of EEMs, even exceeding energy savings alone (e.g. [33], [39]). NEBs are easily underestimated, or even not considered, in the evaluation process of an energy-saving project [40], [41].

Building on the previously described benchmarking tool, the goal of the NEB evaluator tool is to introduce possible NEBs of EEMs, their classification, and their strategical assessment in the decision-making process of an EEM. For this purpose, first, NEBs can be chosen from a pre-defined list and can then be classified concerning their contribution to the strategy according to cost decrease, value proposition increase, and risk reduction for a selected EEM. In a second step, they can be prioritized and assessed qualitatively or quantitatively.

A key feature of the tool is to assess NEBs not only from an individual company perspective but also along the whole cold supply chain. Therefore, an exemplary EEM can be analysed and positive effects for the individual company and other stages of the chain can be considered.

To conclude, the NEB tool provides an advanced strategic assessment of non-energy benefits of specific energy efficiency measures to the particularities of cold supply chains.

4. THE MULTI-CRITERIA DECISION ANALYSIS TOOL (MCDA)

Previous tools allow assessing different key performance indicators (KPI) of the same cold chain which can lead to different results. The multi-criteria decision analysis (MCDA) tool allows us to understand the impact of adjusting temperature levels and storage levels on five of the main impact criteria used in life cycle analysis (assess in the CSC and the LCA tools). Moreover, it is possible to evaluate the potential of the energy efficiency measures while considering the optimization of different KPIs.

Multi-criteria analysis is a well-recognized method 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 criteria [42], [43]. It is possible to select different weights for the impact categories and then carry out an automated multi-criteria assessment based on the TOPSIS algorithm. In TOPSIS, the shortest distance to the ideal solution and the furthest distance from the anti-ideal solution is considered evaluation of alternatives. Similarly, as with other Multi-Criteria Analysis (MCA) methods, TOPSIS has a subjective parameter in form of assignment of weights to each selected criterion [40].

The main MCDA features can be described as being a macro-enabled expert tool to analyze the impact of parameter variation (what-if-analysis) of particular energy efficiency scenarios, the use of quantitative, and yet simple, ranking method for the evaluation of energy efficiency scenarios within the whole CSC, the identification of trade-off between various key performance criteria for the environmental impact in CSC, and a comprehensive approach merging technical, economic and environmental perspectives drawing on the supply chain analysis, the life cycle assessment and adding a multi-criteria approach.

5. Validation and Limitations

The ICCEE toolbox has been designed as an instrument for assessing the sustainability and energy performance of CSCs. Although initially conceived to help small and medium-sized enterprises, its potential is not limited to them. Large companies involved in CSC can also use the toolbox to evaluate potential EEMs at any stage, such as raw material suppliers or transport multinationals.

Using different individual tools, the CSC assessment provides a result (or score) for the different KPIs (i.e. specific energy losses, quality losses, GWP, CED, water scarcity) under evaluation. Then, such outputs are analysed in the MCDA tool (see Fig. 3), to obtain a definitive score considering the performance of the EEM under evaluation.


Results

The results for the base configuration as well as the best alternative from the TOPSIS analysis using the above input parameters and weights is shown below.

	Base	Best	
Raw material temperature	293	270	K
Finished product temperature	285	277	K
Amount of final product in display area	500	500	kg

	Weights	Base	Best	
Specific energy consumption	20 %	0.02	0.02	kWh/kg
Quality losses	30 %	0.13	0.09	%
Global warming potential	15 %	5.30	4.95	kg CO_2eq/kg
Cumulated energy demand	15 %	0.2	0.2	MJ/kg
Water scarcity	20 %	0.85	0.84	m^3eq/kg

Fig. 3. MCDA output.

5.1. Toolbox Testing and Validation

The single tools merged in the toolbox are the result of an iterative development process. The validation process both consisted of a technical validation as well as a user-oriented test.

For the technical validation of the tool, data from companies relevant for the supply chain (e.g., raw material preparation, logistic and warehousing operations, production and processing of products, packaging) per sub-sector were collected to verify tool operation, in particular for the CSC, LCA and LCC tools. In terms of user tests, selected companies from the CSC were contacted to test early drafts. Through interviews, surveys, and meetings, data was collected from suppliers, retailers, and producers. In addition to that, secondary data from already existing databases were incorporated for validating the tools.

5.2. Impact of Results

The tool provides to actors involved in the cold chain important benefits for the evaluation of the consumption of each energy carrier for refrigeration purposes towards storage and transportation activities along the cold chain. The possibility to obtain an assessment of non-energy benefits and behavioural aspects along the whole CSC represents an innovation compared to outcomes from previous research studies. The 61 semi-structured interviews and the organized online survey with 122 participants of companies active in cold chains highlighted that energy efficiency is nowadays considered more for individual companies than for whole cold supply chains. The survey also identified specific aspects such as a variety of priorities among the actors, the lack of know-how and skilled personnel, lack of communication and information exchange along the cold chain which may hinder a more consistent implementation of energy efficiency measures.

The aim of establishing the toolbox was to provide easy-to-use tools to investigate the sustainability performance and energy efficiency of CSCs. For this, a compromise between the level of detail and still meaningful results is necessary. Thus, there are important limitations to the toolbox that needs to be mentioned. First, despite seeking to make the tools as simple as possible, the task of analysing entire CSCs still requires a considerable amount of input parameters, especially for the LCA, CSC, and LCC tools. Second, evidence from other investigations shows that CSCs can be very complex, and they can involve many actors within the same stages of the CSCs. Within the tools, a default setup of stages has been foreseen. For specific analysis of large chains, some real-life stages may need to be merged to fit into the categories of the tools. Third, default values for selected products are required for some of the tools. These may serve as proxies for other products, yet they cannot represent all details for a large variety of different individual cooled products. In sum, the tools are a simplification of reality as any model. During testing, there were several requests to include more options into the drop-down menus in tools where users can choose between different options. Yet, the general feedback from the tool tests was positive and several users expressed the wish to use the tool in the future which is a testament to its usefulness. Likewise, feedback on user-friendliness was generally positive and no inconsistencies within the models were reported. Yet some basic training might be necessary to avoid calculation errors or misusing the tool, especially in the case of the more complex tools.

6. CONCLUSIONS

The toolbox is a contribution to understanding the sustainability and energy efficiency performance of CSCs. It can be relevant for many different users, including students interested in environmental impact assessments or energy efficiency in industrial sectors, technical experts who seek to make estimations on sustainability, and companies operating in CSCs. Thanks to its simplified approach, the tools only need a limited amount of adaptation by any stakeholder who seeks to analyse a known CSC with a defined product system. Moreover, the holistic approach allows different actors to access information from other stages in the supply chain, which would facilitate the evaluation of social issues for several stakeholders. The different options provided by the toolbox help to provide a holistic approach for the evaluation of CSCs, an aspect not always considered from interested parts or actors in the food cold supply sector. Moreover, the toolbox contributes to overcoming challenges such as the usual lack of deep knowledge in assessing methodologies or inconsistent choice of KPI and unsuitable tools that may hinder the efforts to choose a cost-effective measure (EEM) [44], [45].

The toolbox serves as an assessment tool to evaluate potential improvement scenarios for energy efficiency measures in the cold chain exploring technological, logistic and process-based aspects, evaluating the effect of quality losses and non-energy benefits. In addition, the tool provides also benchmarking properties facilitating ranking and sorting of the most sustainable and efficient solutions. Finally, the features presented in the tool can also aid in the future evaluation of the sustainability of CSCs, as environmental and economic dimensions are assessed.

ACKNOWLEDGEMENT

This work has received funding from the European Union's Horizon 2020 research and innovation program ICCEE project under grant agreement no. 84704. The paper's authors would like to thank all the ICCEE project partners for supporting the finalization of this work.

REFERENCES

[1] Adams D., Donovan J., Topple C. Achieving Sustainability in Food Manufacturing Operations and their Supply Chains: Key Insights from a Systematic Literature Review. *Sustain. Prod. Consum.* 2021:28:1491–1499. https://doi.org/10.1016/j.spc.2021.08.019
[2] United Nations. The sustainable development goals report 2019. New York: United Nations Publications, 2019.
[3] Yigit S., Yigit A. M. Responsible Sourcing Practices In Turkey, The Case Of Food And Beverage Industry. *Proceedings of the OÜSOBİAD TEMMUZ 2016* 2016:463–477.
[4] Xue L., *et al.* Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. *Environ. Sci. Technol.* 2017:51(12):6618–6633. https://doi.org/10.1021/acs.est.7b00401
[5] Food and Agriculture Organization of the United Nations. The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction. Rome: FAO, 2016.
[6] Lipinski B., *et al.* Reducing food loss and waste. Working Paper, Installment 2 of Creating a Sustainable Food Future. Washington: WRI, 2016.
[7] Stenmarck Å., *et al.* Estimates of European food waste levels. Stockholm: IVL Swedish Environmental Research Institute, 2016.
[8] Mentzer J. T., *et al.* Defining Supply Chain Management. *J. Bus. Logist.* 2001:22(2):1–25. https://doi.org/10.1002/j.2158-1592.2001.tb00001.x
[9] Manzini R., Accorsi R. The new conceptual framework for food supply chain assessment. *J. Food Eng.* 2013:115(2):251–263. https://doi.org/10.1016/j.jfoodeng.2012.10.026
[10] Beske P., Land A., Seuring S. Sustainable supply chain management practices and dynamic capabilities in the food industry: A critical analysis of the literature. *Int. J. Prod. Econ.* 2014:152:131–143. https://doi.org/10.1016/j.ijpe.2013.12.026
[11] Ahumada O., Villalobos J. R. Application of planning models in the agri-fod supply chain: A review. *Eur. J. Oper. Res.* 2009:196(1):1–20. https://doi.org/10.1016/j.ejor.2008.02.014
[12] Zhao H., *et al.* An overview of current status of cold chain in China. *Int. J. Refrig.* 2018:88:483–495. https://doi.org/10.1016/j.ijrefrig.2018.02.024
[13] Liu G., *et al.* Improving Food safety in Supply Chain based on Big Data. *E3S Web Conf.* 2018:53:1–4. https://doi.org/10.1051/e3sconf/20185303084
[14] Göbel C., *et al.* Cutting food waste through cooperation along the food supply chain. *Sustain.* 2015:7(2):1429–1445. https://doi.org/10.3390/su7021429
[15] Chaturvedi A., Martínez-De-Albéniz V. Safety Stock, Excess Capacity or Diversification: Trade-Offs under Supply and Demand Uncertainty. *Prod. Oper. Manag.* 2016:25(1):77–95. https://doi.org/10.1111/poms.12406

[16] Zanoni S., Zavanella L. Chilled or frozen? Decision strategies for sustainable food supply chains. *Int. J. Prod. Econ.* 2012:140(2):731–736. https://doi.org/10.1016/j.ijpe.2011.04.028
[17] Monforti F., Dallemand J. F. Energy use in the EU food sector: State of play and opportunities for improvement Energy from Waste in Croatia View project. Luxembourg: Publications Office of the European Union, 2015.
[18] Alamar M. del C., *et al.* Minimising food waste: a call for multidisciplinary research. *J. Sci. Food Agric.* 2018:98(1):8–11. https://doi.org/10.1002/jsfa.8708
[19] Sgarbossa F., Russo I. A proactive model in sustainable food supply chain: Insight from a case study. *Int. J. Prod. Econ.* 2017:183(B):596–606. https://doi.org/10.1016/j.ijpe.2016.07.022
[20] Devin B., Richards C. Food Waste, Power, and Corporate Social Responsibility in the Australian Food Supply Chain. *J. Bus. Ethics* 2018:150:199–210. https://doi.org/10.1007/s10551-016-3181-z
[21] Verghese K., *et al.* Packaging's Role in Minimizing Food Loss and Waste Across the Supply Chain. *Packag. Technol. Sci.* 2015:28(7):603–620. https://doi.org/10.1002/pts.2127
[22] Liljestrand K. Logistics solutions for reducing food waste. *Int. J. Phys. Distrib. Logist. Manag.* 2017:47(4):318–339. https://doi.org/10.1108/IJPDLM-03-2016-0085
[23] Willersinn C., *et al.* Quantity and quality of food losses along the Swiss potato supply chain: Stepwise investigation and the influence of quality standards on losses. *Waste Manag.* 2015:46:120–132. https://doi.org/10.1016/j.wasman.2015.08.033
[24] International Dictionary of Refrigeration. Cold Chain Definition [Online]. [Accessed 27.09.2021]. Available: https://dictionary.iifiir.org/index.php?inputLang=en&truncPos=right&srchTerm=cold+chain&outputLang=xx&defnLang=en&submit=View+results
[25] James C., Purnell G., James S. J. A Review of Novel and Innovative Food Freezing Technologies. *Food Bioprocess Technol.* 2015:8:1616–1634. https://doi.org/10.1007/s11947-015-1542-8
[26] Mercier S., *et al.* Time–Temperature Management Along the Food Cold Chain: A Review of Recent Developments. *Compr. Rev. Food Sci. Food Saf.* 2017:16(4):647–667. https://doi.org/10.1111/1541-4337.12269
[27] James S. J., James C. Advances in the cold chain to improve food safety, food quality and the food supply chain. *Deliv. Perform. Food Supply Chain.* 2010:366–386. https://doi.org/10.1533/9781845697778.5.366
[28] Ramírez C. A., Patel M., Blok K. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. *Energy* 2006:31(12):2047–2063. https://doi.org/10.1016/j.energy.2005.08.007
[29] Lezoche M., *et al.* Agri-food 4.0 : a survey of the supply chains and technologies for the future agriculture To cite this version: HAL Id : hal-02395411 Future Agriculture. *Comput. Ind.* 2020:117:103187.
[30] IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: IPCC, 2013.
[31] Boulay A.-M., Benini L., Sala S. Marginal and non-marginal approaches in characterization: how context and scale affect the selection of an adequate characterization model. The AWARE model example. *Int. J. Life Cycle Assess.* 2020:25(12):2380–2392. https://doi.org/10.1007/s11367-019-01680-0
[32] Ciroth A., *et al.* Environmental Life Cycle Costing. New York, 2008.
[33] Worrell E., *et al.* Productivity benefits of industrial energy efficiency measures. *Energy* 2003:28(11):1081–1098. https://doi.org/10.1016/S0360-5442(03)00091-4
[34] Alvarez G. Cold Chain refrigeration innovations the FRISBEE project. *J. Food Eng.* 2015:148:1 https://doi.org/10.1016/J.JFOODENG.2014.11.010
[35] Wernet G., *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 2016:21(9):1218–1230. https://doi.org/10.1007/s11367-016-1087-8
[36] ICCEE. The ICCEE Toolbox, a Coverage from 7 Angles [Online]. [Accessed 27.09.2021]. Available: https://iccee.eu/the-iccee-tool-2/
[37] Simapro manual PRe Consultants. Introduction to LCA with SimaPro 7. Amersfoort: PRé Sustainability, 2008.
[38] Neusel L., *et al.* Energy efficiency from farm to fork ? On the relevance of non-energy benefits and behavioural aspects along the cold supply chain. *ECEEE Ind. summer study Proc.* 2020:101–110.
[39] Thema J., *et al.* The multiple benefits of the 2030 EU energy efficiency potential. *Energies* 2019:12(14):2798. https://doi.org/10.3390/en12142798
[40] Cooremans C. Competitiveness benefits of energy efficiency : a conceptual framework. *Proc. Eceee summer study* 2015:123–131.
[41] Cooremans C. Make it strategic! Financial investment logic is not enough. *Energy Efficiency* 2011:4:473–492. https://doi.org/10.1007/s12053-011-9125-7
[42] Pubule J., *et al.* Finding an optimal solution for biowaste management in the Baltic States. *J. Clean. Prod.* 2015:88:214–223. https://doi.org/10.1016/J.JCLEPRO.2014.04.053
[43] Ishizaka A., Nemery P. Multi-criteria Decision Analysis: Methods and Software. New Jersey: Wiley, 2013.
[44] Thollander P., Palm J. Efficiency in Industrial Energy Systems. Linkoping: Springer London, 2013.
[45] Zanoni *et al.* Improving Cold Chain Energy Efficiency: EU H2020 project for facilitating energy efficiency improvements in SMEs of the food and beverage cold chains. *Proceedings of the 6th IIR International Conference on Sustainability and the Cold Chain* 2020:292878. https://doi.org/10.18462/iir.iccc.2020.292878