TOWARDS SUSTAINABILITY IN COLD CHAINS: DEVELOPMENT OF A QUALITY, ENERGY AND ENVIRONMENTAL ASSESSMENT TOOL (QEEAT)

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ABSTRACT

Quantification of the impact of refrigeration technologies in terms of the quality of refrigerated food, energy usage, and environmental impact is essential to assess cold chain sustainability. In this paper, we present a software tool *QEEAT* (Quality, Energy and Environmental Assessment Tool) for evaluating refrigeration technologies. As a starting point, a reference product was chosen for the different main food categories in the European cold chain. Software code to predict the products temperature, based on validated heat and mass transfer models, were written in Matlab (The Mathworks Inc., Natick, USA). Also, based on validated kinetic models for the different quality indicators of the reference products, (including fruit, meat, fish, vegetables and dairy products) a software code was written to calculate the quality and safety evolutions of the food product, using the predicted product temperature as input. Finally, software code to calculate the energy usage and Total Equivalent Warming Impact (TEWI) value of different refrigeration technologies was also written in Matlab. All three software codes were integrated, and a graphical user interface was developed. Using the *QEEAT*, a user can tailor a cold chain scenario by adding cold chain blocks (different steps of a cold chain) and simulating the quality evolution, energy use and emission throughout the chain. Also, the user can modify properties of a cold chain block, by selecting different technologies, or changing set point values. Defaults are provided for input values, and are based on the current practice, and obtained by extensive literature studies and consultation with different experts of the cold chain. Furthermore, the user can build and simulate several chains simultaneously, allowing him/her to compare different chains with respect to quality, energy and emission.

1. INTRODUCTION

Refrigeration is a commonly used technique to extend the shelf life of food. Up to about 40% of all food products requires refrigeration (Mattarolo, 1990), with about 1 billion domestic refrigerators worldwide (Coulomb, 2008). Refrigeration helps to extend shelf life of food by slowing down the rate of various deteriorating phenomena, such as growth of spoilage microorganisms and biochemical reactions such as respiration and enzymatic reactions in fresh fruits and vegetables. Despite these beneficial effects, refrigeration equipment accounts for about 15 % of global energy use, and is also a major contributor to emissions of greenhouse gases. The subject of sustainability has become a global concern, with various measures being put in place to ensure a sustainable future. Some key examples are the Montreal Protocol on Substances that Deplete the Ozone Layer and the EU "20-20-20" targets, with objectives of a 20 % reduction in EU greenhouse gas emissions from 1990 levels, raising the share of EU energy consumption produced from renewable resources to 20 %, and a 20 % improvement in the EU's energy efficiency. Consumer protection is also very important when ascertaining a sustainable cold chain, and various organisations are tasked with ensuring this, such as the codex alimentarius international food standards. All of these quality

indicators necessitate some form of quantification, in order to reliably assess sustainability of cold chains. Different software tools have been developed to quantify energy use (e.g. Pack calculation II, a freeware application for comparing yearly energy consumption of refrigeration plants developed by the company IPU Innovative factory ; “SuperSim”, developed by Ge and Tassou, 2000, and “Cybermart” , developed by Arias et al.2010), environmental impact (e.g. Vapour Compression Refrigerator Simulator (VCRS), by Eames et al., 2012), and evolution of quality (e.g. “Combase”; “PeaPle”, by De la Calle et al., 2009, and Sym’Previus, a French commercial software). However, no single software tool currently exists that can simultaneously quantify these three sustainability indicators. Furthermore, the various software tools listed above do not offer users the degree of freedom to build different cold chains with different cold chain blocks representing the successive steps of the supply chain of frozen and refrigerated food products.
The objective of the current manuscript is to present a software tool; Quality, Energy, and Environmental Tool (*QEEAT*). The *QEEAT 4.0* can be used to assess the potentials of a number of new and emerging technologies, by comparing them with currently used technologies in terms of quality, energy and emissions. This software was developed within the framework of the European Union FP7 project, FRISBEE (Food Refrigeration Innovations for Safety, consumers’ Benefit, Environmental impact and Energy optimisation along the cold chain in Europe).

2. COMPONENTS OF *QEEAT 4.0*

The different components of *QEEAT 4.0* are shown in Fig. 1. The background material for developing the software were kinetic models for predicting quality evolution for the different food products shown in Table 1, models for calculating energy use of the vapour compression refrigeration cycles, and a formula for calculating the Total Equivalent Warming Impact (TEWI). Software codes were written for all these models, and they were integrated together with a graphical user interface (GUI). Using the GUI, a user can build cold chain(s) by adding cold chain blocks, for all of which they can make changes to properties such as refrigerant type, cold room temperature, compressor efficiency, room dimensions, and product load. Once the user is satisfied with modifications made to their cold chain(s), they can simulate the cold chain. Results can be viewed as a plot, or exported as a data file. Furthermore, the user can build two or more chains, for easy comparison of impact on product quality, energy use, and environmental emissions.

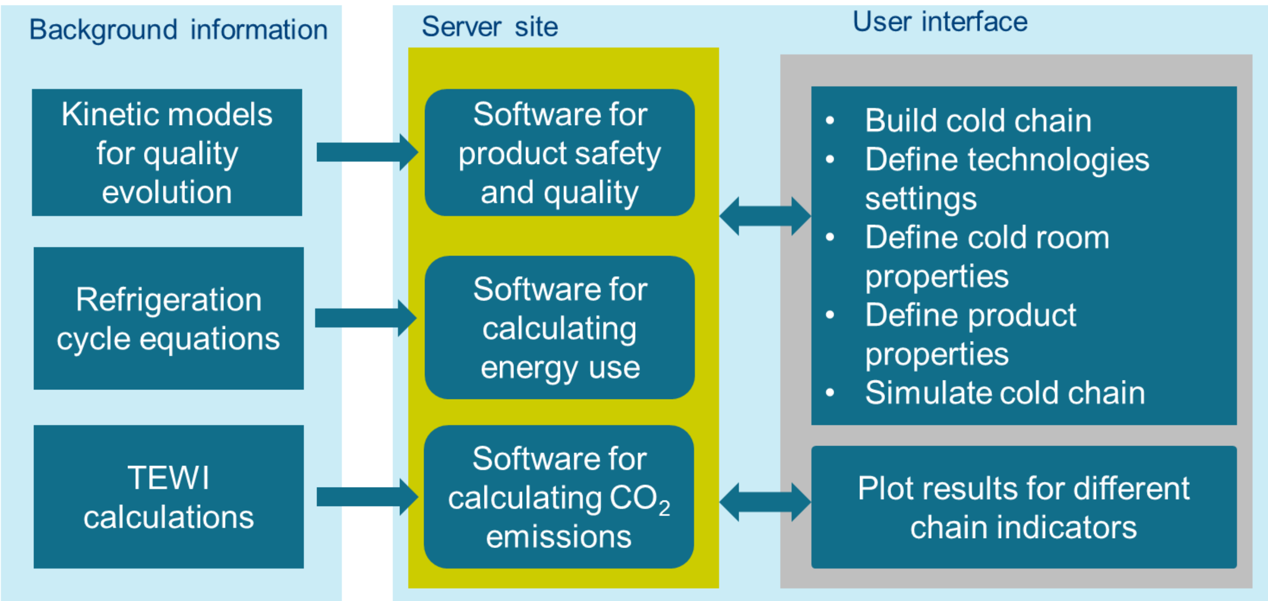

Figure 1. Main components of *QEEAT 4.0*

For each product shown in Table 1, a reference cold chain was defined. The reference cold chain was defined as the series of steps (cold chain blocks) a product goes through from the time when the product is produced (or harvested), to the moment it reaches the consumer. For each of the cold chain blocks in the reference cold chain, the values of the different parameters (such as set points, efficiencies, technologies) were defined based on the most common practice. These reference chains serve as a bench mark for comparing alternative chains. They also provide default settings for users who may not have the necessary knowledge to define certain input or parameter values. The main GUI of *QEEAT 4.0* is shown in Fig. 2.

Table 1. Safety and quality indicators for food products implemented in *QEEAT 4.0*

Category	Reference food products	Quality indicators
Fruit	'Jonagold' apples	Firmness, weight loss, colour, aroma
Ready-to-eat meat	Vacuum packed cooked ham Pasteurized paté Raw smoked & salted ham	*L. monocytogenes*, lactic acid bacteria
Fish	Salmon fillets	Lactic acid bacteria
Meat	Frozen pork neck cutlet	Drip loss
Milk products	Ice cream	Sensory perception of ice crystal formation, viscoelastic properties (damping factor), texture (firmness)
Vegetables	Spinach	Chlorophyll content, sensory overall impression, vitamin C content

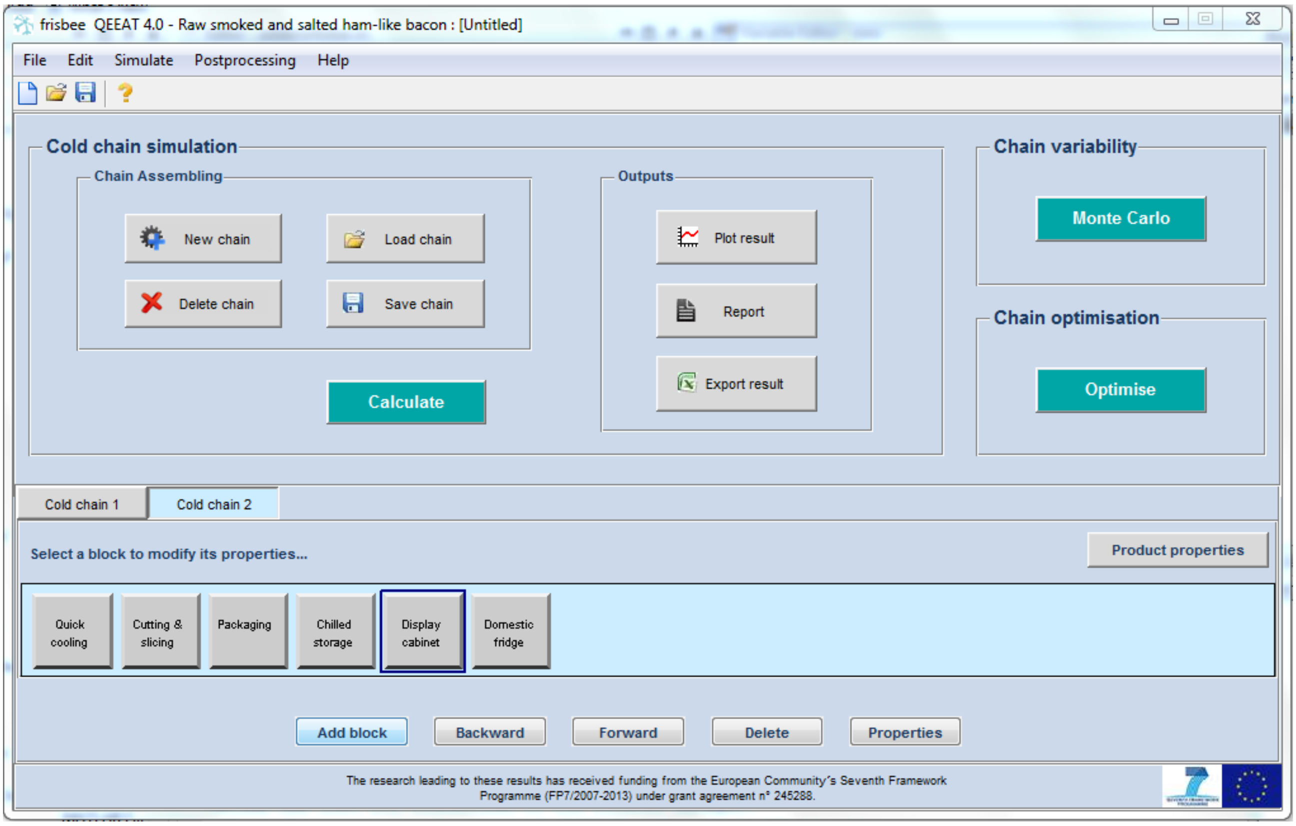

Fig. 2. Main GUI of *QEEAT 4.0*

3. EXAMPLES OF *QEEAT 4.0* SIMULATIONS

Case study 1. Optimizing energy use in the apple cold chain

Apples are typically stored at temperatures as low as possible, without causing chilling injury. However, apple handlers are faced with the question "what if I store my apples at a slightly higher temperature to reduce energy cost? Will the final quality be so inferior that the value of the fruit will be reduced by more than the savings in energy costs?" The *QEEAT 4.0* was used to simulate the firmness evolution of apples stored at 1 °C for 9 months, and at 4 °C for 9 months. The result of the cold chain simulations, in terms of energy use and firmness decay, is shown in Fig. 3. From this figure, it is simulated that 'Jonagold' apples stored at 4 °C for 9 months will have a mean firmness of 64 N at the end of storage, while those stored at 1°C will have a mean firmness of about 74 N. The energy usage for storage 4 °C is about 0.02 kWh per kg of apples, while for storage at 1 °C, it is about 0.035 kWh per kg of apples. Depending on the quality classes and the price per kg of apples, the apple handler may assess whether storage at 4 °C is more advantageous or not. Furthermore, if it is foreseen that the storage duration will only be a few months, then one may consider storing at temperatures 1 or 2 °C above the recommended temperature for long term storage. It may even be a better alternative to store the apples at lower temperatures at night, when energy prices are at the lowest, and store at slightly higher temperatures during the day, when prices are usually much higher. Of course, such simulations are only the first steps in assessing the possibilities of optimizing energy usage. Further considerations such as variability in product quality (this will be implemented as Monte Carlo simulations in the next version of the software, *QEEAT 5.0*) and other quality indicators may also be very important.

A

B

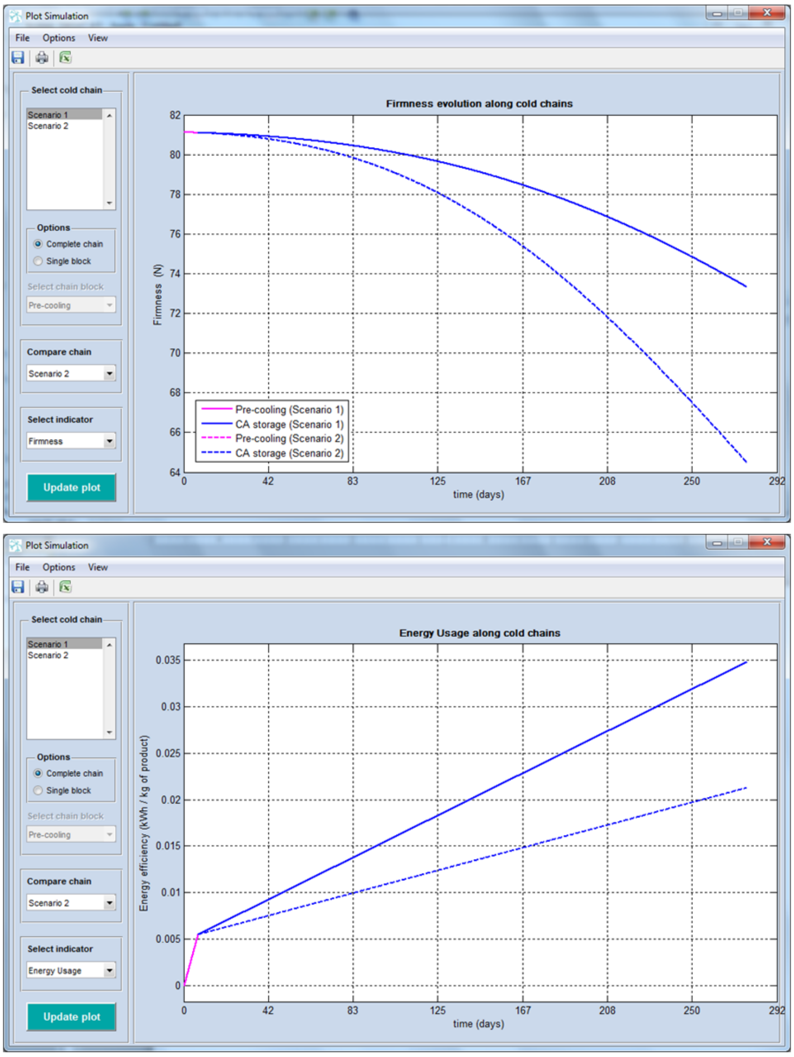

Figure 3. Firmness evolution (A) and energy usage (B) during apple storage at 1°C and 4°C for 9 months.

Case study 2. Attenuating the amplitude of temperature fluctuations in ice cream cold chain

The microstructure of ice cream has an impact on its quality. Particles that are 0.1-2 µm in diameter impart creaminess to ice cream, while particles larger than 3 µm cause a gritty texture (Marshall, 2003). Temperature fluctuations of frozen ice cream storage cause growth of crystal size, leading to this gritty texture. Therefore, reducing the amplitude of temperature fluctuations along the ice cream cold chain will help maintain quality. During transport from production site to, for example, super markets, ice cream is usually transported in refrigerated trucks. However, the energy source of such trucks (mostly diesel fuel) emits a huge amount of CO_2. An alternative is to cover the products with Phase Change Materials (PCMs) and transport the ice cream by non-refrigerated trucks. PCMs are materials that can absorb large amounts of heat without changing their temperature, thereby helping to maintain product temperature inside the cover. In the *QEEAT 4.0*, the properties of several commercial PCMs have been implemented. Using the software, a user can estimate the thickness of the PCM materials, and the duration for which the PCM can last before melting. In this example, we simulate the effect of using E.18 (a PCM with melting temperature of -18°C) in maintaining ice cream temperature during refrigerated transport of frozen ice cream. The result is shown in Fig. 4. Assuming an ambient temperature of 15 °C the E.21 PCM with a thickness of 0.002 m can help maintain the ice cream at -18 °C for more than 24 hours, during non-refrigerated transport. Such simulations mean it could be possible to replace traditional refrigerated trucks with non-refrigerated transport in which the food products are covered with PCM materials. Such PCM materials can be cooled (charged or re-frozen) using more environmentally friendly energy sources, such as solar energy. They can also be used to reduce peak energy demand at times of high throughput (peak hours).

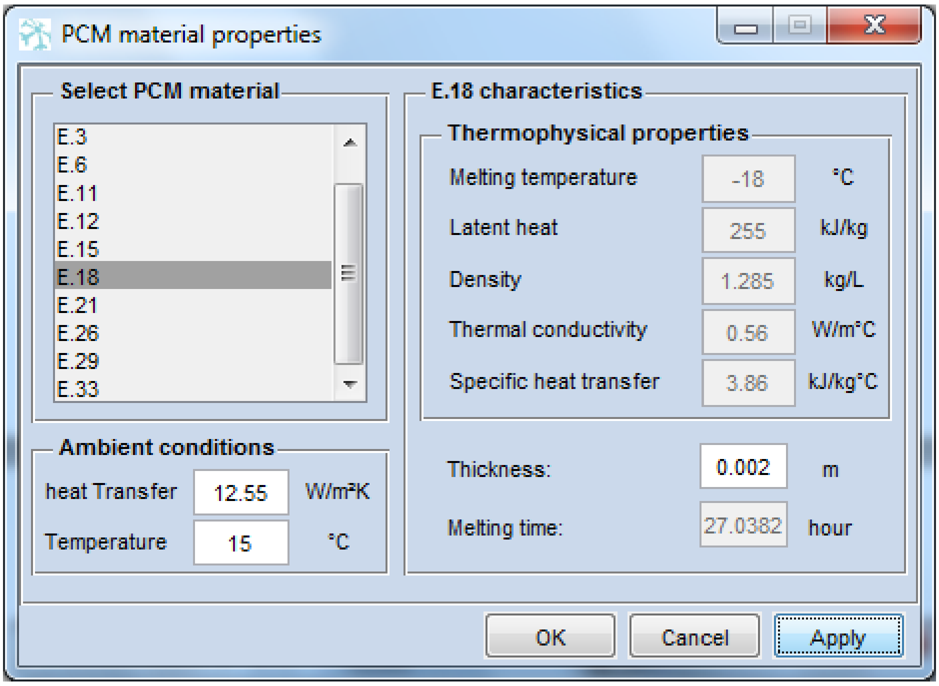

Figure 4. Effect of E.18 PCM cover in maintaining ice cream temperature during non–refrigerated transport.

Case study 3. Predicting microbial spoilage in vacuum packaged cooked ham during retail

The growth of spoilage microorganisms is the most important quality indicator for ham and other read-to-eat meat products (Baird-Parker, 2000). In this third example, we investigate the effect of storage duration at the supermarket on the quality of ham. Two cold chain scenarios were considered (Table 2). In scenario 1, the ham is kept for 7 days in display cabinets, as is typically done, while in scenario 2, the ham is kept for 14 days. The growth of lactic acid spoilage bacteria for both scenarios is simulated and the result is shown in Fig. 5. From this figure, it can be seen that keeping the ham at the supermarket for two weeks will result to a much higher growth of spoilage bacteria. However, the final cell count (less than 3.5 log CFU/g) is still much lower than the levels that could potentially lead to the end of shelf life. This means that retailers may consider larger stocks, which has a relaxing implication in terms of logistical management.

Table 2. The two cold chain scenarios used for case study 3 regarding the impact of storage duration at the display cabinets on the growth of spoilage microorganism.

Cold chain blocks	Scenario 1		Scenario 2	
	Set temperature	Duration	Set temperature	Duration
Quick cooling	0 °C	2 h	0 °C	2 h
Cutting and slicing	2°C	1 h	2 °C	1 h
Distribution storage	2 °C	1 d	2 °C	1 d
Display cabinet	4 °C	7 d	4 °C	14 d

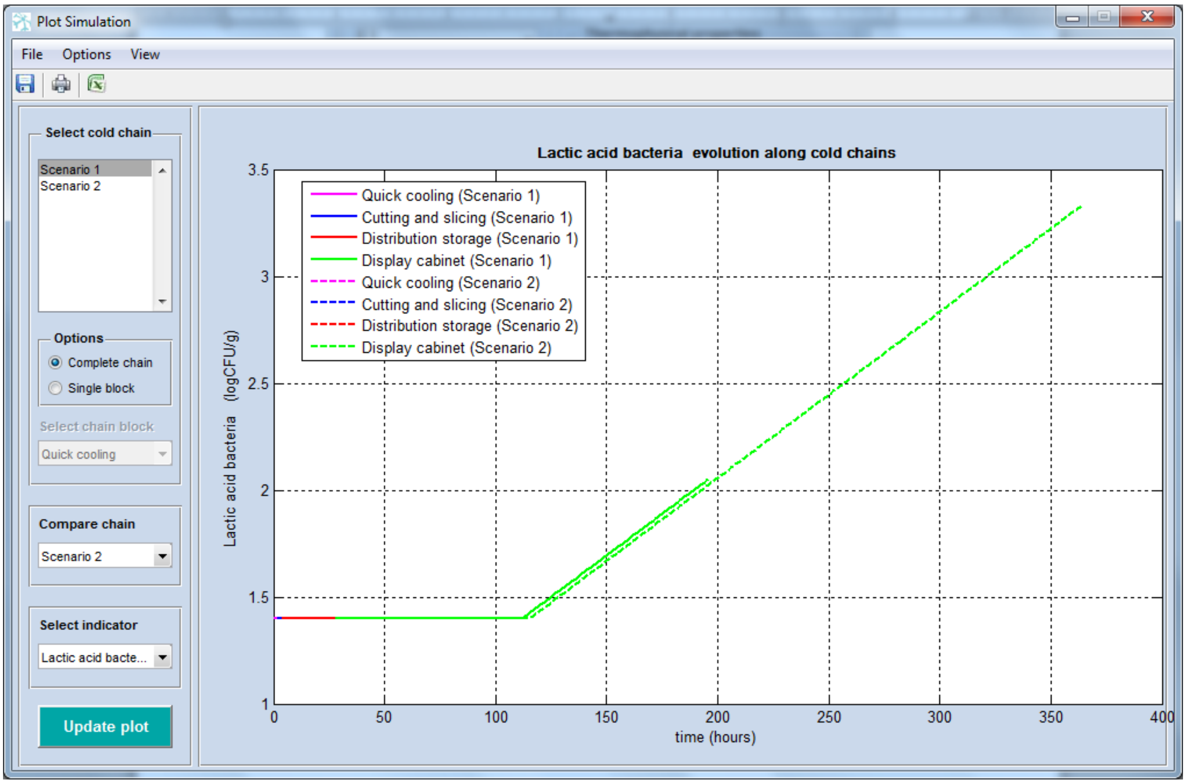

Figure 5. Simulation of lactic acid bacteria growth in ham for the two scenarios shown in Table 2.

4. CONCLUSION

The QEEAT software is a very useful tool that can be used by all stakeholders of the cold chain, to assess the different cold chains, with respect to three key sustainability indicators: quality of the food product, energy, and emissions associated with the use of refrigeration equipment. All the quality models are based on well-designed experiments, and in most cases, have been validated using independent datasets. Most of these models have been published (e.g. Giannakourou and Taoukis, 2003; Gwanpua et al., 2012; Gwanpua et al., 2014). Several experts were involved in developing the tool, ranging from postharvest handlers, microbial quality analysts, producers of frozen product, experts in refrigeration equipment development and installation, heat and mass transfer modelling, and software programmers. The software has been developed using a detailed development cycle, and results have been compared with real data.

5. *QEEAT* SOFTWARE AVAILABILITY

The final *QEEAT* software will be released in two separate versions: a version with limited functionalities, mainly for consumers, will be made freely downloadable through the FRISBEE website (http://www.frisbee-project.eu/). This version will allow simulation of the reference cold chains for each food product and the end-user will have the opportunity to change the temperature in each cold chain block. As such, the end-user can appreciate the difference in quality, energy use and environmental impact between his/her own choice and the reference chains. The second version will be the complete version with all technical details and will be developed further in forthcoming research projects, involving different partners of the FRISBEE consortium.

6. ACKNOWLEDGEMENT

This publication has been produced with the financial support of the European Union (grant agreement no 245288 FP7/2007-2013 – Frisbee). The opinions expressed in this document do by no means reflect the official opinion of the European Union or its representatives.

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