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# The FRISBEE tool, a software for optimising the trade-off between food quality, energy use, and global warming impact of cold chains

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ABSTRACT

Food quality (including safety) along the cold chain, energy use and global warming impact of refrigeration systems are three key aspects in assessing cold chain sustainability. In this paper, we present the framework of a dedicated software, the FRISBEE tool, for optimising quality of refrigerated food, energy use and the global warming impact of refrigeration technologies. The food quality models implemented in the FRISBEE tool are based on validated kinetic models, most of which are available as separate publications in this issue, while the models for calculating energy use and global warming impact have been validated using independent data. The 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). The consumers' version of the FRISBEE tool, with limited functionalities, will be made available as free downloadable software on the FRISBEE website, while the version with full functionalities will be used for consultancy.



## 1. Introduction

Refrigeration plays a vital role in reducing food losses and waste by significantly reducing the rate of growth of pathogens and spoilage organisms, and also slowing down various physiological (e.g., ripening and senescence), biochemical (e.g., pigmentation reactions and lipid oxidations) and physical (moisture loss) processes within food products that can result in inferior product quality. In a study on developing and emerging economy, Van Gogh et al. (2013) reported that the most important cause of postharvest losses is non-optimal temperature control in the cold chain. The cold chain is defined as the set of refrigeration steps that maintain the quality and safety of the food product from production to consumption. With the global population expected to reach over 8 billion in 2030 (United Nations, 2008), refrigeration is expected to play an important role in meeting the increasing food demand, and therefore the number of refrigeration systems will only continue to rise. For example, cold storage capacity in India grew by more than four times between 2008 and 2009 (Salin, 2010), while in the US, a 14% growth in the general refrigerated warehouse capacity between October 2007 and October 2009 was reported by the National Agricultural Statistics Service (NASS, 2010).

Although refrigeration is very important in maintaining the safety and quality of perishable foods, its operation is very energy intensive. This has economic implications for the food industry, with electricity costs accounting for a substantial part of total production costs. Furthermore, the use of refrigeration is a major

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contributor to global energy consumption, accounting for 15% of the electricity consumed worldwide (Mattarolo, 1990; Coulomb, 2008).

In addition, refrigeration is a significant contributing factor to ozone depletion and global warming. This is often due to direct emissions from refrigerant leakage, as well as indirect emissions from the use of fossil fuels to produce the electrical power required to run refrigeration equipment. Most of the electricity used in the EU for operating refrigeration equipment is generated from fossil fuels (Coulomb, 2008). Maykot et al. (2004) showed that irrespective of the market region and type of refrigeration system, indirect $CO_2$ emissions will always be a major contributor to global warming. They estimated that indirect emissions contribute about 98% of the Total Equivalent Warming Impact (*TEWI*) in both commercial and household applications in North American, 95–98% for commercial applications in Europe, and about 98% for commercial application in Asia.

Mathematical tools for quantification of quality and safety of refrigerated food, energy usage, and global warming impact are essential for evaluation of cold chain efficiency and sustainability. Such tools could help in identifying critical points in cold chains where efforts should be concentrated in order to reduce energy consumption and $CO_2$ emissions.

Currently, various software solutions are available to model the evolution (growth, inactivation, survival) of micro-organisms in food products. Product temperature is an important input parameter for microbial growth simulation purposes in most predictive microbiology software, such as the ‘‘Baseline Software Tool’’ (www.baselineapp.com), and ‘‘Combase’’ (www.combase.cc). Other examples are Sym’Previus (www.symprevius.net), and FSSP, Food Spoilage and Safety Predictor (http://sssp.dtuaqua.dk/download.aspx). A comprehensive overview of predictive microbiology was made at a dedicated Software Fair (http://www.icpmf8.org/specialday.html) during the 8th International Conference on Predictive Modelling in Food (ICPMF8) (Tenenhaus-Aziza and Ellouze, 2013). For non-microbial quality aspects, several mathematic models to predict quality evolution along the cold chain for different fruits and vegetables have been developed (Johnston et al., 2001; Giannakourou and Taoukis, 2003), but only a few of these models have been implemented in user friendly software. An example of such a software is ‘‘PeaPle’’ (De la Calle et al., 2009), which is a decision support system created with the objective to simulate quality changes of apples and peaches along different supply chains.

Some software applications have been developed to calculate energy consumption and emissions of $CO_2$ by refrigeration equipment. Examples include Pack Calculation Pro, an application for comparing yearly energy consumption of refrigeration plants developed by the company IPU Innovative factory (http://en.ipu.dk/); ‘‘SuperSim’’ and ‘‘Cybermart’’ developed by Ge and Tassou (2000) and Arias et al. (2010) respectively, both for simulating energy use of display cabinets in supermarkets, and VCRS, Vapour Compression Refrigerator Simulator, developed by Eames et al. (2012) to study the implications of design choices in terms of energy usage and carbon generation by refrigeration systems for chillers, freezers and storage rooms.

Our approach was to develop a common software, the FRISBEE tool, that can be used to simultaneously evaluate the quality of refrigerated products, energy use and global warming impact of refrigeration systems. This is particularly important because these three sustainability indicators (food quality, energy use and global warming impact) are coupled through temperature. The current manuscript outlines the main steps that were used in developing the FRISBEE tool. Moreover, examples of how the FRISBEE tool could be used in optimising cold chains are presented and discussed. The 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. Development of the FRISBEE tool

### 2.1. Definition of reference cold chains

As a first step in developing the FRISBEE tool, reference products were chosen for five main food categories (fruit, meat, fish, milk products, and vegetables), and for each of these reference products, the most important quality indicators were identified (Table 1). Microbiological safety indicators, exemplified by *Listeria monocytogenes* on chilled ready-to-eat meat products, were included in the list of quality indicators. During the first phase of the project, an even larger number of quality indicators were tested, and only those that showed a dependence on the duration and temperature of the cold chain were included for simulation in the software. Furthermore, for each product, a reference cold chain was defined, based on the most common practices in Europe, to serve as a bench mark for comparing other chains. The basis of these chains came from extensive literature studies and from consultation with experts in different fields of the cold chain. For each chain the different steps (the so-called ‘‘cold chain blocks’’) that a food goes through along the cold chain were identified. Process variables (set point temperature, relative humidity, etc.) and the properties of the refrigeration system (e.g., refrigerant type, evaporator type, compressor’s efficiency, and evaporating temperature of refrigerant) in each block of the reference cold chain were determined. In addition, the product properties (e.g., dimensions, thermophysical properties, packaging properties), and residence time of the food in each cold chain block were defined.

### 2.2. Kinetic models for food quality evolution

Mathematical models that describe how storage temperature influences the evolution of different quality indicators for different food products have been developed by several authors (see, for example, Chen et al., 1989; Tijskens et al., 1998; Johnston et al., 2001; De Smedt et al., 2002; Giannakourou and Taoukis, 2003; Poschet et al., 2003; Geeraerd et al., 2004; Hertog et al., 2007; Gwanpua et al., 2012, 2014). Some of these models were developed based on purely empirical relations (empirical or *black box* models), while others were based on equations that attempt to describe the mechanisms up to a certain level of depth regarding the biochemistry involved and/or include interpretable parameters (*grey-box* modelling). Empirical models are often easy to develop and fit the data well, but may not be able to explain data collected in different but similar conditions. Consequently, empirical models are not usually suitable as a tool for predictions. Contrarily, grey-box models are usually rather more difficult to develop, and may suffer from lack of fit. However, because their model structure and/or parameters have valid interpretations, they turn out to be more generic and can reliably be used for testing hypotheses and/or predictions in conditions different from, but similar, to the ones under which the model was developed.

In developing the FRISBEE tool, kinetic models for assessing food quality evolution along the cold chain were developed for each of the quality indicators shown in Table 1. A summary of the guidelines used in developing these models is shown in Fig. 1. The first step was to formulate mathematical equations describing the processes that drive the degradation of the different quality aspects. For example, the loss in green colour of spinach leaves during frozen storage is due to chlorophyll breakdown