Application of a TTI-based Distribution Management System for Quality Optimization of Frozen Vegetables at the Consumer End

M.C. GIANNAKOUROU AND P.S. TAOUKIS

ABSTRACT: The applicability of Time Temperature Integrators (TTI) for frozen chain management was assessed. Shelf life kinetics indices of frozen green peas and white mushrooms and response kinetics of suitable enzymatic TTI were used to confirm the monitoring effectiveness of TTI, in a controlled field test with 200 products. Comparison to actual measurements of quality indices showed that TTI response provides a reliable indication of the relative quality status of the products. The potential of Least Shelf-Life First Out (LSFO) system, a TTI based management system for frozen product distribution and stock rotation, was demonstrated by Monte Carlo technique that showed consistent, acceptable quality and minimization of rejected products at the consumer end.

Keywords: frozen, TTI (Time Temperature Integrators), shelf life, Arrhenius, LSFO (Least Shelf Life First Out), chain management

Introduction

THE GLOBAL FOOD INDUSTRY AND REGULATORY AUTHORITIES increasingly face the challenge to meet conflicting market and society needs. Food products of maximum sensory quality, increased nutritional and functional properties combined with a traditional, wholesome image, less processing, fewer additives and "technological" interventions yet of guaranteed safety and extended shelf life are being demanded by the consumers. Achievement of longer shelf life with minimum processing, besides intense optimization of all production and preservation parameters, requires innovative systems to control food deterioration and ensure quality. These systems rely on prevention through monitoring, recording, and controlling of critical parameters during the entire product's life cycle, which extends to the time of use by the final consumer. Increasing attention is focused on the role and the logistics of transport, storage, and handling, and the benefits of taking a supply chain perspective are being appreciated and pursued (Browne and Allen 1998; Dubelaar and others 2001; Ross 1996; Silver and others 1998; Broekmeulen 2001; Tijkens and others 2001). Temperature conditions in the frozen distribution chain determine the shelf life and final quality of optimally processed and packed frozen vegetables. Since in practice significant deviations from specified conditions often occur, temperature monitoring and recording is a prerequisite for chain control and any logistics management system that aims on product quality optimization at the consumer's end (Wells and Singh 1989). Furthermore, in an effective scheme, variations in temperature exposure of single products within batches or transportation subunits should be considered. Time Temperature Integrators or Indicators (TTI) are a cost-effective way to individually monitor the temperature conditions of frozen food products throughout distribution (Taoukis and others 1991). Development of TTI, principles of operation, and current status are detailed by Taoukis and Labuza (1989) and Taoukis (2001). Prerequisite for application of TTI is the systematic kinetic modeling of the temperature dependence of shelf life of the frozen products. Based on reliable models of the shelf life and the kinetics of TTI response, the effect of temperature can be monitored and quantitatively translated to food quality from production to the point of consumption (Fu and Labuza 1993; Taoukis and Labuza 1999). At the early stages of TTI development, several studies correlating frozen food quality with TTI were published (Schubert 1977; Farquhar 1983; Dolan and others 1985; Singh and Wells 1985; Wells and others 1987; LeBlanc 1988; Yoon and others 1994). Due to switch of focus to application of TTI to chilled foods, and due to difficulties relating to systematic kinetic modeling of frozen foods and response of TTI in the subfreezing range, little current published information is available in this field. A recent study reports on the testing and modeling of the response of current TTI in the subfreezing range and the potential of applying the TTI for estimating the quality status and remaining shelf life of kinetically modeled frozen vegetable products (Giannakourou and Taoukis 2002). This study comprehensively approaches the issue of applicability of TTI as effective decision-support tools of frozen chain monitoring and management. It was based on the kinetic study and modeling of the quality of representative frozen vegetable products and the response kinetics of suitable TTI. In order to confirm the effectiveness of TTI as monitoring and controlling tools for the real distribution of frozen vegetables, an actual wide range field test was conducted, simulating the existing conditions during the transport and the storage of frozen products extending to storage in consumer freezers. The objective was to assess the reliability of estimates of quality and shelf life based on TTI response, in comparison to predictions based on the real, measured temperature history and to actual measurements of the quality indices for a large number of actual products from the frozen distribution chain.

A further objective was to develop and evaluate the application of a TTI based system for optimization of frozen product distribution and stock management. The aim of the implementation of such a system was to actually use the information provided by the TTI for decision making at important points of the chain in order to achieve an optimal distribution of product quality at consumption.

Materials and Methods

Frozen vegetable products

The studied frozen vegetables were commercial products of green peas (*Pisum sativum* variety Pudget) and pieces of white, cut mushrooms (*Agaricus bisporus).* The industrial processing comprised prefreezing treatments, such as rinsing and blanching at 90 °C for 2 min, followed by the freezing process in a freezing tunnel at –25 °C for 2 min (IQF freezing equipment, FloFreeze MA-Model, Frigoscandia, Helsingborg, Sweden), packing and storage in the factory warehouses at –18 °C. Part of the final products were transported to the laboratory at carefully monitored conditions (8 h track transport to the central distribution center at –18 °C, one d storage at –19 °C, 2 h track transport to the lab at –18 °C) ensuring minimal quality loss. From this part, a systematic kinetic study of quality indices that affect the shelf life of the products, such as color and vitamin C content, was conducted for the whole relevant temperature range (–3 to –20 °C). Results of this study were used for evaluation of the results of the field study. The methodology consisted of storing 100 g samples of green peas packed in the laminate film (20 mm BOPP, 48 μm PE) of the commercial products in controlled temperature cabinets (Sanyo MIR 153, Sanyo Electric Co, Ora-Gun, Gunma, Japan) at constant temperatures (from –3 to –20 °C) or programmed variable temperature profiles. Also, pieces of mushroom of uniform size were placed in open 25 mm glass Petri dishes, supported on styrofoam trays in groups of 8, packed in the same film, and stored at the same conditions. Measurements of the quality indices (color and Vitamin C for peas, and color for mushrooms) were conducted at appropriate time intervals in order to model their rate of change.

The other part of frozen products (300g units packed in the same commercial package) was used in the field test as described below.

Field Testing of TTI applicability

A field study was conducted including all stages of the actual distribution chain of frozen vegetables after production. Quality of 100 green pea and 100 sliced white mushroom products from the same production batch as the ones studied for kinetics, as well as response of selected TTI tags attached on each item, were constantly monitored throughout a simulated marketing route from the manufacturer to the final consumer, following all intermediate steps of the wholesale and retail level, the transports, and the final storage at the consumer's end. All pouches were carefully coded and the precise time-temperature history of 20% of individual packages was recorded throughout the simulated marketing route by miniature computer downloadable loggers (COX TRACER™, Belmont, N.C., U.S.A.) placed and sealed in the pouches.

After an initial storage at the producer's warehouse, products were transported to a distribution center, before delivering to the "retail outlet". To simulate realistically the wholesale and the retail stage, products were grouped and stored at laboratory freezers from –8 to –16 °C at ratios and temperatures based on collected data and recent surveys (Anonymous 1995) on current temperature conditions in Supermarkets in Greece that clearly demonstrate deviation from the ideal storage and exposure. For the final, important stage of home storage, products were randomly "purchased" by a hundred volunteer consumers and stored for 60 d in their domestic freezers. Temperatures of all consumers' freezers were measured for a 48-h period by the small, downloadable electronic loggers.

During the field test, at random times of the simulated "wholesale" and subsequent "retail" storage in the lab, the response of the windows of the selected types of TTI that were attached on the individual packages and activated at the factory level was measured, allowing for a direct correlation with the corresponding quality evaluation. Finally, after a total period of 4 mo in the chill chain, packages were brought back in the lab and measurements were taken at the simulated "consumers end" of (a) the important quality indexes of the products, (b) the visible response of the attached TTI, and (c) the actual temperature profile of the food and tag.

Quality indices measurement

Color measurement. Quantitation of the color change was based on measurement of CIELab values (CIE 1978) with a CR-200 Minolta Chromameter® (Minolta Co., Chuo-Ku, Osaka, Japan) with an 8 mm measuring area. A standard white plate (Calibration plate CR-200) was used to standardize the instrument under "C" illuminant condition according to the CIE (Commission International de l' Eclairage). Measurements were conducted for the kinetic study as well as for the field test, and the corresponding results were treated separately. For the purpose of the field test, measurements were taken from all numbered packages of both vegetable products. Sixteen pieces of mushroom or 16 peas, representative of the products, were measured at frequent time intervals during their storage in the lab freezers (mimicking the wholesale and the retail storage), and at the final point, after their domestic storage.

Vitamin C determination. Vitamin C was determined using a high performance liquid chromatography method (HPLC) (Giannakourou and Taoukis 2002), which was compared and standardized with the 2, 6 dichloroindophenol titrimetric method (AOAC 1984, 43.064). For the kinetic study and the field test, all analyses were carried out in duplicate on vegetable tissue, homogenized, using a pestle and mortar, as it was described in the method proposed by Oruna-Concha and others (1998). For the field test, measurements were conducted at zero time (just after production) and at the end of the simulated marketing route, giving the real, experimental, remaining nutritional value. For each package, measurements were conducted for 2 separate samples done in triplicate (6 measurements per package).

TTI and TTI response measurement. An enzymatic TTI (VITSAB AB, Malmö, Sweden), Type M, was attached to all food product units. These TTI are based on a color change caused by a pH decrease, due to a controlled enzymatic hydrolysis of a lipid substrate. Before activation, the lipase and the lipid substrate are in 2 separate compartments (minipouches). At activation, the barrier that separates them is broken, enzyme and substrate are mixed and the color gradually changes from deep green to bright yellow. The tested TTI give a triple response via 3 separate transparent "windows" allowing view of change in 3 different double-pouches with different enzyme concentration each. Color change can be visually graded on a 6 point reference scale constructed from TTI inactivated at a certain level or quantitatively measured on the CIELab scale with the Minolta CR-200 Chroma Meter. Kinetic modeling was based on measurements, at appropriate time intervals for each "window", of the response of multiple TTI samples, isothermally stored in the controlled cabinets at temperatures from -20 to 0 °C. For the field test, color measurements of 20% of the attached tags were taken during their storage in the lab freezers, at the simulated wholesale and retail stage, whereas all TTI attached to products were measured at the end of the study, just after the return of the coded products with the attached TTI to the lab from the volunteer "consumers".

Using the basic principles of TTI modeling and application for quality monitoring (Taoukis and Labuza 1989, 1999; Taoukis 2001), the quality of the monitored product can be estimated from the TTI response. The prerequisite is to have experimentally defined the quality function of the food $f(A)_t$, where A is the selected quality indice; the response function of the TTI $F(X)_t$, where X is the measured TTI response; and the respective kinetic parameters. Briefly:

Table 1—Results of the large field test for the vitamin C content of 10 randomly chosen green pea products, at the consumers end, based on the measurement, the actual T_{eff} (estimated from the actual time-temperature profile), or the T_{eff} estimated with TTI response (SLR is the shelf-life remaining).

Product Code	T_{eff} (°C) (based on TTI[1] response)	T_{eff}(°C) (actual)	Predicted vitamin C (T_{eff} from TTI) mg/100 g vegetable	Predicted vitamin C (T_{eff} actual) mg/100 g vegetable	Measured vitamin C mg/100 g veget.	% error of TTI prediction
1	–10.1(± 0.4)[2]	–8.5	15.3 (± 2.4)	9.0	12.8 (± 1.1)[3]	16.3
2	–10.5 (± 0.4)	–9.9	21.3 (± 2.7)	18.8	18.1 (± 1.0)	15.0
3	–10.1(± 0.4)	–10.6	23.9 (± 2.4)	22.1	18.6 (± 0.9)	22.2
4	–9.0 (± 0.2)	–7.8	15.0 (± 1.2)	10.3	13.0 (± 1.1)	13.3
5	–11.3 (± 0.6)	–10.0	22.0 (± 3.5)	16.6	24.0 (± 2.3)	–9.1
6	–11.4 (± 0.6)	–11.6	25.0 (± 3.4)	25.8	20.5 (± 1.6)	18.0
7	–8.7 (± 0.1)	–8.0	18.1 (± 0.9)	14.8	18.5 (± 2.4)	–2.2
8	–11.4 (± 0.6)	–11.0	23.9 (± 3.5)	22.1	22.6 (± 1.3)	5.4
9	–11.3 (± 0.6)	–10.2	23.6 (± 3.4)	19.1	21.3 (± 1.9)	9.7
10	–11.3 (± 0.6)	–12.1	24.7 (± 3.5)	27.7	21.4 (± 1.1)	13.4

[1] enzymatic TTI, Type M2-102140, window 2
[2] 95% confidence intervals based on the statistical variation of the kinetic parameters of the Arrhenius TTI model
[3] mean value ± standard deviation from 6 measurements of vitamin C content (2 samples in triplicate per package)

$$f(A) = k(T)t = k_{A_{ref}} \exp\left(-\frac{E_A}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)t \qquad (1)$$

where k is the reaction rate constant, $k_{A_{ref}}$ is the rate constant at a reference temperature, T_{ref}, E_A is the activation energy of the reaction that controls quality loss, and R the universal gas constant. The form of the quality function of the food depends on the reaction order of the reaction of the quality index (for example $f(A) = \ln(A_o/A_t)$ for n = 1 order and $f(A) = [A_t^{1-n} - A_o^{1-n}]/(n-1)$ for $n \neq 1$). Similarly, a response function F(X) can be defined for TTI such that $F(X) = k_I t$, with k_I an Arrhenius function of T.

The value of the functions, $f(A)_t$ at time t, after exposure at a known variable temperature exposure, T(t), can be found by integrating Eq. (1). Introducing the term of the effective temperature T_{eff}, which is defined as the constant temperature that results in the same quality value $f(A)_t$, as the variable temperature distribution over the same time period, Eq. (1) gives:

$$f(A) = \int_0^t k(T)dt = k_{A_{ref}} \exp\left(-\frac{E_A}{R}\left(\frac{1}{T_{eff}}-\frac{1}{T_{ref}}\right)\right)t \qquad (2)$$

For an indicator exposed to the same temperature fluctuations, T(t), as the food product, and corresponding to an effective temperature T_{eff}, the response function can be expressed as:

$$F(X) = k_{I_{ref}} \int_0^t \exp\left(-\frac{E_{A_I}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)dt = k_{I_{ref}} \exp\left(-\frac{E_{A_I}}{R}\left(\frac{1}{T_{eff}}-\frac{1}{T_{ref}}\right)\right)t \qquad (3)$$

where $k_{I_{ref}}$ and E_{A_I} are the Arrhenius parameters of the indicator.

Based on the above, instead of a TTI exactly mimicking quality deterioration of the food product, a meaningful, general scheme of translating TTI response to food status is used (Figure 1). From the measured response X of the TTI at time t, the value of the TTI response function F(X) is calculated (Taoukis 2001), and the T_{eff} of the exposure is derived. With the T_{eff} and the kinetic parameters ($k_{A_{ref}}$, E_A) of the food known, the value of the quality indices (A) of the food is found through the developed and validated quality degradation kinetic models (f(A)). This gives the extent of the quality deterioration of the food and allows for the calculation of the remaining shelf life, based on a predefined acceptability limit.

Development and assessment of the TTI-based frozen chain management system

Having established the potential of TTIs as quality monitors of the frozen vegetables, an improved product management and stock rotation system is proposed. The approach currently applied is FIFO (First In First Out) according to which first-arriving products (that is, with the closest expiration date on the label) are advanced, displayed, and sold first. An alternative TTI based system is LSFO (Least Shelf Life First Out), earlier proposed for chilled products (Taoukis and others 1998).

The development of LSFO is based on validated shelf life model of the monitored food, specification of the initial value of the quality index A_0, the value of A_s at the limit of acceptability, and constant time-temperature monitoring in the distribution chain with TTI. Based on the TTI applicability scheme described in the previous section (Figure 1), TTI response can be translated, at any point of the marketing chain, to the extent of quality deterioration of the frozen food and, consequently, to the remaining shelf life. Accordingly, at selected decision points, products with the smaller actual SLR

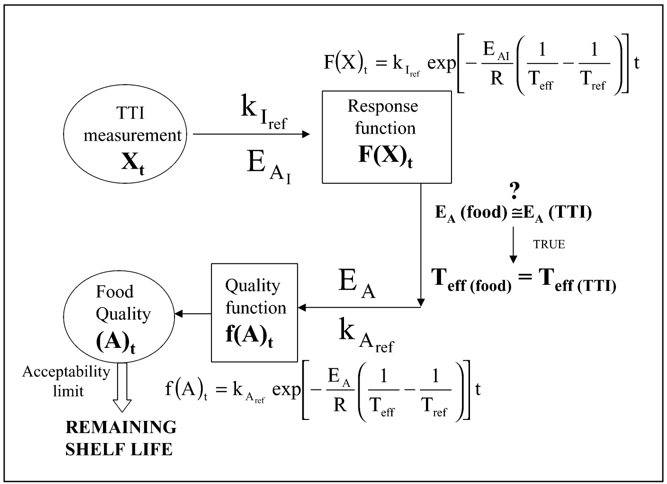

Figure 1—Application scheme of TTI as quality monitors and remaining shelf-life predictors, where E_{AI}, k_{Iref}, E_A and k_{Aref} are the Arrhenius parameters for the TTI and the food respectively.

(Shelf Life Remaining) are advanced first, in order to obtain a more uniform quality with fewer rejected products at the consumer end.

To assess the application of the developed stock management policy based on LSFO, the Monte Carlo numerical simulation technique was applied. It was based on the generation of hypothetical, realistic "scenarios" of handling, storage, and transport throughout the distribution chain, using temperature data provided by surveys. Significant parameters, such as temperatures, do not have a single, fixed value (Lammerdig 2000), but their value is represented by a probability distribution which reflects the uncertainty (lack of sufficient knowledge) as well as the commonly encountered parameter variation (Taoukis 2001). The final quality calculation procedure is repeated many times, including cases of good as well as problematic marketing practice. Each iteration requires the random selection of a single-point-estimate from the corresponding probability distributions in order to calculate a mathematical solution, using the established shelf life model. Eventually, the analysis leads to a frequency, instead of a single point value, for the output of interest (quality status), which has taken into account the probability distribution of temperature conditions.

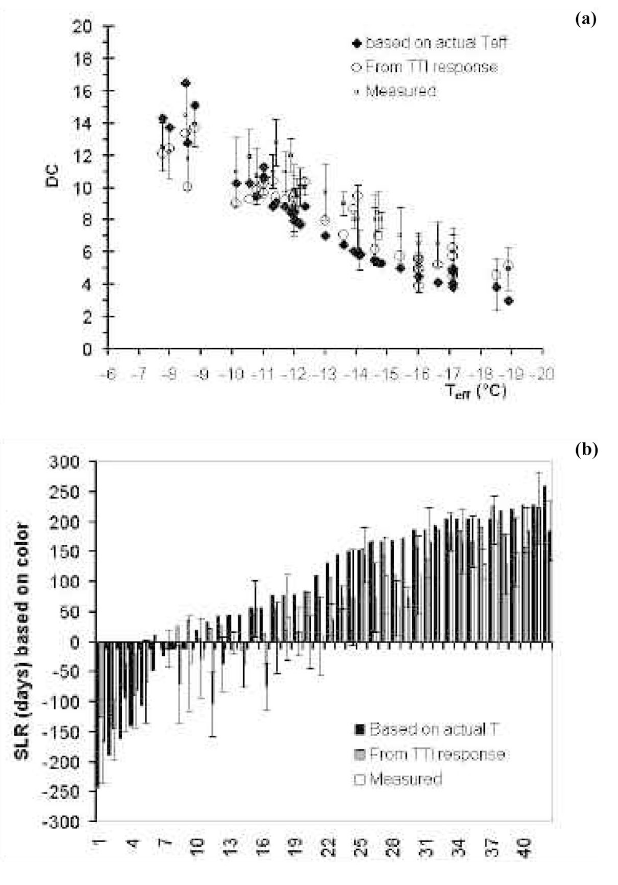

Figure 2—(a) Plot of the color parameter DC (DC = $\sqrt{(a-a_o)^2+(b-b_o)^2}$) for frozen green peas, obtained by measurements (average ± standard deviation bars) and estimated from TTI response or recorded full temperature history, compared with the actual effective storage temperature of the products; (b) Comparison of the shelf life remaining (SLR) of individual frozen green peas products based on the color index obtained by measurements and estimated from TTI response or recorded full temperature history. Negative values indicate products that had become unacceptable (DC > 10) before measurement time.

Results and Discussion

THE TIME TEMPERATURE INTEGRATORS THAT WERE USED in the field study were tested and their kinetics were verified in comparison to the values obtained in the previous study (Giannakourou and Taoukis 2002). The normalized chroma $X_C = \frac{C - C_{min}}{C_{max} - C_{min}}$ was used as the response X of the TTI, where $C = \sqrt{a^2 + b^2}$ (a and b are color values of the CIELab scale). The previously used form of the linearized response function applied well (Eq. (4)):

$$F(X_C) = \sqrt{\ln\left(\frac{1}{1 - X_C}\right)} = k_I t \tag{4}$$

From the $F(X_C)$ compared with time plots the value of k_I, the response rate of the tested TTIs, was determined at each temperature by linear regression analysis. The temperature dependence of the response rate was modeled by the Arrhenius equation. The value of activation energy of the TTI type M (model M2-10, 21, 40) was calculated as 88.2 ± 19.5 kJ/mol ($R^2 = 0.960$) (21.1 ± 4.7 kcal/mol) close to the E_A value calculated for TTI Type M in the previous study (model M2-3510, 99.5 ± 10.7 kJ/mol). Temperature dependence was the same for the 3 windows. The 1st window had the shortest full response time (80 d at –12 °C). Nominally the response times from window 1 to 3 were set at a ratio of 1:2:4 respectively by manufacturing at the appropriate enzyme concentration.

For the frozen vegetables used in the field study, shelf life models from the kinetic study were used. For frozen peas, the chroma change, expressed by parameter $DC = \sqrt{(a - a_0)^2 + (b - b_0)^2}$ (where a_0 and b_0 = the values at zero time) was modeled by a zero-order reaction, whereas vitamin C degradation showed an apparent 1st order behavior. The corresponding quality functions were:

$$f(A_1) = DC = k_{col}t, \quad \text{and} \quad f(A_2) = \ln\frac{(\text{Vitamin C})_o}{(\text{Vitamin C})} = k_{vit}t \tag{5}$$

where, k_{col} and k_{vit} are the respective rate constants, and (Vitamin C) and (Vitamin C)$_o$ are the concentrations of Vitamin C content at time t and zero, respectively.

Temperature dependence of loss of both indices was represented by the Arrhenius model in the studied range. The estimated activation energies, E_A, and 95% confidence range were 79.2 ± 19.2 kJ/mol (18.9 ± 4.6 kcal/mol, with $R^2 = 0.983$), and 136.8 ± 20.5 kJ/mol (32.7 ± 4.9 kcal/mol with $R^2 = 0.993$) for chroma and vitamin C loss respectively, expressing the different temperature sensitivity of the 2 modes of deterioration (Giannakourou and Taoukis 2002).

The main index of white mushroom deterioration was the gradual intense color change, expressed mainly by parameter L. The measured L, describing mushroom "whiteness", showed an apparent 1st order decrease, and the Arrhenius model in the studied range had E_A at 155.1 ± 60.3 kJ/mol (37.1 ± 14.4 kcal/mol with $R^2 = 0.957$)

Using all the above kinetic equations established for TTI response, as well as for vegetable products, quality deterioration was validated at variable time-temperature profiles. Stepwise temperature shifts within the range of interest (-3 to -20 °C), representing abused frozen storage, and the predicted values for the reaction rates were in good agreement with the experimentally defined values (Giannakourou and Taoukis 2002).

"Large" scale field test of TTI application

The philosophy and the experimental design of this part of the

Table 2—Results of the large field test for the color expressed as DC = $\sqrt{(a-a_o)^2+(b-b_o)^2}$, of 11 randomly chosen green pea products, at the consumers' end, based on the measurement, the actual T_{eff}, or the T_{eff} estimated with TTI response (SLR is the shelf-life remaining)

Product Code	T_{eff} (°C) (based on TTI[1] response)	T_{eff} (°C) (actual)	Predicted DC (T_{eff} from TTI)	Predicted DC (T_{eff} actual)	Measured DC	SLR (based on TTI response) (d)	SLR (based on actualT_{eff}) (d)	SLR (based on measurement) (d)	% error (SLR_{TTI} vs SLR meas)
1	–9.5 (± 0.4)[2]	–8.8	13.72(± 0.75)	15.10	13.92(± 1.38)[3]	–138(± 19)	–189	–146(± 51)	–5.3
2	–8.7 (± 0.2)	–8.0	12.48(± 0.35)	13.76	12.21(± 1.64)	–90(± 9)	–139	–82(± 61)	8.9
3	–11.2 (± 0.9)	–11.0	10.29(± 1.17)	10.65	10.34(± 0.82)	–11(± 32)	–24	–13(± 30)	–18.2
4	–11.8 (± 1.0)	–12.0	8.73(± 1.15)	8.50	8.52(± 1.26)	47(± 31)	56	55(± 46)	–17.0
5	–15.3 (± 1.9)	–16.0	5.00(± 1.19)	4.50	5.50(± 1.45)	185(± 36)	204	167(± 54)	9.9
6	–14.2 (± 1.6)	–14.1	5.81(± 1.20)	5.91	6.12(± 1.23)	156(± 35)	152	144(± 46)	7.7
7	–14.5 (± 1.7)	–16.0	5.62(± 1.20)	4.51	5.01(± 0.86)	163(± 35)	204	182(± 32)	–11.7
8	–14.6 (± 1.7)	–16.0	5.51(± 1.20)	4.50	5.50(± 1.13)	167(± 36)	204	167(± 42)	0.0
9	–17.0 (± 2.3)	–16.0	3.90(± 1.12)	4.50	4.56(± 1.07)	227(± 36)	204	202(± 39)	10.9
10	–15.2 (± 1.9)	–18.9	5.15(± 1.21)	3.00	5.01(± 1.36)	180(± 37)	260	186(± 50)	–3.0
11	–14.3 (± 1.6)	–17.1	5.76(± 1.20)	3.84	5.01(± 1.01)	158(± 35)	229	186(± 37)	–17.8

[1] enzymatic TTI, Type M2-102140, window 2
[2] 95% confidence intervals based on the statistical variation of the kinetic parameters of the Arrhenius TTI model
[3] mean value ± standard deviation sixteen color measurements

study, as it is described in the Materials and Methods section, is to systematically assess the application scheme and the monitoring reliability of the TTI. For this purpose, at any point of the distribution path, the experimentally measured value of the chosen quality index for each product item is compared to the prediction, based either on the TTI response or on the actual time-temperature history, acquired from the data logger system. The methodology followed includes the calculation of the predicted effective temperature based on the TTI response and the established kinetic models of the particular TTI type, which is then compared to the actual effective temperature as it is estimated from the recorded product temperature data and the established kinetic characteristics of the reference quality index. Furthermore, at the end of distribution, the reliability of the shelf life correlation is evaluated by comparing the value of the quality index for each individual food product, as it is (i) predicted from the TTI effective temperature and the food kinetics, (ii) predicted from the actual effective temperature and the food kinetics, and (iii) experimentally measured. Comprehensive tables of the general format shown in Table 1 for vitamin C and Table 2 for color of randomly chosen frozen green pea products were generated, tabulating results of all studied product units. Measurements of Vitamin C of the selected pea products are given as mean value and standard deviation of 2 samples, done in triplicate, whereas, for color, as mean value and standard deviation of 16 peas measured in each individual package. In both Tables, the mean value of the estimated T_{eff} of the time-temperature history for each product is shown (2nd column), as well as its 95% confidence range based on the statistical results of the Arrhenius kinetic parameters of the developed TTI model. Based on these confidence intervals of the T_{eff}, the average values, the upper and lower limit of predicted Vitamin C, are also shown in Table 1. Similarly, the average value of the estimated DC, the corresponding shelf life remaining, and their extreme values, based on the calculated T_{eff} range, are given in Table 2. An average absolute error of 14.5% in the prediction of remaining vitamin level is judged acceptable, especially in view of the 48.6 kJ/mol difference in the E_A values of the kinetics of TTI response and vitamin loss. For color change, the E_A, which differs less (9.0 kJ/mol) from E_{A_I}, the error in remaining shelf life estimation did not exceed 22%, with an average close to 10%. A comprehensive and practical overview of the results for each index

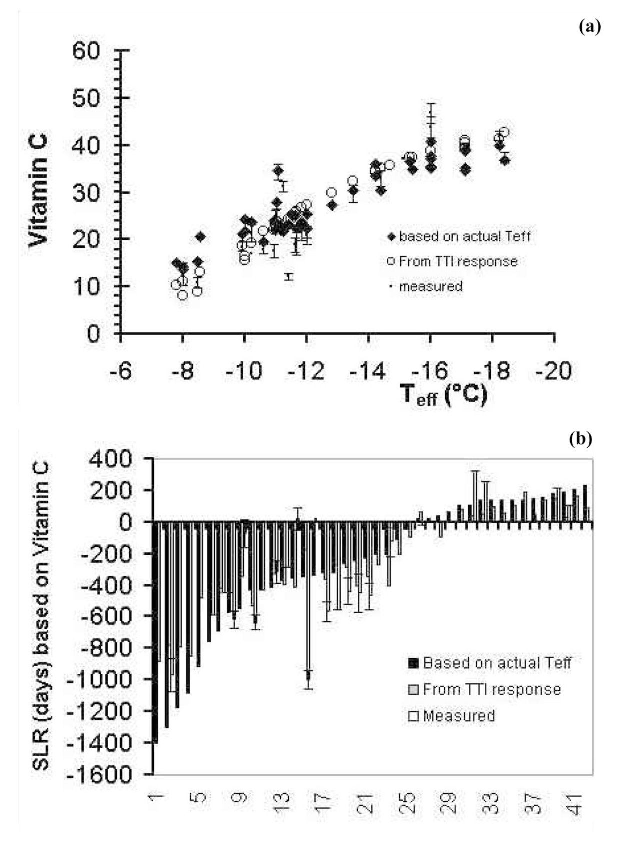

Figure 3—(a) Plot of vitamin C content for frozen green peas, obtained by measurements (average ± standard deviation bars) and estimated from TTI response or recorded full temperature history, compared with the actual effective storage temperature of the products; (b) Comparison of the shelf life remaining (SLR) of individual frozen green peas products based on the vitamin C loss obtained by measurements and estimated from TTI response or recorded full temperature history. Negative values indicate products that had become unacceptable (loss greater than 30%) before measurement time.

is presented in form of diagrams in Figure 2 and 3 for green peas and in Figure 4 for mushrooms.

The obtained results showed that a substantial portion of products was exposed, throughout the distribution, to effective temperatures that deviated significantly from the recommended range. Namely, only 30% had an effective temperature in the –15 to –20 °C range, 52% in the –10 to –15 °C range, and 18% in the –7.5 to –10 °C range. In Figure 2a, the color parameter DC of green peas is depicted as a function of the actual effective temperature throughout the whole distribution, using 3 alternative approaches: (1) experimental measurement of DC, (2) estimated DC based on TTI response, and (3) estimated DC based on the actual temperature history. Similarly, in Figure 3a and 4a, vitamin C content of frozen green peas and color parameter L of white mushrooms are respectively depicted, using the same comparative methodology. For estimations based on TTI response (approach 2) and estimations based on the actual temperature history (approach 3) in Figure 2 to 4, the validated kinetic models of TTI response and vegetable quality degradation are employed. In Figure 2b, the shelf life remaining (SLR) estimation based on actual measurement of the color of green peas, on TTI response, or on electronic recording of the full temperature history is shown for a representative portion of tested products, when the acceptability limit is set at DC = 10. Similarly, the SLR estimation for the green peas products based on 30% vitamin C loss (Figure 3b), and for mushrooms based on 80% "whiteness" retention (expressed by L parameter) (Figure 4b) is illustrated. The limit of acceptability is set at 30% loss, according to common practice in the case of Vitamin C. In the case of color, the limits were set at the levels where the product was judged unacceptable due to color change by a 12-member sensory panel. Comparing Figures 2b and 3b, it can be seen that if shelf life were decided based on nutritional declaration, a substantial portion of the pea products would be considered as expired whereas only a small portion of the products would be past acceptability based on sensory criteria (color).

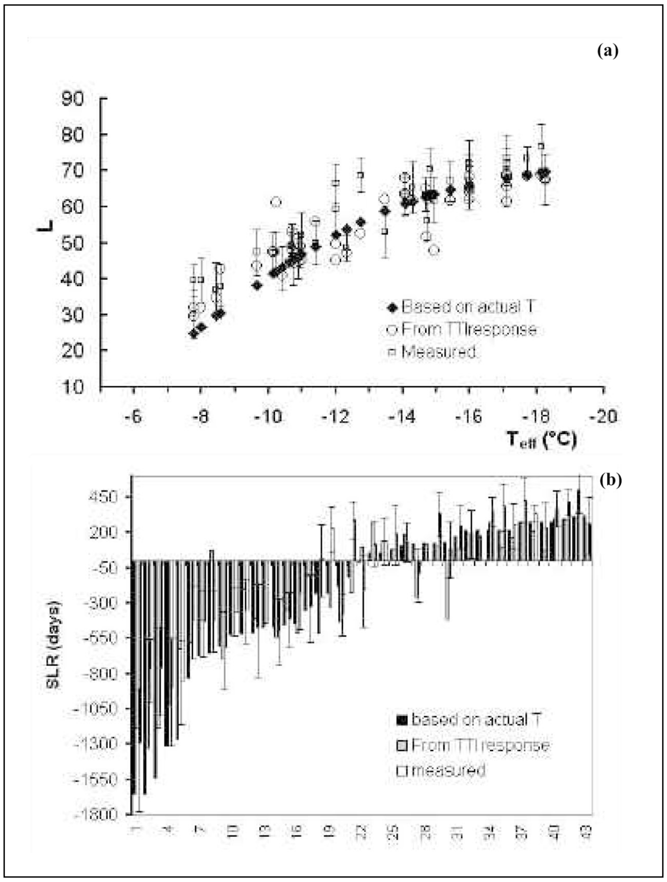

Figure 4—(a) Plot of the L value of mushroom products, obtained by measurements (average ± standard deviation bars) and estimated from TTI response or recorded full temperature history, compared with the actual effective storage temperature of the products; (b) Comparison of the shelf life remaining (SLR) of individual mushroom products based on the color index obtained by measurements and estimated from TTI response or recorded full temperature history. Negative values indicate products that had become unacceptable (L/L_o < 0.8) before measurement time.

Based on the color index, green pea products could be grouped into 3 different quality levels at the point of consumption. (Figure 5). Overall, for both field-tested products, it is evident that the knowledge of the time-temperature history, achieved either directly (data recorder) or cumulatively (TTI response), can provide a reliable indication of the relative quality status of the product. In the error assessment, one must not overlook an additional potential source of variability, namely, the possible differences in the initial quality level between individual products, that was established through multiple measurements at zero time. This variability was not taken into account. An average initial value for the used quality indices was used in the correlation.

TTI application – Least Shelf Life First Out (LSFO) distribution management system

Having assessed the reliability of TTI for quality classification of frozen vegetables from the results of the field test, the development of the optimized inventory management system is proposed, based the principles of LSFO. To demonstrate the advantages of using LSFO instead of the traditional FIFO, a scenario of 160 d maximum total time in the distribution chain was considered as a realistic case-study, mimicking the actual marketing route applied in the large scale field test (Figure 6). It included an initial stage of 30 d stocking in the industry warehouse, 40 d at the distribution center (1st stage), 20, 40, or 60 d at the retail level (2nd stage) and 30 d at the domestic freezers (3rd stage). Real data from surveys for the temperatures at each stage was used. Temperature distributions are shown in Figure 7a and 7b. One decision point is used to apply

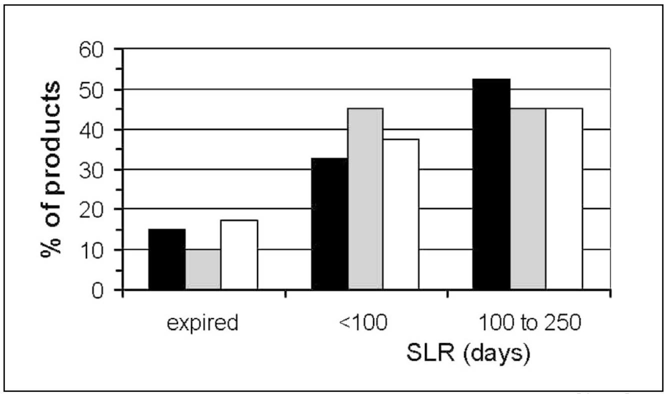

Figure 5—Distribution of the shelf life remaining (SLR) of frozen green peas. Black bars correspond to SLR based on measurements of the color indices, grey to SLR prediction from TTI response and white to SLR prediction from recorded temperature history.

the LSFO policy at the crucial stage of stock display in the retail outlet. At this stage, products are delivered from the supermarket warehouse every 60 d and are subsequently classified into 3 groups for successive stocking of the retail cabinets every 20 d. The products' classification and display is no longer performed randomly, as in the case of FIFO policy, but according to LSFO. LSFO is based on the remaining shelf life, as it is assessed from the attached TTI. TTI response is translated to the level of product deterioration, at any point of the distribution cycle, which enables the classification of products according to shelf life remaining.

Products closer to actual expiration (Least Shelf Life) are advanced 1st. The Monte Carlo simulation approach requires that this 120 to 160 d life cycle is repeated a large number of times, with a different set of values in each iteration. Two thousand (2000) temperature cases representing the actual probability of temperature exposure (as shown in Figure 7) were run, using a developed program code written in FORTRAN 77. By accounting for temperature variability at different steps of the distribution chain, shelf life remaining (SLR) can be estimated at any point of product life-cycle based on the attached TTI response, that cumulatively reflects the time-temperature history. Following LSFO principles, at the decision point, SLR is predicted for all products, based on the TTI response and estimation of T_{eff}, and they are categorized and advanced further in the chill chain (that is, forwarded to retail display) according to their estimated quality, giving priority to the ones "expiring" first. The results of the simulated test of the LSFO system are depicted in Figure 8. The quality distribution at consumption time; that is, the percentage of products that are of a certain quality, is shown. Quality is expressed as SLR, the time for the product to reach color unacceptability (DC = 10). Negative values indicate products that have exceeded the limit of acceptability before reaching the consumer's table. Any point of the continuous curve indicates the probability for the product to be in the ± 20 d range of the SLR read on the x-axis. Alternatively, from this plot one can estimate the percentage of products that have a particular SLR range (± 20 d). The stock rotation and distribution system based on LSFO principles leads—as it is clearly depicted in Figure 8—to a more consistent quality at consumption time and could practically eliminate the "tails"; that is, the products consumed at extreme qualities. With the FIFO system, 5.1% of products were beyond acceptable quality at the time of consumption, whereas with LSFO unacceptable products were eliminated.

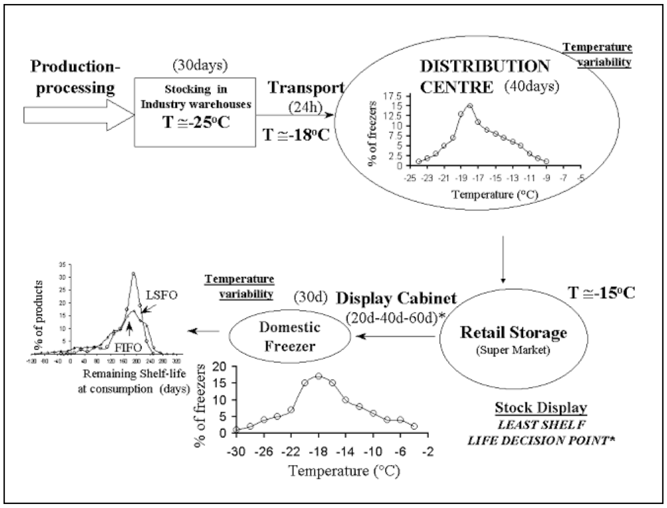

Figure 6—Schematic illustration of the marketing route used for the quantitative evaluation of the application of FIFO and LSFO management policies to the final quality distribution of the food product. Consecutive stages and their time-temperature conditions, the LSFO-decision point at the retail outlet and the final quality distribution are shown.

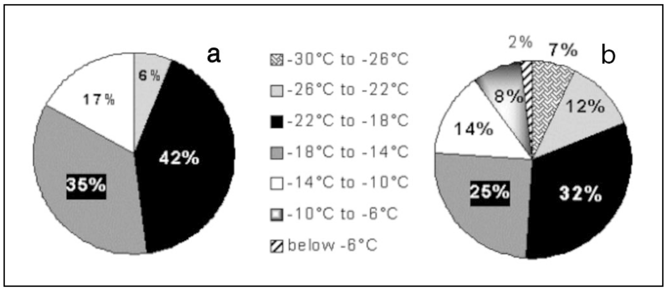

Figure 7—Temperature distribution in (a) warehouses based on average temperature distribution of closed, vertical retail freezers of 4 Mediterranean countries (European survey, Anonymous 1995) on the temperatures of frozen products and (b) domestic freezers, from a survey conducted within this work in 100 households

Monte Carlo numerical technique, besides illustrating the quality optimization achieved with the application of LSFO, allows for sensitivity analysis that is the estimation of the effect of small changes of time-temperature conditions of the distribution scenario on the final quality distribution. Figure 9 demonstrates the significance of storage time at the consumer's freezer for the probability of rejecting the product by the time it is consumed, when all other time parameters of the chill chain are as described before, that is, 40 d at the distribution center and 60 d at the retail cabinet. Three alternative scenarios of consumer practice are considered, ranging from 10 d to 1.5 mo stocking in the domestic freezer, after purchasing the frozen vegetable from the retail level. By reducing this time from 1.5 mo to 30 d, with FIFO policy, probability for unacceptable products is considerably reduced from 7.8 to 5.1%, reaching the percentage of 1.2% when items are stored only for 10 d at

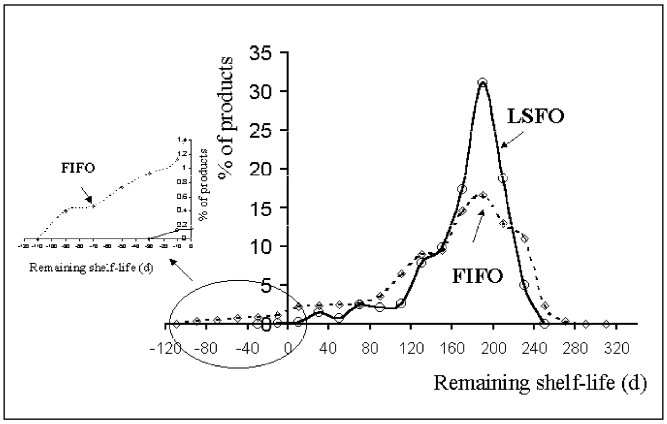

Figure 8—Distribution of quality of frozen green pea products after 4 mo distribution with FIFO and LSFO frozen chain management (the diagram on the left is a magnification of the expired products tail). Shelf life remaining (SLR) is the time the product would remain acceptable after the consumption time if stored at -18 °C. Negative values indicate time at which product had become unacceptable before consumption.

home. From Figure 9, it is obvious that, even in the case of the prolonged domestic storage of 1.5 mo, application of LSFO eliminated rejected products, meeting the consumers' quality requirements.

Conclusions

IN THIS STUDY, THE APPLICABILITY OF TTI AS RELIABLE TOOLS FOR frozen chain optimization was assessed. The effectiveness of TTI as monitoring and controlling tools for the real distribution of frozen vegetables was confirmed by testing in an actual wide range field test, simulating the existing conditions during the transport and the storage of frozen products. The potential of Least Shelf- Life First Out (LSFO) system, a TTI-based management system for frozen product distribution management and stock rotation, was demonstrated by applying a Monte Carlo simulation technique that showed attainment of consistent, acceptable quality and minimization of rejected products at the consumer end. Development of LSFO is based on validated kinetic models of the characteristic quality indexes of representative frozen vegetable products, continuous monitoring of the temperature conditions of the chill chain with TTI, and the correlation of sensory acceptability to a specific quality level. TTI can be consequently considered as useful decision-support tools for the optimization of the current inventory management system, in order to improve consumers' acceptability. With continuous improvement, this stock-rotation policy could encompass information about the initial quality variability of raw material, process parameters, and so on. The accuracy and the size of available data and further refinements of the proposed management system could potentially improve substantially the quality distribution of the final products.

References

Anonymous. 1995. Deep freezing temperatures in shops-temperature control in freezers and foodstuffs. Final report of European Commission sponsored Research project in 4 EU member states (Greece, Italy, Spain, and Portugal). Contract nr: EC 1080/94/000069. 24 p.

AOAC. 1984. Official methods of analysis of the Association of Analytic Chemists. Vitamin C (Ascorbic Acid). In: Vitamin preparations and juices, 2,6 Dichloroindophenol titrimetric methods. Va.: AOAC. 43.064-43.068. P 844-845.

Broekmeulen RACM. 2001. Modelling the management of distribution centers. In: Tijkskens LMM, Hertog MLATM, Nicolaï BM, editors. Food process modelling. 3rd ed. Washington DC: CRC Press. P 432-448.

Browne M, Allen J. 1998. Logistics of food transport. In: Heap, R, Kierstan M and Ford G, editors. Food Transportation. London: Blackie Academic & Professional. P 22-50.

CIE. 1978. Recommendations on uniform color spaces- color difference equations for psychometric color terms. Supplement nr 2 to CIE publication nr 15. Paris: Commission Internationale de l'Eclairage.

Dolan KD, Singh RP, Wells JH. 1985. Evaluation of time-temperature related quality changes in ice cream during storage. J Food Proc Pres 9:253-271.

Dubelaar C, Chow G, Larson P.2001. Relationships between inventory, sales and service in a retail chain store operation. Int J Phys Distrib Log Man 31(2):96-108.

Farquhar JW. 1983. Time/Temperature monitoring of frozen and refrigerated seafood products. In: International Institute of Refrigeration, Commission C2, Paris. Proceedings of the XVIth International Congress of Refrigeration. Volume 3. P 811-819.

Fu B, Labuza TP. 1993. Shelf life prediction: Theory and application. Food Contr 4:125-133.

Giannakourou MC, Taoukis PS. 2002. Systematic application of Time Temperature Integrators as tools for control of frozen vegetable quality. J Food Sci 67(6):2221-2228.

Lammerding AM, Fazil A. 2000. Hazard identification and exposure assessment for microbial food safety risk assessment. Int J Food Microbiol 58:147-157.

LeBlanc DI. 1988. Time-Temperature Indicating devices for frozen foods. J Inst Can Technol Aliment 21(3):236-241.

Oruña-Concha MJ, Gonzalez-Castro MJ, Lopez-Hernandez J, Simal-Lozano J. 1998. Monitoring of the vitamin C content of frozen green beans and Padrón peppers by HPLC. J Sci Food Agric 76:477-480.

Ross DF. 1996. Distribution planning and control. 1st ed. New York: Chapman & Hall. 780 p.

Schubert H. 1977. Criteria for the application of TTI Indicators to quality control of deep frozen food products. In: Bull Int Inst Refr Annexe 1977-1. Ettlingen,

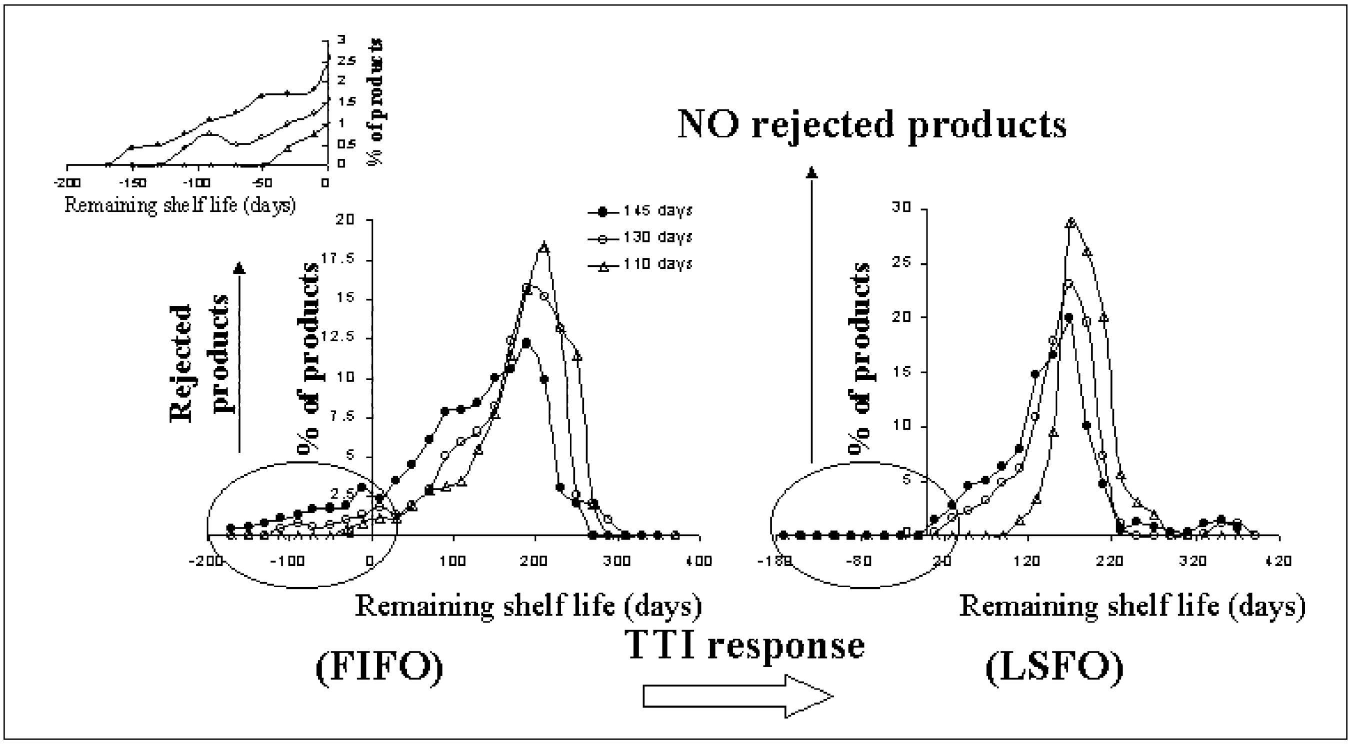

Figure 9—Comparative illustration of the effect of storage time at the consumer's freezer, before consumption, on the final quality of frozen green peas with FIFO and LSFO stock rotation approaches (110, 130, and 145 d are the total time in the distribution chain). Remaining shelf life corresponds to the time the product would remain organoleptically acceptable after the consumption if stored at -18 °C. Negative values indicate the time at which the product had crossed the acceptability limit before consumption.

Germany: I.I.F-I.I.R- Commissions C1/C2. P 407-423.
Silver EA, Pyke DF, Peterson R. 1998. Inventory management and production planning and scheduling. 3rd ed. New York: John Wiley & Sons. 754 p.
Singh RP, Wells JH. 1985. Use of Time Temperature Indicators to monitor quality of frozen hamburger. Food Technol 39(12):42-50.
Taoukis PS. 2001. Modelling the use of time-temperature indicators in distribution and stock rotation. In: Tijkskens LMM, Hertog MLATM, Nicolaï BM, editors. Food Process Modelling. 3rd ed. Washington DC: CRC Press. P 402-432.
Taoukis PS, Bili M, Giannakourou MC. 1998. Application of shelf-life modelling of chilled salad products to a TTI based distribution and stock rotation system. Acta Horticulturae 476:131-139.
Taoukis PS, Fu B, Labuza TP. 1991. Time Temperature Indicators. Food Technol 45(10):70-82.
Taoukis PS, Labuza, TP. 1989. Reliability of Time Temperature Indicators as food quality monitors under non-isothermal conditions. J Food Sci 54(4):789-792.
Taoukis PS, Labuza TP. 1999. Applicability of Time Temperature Indicators as shelf life monitors of food products. J Food Sci 54(4):783-788.
Tijkens LMM, Koster AC, Jonker JME. 2001. Concepts of chain management and chain optimization. In: Tijkskens LMM, Hertog MLATM, Nicolaï BM, editors. Food Process Modelling. 3rd ed. Washington DC: CRC Press. P 448-469.
Wells JH, Singh RP. 1989. A quality-based inventory issue policy for perishable foods. J Food Proc Pres 12:271-292.
Wells JH, Singh RP, Noble AC. 1987. A graphical interpretation of time-temperature related quality changes in frozen food. J Food Sci 52(2):436-439, 444.
Yoon SH, Lee CH, Kim DY, Kim JW, Park KH. 1994. Time Temperature Indicator using Phospholipid-Phospholipase system and application to storage of frozen pork. J Food Sci 59(3):490-493.

MS 20020045 Submitted 1/22/02, Revised 5/15/02, Accepted 6/11/02, Received 7/2/02

This research was supported in part by funds of the Director General of Research of Greece and the European Union , project PABE 97BE254. Parts of the work were presented in the technical oral paper 58-10 “A large scale test of applicability of TTI as monitors of the chill chain of frozen products” at the 2001 IFT Annual Meeting, June 23-27, 2001, New Orleans, La., U.S.A.

The authors are with the National Technical Univ. of Athens, Dept. of Chemical Engineering, Laboratory of Food Chemistry and Technology, Iroon Polytechniou 5, Zografou 15780, Athens, Greece. Direct inquiries to P.S. Taoukis (E-mail: taoukis@ chemeng.ntua.gr).