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Simultaneous Optimisation of Surface Quality during the Sterilisation of Packed Foods using Constant and Variable Retort Temperature Profiles

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ABSTRACT

The differences in temperature dependence between spore inactivation and degradation of quality factors allow the optimisation of thermal processes in terms of maximisation of quality retention by choosing an optimum heating profile. While the maximisation of the retention for a single quality factor has received considerable attention in research, the possibilities of simultaneously maximising the retention of different quality factors have up to now not been addressed.

In this article the possibilities of the simultaneous optimisation for more than one quality factor were theoretically assessed. The use of both constant and variable retort temperature profiles was considered. A special emphasis was given to the formulation of appropriate objective functions for the simultaneous optimisation of the surface retention of quality factors.

For the simultaneous optimisation of quality factors the objective functions should be formulated in terms of maximising final retention and not, as in the case of single component optimisation, in terms of minimisation of cook values. The use of variable retort temperature profiles was shown to be particularly interesting for the simultaneous optimisation of more than one quality factor, as the final retention calculated compared well with the maximum retention achieved using individual calculated optimum constant retort temperature control for each of the components. Copyright © 1996 Elsevier Science Limited

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NOTATION

C	Cook value (min)
D	Time necessary to reduce the concentration of a heat labile component by 90% (min)
F	Processing value (min)
f	Heat penetration rate (min)
j	Lag factor in heat penetration curves
k	Rate constant (s^{-1})
N	Concentration of a heat-labile substance (number of microorganisms/ml, g/ml or other appropriate unit)
Q	Quality retention
T	Temperature (°C)
t	Time (min)
z	Temperature increment necessary for a 10-fold reduction of D (°C)

Subscripts

0	Initial condition
ce	Centre of the product
h	Heating phase
m	Microbiological
p	End of process
q	Quality factor
ref	Reference
s	Surface
T	Temperature

Superscripts

i	Index
t	Target
z	Temperature increment necessary for a 10-fold reduction of D (°C)

INTRODUCTION

Thermal processes are designed to destroy microorganisms present in the foodstuff that can cause spoilage of the food or cause disease. As heat is applied, a concomitant reduction in the quality of the food is observed. However the differences in the temperature-sensitivity between the rate constants of destruction of microorganisms and those of quality factors, such as colour, flavour, texture and nutrients, allow the choice of an appropriate heating policy that minimises the degradation of quality factors while still achieving the necessary destruction of undesirable microorganisms.

A large number of studies on optimisation of quality, minimisation of quality degradation, can be found in the literature. Optimal sterilisation processes have been calculated using systematic search procedures (Teixeira *et al.*, 1969, 1975; Bhowmik & Hayakawa, 1989), graphical optimisation (Ohlsson, 1980aOhlsson, 1980b) and mathematical optimisation techniques (Saguy & Karel, 1979; Martens, 1980; Nadkarni & Hatton, 1985; Hendrickx *et al.*, 1990; Banga *et al.*, 1991; Noronha *et al.*, 1993).

Most of the available work on optimisation of thermal processes considers the calculation of optimum constant retort temperature profiles. Empirical equations that allow the determination of the optimum holding temperatures for the minimisation of mass average and surface quality (Silva *et al.*, 1992, 1993, 1994) have been presented. The use of variable retort temperature profiles has been investigated by several authors. When maximisation of mass average quality was considered (Teixeira *et al.*, 1975; Bhowmik & Hayakawa, 1989; Saguy & Karel, 1979; Nadkarni & Hatton, 1985) it was concluded that no significant improvements over the use of optimum constant retort temperature profiles could be achieved. However when the optimisation of surface quality retention is considered substantial increases in quality retention and decreases in the process time, as compared with optimum constant retort temperature profiles, could be achieved using optimised variable retort temperature profiles (Banga *et al.*, 1991; Noronha *et al.*, 1995). Recently a method based on an empirical equation able to describe the optimum variable retort temperature profiles was presented (Noronha *et al.*, 1996). Using this method the calculation effort necessary for the calculation of optimum variable retort temperature profiles could be substantially reduced.

The aim of the present study was the investigation of the possibilities of calculating optimum processing conditions for the simultaneous optimisation of the retention for more than one surface quality factor. Both the use of constant and variable retort temperature profiles was considered. Special attention was given to the formulation of appropriate objective functions.

THEORETICAL CONSIDERATIONS

Kinetics of degradation of microorganisms and quality factors

In thermal process calculations the thermal destruction of microorganisms as well as of nutrients has been commonly described using first order reaction kinetics (Esty & Meyer, 1922; Hayakawa, 1978). In food sterilisation the empirical *D*-*z* model is often used to express the effect of temperature on the rate of microbial destruction (Ball & Olson, 1957). An expression for the calculation of the sterilising value at a single point can be derived as eqn (1):

$$^{z}F_{T_{ref}} \equiv -D_{T_{ref}}(\log N - \log N_0) = \int_0^{t_p} 10^{(T(t)-T_{ref})/z}\,\mathrm{d}t \qquad (1)$$

Equation (1) provides two ways for the calculation of the processing, F, value. The first is based on the actual measurement of the initial and final loads of the heat-labile substance (N_0 and N, respectively — assuming a first order heat inactivation) while the second is based on the complete knowledge of the temperature history ($T(t)$). For the evaluation of the impact of a sterilisation process in terms of the reduction of the number of spores of *Clostridium botulinum* a reference temperature of 121·1°C and a z value of 10°C are commonly used and the symbol F_0 is employed. For the evaluation of the impact of the thermal process in terms of changes in organoleptic properties or in quality factor contents a reference temperature of 100°C and z values typically in the range 20–40°C are used and the symbol C (instead of F), representing 'cook value' is used.

Objective functions for the optimisation of more than one quality factor

As pointed out by Norback (1980), the maximisation of quality retention can only be done for one nutrient (or other quality attribute), since we can only optimise with respect to one objective function at a time. The optimum processing conditions for a single quality factor will depend on its inactivation kinetics (z_q value) (Silva *et al.*, 1992). However it is possible to reformulate the objective function in order to optimise more than one quality factor. The most straightforward approach is the maximisation of the sum of retentions of the considered quality attributes. A more elaborate approach would involve an evaluation of the relative importance of the different quality factors (using both objective and subjective criteria) and the quantification of this information in terms of weight factors that would allow the construction of a well-balanced objective function.

The minimisation of the C-value has been used as a criterion when the minimisation of the degradation of a single quality factor is of interest (Ohlsson, 1980c). For a critical evaluation of commonly used objective functions the reader is referred to Silva *et al.* (1992b). For surface quality (single point), the minimisation of the C-value is equivalent to the maximisation of the quality retention of a quality factor when a single component is considered.

The relation between cook value and retention is given by,

$$C = -D_{q,ref} \log\left(\frac{N}{N_0}\right) \tag{2}$$

so,

$$\min(C) \equiv \max\left(\frac{N}{N_0}\right) \tag{3}$$

When the maximisation of the quality retention for more than one component is of concern and each component has the same relative importance, the maximisation of the sum of the retentions is the criterion to be used. For the case of i components the objective function to be maximised can be formulated as,

$$\text{Objective function} = \sum_i w_i \cdot \frac{N^i}{N_0^i} \tag{4}$$

with N^i/N_0^i representing the retention for the ith quality factor and w_i representing positive weighting factors.

When more than one component is considered the use of an objective function formulated as the sum of the different C-values leads to a maximisation of the product of retentions and not to a sum of retentions.

$$\sum_i C_i = \sum_i -D_{T_{ref,qi}} \log\left(\frac{N^i}{N_0^i}\right) = \log \prod_i \left(\frac{N^i}{N_0^i}\right)^{-D_{Tref,qi}} \tag{5}$$

and,

$$\min \sum_i C_i \equiv \min \prod_i \left(\frac{N^i}{N_0^i}\right)^{-D_{Tref,qi}} \tag{6}$$

In the case where the simultaneous optimisation of different quality factors is of interest the objective functions must be formulated considering final retentions of the components instead of C-values.

In order to illustrate the possibilities of the simultaneous optimisation of surface quality for more than one quality factor, three case studies were considered. The first two case studies were based on heat penetration and kinetic parameters found in the literature. These two examples are hypothetical model cases for a meal consisting of meat, starches and vegetables processed in a retortable pouch. For the sake of simplicity the D_{Tref} value was considered the same for all components. The third example represents a mixture of four vegetables (corn, green beans, peas and carrots) processed in glass jars. For this case study the heat penetration factors were determined experimentally.

MATERIALS AND METHODS

Determination of temperature evolution

The calculation of the transient temperature history at the slowest heating point was performed using the apparent position numerical solution (APNS) method (Noronha *et al.*, 1995). The APNS method allows the calculation of the centre product temperature from the heating medium temperature (variable heating medium temperatures can be handled by this method) if the heating characteristics of the food in terms of the empirical parameters f_h and j determined under standard conditions (step change in the heating medium temperature) are known.

Formulation of the optimisation problem

The mathematical formulation of the objective function for the maximisation of the surface retention (Q_s) for a single quality factor was as follows.

Maximise with respect to T_h (design variable),

$$Q_s = 10^{C/D_{Tref,q}} \times 100 \tag{7}$$

with,

$$C = \int_0^{t_p} 10^{T_s(t) - T_{ref,q}/z_q}\, dt \tag{8}$$

subjected to: (i) a microbial constraint at $t = t_p$,

$$F_{ce} = \int_0^{t_p} 10^{T_{ce}(t) - T_{ref,m}/z_m}\, dt \geq F_{ce}^t \tag{9}$$

where F^t_{ce} is the target lethality at the centre (cold spot) of the product; (ii) a constraint in the final temperature at the centre of the product,

$$T_{ce}(t_p) \leq T^t \tag{10}$$

where $T_{ce}(t_p)$ represents the temperature at the centre of the food at the end of the process time. T^t_p is a temperature (target value) sufficiently low so that the rate of destruction of microorganisms becomes negligible. When more than one quality factor is considered we are interested in the maximisation of the weighted sum of retentions (eqn (8)). The microbial and final temperature constraints are the same as for the optimisation of one component.

Optimisation approach and algorithm

In this section the methodology used for the calculation of the optimum constant and variable retort temperature profiles is described.

Constant retort temperature profiles
Constant retort temperature (CRT) profiles are defined in the present work as profiles consisting of a holding time at constant heating temperature, followed by a cooling period at a constant temperature. A zero retort come up time is assumed. Process time is defined as the sum of holding and cooling times.

The optimisation of the optimum CRT profiles reduces in this case to the optimisation of a single value, the temperature of the heating medium during the holding phase. The univariate search procedure of Davies–Swann–Campey (Saguy, 1993) was used to perform the optimisation. The durations of the heating and cooling phases are set so that the constraints defined by eqns (9) and (10) are verified (Silva *et al.*, 1992).

Variable retort temperature profiles
Variable retort temperature (VRT) profiles are defined as profiles in which no a-priori assumptions are made in the dependence of the retort temperature with time. In this study, however, VRT profiles were defined using the following empirical equation developed by analysis of a large number of optimum VRT profiles (Noronha *et al.*, 1996),

$$T(t) = a_0 + a_1 t - a_3 \exp(a_2 t) \tag{11}$$

For the determination of parameters a_0 to a_3 in eqn (11) that allow the minimisation of surface quality degradation, the complex method (Saguy, 1983; Noronha *et al.*, 1996) was used.

The complex method allows the incorporation of the constraints on final microbial sterility and final temperature at the centre of the product as implicit constraints. However the incorporation of the constraints as implicit constraints implies that the initial starting point for the optimisation is a feasible one, i.e. a point that complies with all the constraints. Due to the difficulties found in obtaining initial feasible starting points the constraints were incorporated by means of a penalty function,

$$P = W_1(T_{ce}(t_p) - T^t_{ce})^2 + W_2(F_{ce} - F^t_{ce})^2 \tag{12}$$

where W_1 and W_2 represent positive weighting factors. The maximisation of the surface retention for a single component was dealt with as a minimisation problem considering the objective function:

$$\text{Objective function} = -\text{RETS}+P \tag{13}$$

When the optimisation for more than one component is considered instead of eqn (13) the following was considered,

$$\text{Objective function} = -\sum_i w_i \cdot \frac{N^i}{N_0^i} + P \tag{14}$$

where w_i are equivalent if all the components have the same weight or have different values if the different quality factors are to have different importance.

RESULTS AND DISCUSSION

System I (chilli con carne, white rice and peach slices in syrup)

The parameters that characterise this system are presented in Table 1. The heating characteristics (f_h and j values) refer to a meal-set consisting of 'chilli con carne', white rice and peach slices in syrup (Hayakawa *et al.*, 1991). The z_q values chosen are in the range of z_q values normally found for quality factors.

Both for the individual and simultaneous optimisation of quality factors an initial homogeneous temperature of the product of 30°C was considered. The temperature of the cooling medium for the calculation of the optimum CRT profiles was considered to be 15°C. The products were processed until an F_0 value of 7·5 min was reached in the cold spot of the slowest heating component. The cooling phase was extended until the temperature of the slowest cooling product reached 60°C. The duration of the process was defined as the sum of the heating and cooling phases. A reference temperature of 121·1°C was considered both for the calculation of the F and the C-values. Due to the different heat penetration rates product temperature evolution was calculated independently for each of the components, using the APNS method.

In Tables 2 and 3 the results of the optimisation for both constant retort temperature and variable retort temperature policies are presented considering the

TABLE 1
Parameters used for the Optimisation of the Surface Quality for a Three-component System

Component	f_h *(min)*	j_h	z_q *(°C)*	D_{Tref} *(min)*
1 peach slices	18·32	1·17	15·0	200·0
2 white rice	28·30	1·38	25·0	200·0
3 chilli con carne	26·49	1·43	35·0	200·0

TABLE 2
Results from the Individual Optimisation for Case I. $F_{target} = 7{\cdot}5$ min, T_{end} (target) = 60°C

Component			*CRT*		*VRT*	
	T_{opt} *(°C)*	t_p *(min)*	Q_s *(%)*	*C-value (min)*	Q_s *(%)*	*C-value (min)*
1 peach slices	112·2	95·2	77·6	22·1	81·7	17·6
2 white rice	115·6	82·6	61·6	42·1	69·2	32·0
3 chilli con carne	118·7	80·4	54·7	53·3	60·3	44·0
Average	—	—	64·2	39·6	70·4	31·2

individual and simultaneous optimisation, respectively. The VRT profiles were calculated for the same process time as the time of the optimum CRT profile.

For the optimal CRT profiles the comparison between the retentions observed for optimisation of the individual components (Table 2) and the retentions observed when the simultaneous optimisation of the three components is performed (Table 3) show a sensible decrease in the final retentions for the latter. However it should be taken into account that we are comparing the results of the simultaneous optimisation with the best possible results for each of the components and that a reduction should be expected. It is observed that two of the components show final processing values at the cold spot greatly exceeding the set target value of 7·5. This is due to the fact that in the definition of the optimisation problem, a constraint on the minimum processing value was set in the product with the slowest heating rate. The fact that components 1 and 2 show a faster rate of heat transfer (smaller f_h values) explains the high processing values observed at the end of the process when comparing to the much lower value observed for the third component, that shows a slower rate of heat transfer (larger f_h value).

TABLE 3
Results from the Simultaneous Optimisation for Case I. $F_{target} = 7{\cdot}5$ min, T_{end} (target) = 60°C

Comp	*CRT (114°C/109 min)*			*VRT[a] (109 min)*			*VRT[b] (79 min)*		
	F_c *(min)*	Q_s* *(%)*	*C (min)*	F_c *(min)*	Q_s* *(%)*	*C (min)*	F_c *(min)*	Q_s* *(%)*	*C-value (min)*
1	12·9	69·9(−9·9)	31·1	15·0	73·7(−9·8)	26·5	30·72	58·6(−28·3)	46·4
2	9·7	57·5(−6·7)	48·1	10·4	66·0(−4·6)	36·1	14·45	59·8(−13·6)	44·6
3	7·5	51·3(−6·2)	58·0	7·5	60·6(+0·5)	43·6	7·5	59·0(−2·2)	45·8
Average	–	59·5	45·8	–	66·8	35·4	–	59·2	45·6

* Between the brackets are the relative lost in relation to the optimum individual values.
[a] VRT profile for the same process time as the optimum CRT profile.
[b] VRT profile showing approximately the same average retention as the optimum CRT profile.

The simultaneous optimisation of the three quality factors using the VRT policy allowed a substantial increase in the individual quality retentions (5·4, 14·8 and 18·1% for components 1, 2 and 3, respectively) when comparing with the results obtained from the simultaneous optimisation using the CRT policy. When the results of the simultaneous optimisation are compared with the individual optimisation, in terms of the achieved individual retentions, a decrease is found on the individual surface retentions for two of the components and a slight increase for the third component. However a direct comparison between these results can not be performed due to the differences in process time between the different processes.

When considering the possibilities of the VRT profiles as a means of reducing the process time and allowing comparison with the CRT approach, one can use two different criteria. One can calculate the minimum process time below which one of the components shows a retention smaller than the retention achieved using the CRT profile, or as a second criterion one can calculate the process time below which the average of retentions shows a smaller value than the average retention for the optimum CRT profile calculated considering the three components simultaneously (Table 3). Using the first criterion and interpolating (see Fig. 1) it is possible to conclude that for processes approximately below 5500 s (92 min) the retention of the component with a z_q value of 15°C will be smaller than 69·9% (retention obtained using the optimum CRT profile). This means that using this criterion the process time could be reduced from 6510 to 5500 s (109–92 min), i.e. a reduction of about 15%. If the second criterion is used, it is possible to reduce the process time from 6510 s (109 min) to about 4555 seconds (76 min) (representing a 30% reduction on the process time) and still achieve average retentions larger than those obtained using the CRT approach. Further inspection of Fig. 1 shows that the quality factor more sensitive to temperature changes (component 1) suffers from a larger reduction in surface retention when the process time is reduced. This is due to the increase in the overall temperature observed when the process time is decreased. Due to the constraint in the final target value at the centre of the

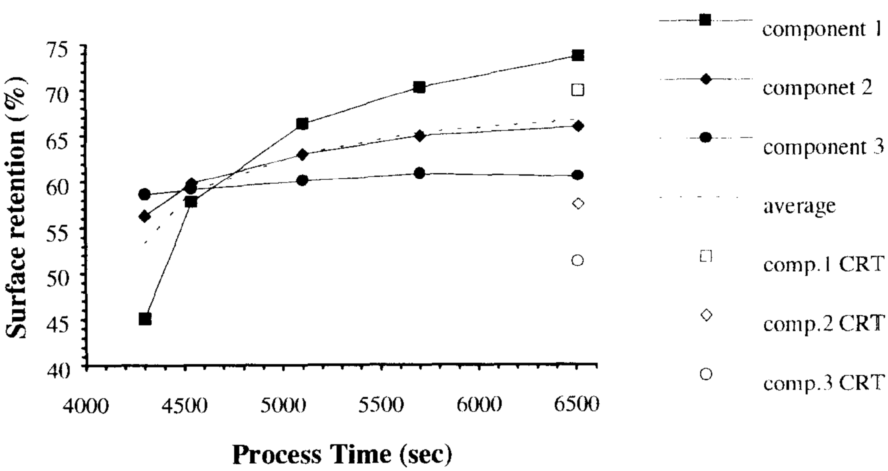

Fig. 1. Graphical determination of the VRT profile that minimises the process time.

TABLE 4
Parameters used for the Optimisation of the Surface Quality for System II

Component	f_h *(min)*	j	z_q *(°C)*	D_{Tref} *(min)*
1 meat	25·50	1·273	40·0	200·0
2 potatoes	28·20	1·273	30·0	200·0
3 spinach	32·80	1·273	20·0	200·0

container, a decrease in the process time will imply an increase in the heating medium temperature in order to comply with this constraint. So the component whose reaction rate of degradation is more sensitive to changes in temperature will be the one showing a larger reduction in the surface quality with reduction in process time.

System II (meat, potatoes and spinach)

The second system represents a meal-set consisting of three components. In Table 4 the parameters that characterise the system are given. The heating parameters are those of spinach, potatoes and meat in a pouch of 3 cm width. In all the considered simulations an initial homogeneous temperature of 40°C was assumed. The simulations were all performed considering a final lethality of 6·0 min. The cooling phase was extended until the temperature at the cold spot of the slowest heating component reached 60°C. The cooling medium temperature was set to 20°C for all the simulations.

In Tables 5 and 6 are the results for the optimisation of the surface quality using the constant and variable retort temperature profiles when the components are considered individually or simultaneously, respectively. The individual surface retention values for the simultaneous optimisation (Table 6) show that in spite of the observed reduction of the quality for each of the quality factors the simultaneous optimisation was possible. It is worth noting that when the simultaneous optimisation is conducted using the VRT approach the individual surface retentions obtained (Table 6) are larger than the retentions obtained with the CRT approach when the surface quality is maximised individually (Table 5).

The use of a VRT profile allows a 25% reduction in the process time in relation to the optimum CRT profile without reductions in the average surface retention.

TABLE 5
Results from the Individual Optimisation for Case II

Component			*CRT*		*VRT*	
	T_{opt} *(°C)*	t_p *(min)*	Q_s *(%)*	*C-value (min)*	Q_s *(%)*	*C-value (min)*
1 meat	120·3	63·2	63·1	40·0	68·2	33·2
2 potatoes	117·0	70·0	62·5	40·8	69·0	32·3
3 spinach	112·2	110·1	67·6	34·1	73·6	26·6
Average	—	—	64·4	38·3	70·3	30·7

TABLE 6
Results from the Simultaneous Optimisation for Case II. $F_{target} = 6{\cdot}0$ min, T_{end} (target) = 60°C

Component		*CRT (115·7°C/84 min)*		*VRT[a] (84 min)*			*VRT[b] (63 min)*	
	F_c *(min)*	Q_s* *(%)*	*C-value (min)*	F_c *(min)*	Q_s* *(%)*	*C-value (min)*	F_c *(min)*	Q_s* *(%)*	*C-value (min)*
1 meat	8·7	56·3(−10·8)	50·0	9·7	62·8(−7·9)	40·4	14·7	61·8(−9·4)	41·8
2 potatoes	7·7	59·5(−4·8)	45·1	8·2	66·2(−4·1)	35·9	10·6	61·2(−11·3)	42·6
3 spinach	6·0	65·6(−3·0)	36·6	6·0	70·8(−3·8)	30·0	6·0	58·1(−21·1)	47·2
Average	—	60·4	43·9	—	66·6	35·4	—	60·4	43·8

*Between brackets are the relative lost in relation to the optimum individual values.
[a] VRT for the same process time as the optimum CRT profile.
[b] VRT showing approximately the same average retention as the optimum CRT profile.

The third component, with the lowest z_q value, is the one showing a larger decrease in surface quality when the process time is decreased.

System III—mixture of four vegetables (green beans, peas, corn and carrots)

The third system consisted of a mixture of vegetables processed in glass jars. The mixture was prepared from individually frozen corn, broken green beans, peas and carrot slices. The heat penetration parameters were determined from a heat penetration run in water cascading mode ($T_1 = 121$°C, coming-up-time = 8 min). In Table 7 the heat penetration and kinetic parameters for this system are summarised. The kinetic parameters were taken from the literature (Villota & Hawkes, 1986; Van Loey *et al.*, 1994a). In all the optimisations a final processing value of 6·0 min was targeted. The cooling water temperature was set at 15°C and the cooling phase extended until the temperature at the cold spot was below 60°C.

In this case study an objective function based on the sum of the average retentions for the different components is not appropriate due to large differences in the D_{Tref} values. This difference implies that the maximum Q_s for the components will largely differ for the same F-target value. In Table 8 the results of the optimal retentions achievable when the individual components are considered separately are

TABLE 7
Parameters used for the Optimisation of the Surface Quality for the Vegetable Mixture Case

Component	f_h *(min)*	j	z_q *(°C)*	D_{Tref} *(min)*
1 green beans	11·98	1·46	14·2	16·3
2 peas	11·98	1·46	32·0	61·0
3 corn	11·98	1·46	59·0	448·0
4 carrots	11·98	1·46	22·0	157·0

TABLE 8
Results from the Individual Optimisation for Case III

Component			*CRT*		*VRT*	
	T_{opt} (°C)	t_p (min)	Q_s (%)	*C-value* (min)	Q_s (%)	*C-value* (min)
1 green beans	112·2	70·8	12·0	15·0	19·0	11·8
2 peas	121·0	30·4	41·1	23·7	48·8	19·1
3 corn	129·4	22·4	89·5	21·6	90·7	18·8
4 carrots	117·3	39·0	72·4	22·0	77·7	17·2
Average	—	—	53·8	20·6	59·1	16·7

presented. It can be seen that the first two components, with relatively lower D_{Tref} values, present an optimum surface retention much lower than that observed for the other two components (with much larger D_{Tref} values). If the simultaneous optimisation for the four parameters is performed using as a criterion the maximisation of the sum of the retention (as considered in system I and system II) the influence of the retention of component 1 (and 2 to a less extent) will be almost negligible and the optimum profiles obtained will be far from the optimum conditions for this component. The components more resistant to the heat destruction will be privileged in the optimisation. In order to avoid this fact an objective function that takes into account the relative heat sensitivity of the different components was considered. This was achieved using weighting factors different from that in eqn (14). The weighting factors were chosen as the inverse of the retentions achieved in the individual optimisation for each of the components.

The weighting factors, w_i, in the objective function [eqn (14)] have the role of transforming the contribution of each of the components into relative contributions based on the optimum (maximum) retentions achievable for the component (the maximum retention when the component is considered individually). The optimum profiles calculated using this objective function will be profiles that minimise the sum of the deviations from the optimum conditions for each of the components.

The use of an optimised VRT (Table 9) profile allows the simultaneous optimisation of the quality retention without significant reductions in the individual retentions obtained when the quality retention for each of the components is maximised individually using the CRT approach. A reduction from 46·7 to 26·7 min in the process time, approximately 40%, is possible without reduction on the average quality observed in the optimum CRT profile. However with the reduction of the process time a dramatic decrease in the surface quality retention for component 1 is observed.

CONCLUSION

The simultaneous optimisation of more than one quality factor is possible. The main problem lies in a proper definition of the objective function to be optimised. While

TABLE 9

Results from the Simultaneous Optimisation for Case III. F_{target} = 6·0 min, T_{end} (target) = 60°C

Component	*CRT (115·5°C/ 46·7 min)*		*VRT^a(46·7 min)*		*VRT^b(26·7 min)*	
	Q_s (%)*	*C-value (min)*	*Q_s* (%)*	*C-value (min)*	*Q_s* (%)*	*C-value (min)*
1 green beans	10·2(−15·0)	16·1	14·8(−22·1)	13·6	1·1(−94·2)	32·2
2 peas	36·4(−11·4)	26·9	47·8(−2·1)	19·7	47·0(−3·7)	20·2
3 corn	84·6(−5·5)	32·5	87·6(−3·4)	25·7	90·6(−0·1)	19·1
4 carrots	72·0(−0·6)	22·4	78·5(+1·3)	16·5	71·6(−7·9)	23·0
Average	50·8	24·5	57·2	18·9	52·6	23·6

*Between brackets are the relative lost in relation to the optimum individual values.
[a] VRT for the same process time as the optimum CRT profile.
[b] VRT showing approximately the same average retention as the optimum CRT profile.

the most straightforward approach is to consider the optimisation of the sum of the surface retentions over the components, for practical optimisation problems the relative importance of the different components to be considered must be taken into account in the objective function by means of appropriate weighting factors.

The use of variable temperature profiles allowed, as in the case of single quality factor, a decrease in the destruction of the quality factors during the sterilisation process when compared to the optimum constant retort temperature profile, and a decrease in the processing time without a reduction on the quality achieved using the constant retort temperature approach.

Optimisation using VRT profiles represents a valuable approach when the minimisation of quality degradation for more than one component is of interest. Using this approach it is possible to achieve in a single process surface retentions comparable (and sometimes slightly superior) to the maximum retentions possible with optimum CRT profiles when the components are considered individually.

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REFERENCES

Ball, C. O. & Olson, F. C. W. (1957). *Sterilization in Food Technology. Theory Practice and Calculation*. McGraw-Hill, New York.

Banga, J. R., Perez-Martin, R. J., Gallardo, J. M. & Casares, J. J. (1991). Optimisation of the thermal processing of conduction-heated canned foods: study of several objective functions. *J. Food Engng.*, **14**, 25–51.

Bhowmik, S. A. & Hayakawa, K. (1989). Quality retention and steam consumption of selected thermal processes. *Lebensm. Wiss. und Technol.*, **21**, 13–19.

Esty, J. R. & Meyer, K. F. (1922). The heat resistance of the spores of *C. Botulinum* and allied anaerobes. *J. Infectious Diseases*, **34**(1), 650–663.

Hayakawa, K. (1978). A critical review of mathematical procedures for determining proper heat sterilisation processes. *Food Technol.*, **32**(3), 59–65.

Hayakawa, K., Wang, J. & Gilbert, S. G. (1991). Simultaneous heat processing of high and low acid foods in semirigid containers—a theoretical analysis. *J. Food Sci.*, **56**(6), 1714–1717.

Hendrickx, M., Van Genechten, K. & Tobback, P. (1990). Optimizing quality attributes of conduction heated foods, a simulation approach. In *Engineering and Food: Preservation Processes and Related Techniques*, Vol. 2, ed. W. E. L. Spess & H. Shubert. Elsevier Applied Science, New York.

Martens, T. (1980). Mathematical model of heat processing in flat containers. Ph.D. thesis, Catholic University of Leuven, Belgium.

Nadkarni, N. M. & Hatton, T. A. (1985). Optimal nutrient retention during the thermal processing of conduction-heated canned foods: application of the distributed minimum principle. *J. Food Sci.*, **50**, 1312–1321.

Norback, J. P. (1980). Techniques for optimization of food processes. *Food Technol.*, **34**(2), 86–88.

Noronha, J., Hendrickx, M., Suys, J. & Tobback, P. (1993). Optimization of surface quality retention during thermal processing of conduction heated foods using variable temperature retort profiles. *J. Food Processing Preservation*, **17**(2), 75–91.

Noronha, J., Hendrickx, M., Van Loey, A. & Tobback, P. (1995). New semi-empirical approach to handle time-variable boundary conditions during sterilisation of non-conductive heating foods. *J. Food Engng.*, **24**, 249–268.

Noronha, J., Van Loey, A., Hendrichx, M. & Tobback, P. (1996). An empirical equation for the description of optimum reliable retort temperature profiles that maximise surface quality retention in thermally processed foods. *J. Food Proc. Preserv.*, **20**, 251–264.

Ohlsson, T. (1980). Optimal sterilization temperatures for flat containers. *J. Food Sci.*, **45**, 848–852.

Ohlsson, T. (1980). Optimal sterilization temperatures for sensory quality in cylindrical containers. *J. Food Sci.*, **45**, 1517–1521.

Ohlsson, T. (1980c). Optimization of heat sterilization using *C*-values. In *Food Process Engineering*, Vol. 1, Paper 14, ed. P. Linko. Applied Science Publishers, Oxford, pp. 137–145.

Saguy, I. & Karel, M. (1979). Optimal retort temperature profile in optimizing thiamin retention in conduction-type heating of canned foods. *J. Food Sci.*, **44**, 1485–1490.

Saguy, I. (1983). Optimization methods and applications. In *Computer-Aided Techniques in Food Technology*, ed. I. Saguy. Marcel Dekker, New York, pp. 263–320.

Silva, C., Hendrickx, M., Oliveira, F. & Tobback, P. (1992). Optimal sterilization temperatures for conduction heating foods considering finite surface heat transfer coefficients. *J. Food Sci.*, **57**(3), 743–748.

Silva, C., Hendrickx, M., Oliveira, F. & Tobback, P. (1992). Critical evaluation of commonly used objective functions to optimize overall quality and nutrient retention of heat-preserved foods. *J. Food Engng.*, **17**, 241–258.

Silva, C. L., Oliveira, F. A. R. & Hendrickx, M. (1993). Modelling optimum processing conditions for the sterilization of prepackaged foods. *Food Control*, **4**(2) 67–78.

Silva, C. L. M., Oliveira, F. A. R. & Hendrickx, M. (1994). Quality optimization of conduction heating foods sterilized in different packages. *Int. J. Food Sci. Technol.*, **29**, 515–530.

Teixeira, A. A., Dixon, J. R., Zahradnik, J. W. & Zinmeister, G. E. (1969). Computer optimization of nutrient retention in the thermal processing of conduction-heated foods. *Food Technol.*, **23**(6), 137–142.

Teixeira, A. A., Stumbo, C. R. & Zahradnik, J. W. (1975). Experimental evaluation of mathematical and computer models for thermal process evaluation. *J. Food Sci.*, **40**, 653–655.

Van Loey, A., Fransis, A., Hendrickx, M., Maesmans, G., Noronha, J. & Tobback, P. (1994). Optimizing thermal process for canned beans in water cascading retorts. *J. Food Sci.*, **59**(4), 828–832.

Villota, R. & Hawkes, J. G. (1986). Kinetics of nutrient and organoleptic changes in foods during processing. In *Physical and Chemical Properties of Foods*, ed. M. R. Okos. American Society of Agricultural Engineering, St. Joseph, MI.