Variable retort temperature optimization benefit in scheduling for retorts of different capacities in food canneries

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ABSTRACT

In the majority of small- to medium-sized canneries, retorting is carried out in a battery of retorts as a batch process. For such canneries, the unloading and reloading operations for each retort are labor-intensive; therefore, a well-designed and well-managed plant should be utilized in order to optimize the whole sterilization process. In other words, it is necessary to develop a suitable mathematical model for the operation of the whole plant and to determine the optimal values of its decision variables. The result of such a model involves the quantities of each product to be loaded onto the retorts for each of the batches, and the optimal solution provides an optimum scheduling. On the other hand, it is well-known that variable retort temperature processing can be used for reducing the sterilization processing time required for sterilization using the traditional constant retort temperature processing. Therefore, the objective of this research consisted of utilizing a variable retort temperature processing in developing a mathematical model for scheduling at food canneries for the case of retorts of different capacities. The developed model was based on mixed-integer linear programming and simultaneous sterilization based on variable retort temperature processing. The adaptive random search algorithm coupled with penalty functions approach, and the finite difference method with cubic spline approximation are utilized in this study to obtain the simultaneous sterilization vectors to be processed under time-variable retort temperature**.** The proposed in this study methodology can be useful for small- and medium-sized food canneries, which work with many different products simultaneously.

Keywords: mixed integer linear programming, simultaneous sterilization, variable retort temperature processing.

INTRODUCTION

In the majority of small- to medium-sized canneries, retorting is carried out in a battery of retorts as a batch process. For such canneries, the unloading and reloading operations for each retort are labor-intensive; therefore, a well-designed and well-managed plant should be utilized in order to optimize the whole sterilization process. In other words, it is necessary to develop a suitable mathematical model for the operation of the whole plant and to determine the optimal values of its decision variables. The result of such a model involves the quantities of each product to be loaded onto the retorts for each of the batches, and the optimal solution provides an optimum scheduling. On the other hand, it is well-known that variable retort temperature processing can be used for reducing the sterilization processing time required for sterilization using the traditional constant retort temperature processing. Therefore, the objective of this research consisted of utilizing a variable retort temperature processing in developing a mathematical model for scheduling at food canneries for the case of retorts of different capacities.

MATERIALS & METHODS

Simultaneous sterilization possibility

In general simultaneous sterilization could be characterized as a capability allowing for sterilization of different products in various container sizes in the same retort [1]. The stumbling-block in this case is that each of the products and container sizes involved to the simultaneous sterilization process require different process times and constant retort temperatures which are related with safety and quality criterions. The simultaneous sterilization approach used in this study was developed by Simpson [2] especially for the case of small canneries with few retorts that frequently process small batches of different products in various container sizes that require different process times and retort temperatures. In practice, the following two F_0 values are considered for each product to be sterilized: F_0^{min} and: F_0^{max}. These values are product-related, but in general, F_0^{min} is chosen according to a safety criterion and F_0^{max} according to a quality criterion (resulting in a safe product of a required quality). All combinations of the retort temperature and processing time correspond to the same F_0 value, and they are called isolethal or equivalent lethality processes [3]. Fig. 1

shows an example of two equivalent lethality curves corresponding to the values F_0^{min} and F_0^{max}. The region between these two curves contains all the combinations of retort temperatures and processing times that are sufficient for the sterilization of a selected product. This region is called permissible region [1].

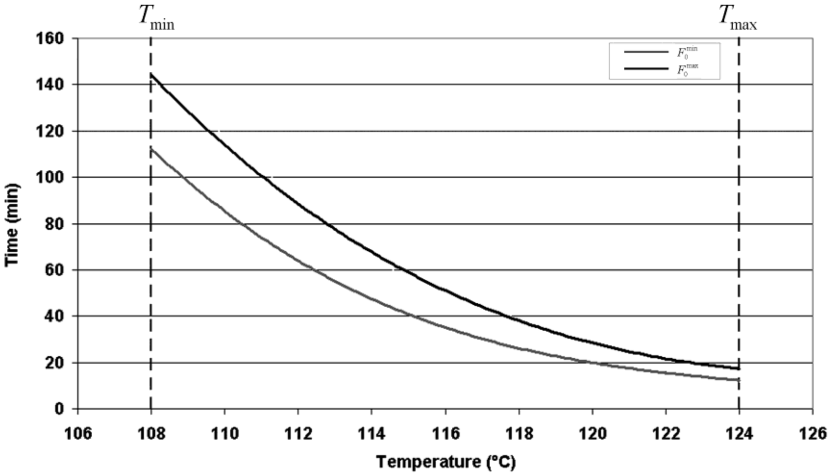


Figure 1. Permissible region related to the equivalent lethality processes corresponded to the F_0^{min} and F_0^{max} values.

Mathematical formulation for simultaneous sterilization

Let us assume that there are $n > 2$ products, say $P_1, \dots, P_n$, which are processed at the plant location. The permissible region R_j for the product P_j can be defined as follows:

$$R_j = \{(T,t) | T_{min} \leq T \leq T_{max}, m_j(T) \leq t \leq M_j(T)\},$$

where $m_j(T)$ and $M_j(T)$ are iso-lethality curves of product P_j.

The interpretation of R_j is that the product P_j can be processed at temperature T for time t if and only if $(T,t) \in R_j$. It is clear that the sub-collection of products $P_{j_1}, P_{j_2}, \dots, P_{j_r}$, $j_1, j_2 \dots, j_r \in X$, $X = \{1,2,\dots,n\}$, $r < n$, where $1 \leq j_1 \leq j_2 \leq \dots \leq j_r \leq n$, can be simultaneously processed at temperature T and time t if and only if $(T,t) \in R_{j_1} \cap R_{j_2} \cap \dots \cap R_{j_r}$. Thus, obtaining all possible sub-collections of products that can be simultaneously processed is equivalent to finding all possible subsets $Q = \{j_1, \dots, j_r\} \subset X$, $1 \leq j_1 \leq j_2 \leq \dots \leq j_r \leq n$, $R_{j_1} \cap R_{j_2} \cap \dots \cap R_{j_r} \neq \emptyset$.

Fig. 2 shows the example of permissible regions R_A, R_B and R_C obtained for three different product A, B and C. The intersection R_{ABC} of the permissible regions R_A, R_B and R_C gives processes that are sufficient for simultaneous sterilization of products A, B and C.

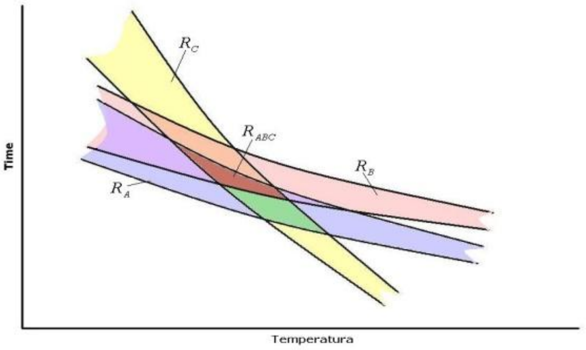


Figure 2. Intersection R_{ABC} of the regions R_A, R_B and R_C contains isolethal processes, which allow to sterilize three different products A, B and C simultaneously.

Any simultaneous sterilization possibility can be presented as the following triple:

$$\langle v, t, T \rangle,$$

where $v = (v_1, v_2, \dots, v_n)$ is called a simultaneous sterilization vector, $v_k = \{0,1\}$, $k \in 1{:}n$, and

$$v_k = \begin{cases} 1, & if\ product\ k\ can\ be\ sterilized \\ 0, & otherwise \end{cases},$$

and t, T are the necessary time and retort temperature, respectively, used to process a subset of products determined by the vector v.

Adaptive random search algorithm

The adaptive random search algorithm belongs to a specific class of global stochastic optimization algorithms [4]. This class of algorithms is based on generating the decision variables from a given probability distribution, and the term ‘‘adaptive” consists of modifications to the probability distribution utilized in the searching process, which, throughout the whole search process, act as minimum computations of the objective function, locating global solutions. The pedestal probability distribution is utilized in the adaptive random search. After every calculation of objective function, the pedestal distribution of decision variables is modified so that the probability of finding the optimal value of the objective function is increased.

Problem definition

The optimization problem in this case consists of finding a given quantity of each product a_j, $j \in 1{:}n$, a subset of simultaneous sterilization vectors $V^{opt} \subseteq V_A$ and its assignment among a given number of retorts of different capacities c_k, $k \in 1{:}s$, such that the given amount of products shall be sterilized completely within the minimum plant operation time. For the optimization problem to be solved in the present research, the following data is given and generated:

- number of sterilization products: n,
- quantity for each product: a_j, $j \in 1{:}n$,
- number of sterilization vectors: m,
- set of non-dominated sterilization vectors: $V^A = \{v^i\}, v_j^i \in \{0,1\}$, $i \in 1{:}m$, $j \in 1{:}n$,
- set of sterilization times: $T_A = \{t_i\}$, $i \in 1{:}m$,
- number of retorts : s,
- capacity of each retort : c_k, $k \in 1{:}s$.

Mathematical model description

Two types of decision variables were used in the mathematical model:

- integer decision variables:

$$u_i^k = \begin{cases} 1, \ if\ vector\ v^i \in V, is\ used\ for\ sterilization\ process\ in\ the\ autoclave\ k, \\ 0, \qquad otherwise \end{cases}$$

- continuous decision variables: x_{ij}^k, $i \in 1{:}m$, $j \in 1{:}n$, $k \in 1{:}s$ corresponding to the quantity of the product P_j loaded into the retort k utilizing the sterilization vector i.

The objective function to minimize plant operation time can be written as follows:

$$\max_k\left\{\sum_{j=1}^{m} u_i^k t_i\right\} \rightarrow \min_{,u} \tag{1}$$

where the goal is to minimize the maximum time $\max_k\left\{\sum_{j=1}^{m} u_i^k t_i\right\}$ spent by one of the retorts k in processing its part of the products and thus minimize the plant operation time.

Given that all products must be completely sterilized, the following constraints should be considered:

$$\sum_{k=1}^{s}\sum_{i=1}^{m} x_{ij}^k = a_j \ , \forall j \in 1{:}n. \tag{2}$$

For all chosen simultaneous sterilization vectors v^i, $i \in 1{:}m$, and for all given capacities of retorts c_k, $k \in 1{:}s$, the amount of products in each batch loaded into retort k should be less than its capacity c_k. Consequently, these constraints can be written as:

$$\sum_{j=1}^{n} x_{ij}^k \le u_i^k c_k \ , \forall i \in 1{:}m, \forall k \in 1{:}s. \tag{3}$$

Since the above mathematical model is non-linear, due to its non-linear (minimax) objective function, the following modifications were made in order to transform it into an equivalent MILP model. The objective function (1) was replaced by the following objective function:

$$MinMax \ \rightarrow \ \min,$$

where $MinMax \in (0, +\infty)$, and the following constraints for each of the given retorts $k \in 1{:}s$, were added to constraints (2) and (3):

$$\sum_{i=1}^{m} u_i^k t_i \le MinMax, \forall k \in 1{:}s.$$

Thus, the minimization of plant operation time by MILP can be written in terms of an objective function:

$$MinMax \ \rightarrow \ \min,$$

subject to:

$$\sum_{i=1}^{m} u_i^k t_i \leq MinMax, \forall k \in 1{:}\, s,$$

$$\sum_{k=1}^{s} \sum_{i=1}^{m} x_{ij}^k = a_j \,, \forall j \in 1{:}\, n,$$

$$\sum_{j=1}^{n} x_{ij}^k \leq u_i^k c_k \,, \forall i \in 1{:}\, m, \forall k \in 1{:}\, s.$$

The obtained MILP model is preferred for use in practice over the model with a non-linear objective function for two reasons. First, algorithms exist, which can guarantee finding a global solution to the linear programming problems, and second, efficient computer tools have been developed based on such algorithms [1].

MILP model and variable retort temperature processing

The presented above MILP model was successfully used for minimizing a plant operation time [1]. The objective of this research is consisted of utilizing a variable retort temperature processing simultaneously with this MILP model for further reduction of optimal plant operation time giving by the MILP model. For that purpose the following two-step procedure is proposed in this research.

Step 1. Find from the MILP model the simultaneous sterilization vectors, required for sterilization a given amount of products.

Step 2. For each of the simultaneous sterilization vectors, obtained on the first step, find a variable retort temperature process, which reduces the sterilization time of chosen simultaneous sterilization vector.

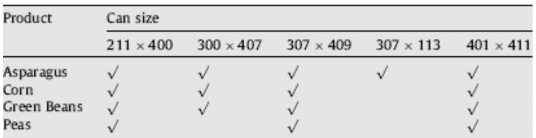
The simultaneous sterilization possibility proposed by Simpson [2] assumes that the sterilization process is realized for each of the simultaneous sterilization vectors under constant retort temperature. Thus, the required subset of simultaneous sterilization vectors is obtained on the first step of the presented procedure. At the same time it is well-known that the utilization of variable retort temperature processing is able to obtain the final food product of the same characteristics related to safety and quality criterions, but for less sterilization time in comparison with constant retort temperature processing. Therefore, this advantage of the variable retort temperature processing is used on the second step of the proposed procedure. The reduction of the sterilization time of each simultaneous sterilization vector reduces in one's turn a total plant operation time giving by the MILP model. Simultaneous sterilization possibility coupled with its optimal VRT profile will be called VRT simultaneous sterilization possibility.

RESULTS & DISCUSSION

Example of simultaneous sterilization problem

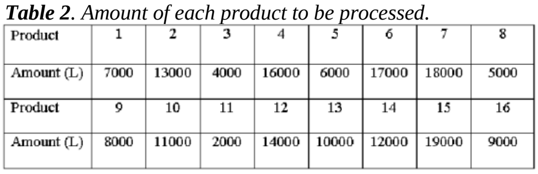
The following 16 food vegetable products were selected for all of solved problems (see Table 1) [1].

Table 1. *Products and can sizes.*



Product	Can size				
	211 × 400	300 × 407	307 × 409	307 × 113	401 × 411
Asparagus	√	√	√	√	√
Corn	√	√	√		√
Green Beans	√	√	√		√
Peas	√		√		√

Table 2. *Amount of each product to be processed.*



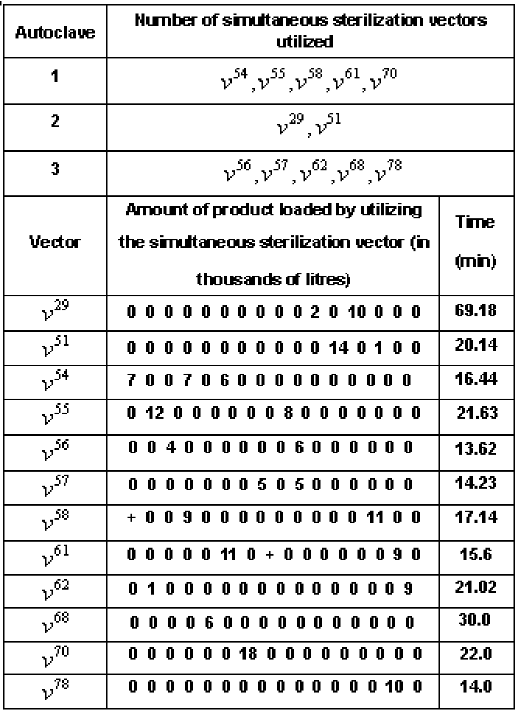
Product	1	2	3	4	5	6	7	8
Amount (L)	7000	13000	4000	16000	6000	17000	18000	5000
Product	9	10	11	12	13	14	15	16
Amount (L)	8000	11000	2000	14000	10000	12000	19000	9000

The following given data were used for presented below simultaneous sterilization problem: 1) number of sterilization products: 16, 2) amount for each product: (see Table 2), 3) number of sterilization vectors: 70, 4) set of non-dominated sterilization vectors, 5) set of sterilization time, 6) Number of autoclaves: 3, 7) Capacities of each autoclave: $c_1 = 20{,}000\, L$, $c_1 = 15{,}000\, L$ $c_1 = 10{,}000\, L$. The following solution of the problem was obtained: Optimal objective values for simultaneous sterilization case is equal to 92.87 min, and for non-simultaneous sterilization case - 111.0 min. Detailed optimal solution of the problem is presented in the Table 3. Thus, the variable retort temperature processing can be utilized for each of the simultaneous sterilization possibilities presented in the Table 3 for reducing the total plant operation time obtained by MILP model.

Example of VRT simultaneous sterilization possibility

Two different products and can sizes were chosen in order to show the workability of the proposed in this study approach. As a first step, it was necessary to find all those combinations of constant retort temperature (CRT) and process time for the conditions listed in Table 4 that would deliver the same final target value of lethality. Obtained experimental results are shown on Fig. 3. We can see from Fig. 3 that required CRT process that delivers minimum processing time and sterilizes the two different products simultaneously is a process with constant retort temperature at 110 °C and a process time of 210 minutes.

***Table 3**. Detailed optimal solution of the problem.*



Autoclave	Number of simultaneous sterilization vectors utilized	
1	$\nu^{54}, \nu^{55}, \nu^{58}, \nu^{61}, \nu^{70}$	
2	ν^{29}, ν^{51}	
3	$\nu^{56}, \nu^{57}, \nu^{62}, \nu^{68}, \nu^{78}$	
Vector	Amount of product loaded by utilizing the simultaneous sterilization vector (in thousands of litres)	Time (min)
ν^{29}	0 0 0 0 0 0 0 0 0 0 2 0 10 0 0 0	69.18
ν^{51}	0 0 0 0 0 0 0 0 0 0 0 14 0 1 0 0	20.14
ν^{54}	7 0 0 7 0 6 0 0 0 0 0 0 0 0 0 0	16.44
ν^{55}	0 12 0 0 0 0 0 0 8 0 0 0 0 0 0 0	21.63
ν^{56}	0 0 4 0 0 0 0 0 0 6 0 0 0 0 0 0	13.62
ν^{57}	0 0 0 0 0 0 0 5 0 5 0 0 0 0 0 0	14.23
ν^{58}	+ 0 0 9 0 0 0 0 0 0 0 0 0 11 0 0	17.14
ν^{61}	0 0 0 0 0 11 0 + 0 0 0 0 0 0 9 0	15.6
ν^{62}	0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 9	21.02
ν^{68}	0 0 0 0 6 0 0 0 0 0 0 0 0 0 0 0	30.0
ν^{70}	0 0 0 0 0 0 18 0 0 0 0 0 0 0 0 0	22.0
ν^{78}	0 0 0 0 0 0 0 0 0 0 0 0 0 0 10 0	14.0

***Table 4**. Parameters utilized in the thermal process simulation study.*

	Product 1	**Product 2**
Can size	307×113	211×400
Thermal diffusivity coefficient	1,71E-07	1,54E-07
F_{min} value	8	9
F_{max} value	9	10

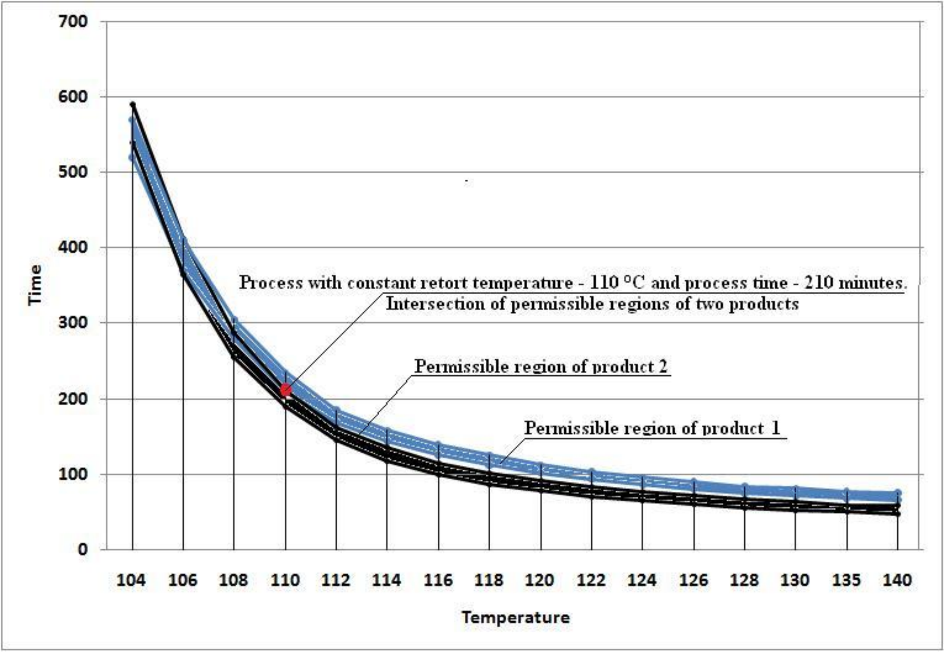


Figure 3. Permissible regions of two products and the process with CRT at 110 °C and a process time of 210 minutes.

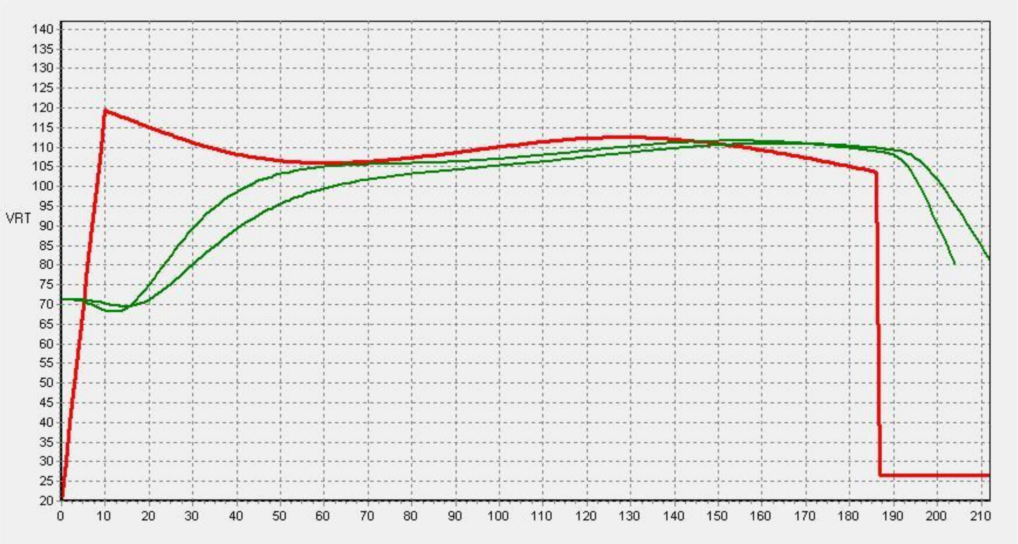


Figure 4. Optimum VRT profile, which sterilizes two different products for minimum processing time.

Obtained VRT profile for two products presented in the Table 4 is shown on Figure 4. From Figures 3 and 4 we can see that minimum processing time corresponded to CRT process was reduced from 210 to 185 minutes.

CONCLUSION

Findings from the work reported in this study would suggest that the proposed VRT simultaneous sterilization possibility makes the MILP model more effective in terms of plant operation time. The proposed in this study approach can be useful for small- and medium-sized food canneries, which work with many different products simultaneously.

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