MULTICRITERIA OPTIMIZATION OF FOOD PACKAGING ON THE THERMOFORMING MACHINES

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Summary

The paper presents results of thermoforming food packaging machine parameters (set-ups) optimization with respect to assumed two criteria: productivity of packaging process and contents of oxygen in the package. In order to accomplish the optimization one performed an active experiment enabling construction of optimization criteria in form of regression function: $W_p = f(t_f, t_z, p_k)$ and $s_p = f(t_f, t_z, p_k)$. To determine set of Pareto optimal variants with respect to the two above mentioned criteria one made use of normalized method of weights, changing values of weights every 0,05. Next, using hierarchical optimization method one made selection of the best variants with respect to opposing criteria. Decision variables of the best variant determine optimal parameters (set-ups) of the thermoforming machine with respect to assumed criteria of optimization.

Keywords: parametric multicriteria optimization, food packaging, thermoforming machines

Wielokryterialna optymalizacja procesu pakowania żywności na maszynach rolowych

Streszczenie

W artykule przedstawiono wyniki optymalizacji parametrów (nastaw) maszyny rolowej uwzględniającej dwa kryteria, tj. wydajności procesu pakowania oraz zawartości tlenu w opakowaniu. Przeprowadzono eksperyment umożliwiający zbudowanie kryteriów optymalizacji w postaci funkcji regresji: $W_p = f(t_f, t_z, p_k)$ oraz $s_p = f(t_f, t_z, p_k)$. Dla wyznaczenia zbioru wariantów Pareto-optymalnych stosowano unormowaną metodę wag – okres zmiany wartości wag – 0,05. Dokonano wyboru wariantu najlepszego ze względu na przeciwstawne kryteria za pomocą metody optymalizacji hierarchicznej. Zmienne decyzyjne wariantu najlepszego stanowią optymalne parametry (nastawy) maszyny rolowej ze względu na przyjęte kryteria optymalizacji.

Słowa kluczowe: wielokryterialna optymalizacja parametryczna, pakowanie żywności, maszyny rolowe

1. Introduction

Specifics of food products, which can be characterized by short freshness date, such as e.g. meat, cured meat products, dairy products, predetermines implementation of a given type of packaging machine. Especially, it concerns

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machines where packaging process runs with usage of vacuum technique or with use of protective gas atmosphere, owing to it is possible to assure prolonged shelf life and freshness date of already wrapped products.

Vacuum packaging consists on evacuation of air from the package, which next is tightly closed, usually in process of sealing. The main condition here is usage of a material having high enough barrierability, enabling to keep vacuum during shelf life of a protected product [1, 2].

Packaging in modified atmosphere means substitution of the air inside package by various gaseous blends, having fixed proportions of individual components during insertion, and none successive change of these proportions is possible after packaging of a product. Basic gases used in the system are: carbon dioxide CO_2, nitrogen N_2, oxygen O_2 and blends composed from nitrogen and carbon dioxide.

Thermoforming machines producing packages from two sheets of film, and making use of thermal forming and sealing process, and generating vacuum or modified atmosphere of protective gases around packed product [3, 4].

Objective of the study was to evaluate optimal parameters (set-ups) of packaging operation, i.e. forming temperature of the bottom web t_f, sealing temperature of the bottom web with the top web t_z and value of final vacuum during evacuation of air from inside of package p_k, with respect to productivity of packaging process W_p and tightness of the package, expressed by content of oxygen inside the package s_p.

2. Methodology and conditions of the experiment

In the thermoforming packaging machine (Fig. 1) are possible to be distinguished the following sub-systems (units) constituting integral machine [5]: unit to unwind and transport the bottom web, unit to thermoforming of the bottom web, unit to evacuation of pressure, sealing of the package, and cutting and labeling of the package. From sequence of packaging operations point of view, the first from the sub-assemblies is feeding unit of the bottom web, consisting of roller-type film feeder and chains which convey the film.

The next sub-assembly is thermoforming unit of the bottom web. Forming of the bottom web under effect of temperature occurs in forming chamber. Heating-up the bottom web is another operation within thermoforming process. Heating up and forming of film occurs at precisely determined value of forming temperature. Required temperature of the forming is controlled from control console of the thermoforming machine. Forming of the bottom web can be run as [4]:

- negative type forming (used in case of forming of so called flexible films),

• positive type forming (used exclusively to forming of so called semi-rigid films).

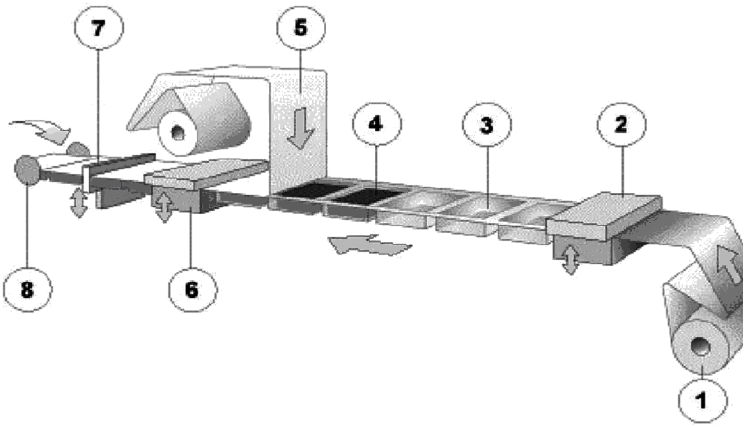

Fig. 1. Construction and principle of operation of the thermoforming packaking machine [5]: 1 – bottom web, 2 – station to form the bottom web, 3 – area of loading a product, 4 – drawpieces with a product, 5 – station to unwind the top web, 6 – sealing head, 7 and 8 – sub-assembly to cut-out the package

Negative forming is accomplished in two steps (Fig. 2). First, due to evacuation of pressure from the forming chamber, the bottom web undergoes stretching, and next heating up. Under effect of pressure growth in the forming chamber, triggered off by aeration, the bottom web undergoes forming and reaches form of drawpiece, which shape depends on shape of negative mould.

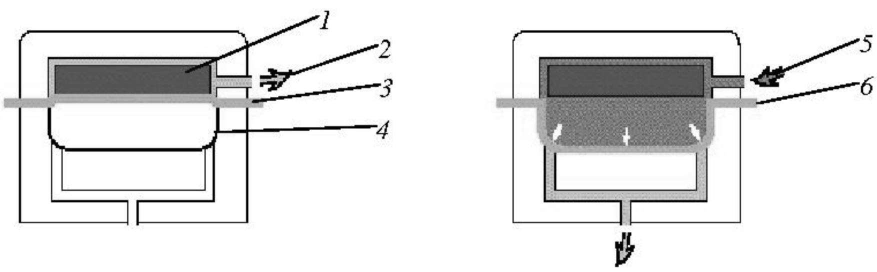

Fig. 2. Standard negative type forming [4]: 1 – heating head, 2 – evacuation of pressure from forming chamber, 3 – bottom web before forming, 4 – negative mould, 5 – aeration of forming chamber, 6 – drawpiece from bottom web

Sub-assembly of pressure evacuation and sealing of the bottom web with the top web is the next unit of the thermoformer. Vacuum pump, accomplishing process of pressure evacuation from inside of package is the main component of this unit. This process enables reduction of pressure value from ambient pressure (about 1013 hPa) to a value corresponding to final vacuum (about 10 hPa). Stages of evacuation process and sealing of formed bottom web with the top web are shown in the Fig. 3.

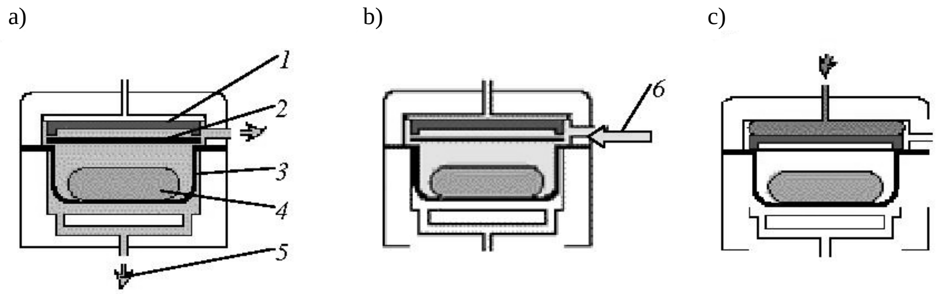

Fig 3. Stages of pressure evacuation and sealing of package [4]: a) evacuation of pressure from sealing chamber, b) dosing of gaseous blend, c) sealing of package; 1 – sealing head, 2 – top web, 3 – drawpiece from bottom web, 4 – packed product, 5 – air, 6 – gaseous blend

Investigation of the packaging in modified atmosphere was performed in form of active experiment, in industrial conditions, on a thermoforming machine of the MULTIVAC R7400 type. As a packed product was use one from a cured meat – “silesian” sausage. It was characterized by the same charge in technological sense, and by the same parameters of thermal processing of raw material, connected with production process. Mass of the product falling into unitary package amounted to 1000 g.

Process of the packaging took into consideration forming of the Peflex ANP 200 bottom web to shape of drawpiece (Fig. 2), bringing the sausage inside the drawpiece, evacuation of pressure from inside the package, dosing of Biogon C20 (20% CO_2 + 80% N_2) gaseous blend to the package, and closing with the Amilen 70 top web (Fig. 3).

During accomplishment of packaging process cycle τ_p it is possible to produce from one to three unitary packages, depending on their basic weight. The most often present situation is such when during a single packaging cycle are produced two unitary packages, each containing 1000 g of the product. In this case, productivity of the packaging process is calculated from the following equation:

$$W_p = \frac{3600 \cdot q}{\tau_p} \text{ [pcs/h]} \tag{1}$$

where: q – number of unitary packages, possible to be produced in course of packaging process, τ_p – lead time of packaging process cycle, s.

Measurement of duration of the packaging process was performed with use of stop-watch. Packaging process comprised operations starting from taking out the bottom web, to the last operation of lateral parting of the package. The experiment was run in a room with stable conditions of air humidity and temperature.

After 20 days from date of packaging, to determine tightness of the package one performed measurement of oxygen content with use of analyzer manufactured by WITT–GASETECHNIK.

Calculations connected with elaboration of measurement results were performed with use of the STATISTICA software [6]. Significance of regression coefficients was verified with use of the t-Student statistics. Verification of significance and adequacy of mathematical model was performed with use of the F-test [7]. In course of the active experiment, in each from configurations of the plan one used repeatability value of 3×.

3. Results of the experiment and their analysis

To reduce number of measurements and duration of the experiment one used multiple factor method, in which are determined simultaneous effects of selected parameters (set-ups) of thermoforming operation on productivity of the packaging process W_p, and tightness of the package expressed by content of oxygen in the package s_p. To model the packaging process was taken a mathematical model in form of second degree polynomial with dual interaction [8]:

$$z = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + \\ + b_{22} x_2^2 + b_{23} x_2 x_3 + b_{33} x_3^2 \tag{2}$$

where: z – productivity of packaging process W_p, pcs/h, or oxygen content in package s_p, %; x_1 – forming temperature t_f, ºC; x_2 – sealing temperature t_z, ºC; x_3 – value of final vacuum p_k, hPa; b_0, b_1, b_2, b_3, b_{11}, b_{12}, b_{13}, b_{22}, b_{23}, b_{33} – regression coefficients.

The experiment was performed according to statistic plan, determined, selective, multiple factor, orthogonal PS/DS–P: α [8-10], taking into account three input values. Basing on technical data of packaging films and taking into considerations specifics of packaging method of the product, one assumed the following ranges of input values:

- $x_1 = 85 \div 110$ºC,
- $x_2 = 130 \div 150$ºC,
- $x_3 = 7 \div 12$ hPa.

Ranges of packaging process parameters were determined on five levels (Table 1), according to coding scheme of input values, taking into considerations technical data of the packaging film.

Table 1. Levels and values of individual variables to accomplish the plan PS/DS–P: α [1,215/3×5]

Investigated factors	x_k	Δx_k	**Code (α = 1,215)**				
			– α	**–1**	**0**	**+1**	**+ α**
Forming temperature t_f, ºC	x_1	10,3	85	87	97,5	108	110
Sealing temperature t_z, ºC	x_2	8,2	130	132	140	148	150
Value of final vacuum p_k, hPa	x_3	2,1	7	7,5	9,5	11,5	12

Sequence of individual tests, used parameters of the packaging process and values of productivity of the packaging process W_p as well as value of oxygen content in the package s_p are compiled in the Table 2.

Performed with use of the Grubbs test [7] elimination of gross errors showed that measurement results of packaging productivity, determined by parameter W_p did not include any gross errors. Whereas, in case of oxygen content in the package, determined by parameter s_p, elimination of gross errors with the Grubbs test resulted in elimination of nine repetitions values from further calculations. Therefore, in further calculations of the s_p value one took into consideration reduced number of repetitions in a suitable systems of the plan. Implementing STATISTICA software package [6] and making use of the data listed in the Table 2, one calculated coefficients of regression: b_0, b_1, b_2, b_3, b_{11}, b_{12}, b_{13}, b_{22}, b_{23}, b_{33} considering adequate number of repetitions within individual systems of the experiment plan.

After insertion of calculated coefficients to the polynomial (2) one obtained the following forms of regression function:

- for productivity of the packaging process, expressed by parameter W_p,

$$W_p = -152{,}58805 - 17{,}30470\, t_f + 17{,}06573\, t_z + 0{,}04650\, p_k + \\ +0{,}08167\, t_f^{\,2} - 0{,}06112\, t_z^{\,2} + 0{,}07749\, p_k^{\,2} + 0{,}00096\, t_f t_z + \\ +0{,}03230\, t_f p_k - 0{,}02896\, t_z p_k \tag{3}$$

- for oxygen content, expressed by parameter s_p,

$$s_p = 21{,}68321 - 0{,}08661\, t_f - 0{,}25787\, t_z + 0{,}50094\, p_k + \\ +0{,}00056\, t_f^{\,2} + 0{,}00094\, t_z^{\,2} - 0{,}01799\, p_k^{\,2} - 0{,}00014\, t_f t_z - \\ -0{,}00048\, t_f p_k - 0{,}00083\, t_z p_k \tag{4}$$

Table 2. Scheme of accomplishment of the experiments and obtained measurement results of productivity of packaging process W_p and tightness of package s_p

Run	**Repetitions**	**Investigated factors**						t_p	**Resultant factors**			
									W_p, pcs/h		s_p, %	
		$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$	$x_1 = t_f$, °C	$x_2 = t_z$, °C	$x_3 = p_k$, hPa		$z = W_p$	$\bar{z} = \overline{W_p}$	$z = s_p$	$\bar{z} = \overline{s_p}$
1	1 2 3	–1	–1	–1	87	132	7,5	46,28 45,46 46,13	155,57 158,38 156,08	156,68	0,8 0,7 0,9	0,80
2	4 5 6	+1	–1	–1	108	132	7,5	52,69 54,12 53,29	136,65 133,04 135,11	134,93	0,7 0,8 0,9	0,80
3	7 8 9	–1	+1	–1	87	148	7,5	47,85 47,06 46,20	150,47 153,00 155,84	153,10	0,6 0,5 0,7	0,60
4	10 11 12	+1	+1	–1	108	148	7,5	54,68 55,13 53,32	131,68 130,60 135,03	132,44	0,6 0,6 0,5*	0,57
5	13 14 15	–1	–1	+1	87	132	11,5	45,56 45,09 46,39	158,03 159,68 155,21	157,64	0,8 0,8 0,7*	0,77
6	16 17 18	+1	–1	+1	108	132	11,5	51,39 52,46 51,16	140,11 137,25 140,73	139,36	0,8 0,8 0,9*	0,83
7	19 20 21	–1	+1	+1	87	148	11,5	46,54 47,65 47,03	154,71 151,10 153,09	152,97	0,6 0,6 0,5*	0,57
8	22 23 24	+1	+1	+1	108	148	11,5	54,28 52,69 53,94	132,65 136,65 133,48	134,26	0,6* 0,5 0,5	0,53
9	25 26 27	0	0	0	97,5	140	9,5	51,64 52,57 50,19	139,43 136,96 143,45	139,95	0,7 0,8* 0,7	0,73
10	28 29 30	–α	0	0	85	140	9,5	44,88 43,67 43,29	160,43 164,87 166,32	163,87	0,6 0,8 0,7	0,70
11	31 32 33	+α	0	0	110	140	9,5	50,68 50,12 52,46	142,07 143,66 137,25	140,99	0,8 0,7 0,6	0,70
12	34 35 36	0	–α	0	97,5	130	9,5	52,14 53,29 54,11	138,09 135,11 133,06	135,42	0,8* 0,9 0,9	0,87
13	37 38 39	0	+α	0	97,5	150	9,5	54,65 55,12 54,23	131,75 130,62 132,77	131,71	0,5 0,5 0,6*	0,53
14	40 41 42	0	0	–α	97,5	140	7	52,11 51,77 53,20	138,17 139,08 135,34	137,53	0,5 0,4 0,6	0,50
15	43 44 45	0	0	+α	97,5	140	12	50,20 51,13 49,95	143,43 140,82 144,14	142,80	0,6* 0,5 0,5	0,53

* – value eliminated from the calculations with use of Grubbs test

From statistical analysis of the regression equations (3) and (4) is seen that these equations are significant. Adequacy test on base of repetitions in systems of the experiment plan confirms adequacy of the both regression equations [5].

Next, there were evaluated extrema for the both equations of complete models (3) and (4), making use of Newton's numeric method. Extremum (in this case maximum) for regression function described by the equation (3), was confirmed for the following combination of the investigated factors: $x_1 = t_f =$ 85,00ºC, $x_2 = t_z =$ 137,43ºC and $x_3 = p_k =$ 12,00 hPa, and amounted to:

$$W_p\left(t_f, t_z, p_k\right)_{\max} = 165{,}64 \approx 165 \text{ pcs/h} \tag{5}$$

Whereas, extremum (in this case minimum) for regression function described by the equation (4), was confirmed for the following combination of the investigated factors: $x_1 = t_f =$ 100,59ºC, $x_2 = t_z =$ 149,64ºC and $x_3 = p_k =$ 12,00 hPa, and amounted to:

$$s_p\left(t_f, t_z, p_k\right)_{\min} = 0{,}41748\% \approx 0{,}42\% \tag{6}$$

For instance, in the Table 3 is shown statistic analysis of the regression equation (3). In result of performed verification of significance of equation coefficients (3) it was evident that the following coefficients: b_0, b_3, b_{33}, b_{12}, b_{13} and b_{23} are insignificant. The lowest values of the t-Student testing function occurred for the coefficient b_3, and next for the b_{12}, b_{33}, b_0, b_{23} and b_{13}, and what is why the elimination commenced from elimination of component with the coefficient b_3 from the regression equation (3).

After elimination of components with insignificant coefficients: b_3, b_{12}, b_{33} and b_{23} the equation (3) became significant and adequate, and took the following form:

$$\begin{aligned} W_p = -163{,}43436 - 16{,}92008 \cdot t_f + 16{,}95804 \cdot t_z + 0{,}08165 \cdot t_f^2 - \\ 0{,}06139 \cdot t_z^2 + 0{,}00651 \cdot t_f \cdot p_k \end{aligned} \tag{7}$$

Statistical analysis of the equation (7), i.e. after elimination of all components having insignificant coefficients, except the free term, are listed in the Table 4. The free term was left in the equation, because from the measurement data is evident that origin of coordinates (0; 0; 0; 0) does not lie in scope of the investigations of packaging process.

Table 3. Statistical analysis of regression equation (3)

Type of estimation	Number of degrees of freedom	Critical value of the test	Value of the test	Verification of hypothesis
Significance of the whole regression equation (*F Snedecor* test)	$f_1 = N_b - 1 = 10 - 1 = 9$ $f_2 = p_d - N_b = 45 - 10 = 35$	$F_{0,05;9;35} = 2{,}161$	$F_c = 102{,}41$	$F_c > F_{0,05;9;35}$ regression equation is significant
Approximation errors			$R^2 = 0{,}9634$	$e_b = 2{,}227$ (1,55%)
Adequacy of the model (*F Snedecor* test)	$f_1 = n_d - N_b = 15 - 10 = 5$ $f_2 = \sum_{u=1}^{n_d} (r_u - 1) = 30$	$F_{0,05;5;30} = 2{,}534$	$F = 0{,}187$	$F < F_{0,05;5;30}$ model is adequate
Significance of regression coefficients (*t Student* test)	$f_1 = \sum_{u=1}^{n_d} r_u - N_b = 45 - 10 = 35$	$t_{0,05;35} = 2{,}030$	$t(b_0) = 0{,}725$	$t(b_0) < t_{0,05;35}$ insignificant
			$t(b_1) = 12{,}718$	$t(b_1) > t_{0,05;35}$ significant
			$t(b_2) = 6{,}358$	$t(b_2) > t_{0,05;35}$ significant
			$t(b_3) = 0{,}009$	$t(b_3) < t_{0,05;35}$ insignificant
			$t(b_{11}) = 14{,}338$	$t(b_{11}) > t_{0,05;35}$ significant
			$t(b_{22}) = 6{,}539$	$t(b_{22}) > t_{0,05;35}$ significant
			$t(b_{33}) = 0{,}518$	$t(b_{33}) < t_{0,05;35}$ insignificant
			$t(b_{12}) = 0{,}178$	$t(b_{12}) < t_{0,05;35}$ insignificant
			$t(b_{13}) = 1{,}492$	$t(b_{13}) < t_{0,05;35}$ insignificant
			$t(b_{23}) = 1{,}019$	$t(b_{23}) < t_{0,05;35}$ insignificant

Next, there was evaluated extremum for the regression equation (7) making use, as in the previous case, from the Newton's numeric method. The extremum (in this case minimum) for the regression function described by the equation (7), was confirmed for the following combination of the investigated factors: $x_1 = t_f = 85{,}00$ºC, $x_2 = t_z = 138{,}13$ºC and $x_3 = p_k = 12{,}00$ hPa, and amounted to:

$$W_p\left(t_f, t_z, p_k\right)_{\max} = 166{,}06 \approx 166 \text{ pcs/h} \tag{8}$$

Table 4. Statistical analysis of regression equation (5)

Type of estimation	**Number of degrees of freedom**	**Critical value of the test**	**Value of the test**	**Verification of hypothesis**
Significance of the whole regression equation (*F Snedecor* test)	$f_1 = N_b - 1 =$ $= 6 - 1 = 5$ $f_2 = p_d - N_b =$ $= 45 - 6 = 39$	$F_{0,05;5;39} = 2,456$	$F_c = 189,77$	$F_c > F_{0,05;4;39}$ regression equation is significant
Approximation errors			$R^2 = 0,9605$	$e_b = 2,191$ (1,52%)
Adequacy of the model (*F Snedecor* test)	$f_1 = n_d - N_b =$ $= 5 - 6 = 9$ $f_2 = \sum_{u=1}^{n_d} (r_u - 1) = 30$	$F_{0,05;9;30} =$ 2,211	$F = 0,378$	$F < F_{0,05;9;30}$ model is adequate
Significance of regression coefficients (*t Student* test)	$f_1 = \sum_{u=1}^{n_d} r_u - N_b =$ $= 45 - 6 = 39$	$t_{0,05;39} =$ 2,023	$t(b_0) = 0,870$	$t(b_1) < t_{0,05;39}$ insignificant
			$t(b_1) = 15,468$	$t(b_1) > t_{0,05;39}$ significant
			$t(b_2) = 6,592$	$t(b_2) > t_{0,05;39}$ significant
			$t(b_{11}) = 14,565$	$t(b_{11}) > t_{0,05;39}$ significant
			$t(b_{22}) = 6,683$	$t(b_{22}) > t_{0,05;39}$ significant
			$t(b_{13}) = 3,362$	$t(b_{13}) > t_{0,05;39}$ significant

The dependence (7) for the optimal value of the forming temperature $t_f = 85^oC$ was shown with use of spatial diagram (Fig. 4).

Due to fact, that assumed mathematic models take into considerations three independent variables: forming temperature t_f, sealing temperature t_z and value of final vacuum p_k, the diagrams: spatial and contour lines one, were drawn for two variables with fixed third variable (Fig. 5).

Statistical analysis of the regression equation (4), illustrating dependence of $s_p = f(t_f, t_z, p_k)$, was performed in analogical way as in case of the dependence $W_p = f(t_f, t_z, p_k)$.

In result of performed verification of significance of coefficients from the equation (4), was proved that insignificant coefficients are: b_1, b_{12}, b_{13} and b_{23}. The lowest value of the t-Student testing value was present for the coefficient b_{13}, and next for the b_{12}, b_{23} and b_1, and therefore the elimination was commenced from elimination from regression equation (4) of a component with the coefficient b_{13}. After elimination of all components with insignificant coefficients, the equation (4) became significant and adequate, and took the following form:

$$s_p = 25,00972 - 0,11031 \cdot t_f - 0,27817 \cdot t_z + 0,33879 \cdot p_k + \\ +0,00056 \cdot t_f^2 + 0,00094 \cdot t_z^2 - 0,01804 \cdot p_k^2 \tag{9}$$

Next, one calculated extremum for the equation (9), using the Newton's numerical method. The extremum (in this case minimum) was found for the following combination of the investigated factors: $x_1 = t_f = 98,23$ºC, $x_2 = t_z = 148,24$ºC and $x_3 = p_k = 12,00$ hPa, and amounted to:

$$s_p \left(t_f, t_z, p_k \right)_{\min} = 0,4427\% \approx 0,44\% \tag{10}$$

For the regression function after elimination of components having insignificant coefficients and described by equation (9) there were plotted diagrams: spatial (Fig. 6) and with contour lines (Fig. 7) for optimal value of the final vacuum $p_k = 12,00$ hPa.

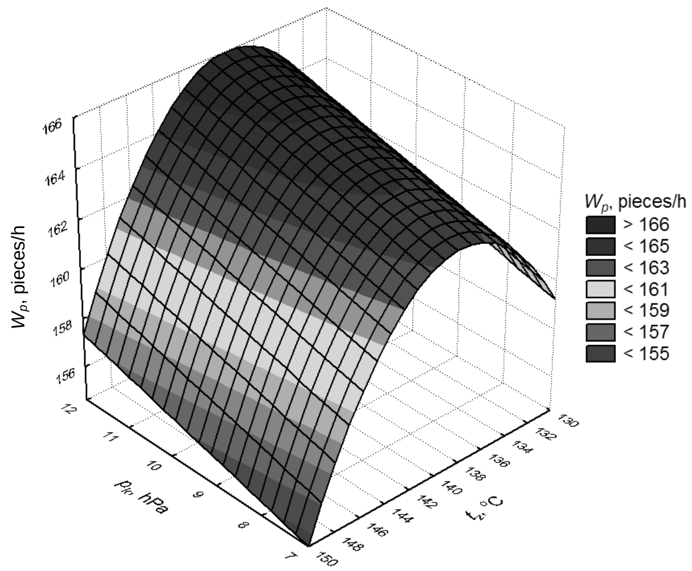

Fig. 4. Spatial diagram illustrating effect of sealing temperature t_z and value of final vacuum p_k, on productivity of packaging process, expressed by parameter W_p, for optimal value of forming temperature $t_f = 85$ºC

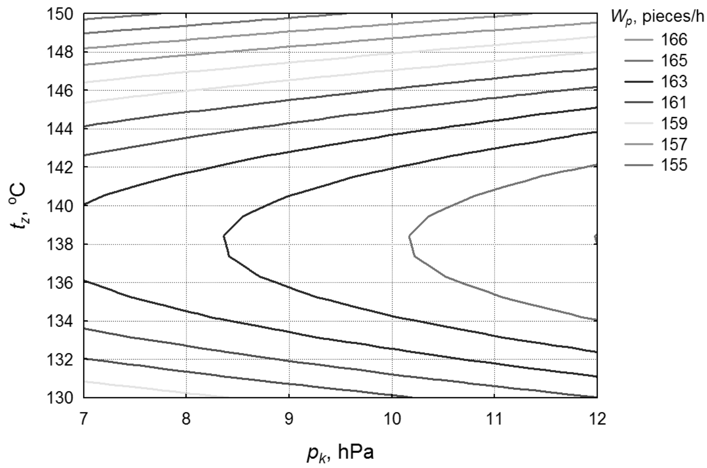

Fig. 5. Contour lines diagram illustrating effect of sealing temperature t_z and value of final vacuum p_k, on productivity of packaging process, determined by parameter W_p, for optimal value of forming temperature t_f = 85ºC

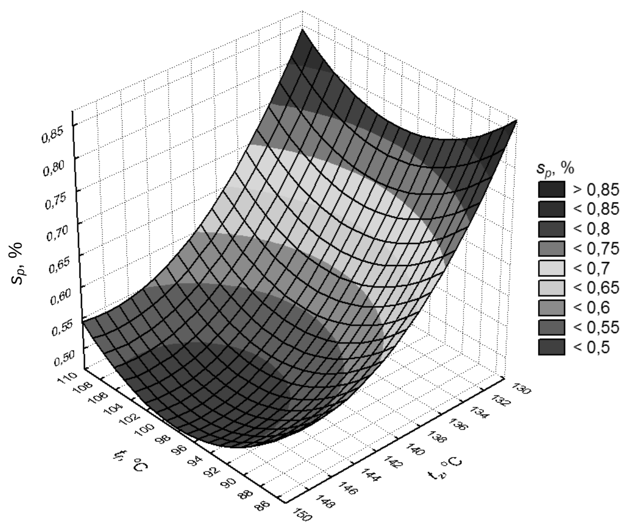

Fig. 6. Spatial diagram illustrating effect of sealing temperature t_z and forming temperature t_f, on oxygen content in package, described by parameter s_p, for optimal value of final vacuum p_k = 12 hPa

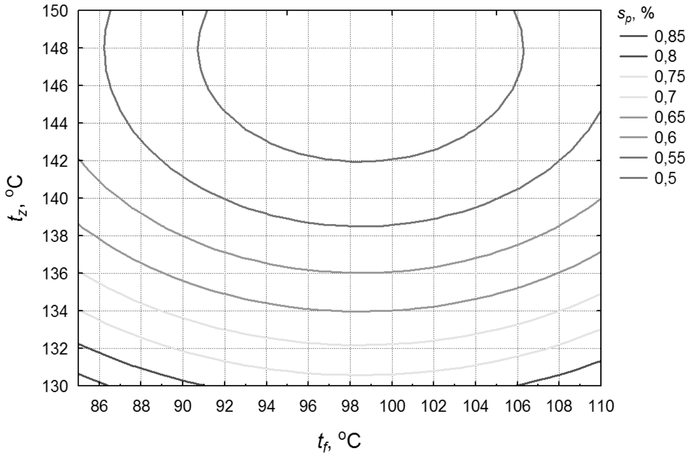

Fig. 7. Contour lines diagram illustrating effect of sealing temperature t_z and forming temperature t_f, on oxygen content in package, determined by parameter s_p, for optimal value of final vacuum p_k = 12 hPa

To evaluate set of optimal variants in Pareto meaning [11, 12], with respect to two above criteria, that is productivity of packaging process W_p and tightness of package s_p, one made use of normalized method of weights [12], changing values of weights every 0,05. To constructed in such way problem of single-criterion optimization one assumed the following form of substitute criterion:

$$k = w_1 \cdot \frac{W_p}{W_p^0} - w_2 \cdot \frac{s_p}{s_p^0} \rightarrow \max \tag{11}$$

where: $w_1 + w_2 = 1$, and W_p^0, s_p^0 are values of optimal optimization criteria.

Generation of the set of non-dominated variants was made with use of numerical method with consideration of constraints connected with the packaging process:

- forming temperature: t_f = 85÷110ºC,
- sealing temperature: t_z = 130÷150ºC,
- value of final vacuum: p_k = 7÷12 hPa.

In result, one obtained Pareto set comprising 21 non-dominated solutions (Fig. 8, Table 5). To select optimal variant from the Pareto set [11, 12] one used method of hierarchical optimization [12]. Due to necessity of protective function of the package (assurance of freshness date of packed product), oxygen content in package s_p was assumed as dominant criterion in the method. Hence, set of dominated solutions was sorted out with respect to s_p, and next value of deviation of a given criterion from optimal solution was assumed on the level of

7% (marked with grey color part of column in the Table 5). The best solution with respect to the both criteria: W_p = 142,2 pcs/h and s_p = 0,481%, occurred for the following combination of thermoforming operational parameters: forming temperature t_f = 93,8ºC; sealing temperature t_z = 146,2ºC and value of final vacuum p_k = 12 hPa.

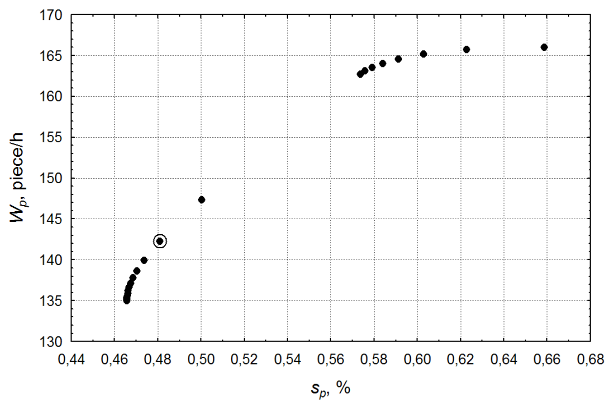

Fig. 8. Set of non-dominated solutions generated with use of method of weights

Table 5. Set of non-dominated solutions generated with use of method of weights

No.	**Set-up of device parameters**			**Assessment criteria**	
	t_f, °C	**t_z, °C**	**p_k, hPa**	**W_p, pcs/h**	**s_p, %**
1	98,5	148,0	12	135,0	0,466
2	98,4	147,9	12	135,2	0,466
3	98,3	147,8	12	135,4	0,466
4	98,1	147,7	12	135,6	0,466
5	98,0	147,5	12	135,9	0,466
6	97,8	147,4	12	136,2	0,466
7	97,5	147,2	12	136,6	0,467
8	97,2	147,1	12	137,1	0,467
9	96,7	146,9	12	137,8	0,469
10	96,2	146,7	12	138,6	0,470
11	95,3	146,4	12	140,0	0,474
12	93,8	146,2	12	142,2	0,481
13	91,1	145,8	12	147,3	0,500
14	85,0	145,5	12	162,7	0,574
15	85,0	145,0	12	163,1	0,576
16	85,0	144,5	12	163,5	0,579
17	85,0	143,8	12	164,0	0,584
18	85,0	142,9	12	164,6	0,591
19	85,0	141,8	12	165,2	0,603
20	85,0	140,3	12	165,7	0,623
21	85,0	138,1	12	166,0	0,659

4. Conclusions

On base of performed investigations of the packaging process of cured meat products in modified atmosphere of the thermoformer one has confirmed that:

- the highest productivity of the packaging process W_p = 166 pcs/h was obtained for the following combination of operational parameters (set-ups): forming temperature t_f = 85ºC, sealing temperature t_z = 138,13ºC and final vacuum value p_k = 12 hPa,
- the lowest oxygen content in the package s_p = 0,42% was obtained for the following combination of set-up parameters: t_f = 100,59ºC, t_z = 149,64ºC and p_k = 12,00 hPa,
- the best solution with respect to the both criteria: W_p = 142 pcs/h and s_p = 0,481%, assuming value of oxygen content deviation in the package s_p on the level of 7% from optimal solution, occurred for the following combination of operational parameters: t_f = 93,8ºC, t_z = 146,2ºC and p_k = 12,00 hPa.

Elimination of components with insignificant coefficients from the regression function for complete models caused slight differences in values of the extremum (in case of productivity the difference amounted to about 0,42 pcs/h, whereas in case of the second criterion, i.e. oxygen content in the package, the difference was considerably higher and amounted to about 0,0252%). It resulted from accuracy of assumed model of the regression. Standard error of estimation for the models describing productivity of packaging process was included in the interval of 1,55÷1,52%, whereas for the models describing oxygen content in the package was more than 7 times higher and amounted to 11,44÷11,09%.

Optimization of the packaging process of food products (cured meat) on thermoforming machine installed in a meat processing plant, performed with respect to two criteria: productivity of packaging process W_p and tightness of the package s_p enables selection of optimal parameters (set-ups) of the packaging device, and in effect bring to preserve required protection and quality level of packed product with simultaneous rationalization of costs of the packaging process.

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