Implicitly defined criteria for vector optimization in technological process of hydroponic germination of wheat grain

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Abstract. To reduce the duration of the process and to ensure the microbiological purity of the germinated material, an improved method of germination has been developed based on the complex use of physical factors: electrochemically activated water (ECHA-water), electromagnetic field of extremely low frequencies (EMF ELF) with round-the-clock artificial illumination by LED lamps. The increase in the efficiency of the "numerical" technology for solving computational problems of parametric optimization of the technological process of hydroponic germination of wheat grains is considered. In this situation, the quality criteria are contradictory and part of them is given by implicit functions of many variables. A solution algorithm is offered without the construction of a Pareto set in which a relatively small number of elements of a set of alternatives is used to obtain a linear convolution of the criteria with given weights, normalized to their "ideal" values from the solution of the problems of single-criterion private optimizations. The use of the proposed mathematical models describing the processes of hydroponic germination of wheat grains made it possible to intensify the germination process and to shorten the time of obtaining wheat sprouts “Altayskaya 105” for 27 hours.

1. Introduction
The development of computer-aided design processes (CAPP) is aimed at reducing the labor intensity and cost of technological preparation of production by designing optimal technological processes for any criteria. The mathematical support of the CAPP parametric optimization subsystem is most often based on mathematical programming and the theory of vector optimization [1]. The choice of a specific method must be related to the peculiarities of the problem being solved, since a method successful for solving one of them can be unsuccessful for solving others. The difficulties can be related to the assignment of an operator describing the topology of the system under study: the operator is specified not in explicit but in algorithmic form, in particular, through numerical solutions of systems of equations (differential or algebraic) describing the functioning of the system under investigation [2]. It is possible to have a set of criteria not only contradictory to each other, but also set not analytically, i.e. in the form of rules that have both formal and non-formal character. There are known developments of interactive procedures for multicriteria selection; research of the structure of preferences of PR using typical generalizing functions [3, 4].
In this paper, an increase in the efficiency of the "numerical" technology for solving computational problems of parametric optimization of the technological process of hydroponic germination of wheat grains is considered. In this situation, the quality criteria are contradictory and some of them are given by implicit functions of many variables.

In order to shorten the duration of the process and to ensure the microbiological purity of the germinated material, there is an improved germination method based on the combined use of physical factors: electrochemically activated water (ECHA-water), electromagnetic field of extremely low frequencies (EMF ELF) with 24 hour artificial illumination by LED lamps [5-7].

The goal of optimization for the process of wheat germination was to shorten the duration of process T and improve the quality of the product, depending on the type and grade composition of the wheat, the processing of the material by electromagnetic fields, etc. The objective function along with the minimization of the duration of process T was to minimize the length of roots LK. The allowed set was set by limitations on the length of the LR seedlings; the desired factor was the pH of the aqueous medium.

2. Materials and methods
An essential factor restraining the mass use of products from wheat germinated in the population's nutrition is the lack of well-founded germination technologies adapted for public catering establishments. For the germination of grain, a sufficient amount of moisture, aeration and optimum temperature is necessary. An effective solution of the problem is the development of technology for germination of wheat grain hydroponically in which growing seeds are carried out on artificial porous moisture- and air-intensive environments [5, 6]. This technology allows one to significantly reduce the production area, but does not affect the time costs for obtaining seedlings of wheat. In order to shorten the duration of the process and to ensure the microbiological purity of the germinated material, the authors propose an improved germination method based on the combined use of the above-mentioned physical factors.

Wheat spring soft varieties "Altaiskaya 105" and "Polba Runo", the 2015-2016 crops were used as research objects. The grain of both varieties was subjected to soaking and germination under the same conditions under different physical factors: medium - water with pH 7,7 and ECHA water (anolyte – with a pH of 3,5 to 6,5 and catholyte with a pH of 8 to 10, 8); round-the-clock artificial lighting with LED lamps (red – 660 nm, blue – 430 nm, infrared – 730 nm); an ambient temperature range of 20-22 °C; treatment of germinated material after soaking EMF ELF (frequency – 20 Hz, current strength – 10 A, duration – 20 minutes).

The process of germination is divided into the stage of preparation of the material and germination itself. For germination, a constant supply of water to the grain is necessary. At the same time, the moisture content in the grain increases from about 12 % to 44 %. Water penetrates into cells of grain tissues not only under the influence of physical laws but also biological forces manifested in the action of thin cellular mechanisms regulating the flow of water into and out of the cell. Absorbed water is included in the biological metabolism in the cell leading to a dynamic change in the physical, chemical and technological properties of the grain.

To produce juice from wheat germs, the germination of the grain was carried out until the stem length of the plant was reached from 12 to 15 cm. Further increase in the length of the sprout is not advisable, which is associated with a change in the structure of the plant cell and a decrease in the content of cell sap, and, therefore, leads to a decrease in the yield of the product during compaction and increased losses.

Traditionally, wheat seeds are germinated to produce sprouts of the required length for 144 hours. During the experiment, after a certain period of time, the length of the primary organs (seedlings and roots) of the wheat grain was determined, depending on the conditions of its germination.

To determine the optimal technological regimes of germination of wheat grain, statistical processing was used by means of the package Statistica v.10 combining all available data (typical and high-quality wheat composition, pH of the aquatic environment, electromagnetic processing of the
material) and presenting them in a visual graphical form describing an adequate reaction grain of wheat to change the main factors that limit the development of primary organs. For the germination of wheat grain, the length of sprouts and the length of the roots is a response in the visual analysis of the interpolation surface, and the sprouting time T and the pH of the aqueous medium are independent variables. It was found that the goals of minimizing T and minimizing LK in this case are contradictory. By changing pH, root growth can be inhibited with weaker suppression of wheat seedlings, which allows us to reach the required lengths of LR_{min} seedlings by increasing the process time.

To optimize the germination process, it is necessary to use conflicting objective functions: along with the implicit LR_{min}=LR(T, pH) time T(pH)→min, the root length LK(T,pH)→min, on the admissible set under natural restrictions T≥0, pH≥0.

The first step in the optimization of the technological process was the construction of bicubic interpolation splines of defect 1 for the LR (T, pH) and LK (T, pH) functions given in a tabular form, with interpolation nodes in the experimental data averaged over 3 replicas. The LR(T, pH) and LK(T, pH) functions were also approximated by regression models, using the Statistica v.10 package. Limitations of LR_{min} on the length of germs of wheat grain gave the equation of the relationship of T to pH as implicit function LR_{min}=LR(T, pH).

It is required to determine minimum soak time T_{min} and pH_{min} of the aquatic environment at which the wheat grain gives sprouts of given length LR_{min} reaching minimum possible root length LK_{min}.

In this situation, the construction of LR(T, pH) and LK(T, pH) level lines allows solving the specified optimization problem graphically using the Statistica v.10 package: the vertical straight lines of the desired T must touch or cross the level line LR_{min}=LR(T,pH) and touch the LK_{min}=LK(T,pH) level lines, where LK_{min} is selected by the expert technologist as a compromise value, and the horizontal line from the point of contact will give the desired pH value. But with a possible increase in the number of arguments (accounting for the hydromodule, EMF ELF parameters, current strength, frequency, exposure time, etc.), i.e. with the number of arguments more than 2 this graphical method loses all its advantages.

In this paper, let us consider a formal algorithm for solving this optimization problem, implemented by means of the MathCAD v.15 package, which gives matching (within the accuracy of regression) results with a graphical method.

3. Regression analysis of dependencies of the root length and length of the sprout versus time and alkalinity of water

Regression models LR(T, pH) and LK(T, pH) for the available experimental data are chosen as a product of a second-degree polynomial in variable pH by a monotonically increasing function at zero with saturation, exponential in variable T (sprouting time).

The obtained parameters of the regression model for wheat "Altaiskaya 105" with germination in ECHA water give the dependence, mm:

\[ LR = (49,3646 + 58,4976pH - 4,1285pH^2) \cdot (1 - e^{-0.902e^{-5pH^{2.30974}}}) \]  \hspace{1cm} (1)

and correlation index R = 0,95;

\[ LK = (13,5127 + 27,5435pH - 1,8062pH^2) \cdot (1 - e^{-0.676e^{-4pH^{1.94722}}}) \]  \hspace{1cm} (2)

with a correlation index of R = 0,9;

and for wheat "Altayskaya 105" with germination in ECHA water and EMF ELF treatment, mm:

\[ LR = (28,2615 + 111,931pH - 7,3166pH^2) \cdot (1 - e^{-0.266e^{-4pH^{1.96125}}}) \]  \hspace{1cm} (3)

and correlation index R = 0,97;

\[ LK = (13,8432 + 37,8703pH - 2,5819pH^2) \cdot (1 - e^{-0.394e^{-4pH^{2.02337}}}) \]  \hspace{1cm} (4)
with a correlation index of \( R = 0.86 \).

For "Polby Runo" sprouting in ECHA water gives a dependence, mm:

\[
LR = (41,6096 + 74,3114pH - 4,4328pH^2) \cdot (1 - e^{-0.182e^{-4T^{2,02619}}})
\]

and correlation index \( R = 0.97 \);

\[
LK = (17,501 + 21,5838pH - 1A07pH^2) \cdot (1 - e^{-0.918e^{-5T^{2,41374}}})
\]

and correlation index \( R = 0.89 \);

and for "Polby Runo", when germinating in ECHA water and EMF ELF treatment, mm:

\[
LR = (15,7373 + 86,5843pH - 5,2542pH^2) \cdot (1 - e^{-0.168e^{-4T^{2,0781}}})
\]

and correlation index \( R =0.98 \);

\[
LK = (14,0756 + 33,9264pH - 2,5879pH^2) \cdot (1 - e^{-0.110e^{-4T^{2,3288}}})
\]

and correlation index \( R = 0.87 \).

The relative error (1)-(8) is 20 %.

4. Minimizing the soaking time to reach 120 mm of the length of the sprout, minimizing the root length and solving the two-criterion problem

The choice of the best solution from the allowed set of variants assumes a certain rule for comparing possible alternatives. A formal solution of the formulated problem usually takes the Pareto set: a set of "effective" points not dominated by the Pareto binary relation. One considers Pareto sets both in the space of alternatives and in the space of vector estimates. In practice, the choice should often be limited to one element or a small number of "best" or "acceptable" solutions. There are various classes of methods of "narrowing" the Pareto set and all of them are based on the attraction of additional subjective information about the characteristics of the sought solution. In the absence of such explicitly or implicitly used information, nothing is possible except for the Pareto set as an objective solution.

The methods of multicriteria selection based on the additional information of the expert-techologist (ET) can be conditionally divided into three classes: methods of direct scaling, methods of the theory of utility and search methods of multicriteria choice. In this paper, to obtain a relatively small number of elements of a set of alternatives that can be perceived by ET as acceptable solutions without constructing the Pareto set, a linear convolution of the criteria with given weights normalized to their "ideal" values from the solution of the problems of one-criterion private optimizations. Relations (1), (3), (5), (7) give implicitly defined objective function \( LR_{\min} = LR(T, pH) \), \( LR_{\min} = 120 \text{ mm} \), where \( T(pH) \rightarrow \min \), under natural constraints \( 0 \leq T \) and \( 0 \leq pH \). It is necessary to find the global minimum, point \( (T_{\min}, pH_{\min}) \) on the allowed set - domain \( 0 \leq T \) and \( 0 \leq pH \).

A well-known algorithm assumes: 1 – search for stationary points (inside the domain) of each objective function; 2 – search for stationary points (on the boundary of the domain) of each Lagrange function; 3 – calculating the values of the objective functions in all the found "suspicious" points; 4 – calculation of the "ideal point" from \( (T_{\min}, LK_{\min}) \) by selecting the solution by increasing the calculated values; 5 – linear convolution of the criteria in minimizing the scalar, with equal weights having form \( J(pH) = \frac{T(pH)}{T_{\min}} + \frac{LK(pH)}{LK_{\min}} \rightarrow \min \); 6 – search for stationary points (inside the domain) of the objective function \( J \); 7 – search for stationary points (on the boundary of the domain) of the Lagrange function for \( J \); 8 – calculation of the values of objective function \( J \) in all the found "suspicious" points; 9 – obtaining \( (T_{\min}, LK_{\min}) \) and \( pH_{\min} \) by selecting the solution by increasing the calculated values.
The steps of this algorithm in this case are as follows. (The expressions for LR(T, pH) and LK(T, pH) are indicated in (1)-(8)).

1 – the search for stationary points (inside the domain) of objective function T (pH) is carried out from the system of algebraic equations and inequalities:

\[ \frac{dT_{dpH}}{dT} (T, pH) = \frac{dT_{dpH}}{dLR(T, pH)} = 0, \quad LR(T, pH) = 120, T \geq 0, \quad pH \geq 0. \quad (9) \]

2 – the search for stationary points (on the boundary of the domain) of the Lagrange function for T (pH) is carried out from the system of algebraic equations:

\[ dT_{dpH}(T, pH) + \lambda = 0, \quad LR(T, pH) = 120, \quad pH = 0. \quad (10) \]

where \( \lambda \) is the required Lagrange multiplier.

3 – calculation of the values of objective function T in all the found "suspicious" points (T\(_{min}\), pH\(_{min}\), \( \lambda \)) has already been performed in the process of solving (9) and (10). For objective function LK(T,pH)\( \rightarrow \)min, it is necessary to solve the mathematical programming problem by a known method:

\[ LK(T, pH) \rightarrow \min, LR(T, pH) \geq LR_{min}, T \geq 0, \quad pH \geq 0. \quad (11) \]

4 – calculation of the "ideal point" from (T\(_{min}\), LK\(_{min}\)) is done in 2 steps.

At the first step it is necessary to find T\(_{min}\) by selecting the solution by ranking by increasing the calculated values according to (9)-(10): for wheat "Altayskaya 105" with germination in ECHA-water pH = 7.1; T = 125 h; LR = 12 cm, LK = 6.6 cm; for wheat "Altayskaya 105" with germination in ECHA-water and EMF ELF treatment pH = 7.6; T = 117 h; LR = 12 cm; LK = 7 cm; for "Polby Runo" when germinating in ECHA-water pH = 8.4; T = 141 h; LR = 12 cm; LK = 7.6 cm; for "Polby Runo" when germinating in ECHA-water and EMF ELF treatment pH = 8.24; T = 125 h; LR = 12 cm; LK = 7 cm.

At the second step it is necessary to find LK\(_{min}\) from (11) the corresponding operator of the package MathCAD v.15: for wheat "Altayskaya 105" - with germination in ECHA-water pH = 1.34; T = 324 h; LR = 12 cm, LK = 4.76 cm; for wheat "Altayskaya 105" - with germination in ECHA-water and EMF ELF treatment pH = 14; T = 1295 h; LR = 12 cm; LK = 2.27 cm; for "Polby Runo" - when germinating in ECHA-water pH = 15; T = 1095 h; LR = 12 cm; LK = 1.1 cm; for "Polby Runo" - when germinating in ECHA-water and EMF ELF treatment pH = 13.5; T = 173 h; LR = 12 cm; LK = 0 cm.

Thus, the "ideal points" are (T\(_{min}\), LK\(_{min}\)) for wheat "Altayskaya 105" with germination in ECHA-water (125 h; 4.7 cm); for wheat "Altayskaya 105" with germination in ECHA-water and EMF ELF treatment (117 h, 2.27 cm); for "Polby Runo" when germinating in ECHA-water (141 h, 1.1 cm); for "Polby Runo" when germinating in ECHA-water and EMF ELF treatment (125 h, 0 cm).

6 – the search for stationary points (inside the domain) of scalar objective function J is carried out from the system of algebraic equations and inequalities:

\[ \frac{1}{T_{min}} \frac{dLR(T,pH)}{dpH} + \frac{1}{LK_{min}} \left( \frac{dLR(T,pH)}{dT} \frac{dLK(T,pH)}{dpH} + \frac{dLK(T,pH)}{dT} \right) = 0, \quad LR(T, pH) \geq LR_{min}, T \geq 0, \quad pH \geq 0. \quad (12) \]

7 – the search for stationary points (on the boundary of the domain) of the Lagrange function for J is realized from the system of algebraic equations:
\[ \frac{1}{T_{\min}} \frac{dL(T, pH)}{dpH} \bigg|_{T=T_{\min}} + \frac{1}{L_{K_{\min}}} \left( \frac{dL(T, pH)}{dpH} \bigg|_{T=T_{\min}} - \frac{\partial LK(T, pH)}{\partial T} \bigg|_{T=T_{\min}} + \frac{dLK(T, pH)}{dpH} \right) + \mu = 0, L_R(T, pH) = L_{R_{\min}}, pH = 0, \]

(13)

where \( \mu \) is the required Lagrange multiplier.

8 – calculation of the values of objective function \( J \) in all the found "suspicious" points \( (T_{\min}, pH_{\min}, \mu) \) already produced in the process of solving (12) and (13).

9 – obtaining \( (T_{\min}, L_{K_{\min}}) \) by selecting the solution by increasing the calculated values.

5. Conclusion

To reduce the duration of the process and to ensure the microbiological purity of the germinated material, an improved method of germination has been developed based on the complex use of physical factors: electrochemically activated water (ECHA-water), electromagnetic field of extremely low frequencies (EMF ELF) with the 24-hour artificial illumination by LED lamps.

The increase in the efficiency of the "numerical" technology for solving computational problems of parametric optimization of the technological process of hydroponic germination of wheat grains was considered. In this situation, the quality criteria are inconsistent, and some of them are given by implicit functions of many variables. The objective function along with the minimization of the duration of the process \( T \) was to minimize the length of the roots \( L_K \). The allowed set was set by limitations on the length of the LR seedlings; the desired factor was the pH of the aqueous medium. A solution algorithm is proposed, in which a linear convolution of the criteria with given weights normalized to their "ideal" values from the solution of the problems of one-criterion private optimizations is applied to obtain a relatively small number of elements of a set of alternatives, without constructing the Pareto set.

A formal algorithm for solving the specified optimization problem is proposed, implemented by means of the packages Statistica v.10 and MathCAD v.15.

The use of the proposed mathematical models describing the processes of hydroponic germination of wheat grains made it possible to establish that the use of ECHA-water as a medium and pre-treatment of the material by EMF ELF and the 24-hour artificial illumination by LED lamps contribute to the intensification of the germination process and to shorten the time of obtaining wheat sprouts “Altaiskaya 105” for 27 hours.

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