

ABOUT A «DIGITAL TWIN» OF A FOOD PRODUCT

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Key words: *digital twin, simulation model, chemical composition, functional-technological properties, food product*

Abstract

The paper presents definitions of digital twins. The authors examine a hypothesis that a digital twin of a food product is a mathematical (simulation) model that includes the whole variety of factors influencing quality and safety. An approach to the mathematical setting of the structural optimization task at different stages of description of the technology for a food product digital twin is analyzed. The first stage, which has several levels, is connected with correspondence of the nutritional and biological values to the medico-biological requirements. The second stage is linked with predetermination of structural forms, the third with perception of sensory characteristics (color, odor and so on). The universal method for assessment of quality and efficiency of a food product digital twin using the generalized function (integral index) is described. Different individual responses can be components of the additive integral index: physico-chemical, functional-technological and organoleptic.

Introduction

The term digital twin appeared in 2003 in the framework of the Course on Product Lifecycle Management (PLM) in Florida Institute of Technology (<https://www.fit.edu/>) [1].

Over the last decade, many definitions of a digital twin have appeared. The most widespread definitions are given in [2]:

- 1) A digital twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system, which uses the best available physical models, sensor updates, history and so on [3];
- 2) A joint model of a real machine, which works on the cloud platform and simulate the health condition with integrated knowledge both from manageable data of analytical algorithms and from other available physical knowledge [4];
- 3) A digital twin is a digital replication of a living or non-living physical entity. Combining physical and virtual worlds, data are transformed unnoticeably allowing a virtual entity to exist simultaneously with a physical entity [5];
- 4) The use of digital replication of a physical system for real-time optimization [6];
- 5) A dynamic virtual representation of a physical object or system throughout the life cycle using real-time data for understanding, learning and reasoning [7];
- 6) A digital twin is a real mapping of all components in the product life cycle using physical data, virtual data and data of their interaction [8].

A digital twin has been introduced in the KAMAZ sites. KAMAZ has already created the 3D models of 28 units of machine tools with CNC and 20 universal machine tools as well as more than 50 units of different technological equipment (robots, manipulators, turn-over devices, roller tables). The 3D models are used in simulation of mechanical processing and assembly as well as for arrangement of equipment in the 3D plant design.

Digital copies came into use for effective operation of trains Sapsan and Lastochka. Virtual models are used for optimization of rail transportation. Thereby, costs of repair work are reduced and operations that duplicate each other are eliminated. In 2018, introduction of a production digital twin was also announced by «Transmashholding». The system calculates the results of production plan fulfillment with given parameters in a matter of minutes and quickly reacts on the customer requests [9].

Definition No.4 is the most suitable for the term digital twin of a food product.

The present paper examines a possibility of using the theory of a digital twin in description of food products. The authors of the paper propose a hypothesis that a food product digital twin is a virtual model of a product, namely its mathematical model (simulation model*) that combines the whole variety of factors from the chemical composition and functional-technological properties to organoleptic indices. Using a digital twin of a food product before its launch into production, engineers-technologists can analyze the nutritional, biological and energy values as well as other product characteristics.

The dispersion of parameters and properties of biological raw materials can be compensated in the real-time operational conditions by selection of optimal strategies of component redistribution and alteration of technological schemes depending on the actual resource and component composition of biological raw materials. Therefore, each possible condition of the input flow of biological raw materials will be contrasted with a certain structural and regime alternative that ensure maximum product processing from a raw material unit at maximum approximation to the normative indices.

* A simulation model is a logical mathematical description of an object that can be used for computer experiments for design, analysis and assessment of object function [10].

Main part

By a mathematical (simulation) model is meant an equation that links an optimization parameter with factors

$$y = \varphi(x_1, x_2 \dots x_k),$$

where $\varphi(x_1, x_2 \dots x_k)$ is a response function.

To design an experiment, a factor should have a certain number of discrete levels. A fixed set of factor levels determines one of possible states of the object under investigation. At the same time, this is a condition for conducting one of possible experiments. If we try all possible sets of states, we will have many different states of the object under investigation. The number of possible experiments is determined by the equation

$$N = p^k,$$

where, N — number of experiments; p — number of levels; k — number of factors.

The real objects usually have huge complexity. For example, a system with 5 factors at 5 levels that might appear at first glance to be simple has 3125 conditions ($N = 5^5 = 3125$), and for 10 factors at 4 levels their number will be above a million ($N = 4^{10} = 1048576$). In these cases, performance of all experiments is practically impossible. Therefore, advantages of using the digital twin technology become immediately evident.

Setting up the task of structural optimization at different levels of description of the digital twin technology for a food product is reduced to minimization of deviations of the actual parameters from the given normative (reference, desired) values with finding a balance regarding the chosen indices between the input and output material flows.

At the first stage of the balance analysis by raw materials for manufactured products, the system structural optimization is reduced to redistribution of raw materials and the supply stream that ensure minimum deviation from the given (reference, desired) product structure under the given conditions and restrictions. The first stage consists of several levels.

The first level represents the description of the product chemical composition, and a criterion of minimum deviation $P(z)$ from the set structure of nutritional value ingredients across the whole variety of product components is introduced for product quality assessment:

$$P(z) = \sum_{i=1}^N \sum_{k=1}^{\chi} \lambda_{ik} \left(z_{ik} - \sum_{j=1}^m b_{jk} x_{ij} \right)^2$$

with λ_{ik} — the coefficients of significance of deviations of the k^{th} index of the chemical composition in the i^{th} product determined depending on the biological value, deficiency, cost and other component characteristics.

The second level is linked with quantitative assessment of mono-structures — ingredients of the product biological value (essential amino acids, polyunsaturated fatty acids and others); that is, components of the chemical composition

elements. In this case, a criterion is expressed as a sum of squared deviations of the content of mono-structure elements from their values in a certain reference balanced product (for example egg protein or breast milk):

$$P(s) = \sum_{i=1}^N \sum_{k=1}^{\chi} \sum_{t=1}^T \beta_{ikt} \left(S_{kt} - \frac{\sum_{j=1}^{m_i} a_{jkt} b_{jk} x_{ij}}{\sum_{j=1}^{m_i} b_{jk} x_{ij}} \right)^2$$

with the coefficients β_{ikt} of significance of deviation of the t^{th} ingredient of the k^{th} element of the i^{th} product.

According to the concept of the minimum degree of assimilability by the body of the elements of the product chemical composition (minimal score),

$$G_{ikt}^{\min} = \min \left\{ \frac{\sum_{j=1}^{m_i} a_{jkt} b_{jk} x_{ij}}{S_{kt} \sum_{j=1}^{m_i} b_{jk} x_{ij}} \right\}; k = \overline{1, \chi}, i = \overline{1, N}$$

which shows the minimum content relative to the reference of the t^{th} microelement of the k^{th} group in the i^{th} product.

The total losses of the biological value of product components can be used as a criterion of the system efficiency and optimization:

$$\Psi(u) = \sum_{i=1}^N \sum_{t=1}^T (1 - G_{ikt}^{\min}) \sum_{j=1}^{m_i} a_{jkt} b_{jk} x_{ij}; k = 1, \chi$$

The second stage is linked with designing structural forms of a food product.

The optimal recipe of a food product at the 1st stage does not guarantee transformation into a stable system with required structural-mechanical and functional-technological indices during technological processing.

Acquisition of certain structural forms (consistency, appearance, cohesiveness, texture and so on) by a food composition is conditioned by peculiarities of colloid-chemical processes of the «protein-protein», «protein-water», «protein-fat» and «water-protein-fat» types. It is impossible to be sure that recipe ingredients will be transformed into a stable disperse system with required properties as a result of technological processing [11].

To realize the second stage, it is necessary to have information about actual values of the functional-technological properties (FTP) of main raw materials, auxiliary ingredients, kinetics of biochemical and colloid-chemical processes (first of all, structurization) in multi-component food systems, analytical and empirical dependencies that characterize the main regularities of behavior of heterogeneous disperse systems upon variation of the physico-chemical factors.

With appearance of more and more convenient tools for processing and storage of large data, an opportunity for increasing the number of variants of using and alternatives for the development of a food product digital twin arises, which in turn, increases adequacy and validity in decision-making.

Nowadays, food product databases should contain not only information about the main indices (moisture, protein,

Table 1. The main functional-technological properties of certain types of meat raw materials [12]

Raw material type	Before thermal processing							
	Water-binding capacity to total moisture, %		Plasticity, $\times 10^{-1} \text{ m}^2/\text{kg}$		Water absorption, % of total mass		Fat absorption, % of total mass	
	3 mm	cutter	3 mm	cutter	3 mm	cutter	3 mm	cutter
Beef, 2 nd grade	78.0 ± 2.8	87.0 ± 5.0	9.74 ± 0.4	11.76 ± 0.8	56.2 ± 4.4	55.3 ± 3.8	28.4 ± 3.0	30.9 ± 1.6
Cutlet meat	85.9 ± 3.4	88.4 ± 4.6	10.6 ± 0.8	12.13 ± 1.0	52.3 ± 3.7	54.8 ± 6.2	26.3 ± 3.0	31.4 ± 1.8
Semifat pork	73.8 ± 6.0	74.6 ± 3.8	9.46 ± 0.3	11.5 ± 0.5	34.9 ± 2.3	64.2 ± 4.2	22.5 ± 1.2	28.6 ± 2.1
Fat pork	-	-	10.52 ± 0.2	12.31 ± 0.3	29.2 ± 2.4	32.2 ± 2.6	19.8 ± 2.0	23.4 ± 1.7
Mutton, single grade	70.4 ± 3.2	78.8 ± 2.6	7.8 ± 0.4	8.9 ± 0.4	40.2 ± 3.7	43.4 ± 3.4	24.9 ± 1.6	35.8 ± 1.3
Meat from beef heads	64.4 ± 1.8	68.6 ± 2.0	6.2 ± 0.2	6.6 ± 0.2	36.9 ± 1.3	37.3 ± 1.2	12.9 ± 0.9	17.5 ± 0.5
Meat from pork heads	-	-	5.8 ± 0.6	6.8 ± 0.5	26.6 ± 2.4	28.7 ± 2.1	18.8 ± 0.7	21.9 ± 1.3
Beef rumen	49.8 ± 3.7	65.4 ± 4.2	5.8 ± 0.6	7.7 ± 0.4	53.2 ± 4.4	58.3 ± 3.8	26.1 ± 2.2	37.8 ± 2.5
Beef lungs	94.3 ± 1.6	96.0 ± 1.2	11.3 ± 0.9	11.5 ± 0.8	30.6 ± 2.8	35.0 ± 4.0	25.2 ± 2.2	32.8 ± 3.1
Beef spleen	66.6 ± 3.4	64.2 ± 4.0	18.1 ± 0.4	18.8 ± 0.3	26.0 ± 2.0	29.3 ± 2.7	16.6 ± 1.1	18.2 ± 0.8
Esophagus meat	78.2 ± 3.3	80.2 ± 2.8	8.1 ± 0.6	8.7 ± 0.4	15.1 ± 1.1	16.5 ± 1.4	9.8 ± 0.9	12.2 ± 1.3
Beef lips	100 ± 0.0	100 ± 0.0	4.2 ± 0.5	4.8 ± 0.5	5.1 ± 0.6	6.1 ± 0.6	9.34 ± 0.8	9.8 ± 0.4

fat, energy value, amino acid, fatty acid, vitamin and mineral compositions) but also information about functional-technological properties of raw materials of animal and plant origin.

The data presented in Table 1 [12], which contain the main characteristics of functional-technological properties of certain types of protein-containing raw materials, can be used to determine conditions of component compatibility in a recipe, optimize a choice of an ingredient ratio with consideration for a probability of inter-regulation of properties of individual constituents and the resulting system in general.

1) a model of the water-binding capacity — $WBC = \sum_{i=1}^N w_i x_i$, where w_i — where is the water-binding capacity of the i^{th} recipe component;

2) a model of the fat-holding capacity — $FBC = \sum_{i=1}^N l_i x_i$, where l_i — is the water-binding capacity of the i^{th} recipe component;

3) a model of the water-holding capacity — $WHC = \sum_{i=1}^N v_i x_i$, where v_i — is the water-holding capacity of the i^{th} recipe component;

4) a model of the ultimate shear stress — $USS = \sum_{i=1}^N q_i x_i$, where q_i — is an index of the ultimate shear stress of the i^{th} recipe component;

5) a model of the dynamic viscosity (η) — $\eta = \sum_{i=1}^N \frac{V_i x_i}{\eta_i}$, where η_i — is the dynamic viscosity of the i^{th} recipe component; V_i is the volume fractions of recipe components;

6) a model of the density (ρ) — $\rho = \left(\sum_{i=1}^N \frac{x_i}{\rho_i} \right)^{-1}$, where ρ_i — is the density of the i^{th} recipe component;

7) a model of the active acidity index (pH) — $pH = -\lg \left(\sum_{i=1}^N x_i 10^{-pH_i} \right)$, where — is the active acidity

index of the i^{th} recipe component; x_i is the mass fraction of the i^{th} recipe component in the given recipes from (1) to (7).

The third stage is the determination of the organoleptic properties of a product under design by the methods of expert assessment with the control of agreement.

Therefore, analysis and control of optimality of different structural variants are carried out based on the complex simulation model of a food product, that is, on a digital twin.

Assessment of the efficiency of the developed food product is possible only upon analysis of many different indices.

It is convenient to generalize (convolve) a set of indices into the united quantitative non-dimensional index. To this end, it is necessary to introduce for each of them a non-dimensional scale, which should be of the same type for all unified indices. This approach makes them comparable.

After building a non-dimensional scale for each index, the next difficulty appears — a choice of a rule for combining initial individual indices into an overall index. There is no unified rule.

One of the most common overall indices is the Harrington generalized function. The basis for building this function is an idea of transformation of natural values of individual indices into the non-dimensional scale of desirability or preference. The desirability scale belongs to psychophysical scales.

The authors use a functional [13], an integral index in a form of an additive convolution, to assess quality and adequacy of a food product.

A functional, first of all, determines a correspondence to specified requirements by the chemical composition, functional-technological properties and organoleptic indices. A functional reflects an average weighted total deviation of actual values of condition parameters from the normative values.

With regard to weight coefficients and separation of certain groups of factors, the equation has the following form:

$$\Phi(x) = 1 - \sqrt[n]{\frac{1}{n} \sum_{i=1}^n a_i \sum_{j=1}^{n_i} b_{ij} \left(\frac{x_{ij} - x_{ij}^0}{\Delta x_{ij}^k} \right)} \rightarrow \max$$

where, n — is the number of the combined indices; x_{ij} , x_{ij}^0 — are the actual and desirable values; Δx_{ij}^k — is the maximum deviation from a desirable value for the k^{th} quality level; b_{ij} — is the weighting coefficient of the j^{th} parameter in the i^{th} group; a_i — is the coefficient of group significance.

A value of the quality coefficient changes from 1 upon complete agreement of the obtained values with recommended (the best quality) to 0 upon reaching the limit of the quality level (the limiting value), so that at negative values of a functional, there is no correspondence to the specified quality level.

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To determine weighting coefficients, the method of a full factorial experiment can be used, when the following values are put into the columns of the response function

y_{kr} of the r^{th} repetition of the k^{th} experiment: 1–0.7 — when a product has a very good quality level; 0.7–0.3 — good; 0.3–0 — satisfactory; 0–(–0.2) — bad; less than (–0.2) — a very bad quality level.

Conclusion

A «digital twin» of a food product is its simulation model associated with processing of a large number of information about the chemical composition, functional-technological properties and organoleptic indices. «New» simulation technologies allow engineers-technologists to use digital twins to carry out tests in the virtual world saving time, money and resources for physical scientific experiments on primary trial of recipes for new food products with complex composition and characteristics.

Acknowledgment

The article is published in the framework of execution of scientific-research work theme No. 0585–2019–0008 of the State task of the V. M. Gorbатов Federal Research Center for Food Systems of RAS.

REFERENCES

- Grieves, M. (2014). *Grieves Digital Twin: Manufacturing Excellence through Virtual Factory Replication* — LLC, 7 p. [Electronic resource: <https://www.researchgate.net/publication/275211047> Access date 20.01.2020].
- Kokorev, D.S., Yurin, A.A. (2019). Digital twins: concept, types and benefits for business. *Colloquium-journal*, 10–2(34), 101–104.
- Claessen, E., Stargel, D. (2012). The digital twin paradigm for future NASA and US Air Force vehicles. *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA*, 8, 7247–7260. <https://doi.org/10.2514/6.2012-1818>
- Lee, J., Bagheri, B., Kao, H.A. (2015). A cyber-physical systems architecture for industry 4.0-based manufacturing system. *Manufacturing letters*, 3, 18–23. <https://doi.org/10.1016/j.mfglet.2014.12.001>
- El, Saddik A. (2018). Digital twins: the convergence of multimedia technologies. *IEEE MultiMedia*, 25(2), 87–92. <https://doi.org/10.1109/mmul.2018.023121167>
- Söderberg, R., Wärnefjord, K., Carlson, J.S., Lindkvist, L. (2017). Toward a Digital Twin for real-time geometry assurance in individualized production. *CIRP Annals*, 66(1), 137–140. <https://doi.org/10.1016/j.cirp.2017.04.038>
- Bolton, R.N., McColl-Kennedy, J.R., Cheung, L., Gallan, A., Orsinger, C., Witell, L., Zaki, M. (2018). Customer experience challenges: bringing together digital, physical and social realms. *Journal of Service Management*, 29(5), 766–808.
- Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C.-Y., Nee, A.Y.C. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, 57(12), 3935–3953. <https://doi.org/10.1080/00207543.2018.1443229>
- Peshkova, N. (2019). How digital twins help the Russian industry. [Electronic resource: <https://rb.ru/longread/digital-twin/>. Access date 20.01.2020]. (in Russian)
- Mukha, V.S. (2010). *Computational methods and computer algebra / 2nd edition, revised and enlarged*. Minsk: BGUIR. — 148 p. (In Russian)
- Zharinov, A.I., Nelepov, Yu.N. (1995). Assessment of the main functional-technological properties of by-products of the 1st category. *Meat industry*, 2, 16–18. (In Russian)
- Zharinov, A.I. (1994). The principles of modern technologies of meat processing. Part 1. Emulsified and coarsely minced meat products / under the editorship of M. P. Voyakin. Moscow: ITAR-TASS. — 154 p. (in Russian)
- Nikitina, M.A., Chernukha, I.M., Nurmukhanbetova, D.E. (2019). Principal approaches to design and optimization of a diet for targeted consumer groups. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 1(433), 231–241. <https://doi.org/10.32014/2019.2518-170x.28>

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All authors bear responsibility for the work and presented data.

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The authors declare no conflict of interest.

Received 23.01.2020 Accepted in revised 25.02.2020 Accepted for publication 05.03.2020