

# Simulation case study of digitalization efficiency evaluation for sustainable regional economy

*Alexander Bekarev*<sup>1\*</sup> and *Alexander Golovin*<sup>1</sup>

<sup>1</sup> Laboratory of Digital Technologies in Regional Development, Karelian Research Center of RAS, 185910 Petrozavodsk, Russia

**Abstract.** The paper is dedicated to digitalization efficiency evaluation methods in view of regional economy. Existing methods are briefly summarized. A modified digital efficiency evaluation method adopted to aquaculture as one of the key fields in regional economy of the Republic of Karelia as well as Finland, is extensively studied by means of simulation based on the statistics of the sector, and optimal parameters of budget devoted to digitalization for various size enterprises are obtained by means of numerical study.

## 1 Introduction

Digitalization as an integral process of the digital economy is increasingly being introduced into all spheres of life. At the level of the user as an ordinary layman, digitalization is perceived as nothing more than a simple manifestation of progress, i.e. something that naturally and gradually becomes a tool for administering the life tasks of a person living in society. From the point of view of business, digitalization is a process during which the solution of the classical problem of maximizing profits and minimizing costs is achieved and can be expressed both through the introduction of individual digital and technical solutions, and in the form of the implementation of a comprehensive digitalization project. For the state, using the example of the Russian Federation, digitalization is the construction of a highly efficient digital environment in the field of economics, covering regulatory regulation, information structure, information security, personnel and education, end-to-end technologies of the digital economy, which is reflected in the national program for the development of the digital economy of the Russian Federation [1].

In the presented work, the team of authors does not assume consideration of digitalization from the position of a citizen of society as an end user. The main focus of the article is aimed at the field of task administration in business and the state, where digitalization is a component of the digital transformation of internal business processes. Digital transformation involves obtaining the changes expected in the future from the introduction and use of digital technologies. These changes are reflected in the parameters of those business processes that have undergone digitalization. One of the approaches to studying such changes involves assessing the economic efficiency and digital maturity of the organization. It is worth noting that the relevance of the tasks of assessing the economic efficiency of digitalization and the

---

\* Corresponding author : [bekarev@krc.karelia.ru](mailto:bekarev@krc.karelia.ru)

development of new applied techniques is very high today and affects a wide range of scientific research in such subject areas as agriculture [2,3], state and municipal administration [4,5] and others.

The Republic of Karelia is the leader of Russia in terms of growing commercial aquaculture. In the Russian market, more than 70% of aquaculture trout are grown in Karelia. More than 50 fish farms of different production capacities are involved in the region annually. As part of the strategy for the development of the agro-industrial and fisheries complexes of the Russian Federation for the period up to 2030, the need to improve production comes to the fore, where digitalization of agriculture plays a key role. To stimulate the industry, the state subsidizes fish farming enterprises in the region to ensure the introduction of innovative solutions, including not only modern technical solutions but also digital technologies. The level of demand for aquaculture products produced in the region significantly exceeds the supply, therefore young trout planted in cages at the beginning of the season for growth are often actually already sold within the framework of pre-concluded contracts between private trout enterprises and customers. For the development of the aquaculture sector in the structure of the regional economy, it is extremely important to achieve a balance of intensification of production, greening and socio-economic development. The authors are convinced that the development of an adapted methodology for solving the problem of evaluating the effectiveness of digitalization on the example of the economy of a single aquaculture enterprise will provide an opportunity to assess the effectiveness of digitalization in total for all fish farming enterprises in the region, which in turn will allow evaluating the effectiveness of digitalization at the macro level for the regional economy.

When calculating the evaluation of the effectiveness of digitalization in a single enterprise, we use a wide range of digitalization scenarios. Each scenario (digitalization project) may contain a different set of digital and technical solutions: - automatic feeding systems, counters and fish sorters with statistics counting, automatic feeding systems, big data processing technologies, bottom monitoring devices, environment monitoring sensors and equipment, video surveillance systems, fish pumps and manipulators, software for fish management farms. The depth and width of the range of digital solutions can vary greatly in many parameters: - the cost, the model, the resulting effect, etc., respectively, there can be many digitalization scenarios themselves, this makes it impossible to calculate on individual conditions and therefore we have to use mathematical modeling based on the appropriate statistics in the fish farming enterprise.

In this paper we continue the mathematical modelling effort started in [6]. The key contribution of this paper compared to [6], however, is in the updated method of time-based digital efficiency estimation. On the contrast to the (per anno) model suggested in [6], we now consider the time-dependent *digitalization strategy* model under budget and return of investments constraints. Mathematically, this gives one more degree of freedom to the model and significantly enlarges the state space for the strategy optimization problem. At the same time, we need to note the following peculiarities:

- on the contrast to [6], in the present paper the digitalization efficiency is evaluated over multiple years of implementation of the digitalization strategy, and thus the novel model can not be directly compared to the one presented in [6] apart from the trivial example of the single-year planning horizon;
- in the model presented in this paper, the strategy planning allows to take into account the (annual) budgeting restrictions and the (planned) return of investment date;
- the effect of the implementation of a strategy allows to incorporate risk mitigation and social effects expressed in monetary terms indirectly, via corresponding production volume percentages.

These benefits, however, come at a price of computational complexity of the problem considered, which is essentially a discrete optimization problem. Note that, similarly to [6],

the numerical experiments are based on the numerical estimates (e.g. production volume) obtained in the fish farming industry survey [7].

The structure of the paper is as follows. A brief review of the digitalization efficiency estimation methods is performed in Section 1.1. The novel efficiency of digitalization strategy evaluation model is presented in Section 2. Numerical experiments of sensitivity study of the model to the budget constraints and production volume are performed in Section 3. We finalize the paper with conclusions and discussion of possible future improvements of the approach.

## 1.1 Literature review

There is a great variety in approaches and methods of evaluating efficiency, which is due to the very definition of efficiency as a complex characteristic. This task in practice is an important problem faced by both commercial enterprises and state organizations [8]. This problem is especially acute when it is necessary to choose a method for identifying and determining parametric changes from the introduction of innovations, in other words, existing methods and approaches for evaluating the effectiveness of digital technologies were developed to measure specific changes and as a result, it is impossible to take even a objectively suitable methodology and get the correct result of evaluating the effectiveness of implementations without significant changes in the methods themselves.

In the context of the subject classification of approaches and methods, the diversity is also great. In our work, the classification reflected in the works was used [9], but realizing that digital products are rapidly becoming obsolete and the process of digitalization of the economy is becoming more active, we considered it necessary to pay attention to more modern methods that are currently being used [10].

Among such techniques, the following can be noted:

- Methodology for evaluating the effectiveness of digital transformation projects [11] used for the fuel and energy complex. The essence of the method is expressed in the evaluation of the final changes from the implemented innovation project. The payback and efficiency of investments are calculated, net discounted income is given, profitability and internal rate of return are determined.
- Methodological approach to evaluating the effectiveness of digital investment projects [12]. This method can be considered an example of the practical need for the authors to create their own algorithm for the multidimensional calculation of the average value of the characteristics of the project, which also convinces us of the correctness of our approach to the stated problem.
- A method for evaluating the effectiveness of the digital transformation strategy [13]. In this approach, applicable in private business, the dynamics of changes in the digital transformation of business processes over time is evaluated.
- A method for evaluating the effectiveness of the digital ecosystem [14]. To assess the efficiency, the authors use the fuzzy logic apparatus by grouping various indicators reflecting the efficiency of the strategy of finance, marketing, branding, etc. and this is yet another author's approach.
- The so-called Total value of opportunities (TVO) methodology [15] developed by Gartner Group in 2003 and, like REJ, it is a more in-depth specification of the TCO. The essence of the method consists in a more detailed reflection of the economic results of the IT project, attention is also paid to how the implementations affect business processes, payback and risk factors are additionally taken into account, and this once again shows us that a modified method is needed for certain tasks, which is based on an already tested approach. The approach of this method implies an analysis of the compliance of the business strategy and its indicators in comparison with the indicators

of the digitalization project, and under the influence of how the implementation affects changes in business processes, while in conjunction with this analysis, efficiency is estimated as the ratio of costs per unit of output.

- An Integrated Real Options (IRF) framework for model-based identification and evaluation of options under uncertainty [16] presents an integrated real options framework for holistic analysis of enterprise architecture projects. IRF allows the evaluation of enterprise architecture alternatives through modeling of uncertainty, flexibility, benefits, and costs.

In essence of the above, we can conclude that any classification, both in the classical sense and in the modern one, is a set of purely author's solutions for evaluating efficiency, where the key aspect is the measurement of changes due to the gradual implementation of digitalization. Thus, to build up an appropriate method for the aquaculture industry in terms of regional economy, it is important to use some classical generic method and modify it in view of the specificity of the field.

## 2 Materials and methods

The goal of the present study is to develop and present an applied method of digitalization strategy efficiency evaluation in aquaculture sector. To do so, we blend the two classical approaches for evaluating digitalization efficiency presented in the work [9]. The method of rapid economic justification (REJ), developed by Microsoft and assuming a simple economic justification of the actual investments in digitalization. REJ involves the analysis of business processes and indicators (financial, risk factors, etc.) reflecting its key parameters that will change in the process of digitalization. In turn, the REJ method is a more specific implementation of the total cost of ownership (TCO) method that uses simple tools such as payback period (PP) and others. Using these approaches, we present our model of digitalization efficiency evaluation based on the selection of the digitalization strategy so as to optimize the digitalization efficiency. To do so, we modify the model suggested in [6]. On the contrast to that, we now consider the discrete time (yearly) model, on the planning horizon of  $T$  years. Here we briefly describe the model parameters.

Denote

$V$  - the annual production volume, expressed in monetary terms;

$ai$  - the cost (capital expenses) for implementation of technical and/or digital solution;

$bi$  - the annual operating expenses, as a percentage per year of the cost ( $ai$ ), related to implementation and usage of technical and/or digital solution, which are charged starting from the implementation year onwards;

$ei$  - the effect that a particular solution gives in reducing the company running costs, mitigating risks, improving customer indices, expressed as a percentage of the company's production volume  $V$ , i.e. the savings that are counted starting from the implementation year;

$ti$  - the purchase/implementation year of the specific solution,  $ti \leq T$ ;

$xi$  - the (binary) purchase indicator,  $xi \in 0,1$ , which indicates that the solution  $i$  is purchased;

where  $i=1,\dots,M$  and  $M$  is the number of technical and digital solutions available in the market.

The aquaculture farm is faced with the question of which solutions to choose, having restrictions on the available budget for digitalization (denoted as  $uV$ , where  $u$  is the percentage of the production volume  $V$  of the company) and on the acceptable payback period (denoted as  $t_0$ ), so as to minimize the capital/operating expenses and maximize the effect (e.g. savings) from the particular set of solutions purchased at appropriate years. Such an effect may be considered as a function  $g(x,t,s)$  of time  $s=1,2,\dots$  defined as follows,

$$g(x, t, s) = \sum_{i=1}^M x_i (Ve_i - a_i b_i)(s - t_i + 1)1_{t_i \leq s} \tag{1}$$

where  $1A$  is the condition checking function equal to one if the condition  $A$  holds good.

The overall gain is then defined as a function  $f(x,t)$  on the digitalization strategy  $(x,t)=(x_1,\dots,x_M,t_1,\dots,t_M)$ , given as

$$f(x, t) = g(x, t, T) - \sum_{i=1}^M x_i a_i$$

Then we can express the problem of maximization of the digitalization efficiency as follows.

$$f(x, t) \rightarrow \max \tag{2}$$

$$\sum_{i=1}^M x_i (a_i 1_{t=t_i} + a_i b_i 1_{t \geq t_i}) \leq uV, t = 1, 2, \dots, T \tag{3}$$

$$\sum_{i=1}^M a_i x_i 1_{t_i \leq t_0} \leq g(x, t, t_0) \tag{4}$$

As such, the goal is to find an optimal strategy  $(x_i, t_i), i=1, \dots, M$  of purchasing the digital solutions in specific years given annual budget constraints (3) and time constraint  $t_0$  on the return of investments performed before  $t_0$  (4).

To proceed digitalization strategy assessment, we note that in the optimization problem (2)-(4) the following simplifying assumptions are made:

- The capital expenses  $a_i$ , (as well as operation expenses fractions  $b_i$  and total effect  $e_i$ ), do not depend on the production volume  $V$ . However, this assumption is only true in a relatively narrow range of the production volumes. Hereafter during the numerical evaluation we study the effect of production volume and the digitalization budget (relative fraction of the production volume spent for the implementation of the strategy annually) on the efficiency of the digitalization strategy for relatively small enterprises. For larger production volume case, the cost dependence on the volume may be non-linear (in such a case, the appropriate costs  $a_i$  and other parameters need to be defined anew).
- The implementation time of the solution is considered to be negligible. This may not be the case for sophisticated software/hardware solutions where commissioning works and test works are used so as to minimize technical risks. However, for the object of study, i.e. relatively small fish farms, the implementation time can be neglected.
- Social effects of digitalization strategy implementation are not taken into account. These effects may include nonlinear dependence of the efficiency on the time since implementation due to the necessity for the workers to pass education and gain experience in working with sophisticated equipment; these could also consider improvement of the quality of work life due to a decrease of the number of routine operations that need to be performed manually, which would improve the employee's loyalty to the enterprise (which finally results in a decrease of technical risks and mistakes).
- the production volume  $V$  is considered to be constant during the time  $T$ . This may be true for a rather small horizon  $T$  in general, however, this assumption is partially supported by the fact that every fish farming enterprise has a specific amount of allowable production volume which is defined in a fish-breeding and biological justification, and this volume is normally used almost completely.
- The risks are not realized during the time horizon  $T$ , or this realization is fully covered. This means that the production volume  $V$  is not affected by the risks and, moreover, the so-called non-implementation risks are not realized (i.e. the solution purchased is always implemented).

- The effects of various technical and digital solutions are considered to be independent. It is not true in general, where there those might be positively/negatively correlated, e.g. the effect of fish farm management software is improved by the implementation of automatic water quality monitoring. However, these subtle effects may be studied separately.
- Money volatility and inflation rates are not taken into account during the time T.

### 3 Results

To demonstrate the feasibility of the approach, we perform a numerical study. In what follows, we build up scenarios of digitalization for three relatively small fish farming enterprises, with annual turnaround of about 5, 6 and 7 mln rub, respectively. We use the range of possible digital solutions from [6] and summarize the necessary parameters in Table 1. The planning horizon T is selected as 5 years, and the payback period  $t_0$  is 2 years. We vary the parameter  $u$  of the fraction of the annual budget of the enterprise which is spent for digitalization from 0.01 to 0.25 with a step 0.05. Due to a large number of possible solutions, we stick to Monte-Carlo estimation by means of randomly generating 106 possible solutions and evaluating their quality/feasibility by (2)-(4). Finally, to evaluate the efficiency of the proposed strategy, we calculate the overall effect relative to the turnaround on the planning horizon,  $f(x,t)/(V T)$ , and depict it vs. the budget fraction,  $u$ , for all three enterprises. The results of the experiments are given on Figure 1. A brief look at the figure allows to conclude that the dependence of the relative effect of digitalization on the fraction of the yearly production volume spent for digitalization is nonlinear. Moreover, the simulation shows that relatively large effect may be obtained by a significantly small fraction of budget spent for finding optimal strategy.

Example 1 As an extreme example of such a strategy, is the following. Consider an enterprise with a yearly turnaround of 7 mln rub, and 25% of the budget are spent for digitalization. Then overall cost spent for 5-year planned period is estimated as 1930730 rub, with the overall effect estimated as 12069270 rub (at the end of 5-th year). The following solution was found

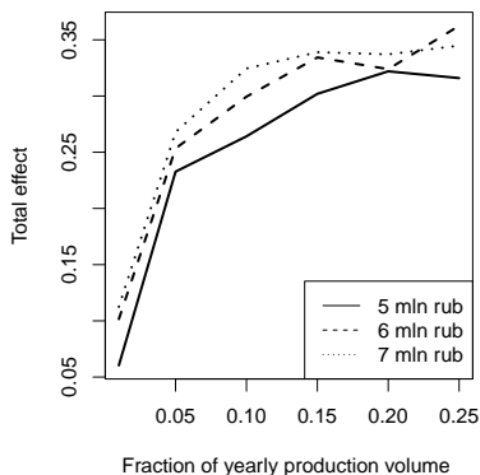
- Year 1: purchase automatic recirculating aquaculture systems; water quality assessment; fish counters; fish pumps, fish manipulators. Expenses: 1027750 rub.
- Year 2: purchase automatic feeding systems; sediment monitoring. Expenses: 230320 rub.
- Year 3: purchase fish farm management software. Expenses: 275420 rub.
- Year 4: purchase nothing. Expenses (operational): 185420 rub.
- Year 5: purchase security, monitoring, video surveillance. Expenses: 211820 rub.

Example 2 Another example is a conservative strategy for the same enterprise as in Example 1 spending 1% of the budget for digitalization. Then overall cost spent for 5-year planned period is estimated as 190080 rub, with the overall effect estimated as 3939920 rub (at the end of 5-th year). The following solution was found

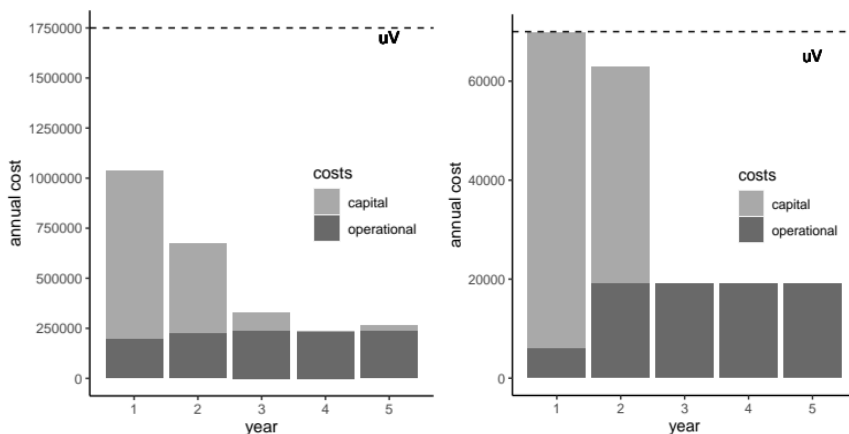
- Year 1: purchase sediment monitoring; customer relationship management systems; security, monitoring, video surveillance. Expenses: 69900 rub.
- Year 2: purchase automatic feeding systems. Expenses: 62970 rub.
- Year 3: purchase nothing. Expenses (operational): 19070 rub.
- Year 4: purchase nothing. Expenses (operational): 19070 rub.
- Year 5: purchase nothing. Expenses (operational): 19070 rub.

Essentially, an optimal strategy was obtained for every system configuration for all three enterprises, and the non-smooth dependence shown on Figure 1 is due to discretization of the

parameter  $u$  of the fraction of the annual budget spent for digitalization, whereas the fluctuations of the graphs are due to the random nature of Monte-Carlo estimates obtained.



**Fig. 1.** The effect, in terms of fraction of the overall production volume over the planning horizon, versus the fraction of yearly production volume spent for digitalization by the relatively small size enterprises (5, 6 and 7 mln rub per year).



## 4 Discussion

We briefly revealed and extensively modified the digital efficiency evaluation method first presented in [6] which is based on a few known methods of digitalization evaluation and is adopted to the specificity of aquaculture sector, the key field of regional economy of the Republic of Karelia. Due to similarity of the regional economy structure, the approach might be also interesting to other Nordic countries, and in particular, Finland. The novel method presented in this paper allows to suggest digitalization strategies to enterprises of various sizes, as it was demonstrated by the simulation experiments. Note however, that the direct comparison of the results and conclusions obtained in the present paper with the real-world experiments have not been performed yet.

After a few modifications, the presented approach may be modified to evaluate digitalization efficiency of the governmental organizations/bodies. This, however, would require modifying the goal, which in the latter case would not be expressed in monetary terms, but rather in specific indicators.

## 5 Conclusion

The article discusses approaches and methods for evaluating the digitalization efficiency. A brief description of the methods is given, their structural tools, scope and differences are revealed. The importance of identifying and measuring the resulting socio-economic effects from the introduction of modern digital and technical solutions necessary to achieve strategic goals in business and in the implementation of government programs on the digital economy is substantiated.

In future, it is planned to extend the method towards the government-to-business interaction, where at the governmental level the problem of metaoptimization of the parameters of subsidizing the growth of aquaculture sector is considered. It might also be interesting to study the sensitivity of the system to the parameters near the optimality point. There are also plans to continue developing the method that will take into account the effect of discounting expressed as inflationary expectations of changes in the value characteristics of money over time; the effect of greening as the amount of pollutants released into the environment from production in aquaculture using technical and digital solutions that reduce environmental damage. These possibilities are, though, left for possible future research.

## Acknowledgments

This research is supported by RSF, project No 23-21-00048. The authors thank Alexander Rummyantsev for helpful discussions.

## References

1. National Program for the Development of the Digital Economy of the Russian Federation: Digital Economy 2024. Ministry of Digital Development, Communications and Mass Communications of the Russian Federation
2. Zh. Telegina, *Economics of Agriculture of Russia* **3**, 26–32 (2020)  
<https://doi.org/10.32651/203-26>
3. Iu. N. Nikulina, *Economics of Agriculture of Russia* **1**, 57–65 (2023)  
<https://doi.org/10.32651/231-57>
4. M.A. Sidorov, M.Ya. Veselovsky, *Bulletin of the NGIEI* **12(115)**, 109–117 (2020)  
<https://doi.org/10.24411/2227-9407-2020-10125>
5. E.I. Dobrolyubova, V.N. Yuzhakov, *Russian Academy of National Economy*, 2020
6. A. Bekarev, A. Golovin, Springer LNCS (2023)
7. A. Bekarev, E. Ivashko, V. Ivashko, *Agriculture Digitalization and Organic Production*, Springer Nature Singapore pp. 363–372 (2023)  
[https://doi.org/10.1007/978-981-99-4165-0\\_33](https://doi.org/10.1007/978-981-99-4165-0_33)
8. A. Bekarev, E. Konovalchikova, E. Ivashko, *Digital Technologies in Education, Science, Society*, pp. 30–33 (2019)

9. A. B. Anisiforov, L.O. Anisiforova, *Methods of evaluating the effectiveness of information systems and information technologies in business* (Saint Petersburg State Polytechnic University, Institute of Engineering, 2014)
10. T.V. Kokuytseva, O.P. Ovchinnikova, *Creative Economy* **15(6)**, 2413–2430 (2021) <https://doi.org/10.18334/ce.15.6.112192>
11. A.V. Trusov, V.A. Trusov, A.S. Bochkarev, *Bulletin of Scientific Conferences* **4–1(44)**, 106–108 (2019)
12. D.A. Lyubimenko, E.D. Vaisman, *conomics. Information technologies* **47(4)**, 718–728 (2021) <https://doi.org/10.18413/2687-0932-2020-47-4-718-728>
13. N.V. Perevoznikova, M.A. Myznikova, *Evaluating the Effectiveness of the Digital Strategy Transformations*, in *Donetsk Readings 2020: Education, Science, Innovation, Culture and Modern Challenges: Proceedings of the V International Scientific Conference* **3**, 411–414 (2020)
14. V.S. Kokhanova, *Vestnik Universiteta* **2**, 36–41 (2021) <https://doi.org/10.26425/1816-4277-2021-2-36-41>
15. A. Apfel, M.B. Smith, “TVO Methodology: Valuing IT Investments via the Gartner Business Performance Framework, Strategic Analysis Report,” Gartner, USA, techreport, 2003
16. T. Mikaelian, “An Integrated Real options Framework for model-based identification and valuation of options under uncertainty,” phdthesis, Massachusetts Institute of Technology, Dept. of Aeronautics, 2009