Rethinking the Solow Paradox by the Means of Information Use Formalisms

Alexander Geyda
St.-Petersburg Federal Research Center
of the Russian Academy of Sciences
St. Petersburg, Russia
geida@iias.spb.su

***Abstract*—This article explores "information paradox" in economic theory, formulated by Robert Solow - from a wider perspective, i.e. drawing insights from fields such as system science, cybernetics, complexity science, and action theory. The aim is to develop a formal representation and predictive explanation of information application, which could lead to predictions of the impact of information use, based on mathematical models. The author proposes a graph theoretic model in the form of a possible sequences of complex states and transitions, which can be applied to create graph theoretic and formal algebraic models which allows calculations of quantitative measures of success for information application in systems, as well as measures of entropy change. The article highlights several research directions in this area, related to creation of required mathematical models. The article presents a new approach to solving Solow Paradox as well as the multidisciplinary problem of formal assessment of information application, using mathematical models and methods to provide predictive insights.**

I. INTRODUCTION

In 1987, Nobel laureate Robert Solow [1] introduced his information technology paradox, which states that:

Definition 1. *Solow"You can see the computer age everywhere but in the productivity statistics."*

Despite partial explanations of the paradox 1 over the past half-century [2]–[4], it continues to resurface in various forms, as in Fig 1. For instance, a new report published in 2023 [5] discusses the same paradox in the context of artificial intelligence applications by businesses. This article aims to discuss the paradox from a broader perspective and in its relation to possible mathematical formalization. First, it considers the paradox as a multidisciplinary issue, not just one that pertains to productivity or economic theory. Rather, it is a problem of understanding the peculiarities of information use in human activities of various kinds and the quality of practical results obtained through information use. Second, the article discusses the paradox from a more general viewpoint of activity theory and information use by humans in activity, not as a separate issue of abstract information quality regardless of the activity it is used for. Finally, it considers the paradox as a problem of cybernetics, operations research, system sciences, and complexity science. Surprisingly, these issues have not been studied enough even though information use is a cornerstone of activity theory [6], cybernetics, systemics, and complexity science [7]. We can predict space missions with high accuracy, design and build rockets to fly to other planets at specific times and points in the universe and know almost for certain where spacecraft will be years from now based on cybernetics and system science, among other sciences. However, predicting the results of information use remains a challenge. Although we can measure the entropy and other characteristics of information, we cannot predict the results obtained through information use. The situation we currently find ourselves in is extremely perplexing, given the pivotal role that information use plays in human society. Our emergence as a species is largely the result of our ability to process and communicate information, which has allowed us to socialize and advance our activities. However, despite this, we still cannot predict the outcomes of information use. As the Russian poet Fedor Tutchev once wrote, "We cannot know further ways of our word – how it'll be drifted." Throughout history, numerous examples exist where "our word" has changed almost everything, and note it is always "The Word" that precedes all changes made by humans. This system theoretic, cybernetic, and action theoretic statement is directly reflected in the first part of the Old Testament, which reads, "In the beginning was the Word, and the Word was with God, and the Word was God" (John, 1:1). Despite this, we remain unable to measure and predict how, when, and what our own words will change in us and the world around us. This is vastly different from the case of spacecraft. Moreover, the creation of the first societies and multiple civilizations has a direct cause in progress made using information. Some stunning facts about the first known cases of information use in history come from Kushim of Mesopotamia, who lived over 5,000 years ago. Kushim used information for bookkeeping and human activities and signed it. Now we know him and his activity, for which he used information he left. Another known case from the same time is the Mesopotamian beer recipe, which is still used today for our pleasure and taste. Finally, if we examine what has been left behind by our ancestors, we will find that the most valued artifacts from history are information artifacts. These include religious texts, myths, writings, books, photos, letters, and records. It is not the material production things that civilizations used to produce or consume that have been preserved, but rather, the informational artifacts. Yet, we have made little effort to understand how this information is used and what

Fig. 1. Goldman Sachs research report of “Solow paradox” (1) as still valid

results we can predict. However, we are currently experiencing a clear “digital revolution,” but we are still largely unable to predict its outcomes. For example, many of the modern creators of artificial intelligence (AI) openly discuss their inability to predict the results of the latest AI incarnations, due to the potential harm they may cause to human activities. This is vastly different from the results of rocket science. The author proposed concepts of complex states and information use as these states change, which were further used to model of a possible sequences of complex states and transitions as graphs. Models suggested were applied to create formal algebraic models used for calculations of quantitative measures of success for information application in systems, as well as measures of entropy change. Author suggests information application success measures calculated with formal models build as information pragmatics measures.

The paradox of Robert Solow, which states that “We can see the computer age everywhere but in the productivity statistics,” should be considered as part of a larger problem concerning the quality of information use in human activities and the difficulty of predicting practical results obtained through information use with formal models—i.e., that is not the question of information quality by itself, but the question of its application quality. To address this issue, formal explanations of information use results must be developed, which would allow for the creation of mathematical models to predict the effects of information use. These formalisms could be used in a variety of disciplines, including system science, cybernetics, complexity science, and activity theory, to build models of information use and methods to predict its effects. These problems have been the subject of research for decades. H. Tohonen, M. Kauppinen, and T. Manisto [8], [9] conclude that evaluating the business value of information technology is challenging and has been on the research and practitioner agendas for more than two decades. They note that value, as a multidimensional concept, is recognized as a central factor for software and information technology (IT) development and decision-making within value-based software engineering. However, measures of successful information use for human activities, such as design, production, and services, have not been studied in enough detail to make predictions using fundamental models. One reason for this is that such measures must, among other facets, represent the quality of purposeful changes in activity caused by obtained information, particularly in changing conditions. This facet is closely related to the concept of information pragmatics. As it stated by J. Talburt [10]: “That concept is the intent of the message—that is, to what use will the receiver put the information, and more important, will the information have value (utility) for the receiver in the context of its intended use? These three concepts of information format, meaning, and purpose form the foundation of information quality and allow it to be anchored in measurable terms. The same three concepts also underpin the study of signs and symbols known as semiotics, where they are called syntactics, semantics, and pragmatics.” J. Talburt [10] formulated main principles of information quality (IQ) s follows:

IQ Principle 1: Information only produces value when it is used in an application.

IQ Principle 2: The quality of an information is proportional to the value of the application it supports.

IQ Principle 3 The quality of an information depends on its application. The same information can have different quality when used for different purposes.

These principles are used in the article to suggest predictive measures of IQ. The need for IQ measures includes measurements of the quality of deliberate potential changes in actions due to information obtained, as well as fitness of the results to changing demands. Predictive mathematical models for such measures, based on mathematical formalisms, have not been developed yet. This is particularly the case for predictive mathematical modeling of the use of information for actions and the success of systems in changing conditions. This approach requires a description of the characteristics of the use of information for actions and measures of the success of such actions in changing conditions. This approach can be seen as an extension of the Batini [11] and Scannapieco approach to evaluating the quality of information. “We aim to investigate the relationship between the quality of information and the quality of the processes output (or, simply, the process quality) that make use of information to be produced. Since processes are made of decisions and actions, we aim in turn to relate information quality with the quality of actions and decisions that make use of information.… We want to deepen our understanding on how the information processor, be it a human being or an automated process, can manage the fitness for use of the information consumed” [11], [12]. This approach is based on the concept, described by Y. Lee, R. Wang and D. Strong as: “the concept of “fitness for use” is now widely adopted in the quality literature” [12]. The efficiency of decision-making and the relationship between IQ, its peculiarities, and available measurement approaches were studied. A literature review on the issue of IQ and the estimation of decision efficiency was carried out by the authors mentioned above. A review of the approaches for estimating the value of information, with a focus on fundamental and mathematical methods, was provided in [9] and by many other researchers using an empirical approach. As it is noticed by Y. Lee, R. Wang and D. Strong about this approach: "the disadvantage is that the correctness or completeness of the results cannot be proven via fundamental principles" The fitness for use is investigated by [12]. As it is noticed by L. Floridi and P. Illari: "Qualitative descriptions of the meanings of words or phrases such as 'information quality', or 'timeliness' are not the same as formal metrics required to measure them, and which are needed for implementation" [13], [14]. The approach suggested in the article is based on fundamental, predictive mathematical modelling approach to compute formal IQ measures. Approach further elaborates concepts and models suggested in [15]. New measures, suggested in the article, are based on probabilistic and entropy measures, which are calculated with mathematical models of information use and of its possible use success levels. Such measures and formal models may allow solving various problems of information use, digital transformation as mathematical problems, such as operation research and mathematical programming problems. Models suggested are graph-theoretic models, built on the base of suggested schemes of information application for actions in systems. Based on constructed graph theoretic models, probabilistic functional models were built. Such approach is like the approach to information processes modeling, suggested by C. Batini and M. Scannapieco in [11]. However, approach has some deficiencies, mentioned by its authors: "in it does not distinguish between or provide specific formalisms for operational processes, which make use of elementary data, and decision processes, which use aggregated data" [11]. The reason for such situation is defined by the nature of information processing. Such processing inevitably leads to the purposeful change of the human action and to the exchange with environment [16]. But the mathematical models of such changes in human action are not yet available in the needed details. The situation could be improved with the use of various approaches available to describe the changeable activity, like theory of functional systems [17] – if it is operationalized with appropriate mathematical means. The article is devoted to the creation and use of such models.

II. HYPOTHESIS AND PROPOSED DIRECTIONS OF THE RESEARCH

Below are suggested hypotheses and formalisms to explain and formalize various research results related to the wider explanation of the "Solow paradox." (1).

1. Robert Solow definition: (1). Possible system science, cybernetics, complexity science, and action theory explanation: The economy does not produce more output with the same number of inputs because of IT use. IT does not change physical laws but changes the possibilities to act, innovate, helps explain possible future results of actions, change decisions and intentions (knowledge work made, information states produced). It is necessary to research possible changes caused by information due to further realized cause-and-effect relations, not just relations of inputs and outputs. Various authors have tried to explain the "Solow paradox." (1) Let us try to classify their main explanations, simultaneously suggesting system theoretic, cybernetic, action theory versions of such explanations. Three classes of explanations have been selected: prominent researchers of the IT value problem, Eric Brynjolfsson explanations, further authors' explanations, and modern explanations.

2. First "wave" explanations (Eric Brynjolfsson, Paul Strassman, John Thorp from "Fujitsu consulting group" [2], [18], [19]:

2.1. Uneven and concentrated distribution of labor productivity gains can be explained through the lens of system science, cybernetics, complexity science, and action theory: Physical enhancements may not occur immediately or uniformly due to changes in cause-and-effect relationships, which may require additional actions and events to enhance efficiency. Furthermore, information can change the goal and requirements of an action entirely, making it difficult to compare the efficiency of the old and new actions. For example, to enhance the ratio of input and output, additional actions may be required to lead to events that promote efficiency. Additionally, enhanced actions may result in products or services of better quality, or results that satisfy other needs or tasks.

2.2. Implementation lags can be explained through the lens of system science, cybernetics, and complexity science: Time is required to realize cause-and-effect relationships once information has changed. To modernize, innovate, and progress, chains of requirements may need to be satisfied, which may require various resources, complex efforts, and time.

2.3. Mismeasurement can be explained through the lens of system science, cybernetics, and complexity science. Input and output measures alone do not fully characterize changes in actions. The quantity and quality of inputs and outputs, as well as their changes, should also be considered. Additionally, other facets of actions and their results, as well as changes, may be required to measure, not just inputs and outputs.

3. Other prominent authors' explanations.

3.1. Free products and services created due to modern information technologies that cannot be measured in terms of economic efficiency can be explained through the lens of system science, cybernetics, complexity science, and action theory. Modern IT may lead to various free products and services due to business model innovations, including the use of non-financial results, with hopes for future or indirect monetization. These products and services cannot be easily compared with traditional products and services due to differences in business models and need to consider other related activities.

3.2. New products and services or higher quality products and services created due to modern information technologies can be explained through the lens of system science, cybernetics, complexity science, and action theory. Modern IT may lead to various products and services creation or radical changes in their quality. Many of them are incomparable with traditional products and services, resulting from innovation and creative thinking, and cannot be easily measured in relation to traditional products and services. For example, socalled ”uberization” results are hard to compare to traditional businesses.

4. Newest explanations of modern digital technologies paradoxes [5], [20].

4.1. Competition mechanisms. Businesses that do not properly use modern IT tend to disappear. Possible explanations from system science, cybernetics, action theory, and complexity science: The use of IT allows for new, innovative, and creative reactions to changes in markets and environments and appropriate competition changes. Such reactions require information processing before they can be realized. Competition is exceptionally dynamic, and this system dynamics should be measured predictively with mathematical models. Competition helps to create new, innovative products and services and is one of the facets of using information.

4.2. Price increase due to higher quality. Products and services of different qualities cannot be compared by their input-output relation. Possible explanations from system science, cybernetics, action theory, and complexity science: A product or service with better quality should be considered as a new product. The new product may solve other tasks, have other functions, have other stakeholders, and other requirements. For example, a traditional wired phone cannot be compared with a modern smartphone. The traditional one may be 1000 times cheaper and consume 1000 times less energy, but it cannot perform all the 1000 tasks that modern smartphones can. We should compare products and services by all possible functions, goals, and requirements they can fulfill in various and changed conditions. Such a measure is not a measure of economic efficiency but a more complex measure. For example, dynamic capability measures or the measure of the system potential can be used [21].

4.3. Monopolistic behavior. No comparison may exist for products and services of monopolists. Possible explanations from system science, cybernetics, complexity science, and activity theory: Regardless of market position, the use of information brings results. The measure of the correspondence of those results to changing market and environment conditions can be measured. This measure of correspondence can be enhanced in relation to the measure before the enhancement was made. The conceptual explanations provided should lead to further research, which could potentially lead to the creation of a modern theory capable of formally explaining the formation of information use and predicting the results of information use on mathematical models. Such formalisms, if created, could be used as part of system science, cybernetics, complexity science, and activity theory to build models of information use and methods to predict such use results.

III. CANDIDATE FORMALISMS TO OVERCOME THE EXISTING GAP

Based on a conceptual analysis of information use explanations and previous works [15], [22], [23], I suggest several directions for developing formal techniques to overcome the existing gap in information use research. These directions are listed below, with graph theoretic illustrations: 1. Modeling complex states of the system regarding information use, including information substates that may be obtained through information processing by means of information action. These substates are not obtained through measurement or direct reflection. The model is intended to capture the cause-and-effect relationships between information states obtained and other states of actions that can be further realized. Relations between such (information and “material” states) are shown as arrows in Figure 2. Such states and relations are, in general, nested ones.

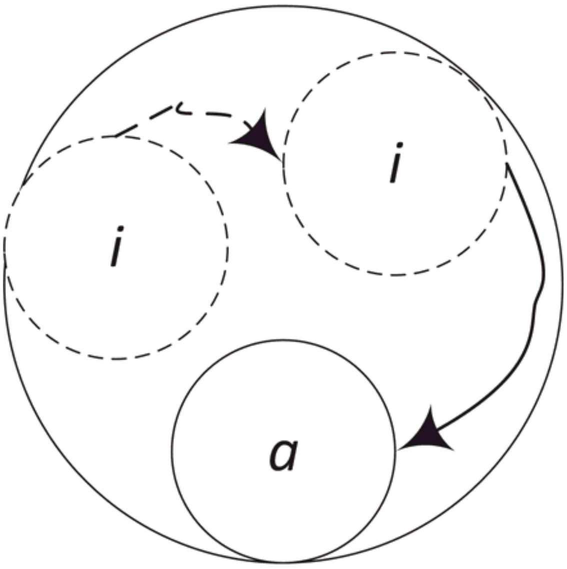

Fig. 2. Complex state with two information substates (dotted)

Substates may describe possible future desired and projected states, plans of actions to move the system to projected future states, and relations between possible projected states and actions performed according to plans. 2. Modeling transitions between complex states, due to both information and ”material” actions. The model is intended to capture purposeful changes of complex states, possible cause-and-effect relationships realized, and structures of such transitions. Example shown in Figure 3. It reflects the effect of the information action on projected states: due to information application substate of complex state can be realized in the example considered.

This schema is, in fact, one of a kind of possible metamodels of information application for the particular example. It allows model of information and “material” actions chains generation for different information inputs. Other metamodels may take the form of graph automata, which can be used for other kinds of information application.

3. Information use, causation, and computations are modeled during actions to represent various complexes of patterns of information use with cause-and-effect relationships (as shown in Figure 3) and complex structures of information use (as shown in Figure 4). Such models take the form of trees of possible scenarios of information application. Their

construction can be formalized, for example, with use of graph automata and graphoids.

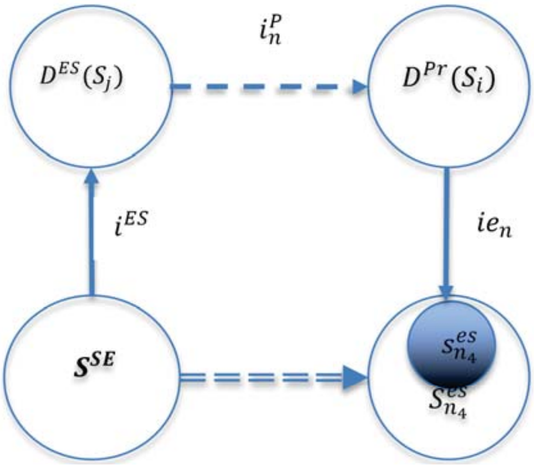

Fig. 3. Complex states transitions

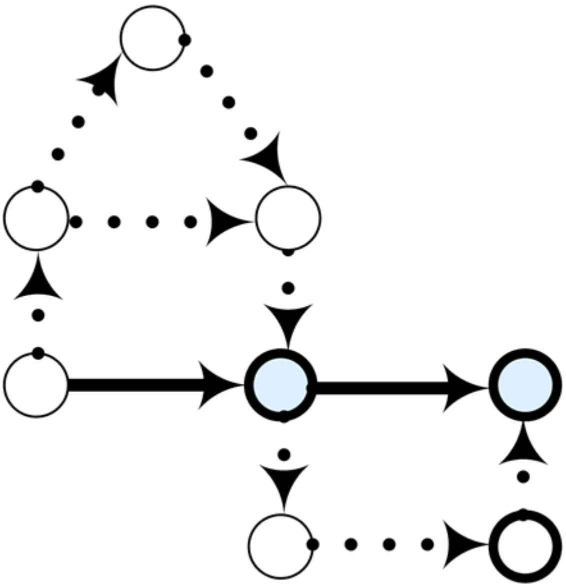

Fig. 4. Pattern of information Complex states transitions

4. Patterns-based parsing is used to generate models of information use by building models that capture the possible sequences of information obtained and the cause-effect relationships between different states that are realized because of this information use, as shown in Figure 5.

5. System structure and functions dynamics modelling with information use models. Such transition intended to build models of possible sequences of system and its functioning structures changes due to information obtained and cause-effects relations between states realized/changed because of this information use, as in Figure 6.

6. Possible structures (can be formalized as lattices) of information-effect chains can be generated to build tree-like complex graph theoretic models marked with entropy, efficiency, and capabilities measures. These models represent a special kind of lattice that reflects sequences of changes in entropy/efficiency/capability measures in the branches of a tree, depending on the information obtained and actions performed. The branching structure of the lattice-like models is suggested to reflect the actions taken and information obtained, which contribute to the changes in entropy, efficiency, and capabilities measures.

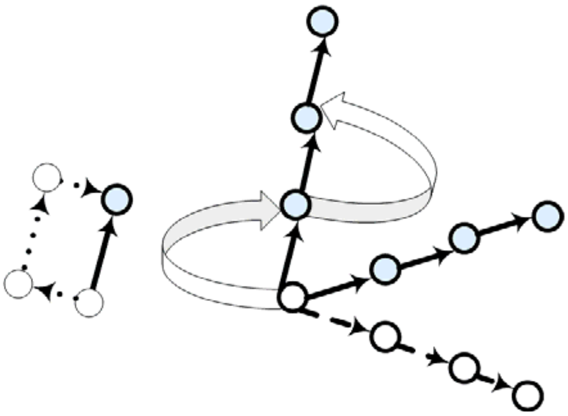

Fig. 5. These models are designed to alter possible complex states

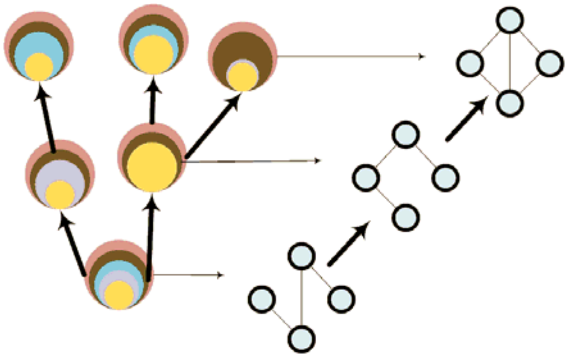

Fig. 6. Parsing system / functioning structures changes

7. Chains of entropy/efficiency measures can be computed to model cause-and-effect chains and changes in entropy and efficiency (capabilities) measures under changing conditions due to information use. These sequences of functional dependencies represent realized chains of complex states and are shown in equations 1 - 3. The details of the elements in these dependencies meaning can be found in [22]–[24]. These models provide a way to understand how information use affects system states and how those changes impact efficiency and entropy.

$$p_{n_i}(c_{n_i}) = \prod_{i=(1,I)} p_{n_i}(c_{n_i}) \tag{1}$$

$$\mu(c_{n_i}) = Poss(w(c_{n_i}) \sim r(c_{n_i})). \tag{2}$$

$$\Delta\xi(c_{n_i.1}, c_{n_i.j}) = \\ = \frac{\mu(c_{n_i.1}))p(c_{n_i.1}) - \mu(c_{n_i.j})p(c_{n_i.j})}{e(c_{n_i.1}) - e(c_{n_i.j})}. \quad (3)$$

8. To solve problems related to information use in systems actions, mathematical techniques from system science, cybernetics, and complexity science can be applied. Measures (1–3) can be used to solve various types of problems represented as mathematical tasks, such as optimization, operations research, and machine learning tasks. Objective functions used to represent these problems can take the form of equations 4, 5:

$$E(S,P,I) = \\ = - \sum_{c_{n_5} \in Tr(S,P,I)} p_{n_5}(c_{n_5}) log(p_{n_5}(c_{n_5}) \quad (4)$$

$$\mu(Tr(S,P,I)) = \\ = \sum_{c_n \in Tr(S,P,I)} \mu(c_n)p(c_n) \quad (5)$$

IV. CONCLUSIONS

The article provides an attempt for multidisciplinary and transdisciplinar, based on mathematical formalisms exploration of Solow's "information paradox" (1) in economic theory. Drawing insights from fields such as system science, cybernetics, complexity science, and action theory, the article develops formal representations and predictive explanations of information use with the goal of accurately predicting the impact of information use based on mathematical models. The author proposes a variety of new concepts and models to build such formalisms for accurate prediction, including a sequence of complex states and transitions that can be used to create graph theoretic and formal algebraic models that calculate quantitative measures of the success of information use in systems. Additionally, measures of entropy change caused by information use and a variety of graph theoretic models based on this concept can be used to represent possible chains of complex state changes and related complex measures of efficiency, capability, and entropy. This article presents an approach to solving the multidisciplinary problem of formally assessing information use using conceptual and mathematical models and methods to provide predictive insights. As a result, it is possible to address a variety of problems related to enhancing information use and purposefully altering systems and their functioning under changing conditions.

REFERENCES

[1] D. Acemoglu, D. Autor, D. Dorn, G. H. Hanson, and B. Price, "Return of the solow paradox? it, productivity, and employment in us manufacturing," *American Economic Review*, vol. 104, pp. 394–399, 2014.

[2] E. Brynjolfsson and L. M. Hitt, "Beyond computation: Information technology, organizational transformation and business performance," *Journal of Economic Perspectives*, vol. 14, pp. 23–48, 2000.

[3] R.-J. B. Jean, R. R. Sinkovics, and D. Kim, "Information technology and organizational performance within international business to business relationships," *International Marketing Review*, vol. 25, pp. 563–583, 2008.

[4] J. E. Triplett, "The solow productivity paradox: What do computers do to productivity?" *The Canadian Journal of Economics / Revue canadienne dEconomique*, vol. 32, p. 309, 1999.

[5] A. Bäck, A. Hajikhani, A. Jäger, T. Schubert, and A. Suominen, "Return of the solow-paradox in ai? ai-adoption and firm productivity: Papers in innovation studies." [Online]. Available: \url{https://EconPapers.repec.org/RePEc:hhs:lucirc:2022_001}

[6] S. Karanasios, "Toward a unified view of technology and activity," *Information Technology & People*, vol. 31, no. 1, pp. 134–155, 2018.

[7] A. B. Downey, *Think Complexity: Complexity Science and Computational Modeling*. O'Reilly Media, March 12, 2012.

[8] H. Töhönen, T. Itälä, T. Männistö, and M. Kauppinen, "Towards systemic evaluation of the business value of it," in *Proceedings of the Fifth International Symposium on Business Modeling and Software Design*. Setúbal: SCITEPRESS - Science and and Technology Publications, 06.07.2015 - 08.07.2015, pp. 163–170.

[9] H. Tohonen, M. Kauppinen, and T. Mannisto, "Evaluating the business value of information technology: Case study on game management system," in *2014 IEEE 22nd International Requirements Engineering Conference (RE)*. Karlskrona, Sweden: IEEE, 25.08.2014 - 29.08.2014, pp. 283–292.

[10] J. R. Talburt, *Entity resolution and information quality*. San Francisco Calif.: Morgan Kaufmann/Elsevier, 2011.

[11] C. Batini and M. Scannapieca, *Data quality: Concepts, methodologies and techniques / Carlo Batini, Monica Scannapieca*, ser. Data-centric systems and applications. Berlin and New York: Springer, 2006.

[12] Y. W. Lee, D. M. Strong, B. K. Kahn, and R. Y. Wang, "Aimq: a methodology for information quality assessment," *Information & Management*, vol. 40, no. 2, pp. 133–146, 2002.

[13] L. Floridi, "Information quality," *Philosophy & Technology*, vol. 26, no. 1, pp. 1–6, 2013.

[14] L. Floridi and P. Illari, *The Philosophy of Information Quality*. Cham: Springer International Publishing, 2014, vol. 358.

[15] A. Geyda and L. Fedorchenko, "Digital twins of activities: Role of information actions," in *2022 32nd Conference of Open Innovations Association (FRUCT)*. Tampere, Finland: IEEE, 09.11.2022 - 11.11.2022, pp. 102–111.

[16] R. P. Smiraglia, "The nature of information," in *Cultural Synergy in Information Institutions*, R. P. Smiraglia, Ed. New York, NY: Springer New York, 2014, vol. 57, pp. 9–16.

[17] V. Rusalov, "Functional systems theory and the activity-specific approach in psychological taxonomies," *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, vol. 373, no. 1744, p. 299–311, 2018.

[18] J. Thorp and Fujitsu Consulting's Center for Strategic Leadership, *The Information Paradox: Realizing the Business Benefits of Information Technology*. McGraw-Hill Ryerson, 2003. [Online]. Available: \url{https://books.google.ru/books?id=UF2BSnsF3nAC}

[19] P. A. Strassmann, *The Economics of Corporate Information Systems*. Information Economics Press, 2007. [Online]. Available: \url{https://books.google.ru/books?id=JHZEa8j3GIcC}

[20] R. Capello, C. Lenzi, and G. Perucca, "The modern solow paradox. in search for explanations," *Structural Change and Economic Dynamics*, vol. 63, no. 4, pp. 166–180, 2022.

[21] A. S. Geyda, "Toward the theory of using information for actions in systems: Prospects for research and reviews," *2021 30th Conference of Open Innovations Association FRUCT*, vol. 30, pp. 52–63, 2021.

[22] ——, "Families of alternative stochastic action networks: Use for process science," *FRUCT 28 Proceedings*, p. 9347589, 2021.

[23] A. Geyda and I. Lysenko, "System potential estimation with regard to digitalization: Main ideas and estimation example," *Information*, vol. 11, no. 3, p. 164, 2020.

[24] A. Geyda, "Concept and models of information application for actions in systems," *IJERTS*, 2023.