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Reverse stress testing of bank's credit portfolio based on system dynamics models of borrowers

Dissertation summary

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Relevance

Stress testing[1] is an important modern tool for analyzing the risks of financial organizations, which allows assessing stability concerning various potential scenarios that can cause sharp and significant (hereinafter referred to as shock) changes in significant factors of a particular type of risk. The classical procedure of capital stress testing, in particular, makes it possible to assess the level of unforeseen losses of the organization due to the realization of credit risk, due to the implementation of a specific stress scenario.

However, the financial crisis of 2008 revealed several shortcomings in this approach related to its low accuracy in a rapidly changing economic environment. The fact is that stress scenarios of risk factors developed as a result of macroeconomic analysis differ significantly from shock events that occur. On the other hand, stress tests based on historical data on changes in risk factors may not fully take into account all the conditions and nuances of the upcoming economic crisis. Stress testing methods based on testing hypothetical scenarios also face the problem of assessing the probability of considered hypothetical shock events. Therefore, at present, regulators of the banking sector, as one of the main risk assessment procedures, require banks to conduct *reverse stress testing*[2].

Reverse stress testing consists in constructing the most realistic shock scenarios, leading to a given level of financial losses, or in constructing the most dangerous stress scenarios that maximize financial losses within a given probability criterion. Results of reverse stress testing can be used, in particular, for making management decisions, allowing to mitigate consequences of negative scenarios realization.

As part of the credit risk assessment, the reverse stress testing of the loan portfolio is carried out, which consists of the construction of stress scenarios that

[1] Principles for sound stress testing practices and supervision / Basel committee on banking supervision. 2009. [Электронный ресурс]. – URL: https://www.bis.org/publ/bcbs147.pdf (дата обращения 09.10.2018).

[2] Guidelines on stress testing / Committee of European banking supervisors. 2010. [Электронный ресурс]. – URL: https://www.eba.europa.eu/documents/10180/16094/ST_Guidelines.pdf (дата обращения 09.10.2018).

cause unexpected losses that arise due to the default of borrowers, forming a loan portfolio.

This work demonstrates the possibility of solving the problem of reverse stress testing for a bank's loan portfolio based on system dynamics models of borrowers[3].

System dynamics is a simulation modeling paradigm designed to describe the structure and dynamics of complex systems based on the concept of flows, stocks and feedback loops, which corresponds to a formal representation in the form of a system of differential equations. This method was first proposed by Jay Forrester in the 1950s to analyze employee turnover in a company with which he worked. Using the system dynamics models, he was able to show that the main cause of job instability was related to the internal structure of the firm itself and did not depend on external factors. In subsequent years, the idea of representing complex objects and phenomena in the form of system dynamics models was actively spread, with formal descriptions and own computer modeling tools.

The development of a system dynamics model involves describing the structure of the object or phenomenon under study in the form of flow diagrams, as well as determining the characteristics of the interaction of its various parts. The model presented in this form is refined using computer simulation, testing various hypotheses about its behavior and checking the relationships built on historical data.

Thus, the solution to the optimization problem of reverse stress testing of the loan portfolio based on system dynamics models is the current research at the moment.

Problem statement

Existing shortcomings of stress testing make banks conduct the procedure of reverse stress testing, which consists of the construction of stress scenarios, having certain properties of probability and danger, expressed in financial losses of the

[3] Forrester J. W. Industrial Dynamics / MIT Press. 1961.

bank. However, not all models of credit risk assessment, common at the moment, are adapted to the tasks of reverse stress testing. For example, models may not take into account peculiarities of the organizational and business structure of particular companies, do not allow to study of the development of crisis phenomena in time and/or assume the obligatory presence of large data samples of similar enterprises and situations. Therefore, at the moment there is an urgent need to create and develop methods, implement the procedure of reverse stress testing, and solve at least part of these problems.

The purpose and objectives of the study

This dissertation work aims to develop and study an algorithm for solving the problem of reverse stress testing of the loan portfolio represented by system-dynamic models of borrower enterprises. To achieve the goal of the research the following tasks were set:

1. Build system dynamics models of enterprises from several key sectors of the Russian economy, taking into account the structure and dynamics of the production and financial activities of each company. To carry out the analysis of the obtained models.
2. Construct a multivariate ARIMA-GARCH model of macroeconomic variables, which is the basis for building scenarios of significant credit risk factors, capable of causing maximum financial losses to the loan portfolio as a result of borrower's defaults.
3. Develop and study an algorithm, based on the principles of approximate dynamic programming and solving the problem of reverse stress testing. Study key properties of the obtained algorithm.
4. Implement the developed method employing modern programming tools and conduct several numerical experiments, realizing the procedure of reverse stress testing based on the obtained algorithm and using the constructed system dynamics models. Compare the results of the developed method with the classical genetic algorithm.

Level of development of the problem

The main approaches to the modeling of credit risk are devoted to many scientific papers, in particular, the articles Sorge M.[4], Quagriariello M.[5] и Drehmann M.[6]. The key object of analysis considered in the mentioned works is stress testing, which allows to calculate the level of losses of financial organizations, caused by the implementation of a particular stress scenario. In the mentioned works the basic methods used within stress testing are described and their classification is given.

However, they do not describe reverse stress testing, the key aspects of which are contained in the methodological guidelines for banks by banking regulators[7,8,9]. Despite the importance of reverse stress testing, not much research has been devoted to this procedure. In the works Flood M.D., Korenko G.G. and Glasserman P., Kang C., Kang W. outline and explore the basic concept of this approach. The authors of the first paper[10] describe an algorithm for constructing the most plausible macroeconomic scenarios with a known distribution of risk factors, leading to a fixed level of financial losses. The second paper[11] is devoted to describing approaches to building stress scenarios with an unknown distribution of risk factors, leading to a given level of losses. An alternative approach[12] that solves the problem of identifying macroeconomic scenarios of risk factors that maximize financial losses of the loan portfolio and satisfy a given level of plausibility has been proposed. These works are mainly theoretical. The structure and dynamics of

[4] Sorge M. Stress-testing financial systems: an overview of current methodologies // BIS Working Papers. - 2004. - N 165.

[5] Quagriariello M. Stress-testing the banking system: methodologies and applications / Cambridge University Press. 2009.

[6] Drehmann M. Macroeconomic stress-testing banks: a survey of methodologies. In Stress-testing the Banking System: Methodologies and Applications / edited by Quagliariello M. Cambridge University Press. - 2009.

[7] Supervisory and bank stress testing: range of practices / Basel committee on banking supervision. 2017. [Электронный ресурс]. – URL: https://www.bis.org/bcbs/publ/d427.pdf (дата обращения 09.10.2018).

[8] Указание Банка России от 07.12.2015 N 3883-У [Электронный ресурс]. – URL: http://www.consultant.ru/document/cons_doc_LAW_190733/ (дата обращения 09.10.2018).

[9] Указание Банка России от 15.04.2015 N 3624-У [Электронный ресурс]. – URL: http://www.consultant.ru/document/cons_doc_LAW_180268/ (дата обращения 09.10.2018).

[10] Flood M.D., Korenko G.G. Systematic scenario selection: stress testing and the nature of uncertainty // Office of financial research. – 2013.

[11] Glasserman P., Kang C., Kang W. Stress scenario selection by empirical likelihood // Office of financial research. 2012.

[12] Breuer, T., Jandacka, M., Mencia, J., and Summer, M. A systematic approach to multi-period stress testing of portfolio credit risk. Technical Report Working Paper 1018 // Banco de Espana. – 2010.

specific companies in these works are not considered. The potential mutual influence of macroeconomic factors that make up the stress scenarios is also not assessed.

Author's contribution to the issue

The personal contribution of the applicant consists of direct participation in the formulation of research tasks and obtaining the results described in the paper. The author has developed and proposed an algorithm that implements the procedure of reverse stress testing; implemented the above algorithm by writing appropriate code in Matlab programming language; conducted experiments and tested the described approach; prepared the text of articles with research results; prepared visualization of research results to present them at Russian and international conferences, as well as at numerous scientific seminars.

The author of the research analyzed the results and formulate conclusions for the dissertation work.

Description of research methodology

When solving the problems we used mathematical methods of operations research, including simulation modeling, mathematical modeling, optimization theory, probability theory and mathematical statistics, statistical methods of time series analysis and regression analysis, as well as programming methods.

The main results to be defended

1. Field of modeling:

1.1. System dynamics models of companies from different sectors of the Russian economy, describing the structure and dynamics of the studied enterprises, were developed and investigated. Models are used to set the target function for reverse stress testing.

1.2. The possibility of using a system dynamics model to estimate the probability of a relevant company default is demonstrated. The closeness of the

obtained assessments of the default probability to the corresponding assessments of the rating agencies testifies to the adequacy of the model to the real realization of the credit risk of borrower enterprises.

1.3. The multivariate ARIMA-GARCH model, which is the basis for macroeconomic stress scenarios of risk factors, is identified.

2. Field of numerical methods:

2.1. A method for solving the optimization problem of reverse stress testing, which belongs to the class of approximate dynamic programming methods, is developed.

2.2. Assertions allowing concluding the properties and applicability of this algorithm are proved. These statements describe the properties of functions appearing in subtasks of the developed algorithm and substantiate the correctness of the application of the sequential quadratic programming method to these subtasks.

3. Programming:

3.1. A research software package that implements the developed algorithm and provides the ability to conduct experiments that evaluate the effectiveness of the method is created.

3.2. Results confirming the advantage of the developed algorithm over the classical genetic algorithm in running time and finding stress scenarios that lead to the greatest losses are obtained.

Scientific novelty

1. Field of mathematical modeling:

1.1. A new approach to the reverse stress testing procedure that takes into account the structure of borrower enterprises and the dynamics of their indicators over time is proposed.

1.2. System dynamics models of enterprises are developed which provide the opportunity to analyze the production and financial activities of the companies under study.

1.3. The possibilities of using system dynamics model for the estimation of enterprise bankruptcy probability are demonstrated. The adequacy of system-dynamic models is confirmed by comparing the estimates of enterprise default probability obtained using the developed models with the corresponding estimates obtained by rating agencies.

1.4. The multivariate ARIMA-GARCH model, which is the basis for determining the scenarios of risk factors that cause maximum financial losses of the loan portfolio, is identified.

2. Numerical methods:

2.1. Method of solving the optimization problem of reverse stress testing of bank loan portfolio based on system-dynamic models of borrowers is developed and investigated.

2.2. The statements which allow to conclude properties and applicability of the given method have been proved. These statements indicate the properties of the functions appearing in the subtasks of the developed algorithm, and substantiate the correctness of the application of the method of sequential quadratic programming to these subtasks.

3. Programming:

3.1. A research software package, which implements the obtained algorithm and allows to build of scenarios of reverse stress testing, is created.

3.2. Numerical experiments of building reverse stress testing scenarios for a loan portfolio of six borrowers over a time horizon of five years have been carried out, which demonstrate the application of the developed method to the task of building macroeconomic scenarios. The results of the developed numerical method are compared with the results of solving the problem using the classical genetic algorithm.

General conclusions of the study

Within the framework of the present dissertation research the following scientific tasks are realized:

1. The system dynamics models of borrowers are developed, and the general approach to the construction of system dynamics models of borrowers used to solve the optimization problem of reverse stress testing of the loan portfolio is presented. The system dynamics models of companies are presented, and the potential possibility of their use for estimating the probability of default of the company is presented.

2. An algorithm is developed that allows to formation of scenarios that can lead to a credit portfolio loss, which corresponds to the local extremum of the optimization problem. At the same time, the given level of the plausibility of scenarios is provided. The proved statements justify the correctness of some stages of the developed algorithm.

Results of the algorithm's application can be used for making management decisions which allow to mitigate consequences of the implementation of obtained scenarios.

3. The multivariate ARIMA-GARCH model, which is used in the described algorithm of reverse stress testing as a basis for scenarios of risk factors maximizing financial losses of the loan portfolio, is identified.

4. A research software package corresponding to the developed method is presented, which allows obtaining stress scenarios as a result of the inverse stress testing procedure.

List of published articles reflecting the main scientific findings of the dissertation

Works published by the author in peer-reviewed scientific journals included in the international citation system Scopus:

1. **Kurennoy D.** The use of the system dynamics model to determine the probability of company default / Kurennoy D., Golembiovsky D. // IOP Conference Series: Materials Science and Engineering. 2021. Vol. 1047. No 1. 012033. P. 1-9.

Works published by the author in a peer-reviewed scientific journal included in the list of recommended journals of the National Research University Higher School of Economics:

2. **Kurennoy D.**, Golembiovskiy D. Construction of business default scenarios based on system dynamics models // Journal of applied informatics. 2017. №05. С. 11-28.

Works published in other publications:

3. **Kurennoy D.**, Golembiovskiy D. System dynamics credit risk model of an oil company // Issues of risk analysis. 2017. №01. С. 6-22.
4. **Kurennoy D**., Golembiovskiy D. Estimating the probability of oil company default based on system dynamics model // Issues of risk analysis. 2018. №02. С. 86-92.
5. **Kurennoy D.** Algorithm for solving the reverse stress testing problem of the bank's loan portfolio on basis of system dynamic models of borrowers // International Journal of Open Information Technologies. 2018. №10. С. 9-21.
6. **Kurennoy D**. Algorithm for solving the optimization problem of reverse stress testing of the loan portfolio // Tikhonov readings: Научная конференция / Lomonosov Moscow State University. – М.: MAKS Press, 2018.
7. **Kurennoy D.** System dynamics credit risk model of a corporate borrower // VIII Moscow International Conference on Operations Research (ORM 2016): Moscow, October 17-22, 2016: PROCEEDINGS: Vol.1. – М.: MAKS Press, 2016. P. 102-104.
8. **Kurennoy D**., Golembiovskiy D. Estimating the probability of company default based on system dynamics model. // IX Moscow International Conference on Operations Research (ORM 2018): Moscow, October 22-27, 2018: PROCEEDINGS: Vol.1. – М.: MAKS Press, 2018. P. 218-222