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Automation of the high-level network-on-chip modeling

Dissertation summary
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Candidate of Technical Sciences,
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The relevance of research

Due to the constant increase in the complexity of the tasks being solved and in the volume of processed information, as well as in order to reduce the time of information processing, the requirements for the performance of computing systems are constantly growing. Single-processor systems cannot always cope with the tasks that require high computing performance and are inefficient when working with the large data streams. Increasing the performance of the computing systems by increasing the density of the transistors is no longer possible, which has led to the evolution of computing systems based on multi-core and multi-threading, as well as the use of specialized computing cores and computing accelerators. A striking example of an extensive increase in the number of cores on a single chip is the WSE2 chip from Cerebras. This chip is made on a 7 nanometer process technology and consists of 850,000 computing nodes. There is also a trend to replace the cumbersome CISC architecture with the networks of RISC architecture processor cores. This implies an increase in the requirements for the communication subsystem to combine many heterogeneous cores into one system - a network-on-chip (NoC).

The NoC design can be divided into several main successive stages: specification, design, high-level (h/l) modeling, low-level (l/l) modeling, prototyping or co-simulation, and production.

The stage of h/l modeling allows selecting a limited number of sets of parameters and characteristics of the network suitable for further design specified at the stages of drawing up the terms of reference and NoC design. Mistakes at the stage of l/l modeling are costly as h/l modeling is a much longer and labor-intensive process. For example, a 100-node network modeling using a h/l OCNS (On Chip Network Simulator) may take a few minutes, while l/l modeling of the same network in ModelSim takes several days.

It should also be noted that different l/l models solve different, often highly specialized, tasks; there are many different NoC modeling automation tools and

other support tools created by different developers. But at the same time, there is no single universal trend that combines various approaches in the implementation of the NoC design automation systems at the architecture level, which would allow implementing the principle of end-to-end NoC design, where different models and design automation tools could be used at different stages of development, and at the same time compatibility through universal interfaces and data presentation could be provided. Thus, the development of the accurate and high-performance h/l NoC models, as well as unified means for processing the results of their work and automating the process of h/l modeling, is an important and relevant scientific and practical task.

The degree of research topic elaboration

A significant contribution to the development of h/l modeling was made by such well-known foreign scientific teams and scientists as: A. Colaso, P. Fidalgo, J. Gregorio, L. Menezo, P. Prieto, V. Puente (the developers of the TOPAZ model); M. Jones (the developer of the NoCsim model); M. Ahmed, M.M. Akbar, A. Al-Nayeem, H. Hossain, T.Z. Islam (the developers of the gpNoCsim model), and others. Of the Russian teams working on the problem of h/l modeling, we can distinguish: N.M. Myachin, A.Yu. Romanov, A.M. Sukhov (the developers of the NewXim model); as well as A.Yu. Romanov is the developer of the UOCNS model. The scientists, who also work in the field of the NoC design, are: S.O. Bykov, A.D. Ivannikov, A.S. Kozhin, E.S. Kozhin, E. Short, A.N. Lysenko, O.G. Monakhov, E.A. Monakhova, Yu.A. Nedbaylo, A.L. Pereverzev, E.V. Primakov, Yu.V. Savchenko, E.A. Suvorova, S.R. Tumkovsky.

Among foreign colleagues, working in the field of NoC design, we can distinguish: N. Bagherzadeh, L. Benini, D. Bertozzi, S. Chattopadhyay, M. Daneshtalab, G. De Micheli, M. Ebrahimi, A. Ganguly, K. Goossens, H.X. Gu, A. Jantsch, P. Liljeberg, W.C. Liu, A. Louri, Z.H. Lu, T. Mak, R. Marculescu, S. Murali, M. Palesi, P.P. Pande, S. Pasricha, J. Plosila, H. Sarbazi-Azad, H. Tenhunen, K. Wang, N. Wu, J. Xu, L. Yang, M. Yang, Y.T. Yang, L. Zhang.

Usually, simulation models are used at the stage of the h/l modeling. The NoC simulation model is the one that describes the main simulated network elements and sets the rules for the interaction between them. As a rule, the h/l models are used to describe the process of the data transfer to a NoC and obtain the preliminary estimates of its performance under the given parameters. The data transfer process is a critical element in the functioning of the network. At the stage of the h/l modeling, the accuracy of representation of some aspects of the network operation can be neglected by increasing the speed of the calculation of the characteristics.

Analyzing the degree of development of the topic of this study, it should be noted that at present, there are many top-of-the-line models proposed for the practical use for NoC modeling. The author of the work has studied more than 100 different implementations of the h/l models which can be used for a NoC. They differ in the functionality, development languages, modifiability, supported NoC topologies, packet switching methods, router architectures, traffic types, supported routing algorithms, traffic arbitration algorithms, areas of application of simulation results, and many more parameters. At present, the apparent diversity has not led to the emergence of any universal model that would support all kinds of the NoC characteristics and perform their calculation. Typically, the model is selected, depending on the technical requirements and decisions made at the design stage. At the same time, most models do not have any built-in tools for automating calculations (for example, the ability to run several models at the same time or automatically select parameters, depending on the goals of modeling).

From the foregoing, it follows that there is a need to create the new tools and methods for automating the NoC modeling, as well as creating of unified CAD tools for conducting research on the characteristics and NoC design; i.e., there is a need to create a CAD system that would be able to combine and allow comparing several h/l models, as well as to make it possible to compare the results of their work, thereby increasing the accuracy of modeling. Also, the combination of many h/l models in a single CAD system will reduce the simulation time by applying various optimization methods when searching for the various NoC parameters.

Thus, the **problem** solved by this dissertation research is the existence of many heterogeneous h/l NoC models and the absence of a CAD system that would allow them to be combined within a single design environment, evaluate the reliability of the results, and save the results of previous modeling cycles. This defines the object and subject of research:

The **object** of research is the process of transferring the data in the NoCs.

The **subject** of research is h/l NoC modeling.

The purpose and research problems

The purpose of research is to improve the accuracy, speed of obtaining, and reproducibility of the results of the h/l modeling by combining various h/l models of the data transfer to the NoC in a single CAD system by developing automation tools and analyzing the results of the h/l NoC modeling.

This purpose is achieved by sequentially solving the following logically linked tasks:

– analysis of the classic NoC design cycle, substantiation of the NoC end-to-end design methodology between the stages of the h/l and l/l computer simulation;

– development of a methodology for the synthesis and modification of the h/l simulation computer models that combines them into a single CAD of the NoC design;

– development of a new CAD architecture, which differs from the existing ones by using the end-to-end design methodology for transferring the data between the h/l and l/l computer modeling stages and by the presence of a seamless interface for working with the various h/l models and a decision support system (DSS);

– creation of the application software that implements the CAD that supports the multiple launch of models, comparison and unified processing of the results of h/l modeling;

– development of DSS based on the analysis of the influence of various NoC parameters on their final performance;

– approbation and implementation of the research results exemplified by solving the problem of analyzing the influence of various input modeling parameters on the output NoC characteristics.

Research methodology and methods

The dissertation is based on the methods of simulation modeling, parallel computing, Monte Carlo, binary search, methods of structured and object-oriented programming, statistical processing, and comparative data analysis.

Author's personal contribution

All the results and provisions, submitted for the defense, were obtained by the author personally. Based on a deep and comprehensive review and analysis of the subject area, a study of literature sources and features of the NoC design, the problem in the absence of CAD for h/l NoC modeling and methods for optimizing the modeling process to reduce time costs and increase the modeling accuracy was identified.

The author personally formulated the object of research, identified the problem and disclosed the subject of research as a description of the means for solving the scientific problem of automating the stage of high-tech modeling in the NoC design.

The purpose of the work was set and a logically linked set of tasks for its achievement was defined; when solving them, the author personally obtained the new scientific results which are of great scientific and practical importance for the electronics design industry.

The author's personal contribution is also reflected in a sufficient number of publications in the peer-reviewed and indexed journals.

The main results of research

1. Based on the review of literature and an analysis of the current state of the problem of automation of h/l NoC modeling, the scientific task of the dissertation research was formulated.

2. The review and analysis of the h/l models was carried out, which made it possible to highlight the common characteristic features of the models and develop a methodology for ensuring the functioning of several models within one CAD.

3. The CAD architecture was developed that allows combining several models within one design environment, applying optimization and automation methods when searching for the NoC parameters, saving, processing, and reusing the simulation results.

4. Based on the results of NoC modeling with different conditions, regularities were derived that formed the basis of the DSS, which allows choosing the best option for launching the set of h/l models in terms of a combination of the parameters.

5. Experimental studies, confirming the reliability of the results obtained and the effectiveness of the practical application of the developed CAD, were carried out.

6. The results of the research were tested at significant all-Russian and international conferences and found support among the scientists and specialists in the field of design automation and modeling digital systems and NoCs.

The **reliability** and **validity** of the results obtained is confirmed by the correctness of the problem statement and the applied research methods, the consistency of the experimental results using modern and widely tested design and mathematical modeling tools.

The reliability is also confirmed by approbation of the main results of the work over a number of years at many all-Russian and international conferences and publications in the peer-reviewed journals indexed in international and domestic citation databases WoS, Scopus, and RSCI. The new results, proposed in the research, were introduced into the educational process at the MIEM HSE University and applied in the research projects of the CFS of the HSE University and in the design work of the MIEM HSE University, which is confirmed by the relevant acts:

– the act of introduction into the educational process of the Department of Computer Engineering of the Moscow Institute of Electronics and Mathematics of the National Research University Higher School of Economics. The implementation of the results of the research made it possible to use modern theoretical and practical developments in the field of NoC modeling in the educational and scientific activities of students of the Department of Computer Engineering. The developed CAD system is used by students to study various NoC configurations and apply their theoretical knowledge in the field of graph theory in the practice of research and development of routing algorithms for the various topologies;

– the act on the use of the results of the dissertation in the project work "Hardware and software complex for training in remote access to laboratory equipment". The results of the research are used in part of laboratory work adapted to be performed on the equipment of a CAD laboratory in a remote mode, which opens up new opportunities for studying of the NoCs;

– the research project of the CFS of the HSE University "Synthesis of circulant topologies for application in networks-on-chip", reg. No. R&D AAAA-A18-118051690145-1, 01.02.2018–29.12.2018;

– the research project of the CFS of the HSE University "Modeling networks-on-chip with a communication subsystem based on circulant topologies", reg. No. R&D AAAA-A19-119061490099-1, 01.02.2019–31.12.2019;

– the research project of the CFS of the HSE University "Development of a hybrid model for the design and simulation of networks-on-chip", reg. No. R&D AAAA-A20-120070390136-2, 03.02.2020-31–31.12.2020;

– the research project of the CFS of the HSE University "Development of routing algorithms in networks-on-chip", reg. No. R&D 121051100322-4, 01.02.2021–31.12.2021.

Scientific novelty of research is there were developed:

1. The end-to-end design method that differs from others by the automated data transfer between the h/l and l/l simulation stages and allows reducing the time of data transfer between the simulation stages by 80%.

2. The CAD architecture that allows multiple launching of the h/l models (based on the use of processor architectures that support multithreading) and comparison of simulation results, their unified processing, as well as makes it possible to increase the simulation speed up to 3 times.

3. The CAD software integrated with dichotomy, Monte-Carlo, ascending accuracy and similarity methods, which reduces the time of parameter selection up to 8 times.

4. The automated DSS based on data clustering and supporting the adoption of multi-criteria decisions based on the user-specified parameters of the models used and the modeling constraints.

Theoretical significance and practical usefulness

The theoretical significance of the study lies in the development of the NoC end-to-end design theory and optimization methods that reduce the time costs and improve modeling accuracy. The practical utility is:

– the software that allows synthesizing a task for the l/l simulation based on the results of the h/l simulation was developed;

– the method for adding the models to the CAD of h/l simulation, which allows adding an unlimited number of new models to CAD and expanding its functionality was developed. As part of the dissertation, 6 new models were added which provide the research with all the main NoC characteristics;

– the developed mathematical software as part of CAD allows you to increase the accuracy up to 5 times and increase the simulation speed up to 6 times.

Provisions to be defended

1. End-to-end NoC design methodology based on two-way communication via data transfer between the h/l and l/l stages of NoC modeling.

2. Methodology for the synthesis and modification of h/l models combined as part of a single integrated CAD system for the NoC design.

3. The CAD for the h/l NoC simulation supporting multiple model launch, comparison, and unified processing of simulation results.

4. The automated DSS for analyzing the influence of NoC parameters on its final characteristics.

5. The developed software as part of the CAD for formalizing the estimation of the accuracy and time of modeling.

Work approbation

The main results of the research were reported and discussed at the all-Russian and international conferences:

1. Moscow Workshop on Electronic and Networking Technologies (MWENT), Moscow, Russia, June 9–11, 2022 the report “Automation of NoC throughput search in high-level modeling”;

2. International Russian Automation Conference (RusAutoCon), Sochi, Russia, September 5–11, 2021; the report “Universal On-Chip Network Simulator for Networks-on-Chip Developmen”;

3. All-Russian scientific and technical conference “Problems of advanced micro- and nanoelectronic systems development (MES), Zelenograd, IDPM RAS, March 1 – November 1, 2021; the report “Automation of h/l modeling of networks-on- chip”;

4. Scientific and technical conference of students, graduate students, and young professionals HSE University named after. E.V. Armensky, Moscow, HSE University, February 18–28, 2019; the report “Development of a routing algorithm in the third-order circulants”;

5. VII International Scientific and Practical Conference “Actual problems of system and software engineering (APSSE-2021)”, Moscow, Russia, November 12–14, 2019; the report “Modification of the BookSim simulator for modeling networks-on-chip based on two dimensional circulant topologies”.

The results of the research are reflected in 12 published works, 7 of which are indexed in the international scientometric databases (WoS, Scopus, IEEE Xplore).

List of published articles reflecting the main scientific findings of research

The author's works published in the peer-reviewed scientific journals included in the international citation system Web of Science and Scopus:

1. Romanov, A.Yu. Development of routing algorithms in networks-on-chip based on two-dimensional optimal circulant topologies / A.Yu. Romanov, E.V. Lezhnev, A.Yu. Glukhikh, A.A. Amerikanov // Heliyon, 2020. – Vol. 6. – No. 1. – P. e03183. (Q1 Scopus, WoS).

2. Amerikanov, A.A. Automation of NoC throughput search in high-level modeling / A.A. Amerikanov, A.S. Ponomarev, T.V. Tarzhanov // 2022 Moscow Workshop on Electronic and Networking Technologies (MWENT). – IEEE, 2022. – P. 1–5. (Scopus).

3. Amerikanov, A.A. Universal On-Chip Network Simulator for Networks-on-Chip Development / A.A. Amerikanov, A.S. Ponomarev // International Russian Automation Conference (RusAutoCon). – IEEE, 2021. – P. 677–682. (Scopus).

4. Ryazanova, A.E. Development of multiprocessor system-on-chip based on soft processor cores schoolMIPS / A.E. Ryazanova, A.A. Amerikanov, E.V. Lezhnev // Journal of Physics: Conference Series, 2019. – Vol. 1163. – No. 1. – P. 012026. (Q4 Scopus).

5. Romanov, A.Yu. Modification of the BookSim simulator for modeling networks-on-chip based on two dimensional circulant topologies / A.Yu. Romanov, E.V. Lezhnev, A.A. Amerikanov // Proceedings of the 6th International Conference Actual Problems of System and Software Engineering (APSSE). – Moscow: HSE University, 2019. – Vol. 2514. – Ch. 107. – P. 182–192. (Scopus).

6. Schegoleva, M.A. Routing in Networks on Chip with Multiplicative Circulant Topology / M.A. Schegoleva, A.Yu. Romanov, E.V. Lezhnev,

A.A. Amerikanov // Journal of Physics: Conference Series, 2019. – Vol. 1163. – No. 1. – P. 012027. (Q4 Scopus).

7. Amerikanov, A.A. Analysis of Approaches for Synthesis of Networks-on-chip by Using Circulant Topologies / A.Yu. Romanov, A.A. Amerikanov, E.V. Leghnev // Journal of Physics: Conference Series, 2018. – Vol. 1050. – No. 1. – P. 1–12. (Q4 Scopus).

The author's other works:

8. Americanov, A.A. Automation of high-level modeling of networks-on-chip // Problems of advanced micro- and nanoelectronic systems development. – 2021 (MES-2021). – Moscow: IDPM RAS, 2021. – No.1. – P. 39–45.

9. Fedotova, A.A. Development of a hybrid network model on-chip / A.A. Fedotova, A.O. Zavialov, A.A. Americanov // System administrator. 2019. – No. 07–08. – P. 110–114.

10. Sidorenko, M.V. Development of a routing algorithm in circulants of the third order / M.V. Sidorenko, A.A. Americanov // Interuniversity scientific and technical conference of students, graduate students, and young professionals HSE University named after. E.V. Armensky. – Moscow: HSE University, 2019. – P. 82–83.

11. Ponomarev, A.S. Development of a unified environment for the high-level modeling of networks-on-chip / A.S. Ponomarev, A.A. Americanov // Interuniversity scientific and technical conference of students, graduate students, and young professionals HSE University named after. E.V. Armensky. – Moscow: HSE University, 2021. – P. 74–75.

Copyrights and Patents:

12. Certificate of state registration of the computer program 2021668288 "Universal environment for high-level modeling of networks-on-chip Universal High-Level Network-on-Chip Simulator (UHLNoCS)". Authors: A.A. Americanov, A.Yu. Romanov, A.S. Ponomarev; applicant and copyright holder Federal State Autonomous Educational Institution of Higher Education National Research

University Higher School of Economics (RU). – No. 2021667238; dec. 11/01/21; publ. 12.11.21, Register of computer programs.

Contents

The dissertation consists of an introduction, five chapters with conclusions, a conclusion, a list of references, and an appendix with the acts of implementation of the research results.

The **introduction** substantiates the relevance of the dissertation topic, formulates the purpose and objectives of the study, determines the scientific novelty and practical value of the results obtained, and provides the data on their approbation.

Chapter 1 is devoted to the review and analysis of the subject area based on the study of literature and modern experience in the NoC design. The analysis of the classic NoC design cycle was carried out; it consists of the following stages: the preparation of technical specifications, design, h/l modeling, l/l modeling, prototyping or co-simulation, and production stage.

It is shown that the l/l modeling is an important step in the NoC design (Fig. 1). The cost of an error at this stage is very high, since it leads to an additional l/l simulation, which is several orders of magnitude more time consuming than the h/l simulation.

The statement of the problem of scientific research is formulated and brief conclusions on the chapter are presented.

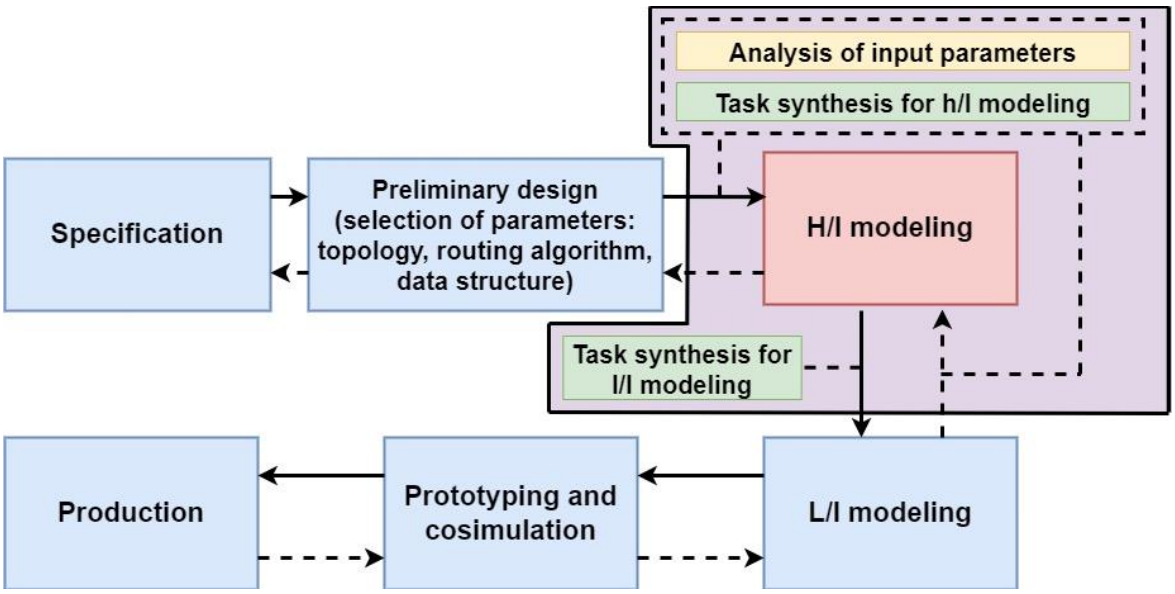

Fig. 1. Diagram of the typical NoC design.

Chapter 2 provides an overview of the most well-known h/l NoC models; it shows that there are a large number of different solutions and approaches to conducting, automating and analyzing the results of the h/l NoC simulations. The considered models mainly support a limited number of topologies, which limits their application for the arbitrary topologies. As it follows from the review, out of more than 100 considered topologies, only 22% support the arbitrary topologies. The same applies to the output characteristics of the models. It is also worth noting that the arbitrary packet routing algorithms in the network are supported by only 8% of the considered models. In addition to such significant indicators as topology and routing algorithm, the following parameters should also be taken into account: the switching method, router architecture, arbitration algorithm, which are also not supported by all the models. In this regard, there is a need to analyze and refine the existing h/l models that could calculate all the most significant output characteristics for the NoCs with the arbitrary topologies.

It also follows from the review that the models mainly solve the particular problems; there are no exhaustive and universal models, all of them are not standardized and often not compatible with each other. In order to simulate the NoC with one's own combination of the topology parameters, routing type, traffic control and generation method, arbitration, etc. one needs to create one's own model or modify the existing one. At the same time, there are practically no simulation

automation tools that would facilitate the analysis of simulation results and their verification, multiple launch of the model with different parameters, etc. There are no means of integrating models with each other. This state of the problem area determines the need to develop the CAD system that would allow solving the identified problems.

Chapter 3 is devoted to the development of the CAD for the NoC simulation. The architecture was proposed, and the generalized algorithm of the CAD operation was formalized; the latter implements the division of the system into blocks dedicated to the stages of synthesis and analysis, due to which it allows combining a lot of top-of-the-range simulation models within a single modeling environment (Fig. 2).

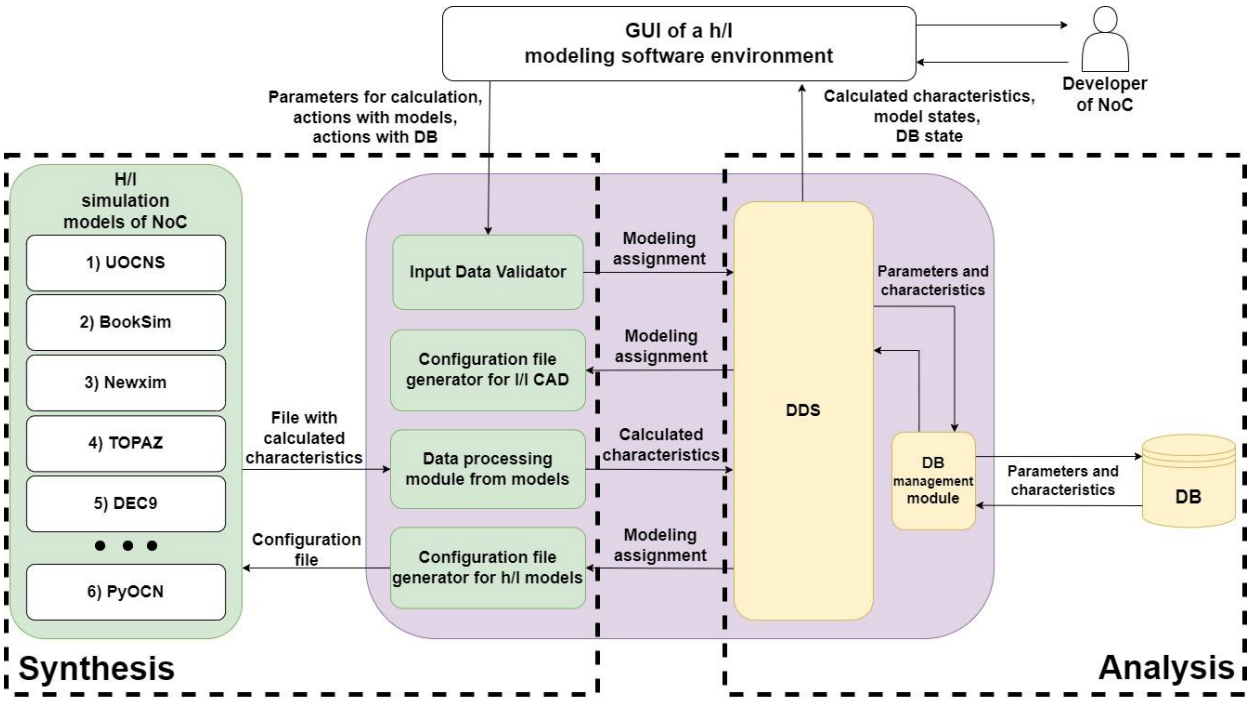

Fig. 2. Architecture of the CAD developed.

The method for adding the h/l models to CAD of the h/l modeling was proposed, due to which 6 of the most relevant NoC models were integrated into the created CAD system that covered all the main NoC characteristics. At the same time, thanks to the developed methodology and modular organization, the CAD can always be easily supplemented with the new models without losing its functionality and previous results.

Chapter 4 is devoted to the implementation of the single CAD system, where several models can be executed simultaneously; the creation of the unified system for presenting the model parameters and simulation results opened up the possibility of using various methods for the automating modeling, data processing, and interpretation. In order to improve the accuracy and speed of modeling, it was proposed to use the following methods:

– the dichotomy and Monte-Carlo methods, which are used to reduce the number of the model runs, providing a faster approach to finding the inflection point on the throughput graph in order to find the maximum throughput for a particular NoC configuration;

– the accuracy-up method, which reduces the simulation time by using less accurate but fast models to quickly obtain the desired values in the first approximation that can then be refined using the more accurate model;

– the method of the parallel launch of several models (parallelization of calculations), which ensures the simultaneous launch of many instances of the same model with different settings or different models;

– the similarity method that allows, based on the saved results of previous runs of models with other parameters, reducing the search range for NoC characteristics with the new parameters;

– the comparator method, which compares the results of the different models with the same initial settings, so that the balance between the accuracy and simulation speed can be ensured.

Chapter 5 is devoted to the description of the DSS module, which is the separate architectural block and serves to evaluate the user's task. At the output, the DSS module offers the user the optimal combinations of models and optimization methods to speed up the calculations and improve their accuracy.

The chapter also presents the results of approbation of the developed CAD for the study of various NoC configurations. The data obtained demonstrates that the integration of models in CAD was successful, and the data obtained is comparable to the data obtained when using the models without CAD. The chapter also provides

the estimates of the gain in accuracy and speed of modeling due to the use of methods and automation tools for the high-speed modeling proposed in Chapter 3.

In **conclusion**, the main results obtained in the course of the dissertation work are listed, and promising areas for further research are indicated.

The main result of the dissertation work is the solution of an important and relevant scientifically applied problem related to increasing the speed and increasing the accuracy of the NoC modeling by developing the specialized CAD containing the DSS, tools for integrating models, storing and processing simulation results, and modeling automation.