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Development of sub-symbolic distributed models in multi-criteria decision-making tasks

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General work characteristic

Dissertation relevance.

Radically new conditions of information processing, planning and strategic management in digital enterprises based on the self-organization principles necessitate the implementation of such flexible organizational forms as virtual [1], agile [2] and distributed enterprises [3]. The pace of production processes and the frequency of process modifications are substantially increasing in such companies, consequently, managers constantly face tasks related to multi-criteria decision making. In present conditions of organizational transition toward widespread digitalization, the importance of developing new approaches to address such challenges increases.

Generally, multi-criteria decision making are handled as a part of decision support systems (DSS) [4] for different categories of management personnel. Modern methods of DSS development originate in the works of the following researchers: Pospelov D.A., Podinovsky V.V., Larichev O.I., Finn V.K., Osipov G.S., Osipov V.P., Golicyn G.A, Turban E., Haagsma I., Johanns R., Fox D., Das S. [5—12].

When developing a DSS to solve multi-criteria decision making tasks, it is important to take into account the existence of uncertainty in information and knowledge about the issue, as well as to use different techniques to decrease uncertainty, for example, by introducing convolution or ranking contradicting criteria and expert assessments [13]. Furthermore, the decision-making process can be iterative.

The studies of the challenges associated with multi-criteria decision-making techniques in the DSS are represented in the works of Aleskerov F. T., Larichev O. I., Nogin V. D., Pospelova I. I., Osipov V. P., Sudakov V. A., Doumpos M., Grigoroudis E., Ishizaka A., Nemery P. and other scientists [12; 14—22].

Expert evaluations may be quantitative or qualitative. Qualitative evaluations are becoming more preferred in difficult circumstances because, unlike quantitative assessments, they represent ambiguous data more accurately (for example, if an expert doubts and cannot give an accurate assessment). Significant contributions to the creation of dependable and adaptable models and algorithms that integrate quantitative and qualitative estimation approaches in the DSS have been made by prominent scientists such as Pospelov D.A., Borisov A.N., Alekseev A.V., Krumberg O.A., Yager R., Zadeh L., Hu Z., Martinez L., Herrera F., Herrera-Viedma E. [23—29]. As a result of the work of Russian and international scholars, a concept known as «linguistic multi-criteria decision-making» has been developed. [28—33].

One of the primary directions in the development and implementation of DSS is the incorporation of artificial neural networks (ANN) into their architecture [34]. This approach is usually referred to as neurosymbolism [35].

The study of the issues of developing intelligent neuro-symbolic systems is covered in the works of Golicyn G. A., Fominykh I. B., Arlazarov V. L., Zhuravlev Y. I., Larichev O. I., Lokhin V. M., Borisov, A. N., Makarov I. M. Rakhmankulov V. Z., Finn V. K., Kuznetsov O. P., Pospelov D. A., Komartsova L. G., Sottara D., Tarek R., d'Avila Garcez A., Medsker L., Hitzler P., Ginzberg M., Gallant S. [5; 6; 8; 35—47] and others.

Contemporary scientific literature dedicated to the research and development of concepts for creating a strong or general artificial intelligence emphasizes the need of developing integrated solutions that would be based on both deep learning and symbolic reasoning. This is due to the fact that a system that includes elements of a general AI must be semantically justified, interpretable, and reliable, and its solutions must be completely trusted by all concerned parties. Thus, the development of a general AI is unachievable without the mutual integration of these approaches and the development of neurosymbolic techniques. This issue is studied in the works of Golicyn G. A., Fominykh I. B., Pospelov D. A., Borisov A. N., Kolesnikov A.V., Medsker L., Sima D., d'Avila Garcez A., Besold T., Lamb L., Pinkas G. [8; 35; 41; 43; 48—52] and others.

Additionally, the author identified and researched new directions for the DSS development in accordance with Design Science Research Methodology (DSRM) [A1]. As a result of the collection and analysis of a large number of recent scholarly sources, a consistent tendency towards developing neurosymbolic DSS utilizing integrated neural-network approaches was discovered.

Additionally, it was discovered that further motivation for the development of neuro-symbolic DSS is the necessity of the distributed structure for new types of such systems. One of the primary reasons for the emergence of this requirement is the ongoing development of a variety of massively parallel and distributed computing technologies and communication solutions within the context of the business information technology environment. This enables the practical viability and economic feasibility of developing new generations of information systems on the basis of multi-agent systems (MAS), Internet of Things networks, and so-called Fog computing architectures [53]. The aforementioned distributed computing infrastructures can include millions of autonomous components interacting in a decentralized manner under dynamic and software-defined networking. Under these circumstances, certain components of computing infrastructures (for example, neurons as agents) may be directly linked with the structural elements and communication algorithms employed in parallel models of the dynamics of ANNs [54—61].

Indeed, various researchers [62—65] agree that a single device (in Internet of Things networks, in Fog computing infrastructure) or a distinct intelligent agent (in the MAC) performs the function of a separate neuron or implements a particular fragment of a global multi-level neural network. In this case, the ANN dynamics can be effectively implemented utilizing shared memory or message transmission methods.

DSS open issues The results of the conducted literary analysis indicate that the necessity of developing decision support systems (DSS) is determined by the increasing complexity of decision-making in a rapidly changing environment, the expanding amount of data, and the growing number of interconnected factors affecting the decision-maker's actions.

It is important to note that a significant part of contemporary DSS is hybrid. Modern DSS include several key technical components simultaneously, such as data, models, and knowledge. In this case, the lack of data during the DSS development stage may be compensated by business rules and predefined scenarios. Whereas the steady accumulation of data will enable the usage of data analysis technologies and the creation of new mathematical models to provide more effective suggestions for decision-makers.

As described in [A1], there is a trend towards incorporating artificial intelligence (AI) techniques, such as ANN and case-based reasoning into DSS, since these techniques enable to enhance predictive capability of the DSS and discover hidden patterns within the given data [66]. The DSS incorporating AI are generally called intelligent DSS (IDSS).

Despite active research in the field of hybrid expert systems, hybrid IDSS, numerous questions remain open, such as:

1. implementing explanatory abilities for distributed IDSS,
2. integrating prospective neural network architectures into IDSS,
3. developing methods and models for both symbolic and sub-symbolic knowledge representation,
4. developing the nomenclature of configurations and possible options for the implementation of neuro-symbolic DSS.

Due to the importance of developing IDSS to resolve multi-criteria decision making problems, there are a number of open research questions in the context of developing modern decision-making methods. Significant disadvantages of traditional decision-making methods which helps experts choose the best alternative, for example, TOPSIS [67] or ELECTRE [68; 69], is their heavy reliance on quantitative estimates, even in the form of fuzzy sets. [70].

Thus, on the one hand, there is a noticeable tendency toward the development of hybrid IDSS including various ANNs as their own modules, and, on the other hand, in response to the growing demand for new multi-criteria decision-making methods, approaches to working with qualitative assessments expressed in linguistic form are being developed.

On this premise, the tasks of developing IDSS under conditions of multi-criteria decision making, issue of representing knowledge on both symbolic and sub-symbolic levels, and the tasks of integrating the ANN into the IDSS to enable them to learn and adapt to the environment are relevant and significant.

The open problem considered in the paper in the field of decision-making methods: the lack of algorithms and software systems that contribute to the design and implementation of effective intelligent neuro-symbolic decision support systems based on ANN.

Object of research: intelligent neuro-symbolic decision support systems that use ANN, in terms of solving multi-criteria decision making problems in conditions of weak structuring of the problem situation.

Subject of research: mathematical software for neuro-symbolic intelligent decision support systems used to perform multi-criteria decision making in conditions of weak structuring of the problem situation.

Dissertation aim is the creation, research, and improvement of models, as well as the software implementation of neural network methods and algorithms for the purpose of developing intelligent decision support systems capable of aggregating linguistic assessments in multi-criteria decision making tasks in a distributed sub-symbolic form.

To accomplish the aim of the work, a number of tasks have been designated and completed **objectives**:

1. carried out a critical analysis of the issue of building IDSS based on integration with ANN;
2. developed and investigated a new multi-criteria decision-making model based on linguistic assessments taking into account multiple hierarchically structured aspects of the problem situation;
3. developed and investigated new algorithms for representing linguistic assessments in multi-criteria decision making tasks in the form of trees and their corresponding distributed form;
4. developed and investigated new sub-symbolic distributed aggregation methods for linguistic assessments using the neural network paradigm;
5. developed and implemented a collection of software tools to facilitate the encoding, decoding, and modification of trees on the sub-symbolic level;
6. developed and implemented a collection of software tools to enable aggregation of linguistic information in multi-criteria decision-making tasks in a sub-symbolic manner;
7. studied the effectiveness of the developed methods, algorithms, and software complexes applied to a variety of model multi-criteria decision-making tasks with linguistic assessments.

Scientific novelty: The scientific novelty is in the characteristics of the research program and the results obtained, which provide new opportunities for modeling and algorithmization of linguistic decision-making procedures solutions in a sub-symbolic form in the IDSS, which were previously described in scientific papers but not analyzed. As a result of the research, a new model of multi-criteria choice is proposed based on a multi-level approach to multi-criteria decision-making using linguistic evaluations. This method enables the evaluation of choices using J. Van Gigch's hierarchically constructed scale [71]. The findings of the research enable the construction and programmatic development of distributed hierarchical models of optimization and multi-criteria selection.

Additionally, the research introduces the issue of presenting a problem and expert evaluations in the form of a tree with further transformation of the latter into a distributed form utilizing the tensor representation approach [72]. Furthermore, no previous scientific effort has addressed the challenge of representing language aggregation operations in a functional manner. This form is applicable to both the implementation of IDSS and the creation of theoretical approaches and decision-making models based on linguistic evaluations.

According to the findings of the bibliographical study and comparison to related works, it was determined that the author's approach is scientifically novel.

Despite the theoretical basic nature of the principles, the selected approach of developing ANN for working with trees, presented by P. Smolensky, was previously employed primarily to handle issues of textual analysis. Through the application of this approach in the proposed study, we will be able to assess its applicability in other scientific domains. When discussing the author's method, P. Smolensky, the creator of the tensor representation approach, stated that the results obtained are innovative (link to a recording from the international seminar VSA ONLINE[1]).

Practical significance Algorithms and software implementation can be brought to practical usage in the form of the IDSS core. Namely, to ensure the relationship between neural network modules and symbolic reasoning. For instance, in the context of medical tasks, the IDSS may be represented as a collection of specialized neural network assistants controlled by a symbolic coordinating module. With the development and standardization of methods for describing the tasks and the knowledge required for decision-making, as well as the accumulation of historical data, it is possible to create a larger number of neural network modules capable of performing some of the symbolic reasoning previously performed by the coordinator module. Simultaneously, the benefit would be that such reasoning is now based not only on expert knowledge, which is updated in the IDSS knowledge base with a long delay, but also on historical experience, where neural network methods are capable of detecting difficult-to-grasp patterns and offering the decision-maker the best course of action [73], adequate, extraordinary, and useful recommendations. A similar approach might be used for other engineering and technology domains, such as smart city systems and autonomous transportation.

Methodology and research methods.

[1] `https://youtu.be/MFCuxdiJ3ds`

Theoretical and practical research are conducted using modern system analysis method [74], decision-making theory [16], theory of fuzzy logic [23]. DSRM [75] was used to conduct a critical examination of the challenge of integrating ANN with contemporary IDSS on the basis of current scientific literature. Over 160 relevant scientific sources were collected and analyzed.

The tensor representation method [72] and the neural network architecture project, that allows manipulating the distributed representation of any symbolic structure, developed by P. Smolensky [76] were used to represent recursive structures in a distributed manner, manipulate structures at the symbolic level, and decode recursive structures from a distributed representation. The tensor representations method and the neural network architecture project allow manipulating the distributed representation of any symbolic structure.

Due to the focus of this study on the tasks of aggregation of linguistic estimates for modeling purposes, a two-tuple (2-tuple) [77] model and the evaluation aggregation operator MTA (multigranular 2-tuple average) [28] were employed for linguistic evaluations.

To validate the appropriateness and efficacy of the suggested models and algorithms, computational experimentation approaches were applied. Two software packages have been developed for this purpose. A series of experiments were carried out with these packages, confirming the correctness of the proposals made on the sub-symbolic aggregation of linguistic assessments.

The software implementation of the packages was carried out in full the software development cycle: from the design step to the verification of results and performance evaluation. The choice of the software framework was made in accordance with the elements *GOST R ISO/IEC 20741-2019 Systems and software engineering. Guideline for the evaluation and selection of software engineering tools* [78]. The architecture of software packages was described using the graphical description language for object modeling ArchiMate® *3.1* [2]. When developing software packages, the following were employed: software framework TensorFlow, NumPy, SciPy and other libraries, included in the Python programming language ecosystem.

Main results:

1. a model of multi-criteria hierarchical decision-making of ill-structured problems taking into account their multidimensional nature and the uncertainty of the context u sing linguistic assessments and J. Van Gigch's hierarchy of abstractions. The result allows working with both qualitative and quantitative evaluations throughout the whole decision-making process at multiple levels of abstraction, and also offers a dependable system for automatically weighting expert estimates based on their correctness,

[2] https://pubs.opengroup.org/architecture/archimate3-doc/toc.html

2. neural network aggregation model of linguistic evaluation based on the Neural Turing Machine's (NTM) architecture and enabling the transfer of calculating symbolic expressions to the sub-symbolic level,
3. method of automatic generation of the structure and weights of ANN for performing special tasks of encoding, decoding and manipulating symbolic structures at the sub-symbolic level. This result enables the translation of symbolic information represented as a recursive structure into a distributed form suitable for sub-symbolic distributed computing,
4. a method of encoding expert assessments in a tree view in multi-criteria decision-making tasks. This finding enables the expression of symbolic algorithms for the aggregate of language evaluations in multi-criteria selection situations using neural network technology. This finding enables the use of neural network technology for the expression of symbolic algorithms of aggregation of language evaluations in multi-criteria decision making,
5. software complex on encoding symbolic structures (binary trees, linguistic assessments) into a distributed representation, generation of special neural network topologies, and decoding symbolic structures from a distributed representation. This result enables the evaluation of the suggested methodologies on a number of example decision-making problems, and the software package is unique in this regard. Additionally, specific characteristics for evaluating current software frameworks and making a justified choice of a software framework for developing a software package were identified,
6. software complex for training and executing trained ANN, built on the current implementation of the Neural Turing Machine's neural network architecture, which has been considerably modified, refined, and adapted to include the IDSS into the neuro-symbolic models. The software package allows solving a variety of tasks, including sums of fixed-accuracy numbers, weighted sums of fixed-accuracy numbers, aggregations of linguistic assessments with different rules for coding linguistic assessments: by individual elements of the structure of the coded linguistic assessment, by the full distributed representation of the linguistic assessment with and without the inclusion of significance weight. This finding enables an experimental investigation of the suggested approach's efficacy and the solution of a number of model decision-making issues,
7. results of experimental evaluation of the created models of algorithms and software. A comparative analysis of the usefulness of methods for encoding symbolic structures in tensor representations revealed that the dimensionality of the recursive structure rapidly grows as the depth of the recursive structure increases. Additionally, it has been

demonstrated that sparse computing methods may significantly speed up the execution of encoding and decoding operations. This result allows inferring that selected approaches are suitable for integration into current IDSS and offers solutions for increasing the efficiency of symbolic structure encoding and decoding options.

Reliability of the proposed methods is confirmed by the results of computational experiments with specialized neural network primitives, automatically obtained as a result of of the software tools, comparison of the aggregation results with the results of of the symbolic implementation of the hierarchical MCDM approach ML-LDM as well as solving the actual MCDM problem of food security strategy.

Probation. The main findings of the work were presented at:

1. Annual Interuniversity Scientific and Technical Conference for Students, Postgraduates, and Young Specialists named after E.V. Armensky. Dates: February 18 - 28, 2019
2. Intelligent Systems Conference 2019 (IntelliSys 2019). Dates: September 5 - 6, 2019
3. XXI International Conference on Neuroinformatics. Dates: October 2-6, 2019.
4. International Conference «Neural networks the day after tomorrow: problems and prospects». Dates: November 30 - December 2, 2019
5. XXIII International Conference on Soft Computing and Measurement (SCM'2020) Dates: May 27 - 29, 2020
6. 2nd International Conference on Electrical, Communication and Computer Engineering. Dates: June 12 - 13, 2020
7. XIII International Conference New Information Technologies in the Study of Complex Structures. Dates: September 7 - 9, 2020
8. Eighteenth National Conference on Artificial Intelligence Dates: September 10 - 16, 2020
9. 25th Nizhny Novgorod Session of Young Scientists Dates: November 10 - 13, 2020
10. 3rd International Conference on Electrical, Communication and Computer Engineering. Dates: June 12 - 13, 2021
11. VSA ONLINE Workshop organized by the Joint Working Group of Lulea University of Technology (Sweden) и UC Berkeley (USA). Dates: June 28, 2021.
12. VII International conference and youth school «Information technologies and nanotechnology (ITNT-2021)» Dates: September 20 - September 24, 2021
13. 5th International Scientific Conference «Intelligent Information Technologies for Industry». Dates: September 30 - October 4, 2021

Personal contribution. The author conducted the entire scope of theoretical and experimental research outlined in the dissertation work, including the development of theoretical models and experimental research methods, as well as the research, analysis, and presentation of the results in the form of publications and scientific reports.

Publications. The main results on the topic of the dissertation are presented in 13 printed editions, 0 of which are published in journals recommended by the Higher Attestation Commission[A1; A9; A2],

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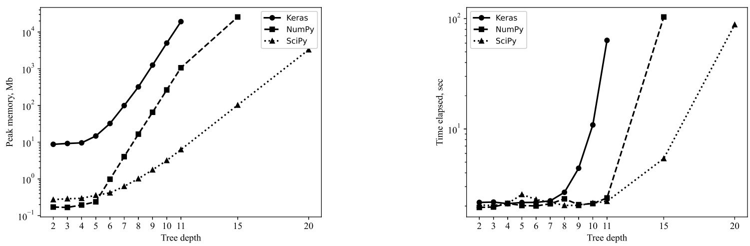
Dissertation content

In **introduction** the relevance of the research conducted as part of this dissertation work is established, a review of the scientific literature on the subject is provided, the purpose of the work is defined, the tasks of the work are defined, and the scientific novelty and practical significance of the presented work are stated.

Chapter 1 is focused on the examination of modern techniques of IDSS building. The approaches for multi-criteria decision-making in conditions of fuzzy initial techniques are analyzed, as is the utility of applying linguistic evaluations while dealing with fuzzy data is substantiated. In particular, The section explains multi-criteria decision-making using linguistic evaluations. A review of contemporary methods to multi-criteria decision-making challenges is provided. Additionally, Chapter 1 formulates the issue of distributed representation of information as a critical component of sub-symbolic computations, as well as the need of establishing a protocol for the interaction of symbolic and sub-symbolic systems. The existing approaches of knowledge representation and symbolic reasoning at the sub-symbolic level are discussed. A detailed overview of the approach of tensor representations to the construction of high-dimensional representations for recursive structures is presented. The conclusion is drawn about the suitability of tensor representations for IDSS usage owing to the assured lack of information loss during the transition from the symbolic to the sub-symbolic level and vice versa.

Chapter 2 provides a description of the author's model of multi-criteria decision-making based on linguistic evaluations, which identifies decision-making process solutions under circumstances of ambiguity and heterogeneity in the context of the issue. The issue of linguistic multi-criteria decision-making is formulated, and the hierarchy of abstraction levels is thoroughly examined while assessing a problem that plays a critical part in the suggested model. A theoretical explanation of the suggested model is provided, as are the particular stages involved in operating inside a given model. A comparative analysis of the suggested technique and current equivalents using a set of defined criteria is conducted.

Chapter 3 contains a description of the suggested model for developing and integrating neural network technologies into the IDSS in order to tackle the problem of linguistic assessment aggregation. A compiled ANN architecture has been developed for the purpose of encoding a recursive structure into a distributed representation and recovering it in reverse. A comparative analysis of methods for constructing high-dimensional representations in the form of a recursive structure is carried out. An analysis of the algorithm for constructing tensor representations and their decoding is presented on an example. A schematic diagram of an ANN encoder is proposed. A schematic diagram of the ANN for the restoration of the structure is proposed. The suggested architecture of the ANN is analyzed for the purpose of coding and recovering the structure. The issue of using a recoverable distributed representation to serve as the contract between the IDSS symbolic and sub-symbolic modules.

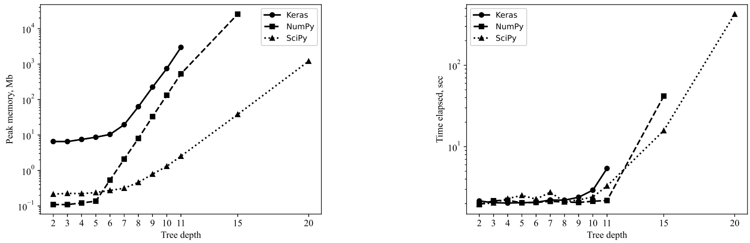


a) б)

Figure 1 — Estimation of the required a) amount of memory and b) time for encoding binary trees of various depths using the tensor representation method. Coding mechanics included a variety of software tools: neural network framework Keras, NumPy, and SciPy libraries.

The first approach to estimate aggregation is based on the integer arithmetic with integers suggested in the dissertation research, which is expressed via symbolic structure manipulation. Additionally, due to the possibility of encoding and decoding symbolic structures, as well as structural transformations equivalent to symbolic structures performed without loss of information, it is proposed to express the aggregation of linguistic assessments using a cascade of compiled ANN that do not require training. Tensor representations are used as the basic method.

The design of a trainable ANN for the sub-symbolic aggregation of linguistic assessments based on a neural Turing machine (NTM) is proposed (Figure 3). The external interface of the developed neural network module, the



a) б)

Figure 2 — Estimation of the required a) amount of memory and b) time for encoding binary trees of various depths using the tensor representation method. Coding mechanics included a variety of software tools: neural network framework Keras, NumPy, and SciPy libraries.

structure and format of synthetic data are proposed. A schematic diagram of an ANN aggregator is proposed. The trained ANN aggregator is analyzed.

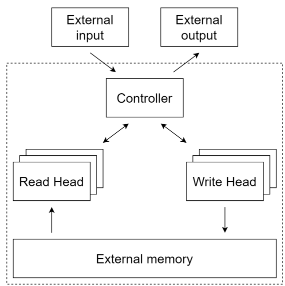


Figure 3 — NTM design.

Finally, a general scheme is proposed for expressing the aggregation step of linguistic assessments at the sub-symbolic level, which includes coding knowledge about the problem situation in the form of a recursive structure, further processing of aggregation rounds using a cascade of compiled ANN, as well as the aggregation itself using a module of a trained ANN built on the basis of NTM.

Chapter 4 describes the implementation of neural network modules of IDSS within the framework of the program complex. An overview of software tools for the creation, training and execution of ANN is presented. The technology and techniques utilized to develop neural network modules, as well as the programming languages and methodologies used, are described in detail. A program complex has been created for developing, compiling, and running ANN for encoding recursive structures and decoding them from a distributed representation. A software complex has been developed for creation, training and execution ANN for neural network aggregation (Figure 4). In particular, it is shown that the challenge of aggregating linguistic evaluations may be handled with zero error by training an ANN based on NTM. A description of the operation of software complexes on a basic example is presented. The implementation of the developed complexes in production is described.

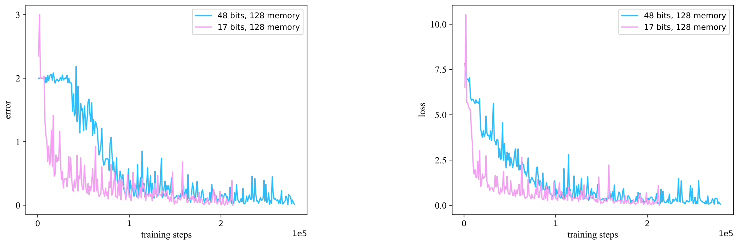


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Figure 4 — The dynamics of ANN training based on NTM for assessment aggregation on the linguistic operator MTA. Expert assessments are presented according to the proposed method of distributed representation: a) Packed in a sequence of *elements* encoded using the rules of tensor representations of the structure two-tuple linguistic assessment. b) Packed in a sequence of *whole* two-tuple linguistic assessments presented as structures of two placeholders and encoded using tensor representations.

In **Conclusion** the main conclusions and results are formulated. Namely: was a goal reached of development of new models, methods, algorithms, and new software complexes containing software implementation of the proposed methods and algorithms, which allow creating intelligent decision support systems capable of aggregating linguistic assessments in multi-criteria decision-making tasks in a distributed sub-symbolic form. All tasks have been completed: a critical analysis of the issue of IDSS construction was carried out, a new model of multi-criteria decision-making based on linguistic assessments was developed and investigated, taking into account multiple hierarchically structured aspects of the problem situation, new algorithms for the representation of linguistic assessments in multi-criteria selection problems have been developed and investigated, in the form of trees and in their corresponding distributed form, new sub-symbolic distributed methods of aggregation of linguistic assessments using the neural network paradigm were developed and investigated, two main program complexes [3] [4] и four auxiliary

[3] https://github.com/demid5111/ldss-tensor-structures
[4] https://github.com/ldss-hse/ldss-neural-aggregator

ones [5] [6] [7] [8] were designed and implemented, efficiency of the developed methodologies, algorithms, and program complexes was examined using the example issue of multi-criteria decision-making with linguistic evaluations.

The primary distinction between the proposed method and previous approaches to the design of IDSS to assist decision-makers in multi-criteria selection tasks, the primary objective of which is to either build symbolic rules for aggregating estimates or to develop a trainable neural network module based only on quantitative estimates, consists in the proposed decision-making model based on linguistic assessments, as well as in a set of algorithms for representing linguistic assessments in a distributed form, their decoding from a distributed representation, and aggregation at the neural network level using a trainable neural network module.

The scientific novelty of the conducted research is as follows:

1. formulated a number of research questions based on a systematic analysis of existing approaches and methods to the construction of the IDSS, requiring development of new models, algorithms and program complexes,
2. proposed a novel model of multi-criteria selection based on a multi-level method to multi-criteria decision-making with the use of linguistic evaluations that takes numerous hierarchically organized features of the issue scenario into consideration,
3. on the basis of the tensor representations technique, proposed novel methods for creating distributed representations for linguistic evaluations, their neural network aggregation, and decoding from distributed representations.

As part of the practical part of the work, prototypes of neural network modules for IDSS have been implemented. The created prototypes confirm the proposed models and algorithms, adhere to modern software development standards, and provide the user with capability for solving multi-criteria selection issues utilizing sub-symbolic linguistic evaluations. Unlike prior systems for training neural networks using NMT, the given software prototypes include independent modules for generating synthetic data, preserve compatibility with previously supported tasks, and exhibit extensibility and maintainability, as shown in this paper. As a consequence of the development of program complexes, reusable data structures and algorithms have been created in the form of Python modules and packages, laying the groundwork for the future growth of this approach from both a research and technical perspective. Thus, it is possible to include created modules into the IDSS and commercialize them further.

[5] https://github.com/ldss-hse/ldss-core-aggregator
[6] https://github.com/ldss-hse/ldss-bdi
[7] https://github.com/ldss-hse/ldss-core-api
[8] https://github.com/ldss-hse/ldss-benchmark

The effectiveness and flexibility of the proposed approach are demonstrated by several typical examples, such as the aggregation of linguistic assessments presented in a distributed form from a different number of experts: two or three. Additionally, with the help of program complexes, the possibility of creating compiled ANN that do not require training and perform intellectual tasks of coding, decoding recursive structures, as well as performing operations on distributed representations of recursive structures, including those requiring conditional branching, is demonstrated. It is important to highlight that the offered approaches to dealing with sub-symbolic linguistic evaluations are universal, as evidenced in the cases discussed.

It is important to show the results obtained on the conceptual model diagram of the DSS, discussed in Chapter 1. The conceptual model of IDSS with an indication of where the new results, obtained from this study, extend the set of existing tools and models, is presented in Figure 5. The proposed method for creating subsymbolic modules of computational systems, such as IDSS, is presented in Figure 6.

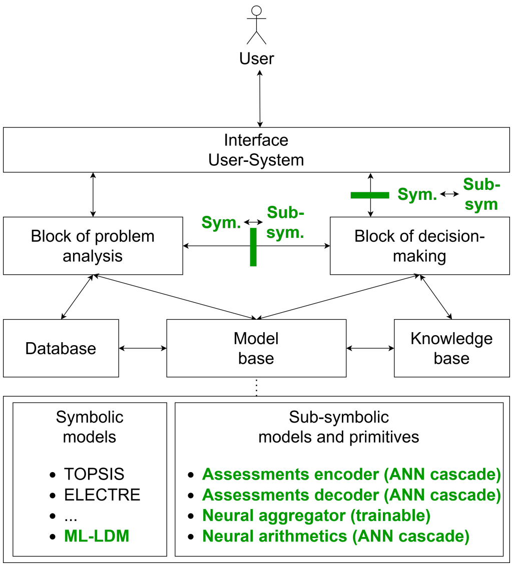

Figure 5 — The conceptual model of neuro-symbolic IDSS with the indication of new elements proposed in this paper. *ML-LDM* - designation of multicriteria decision making model. All proposed models and methods are marked in bold and green. Similarly marked is the transition between symbolic and sub-symbolic representations of knowledge, appearing in neuro-sub-symbolic IDSS, which becomes possible with the implementation of the proposed models for encoding and decoding of symbolic structures. Abbreviations: *sym.* - symbolic, *subsym.* - subsymbolic.

From the point of view of the prospects for the development of this research topic, several directions can be distinguished. Firstly,it is critical to investigate the issue of formalizing the principle of representing a problem situation as a recursive structure, as this will enable a complete cycle of decision support: from the generation of alternative solutions and hierarchically structured criteria to the aggregation of linguistic assessments. Secondly, it is necessary to investigate critical aspects of the proposed designs of compiled ANN for solving intellectual problems, such as the possibility of optimizing the ANN through the reuse of common calculation subgraphs, and the possibility of generating ANN via an arbitrary functional expression composed of operations *cons* and *ex*. Thirdly, according to the performance analysis and highlighted limitations of the current designs of compiled ANN, as well as recent advances in the area of sparse computing [79; 80], The usage of sparse ANN appears promising, especially since the necessary functional blocks are accessible inside the software framework TensorFlow[9] selected as the primary part in created program complexes. Fourthly, it is necessary to compare the proposed models of sub-symbolic aggregation of linguistic evaluations in conditions of mass parallelism to symbolic approaches. Based on the findings of such an examination, it is intended to demonstrate the computational validity of suggested neural network architectures. In the fifth place, it is recommended to investigate the potential of using NTM to express other aggregation operators for linguistic evaluations, such as a weighted version of the MTA operator. In the sixth place, it is necessary to integrate the obtained algorithms into a fully functional IDSS based on the sub-symbolic paradigm. In the seventh place, the challenge of formalizing the task of training the ANN to perform linguistic assessment aggregation as a task of predicting a sequence given a sequence (sequence-to-sequence, seq2seq) is of interest.

With the successful completion of this step, it becomes possible to study the applicability of promising neural network technologies to the task, such as Transformer [81] and BERT [82], which enable the usage of a much larger operational context, compared with LSTM, used as an NTM controller in the trained neural network aggregator of linguistic assessments proposed in this paper. A broader operational context enables the development of neural network aggregators for a bigger number of experts. In the eighth place, a promising direction for future study is to compare the suggested approach for building distributed representations based on tensor representations to other methods utilized in vector symbolic structures. Lastly, it seems reasonable to compare the key characteristics of the trained neural network aggregator in the case of using methods for obtaining a distributed representation used in the creation of modern multi-modal ANN [83; 84]. For example, within the multi-criteria selection problem under consideration, it is possible to consider the possibility of using as input a raw description of expert estimates in the form

[9] `https://www.tensorflow.org/api_docs/python/tf/sparse/SparseTensor`

of text, without turning these estimates into elements of a two-tuple model, or using methods for constructing high-dimensional representations for graphs [85; 86] to encode linguistic assessments and a general description of the problem situation, expressed in the form of a recursive structure. The development of such solutions provides the basis for the construction of distributed hybrid neuro-symbolic IDSS.

Combining sub-symbolic and symbolic computational paradigms is a promising and relevant idea, and their integration will enable significant progress toward solving problems that cannot be solved exclusively through one of these two approaches, most notably when developing DSS capable of aggregating linguistic assessments in multi-criteria selection tasks in a distributed sub-symbolic form.

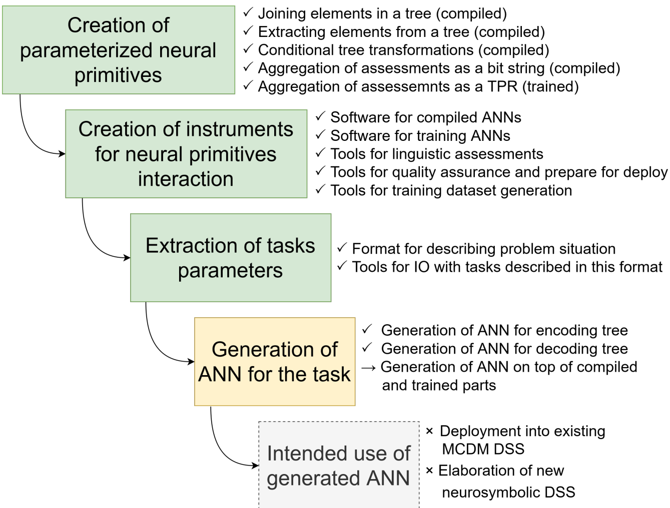

Figure 6 — The process of creating neurosymbolic modules for the IDSS. Blocks that are marked in green mean that they are complete with ready-made models, algorithms, and software complexes, yellow blocks denote blocks that require finalization of ready-made solutions, gray blocks require further research. To the right of each block there are results obtained, or the steps that need to be finalized.

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