Final scientific report

1. Project Information

Competition:	Young Research Teams 2021 (Proiecte de cercetare pentru stimularea tinerelor echipe independente)
Contract number:	TE 162⁄2022
Project code:	PN-III-P1-1.1-TE-2021-0676
Research Domain:	Computer Science
Title:	A Symbiosis of Satisfiability Checking, Graph Neural Networks and Symbolic Computation / O Simbioză între Verificarea Satisfiabilității, Rețele Neuronale pe Grafuri și Calculul Simbolic
Acronym:	SAGE
Project start date:	September 1st, 2022
Project end date:	August 31st, 2024
Duration (months):	24
Budget (State budget):	449 916 RON
Webpage:	https://merascu.github.io/links/SAGE.html
Host institution:	West University of Timișoara
Director:	Conf. Univ. Dr. Habil. Mădălina Eraşcu

2. Project Overview

Our life depends on software and systems using software. Nowadays, software is complex and, hence, error prone. To overcome this problem, we need methods for assisting software development.

The SAGE project addressed the challenging problem of program analysis by developing rigorous mathematical techniques dealing with the logically complex parts of software. At this aim, we used, refined, and combined methods from satisfiability checking, graph neural networks and symbolic computation. These made possible the analysis of software that is beyond the power of existing methods since advanced symbolic computation techniques (invariant theory) and graph neural networks combined with satisfiability checking

(SAT/SMT solving) was not exploited in the state-of-the-art program analysis methods and tools. We developed new theory and algorithms that detect the problem symmetries and similarities in the family of problems by combining invariant theory, graph neural networks and SAT/SMT solving which, unlike state-of-the-art, would allow solving efficiently theoretically intractable problems.
Our research project targeted the analysis of complex software and follows three main research directions:

- Methods for symmetry breaking and similarities learning.
- Theory and algorithms
- Tools and evaluations

3. Project Objectives and Results

The ***general objective*** of this project was to advance the state-of-the-art theory and algorithms of satisfiability checking, symbolic computation and GNNs for solving *constraint satisfaction problems* at *scale*.We aimed to:

(O1) ***provide an understanding*** of what the (**O1.1**) *symmetries* and (**O1.2**) *similarities* are for important practical problems like (a) *resource management in the Cloud*, (b) *verification of binarized neural networks*

(O2) ***develop methods*** (**O2.1**) *for breaking the symmetries in* and (**O2.2**) *for learning templates from* the problems enumerated above

(O3) ***invent theory and algorithms*** for (**O3.1**) *abstracting* away the symmetries of these case studies and for *capturing* the commonalities of the symmetry breaking techniques using the *theory of invariant groups* and *SAT/SMT solving*; (**O3.2**) *learning problem templates* by formalizing the problem as a GNN and applying on-the-shelf GNNs libraries for different predictions

(O4) *study the computational effectiveness* of the newly developed symmetry breaking and similarity breaking techniques;

(O5) for ultimately, *performing automatic solving of constraint satisfaction problems (CSP) at scale*.

To achieve these objectives, a series of related activities were carried out in 3 annual stages according to the initial work plan with a series of additional caused by the evolution of research and development.

Phase 1 (September - December 2022). Planned activities	
Activity 1.1	Identifying symmetries and investigating symmetry breaking techniques for the case study: cloud resource management (intermediate version)

Activity 1.2	Identifying symmetries and investigating symmetry breaking techniques for the case study: verifying the properties of binary neural networks (intermediate version)
Activity 1.3	Identifying similarities and investigating how learning templates are applicable for the case study: cloud resource management (preliminary version)
Activity 1.4	Website creation

Phase 2 (January - December 2023). Planned activities	
Activity 2.1	Identifying symmetries and investigating symmetry breaking techniques for the case study: cloud resource management (final version)
Activity 2.2	Identifying symmetries and investigating symmetry breaking techniques for the case study: verifying the properties of binary neural networks (final version)
Activity 2.3	Identifying similarities and investigating how learning templates are applicable for the case study: cloud resource management (preliminary version)
Activity 2.4	Appropriate abstraction techniques for symmetries and symmetry breaking
Activity 2.5	Theoretical framework for symmetry breaking techniques
Activity 2.6	Algorithmic framework for template learning

Phase 3 (January - August 2024). Planned activities	
Activity 3.1	Defining the architecture and supporting tools
Activity 3.2	Implementation of symmetry breaking algorithms/methods
Activity 3.3	Implementation of templates
Activity 3.4	Validate implementation

Note that the activities listed above are applied to two different case studies, namely *cloud resource management* and *verifying the properties of binary neural networks*, respectively.

3.1 Cloud Resource Management

Result 1 (Related to Activities 1.1, 2.1, 3.1, 3.2, 3.4). Benchmarking Optimization Solvers and Symmetry Breakers for the Automated Deployment of Component-based Applications in the Cloud. Optimization solvers based on methods from constraint programming (OR-Tools, Chuffed, Gecode), optimization modulo theory (Z3), and mathematical programming (CPLEX) are successfully applied nowadays to solve many non-trivial examples. However, for solving the problem of automated deployment in the Cloud of component-based applications, their computational requirements are huge making automatic optimization practically impossible with the ..current general optimization

techniques. To overcome the difficulty, we exploited the sweet spots of the underlying problem in order to identify search space reduction methods. We came up with 15 symmetry breaking strategies which we tested in a static symmetry breaking setting on the solvers enumerated above and on 4 classes of problems. As a result, all symmetry breaking strategies led to significant improvement of the computational time of all solvers, most notably, Z3 performed the best compared to the others. As an observation, the symmetry breaking strategies confirmed that, when applied in a static setting, they may interact badly with the underlying techniques implemented by the solvers.

Result 2. SAGE - A Tool for Optimal Deployments in Kubernetes Clusters (Related to Activities 1.1, 2.1, 3.1, 3.2, 3.4; In account to Activities 2.4, 2.5) . Cloud computing has brought a fundamental transformation in how organizations operate their applications, enabling them to achieve affordable high availability of services. Kubernetes has emerged as the preferred choice for container orchestration and service management across many Cloud computing platforms. The scheduler in Kubernetes plays a crucial role in determining the placement of newly deployed service containers. However, the default scheduler, while fast, often lacks optimization, leading to inefficient service placement or even deployment failures.This paper introduces SAGE, a tool for optimal deployment plans in Kubernetes clusters that can also assist the Kubernetes default scheduler and any other custom scheduler in application deployment. SAGE computes an optimal deployment plan by fulfilling the constraints of the application to be deployed and by taking into consideration the available Cloud resources with the aim of minimizing the infrastructure rental cost. We show the potential benefits of using SAGE by considering test cases with various characteristics. It turns out that SAGE surpasses schedulers by comprehensively analyzing the application demand and cluster image. This ability allows it to better understand the needs of the pods, resulting in consistently optimal solutions across all test scenarios. The accompanying material of this paper is publicly available at https://github.com/SAGE-Project/SAGE-Predeployer.

Result 3 (Related to Activities 1.3, 2.3, 2.6, 3.1, 3.2, 3.4). Fast and Exact Synthesis of Application Deployment Plans using Graph Neural Networks and Satisfiability Modulo Theory. Learning-augmented algorithms use machine learning predictions to boost optimization algorithms performance. The extra information incorporated into learning-augmented algorithms is, for example, the input which resembles prior instances, potentially aiding in circumventing the need to compute solutions from scratch or facilitating the utilization of existing solutions for deriving new ones. In previous works, we synthesized leasing cost optimal, subsequently named optimal, Cloud deployment plans by solving the corresponding constrained optimization problem using Satisfiability Modulo Theory (SMT) solvers and symmetry breakers. In this paper, we leverage the previously generated deployment plans to create a model of the deployed application. We employ graph neural networks (GNNs) for this purpose, encoding past deployment plans as graphs, with components and virtual machines as nodes and their interactions as edges. The GNN model trained can learn from historical data to predict optimal assignments by solving the corresponding edge classification problem. These predictions are then used as soft constraints

in the exact SMT solver Z3, efficiently guiding the solver towards the optimal solution. We exemplify our approach on a Secure Web Container application. The accompanying material of this paper, as well as the application of our approach to other case studies, is publicly available at https://github.com/SAGE-Project/SAGE-GNN/tree/IJCNN2024.

Remark 1. Result 2 was not initially planned but it arose after the feedback received during the participation in the start-up accelerator ADRVest Accel.

Remark 2. Until now we did not manage to obtain publishable results for Activities 2.4, 2.5 the main drawback being the scalability of the approach. However, we consider the activities fulfilled by carrying out those for obtaining Result 2.

3.2 Verifying the Properties of Binary Neural Networks

In order to carry out the activities initially planned for the project, we needed trained binarized neural networks (BNNs) whose properties to verify. After an in-depth state-of-the-art analysis, we found no publicly available BNNs. Hence, we had to train BNNs models ourselves. We chose the problem (classification of traffic signs) and the method (supervised learning). We trained BNNs with different architectures and performance. The importance of our work was published in the **paper** Postovan, A., Eraşcu, M. (2023). Architecturing Binarized Neural Networks for Traffic Sign Recognition. In: Iliadis, L., Papaleonidas, A., Angelov, P., Jayne, C. (eds) Artificial Neural Networks and Machine Learning – ICANN 2023. ICANN 2023. Lecture Notes in Computer Science, vol 14254. Springer, Cham. https://doi.org/10.1007/978-3-031-44207-0_8. The models trained were sent at the Verification of Neural Networks Competition (VNN-COMP) 2023, a yearly competition where several benchmarks (neural networks models together with the properties to be verified) are handled by dedicated tools. We decided to propose our benchmark in the competition to see what difficulties tools have to tools to provide the verification answer for local robustness properties. Our benchmark was appreciated by the organizers and won the outstanding benchmark award. There were only 4 tools (out of 7) which tried to verify the robustness property of our benchmarks. The description of the benchmark was presented in the **paper** Postovan, A., Eraşcu, M. Benchmarking Local Robustness of High-Accuracy Binary Neural Networks for Enhanced Traffic Sign Recognition. In Horaţiu Cheval, Laurenţiu Leuştean and Andrei Sipoş: Proceedings 7th Symposium on *Working Formal Methods* (FROM 2023), Bucharest, Romania, 21-22 September 2023, Electronic Proceedings in Theoretical Computer Science 389, pp. 120–130. Published: 22nd September 2023. https://dx.doi.org/10.4204/EPTCS.389.10. Currently, we are checking the quality of the results obtained by the tools in order to see their shortcomings.

Remark. Given the facts above, the Activities 2.4, 2.5 were delayed and, as of today, we did not manage to publish results related to them.

We summarize the results obtained. The first 2 results were published in conference proceedings. The Result 3 is in preparation.

Result 1. **Architecturing Binarized Neural Networks for Traffic Sign Recognition (Related to Activities 3.1, 3.3, 3.4; In account to Activities 2.4, 2.5)**. Traffic signs support road safety and managing the flow of traffic, hence are an integral part of any vision system for autonomous driving. While the use of deep learning is well-known in traffic signs classification due to the high accuracy results obtained using convolutional neural networks (CNNs) (state of the art is 99.46%), little is known about binarized neural networks (BNNs). Compared to CNNs, BNNs reduce the model size and simplify convolution operations and have shown promising results in computationally limited and energy-constrained devices which appear in the context of autonomous driving. Our work presents a bottom-up approach for architecturing BNNs by studying characteristics of the constituent layers. These constituent layers (binarized convolutional layers, max pooling, batch normalization, fully connected layers) are studied in various combinations and with different values of kernel size, number of filters and of neurons by using the German Traffic Sign Recognition Benchmark (GTSRB) for training. As a result, we propose BNNs architectures which achieve an accuracy of more than 90% for GTSRB (the maximum is 96.45%) and an average greater than 80% (the maximum is 88.99%) considering also the Belgian and Chinese datasets for testing. The number of parameters of these architectures varies from 100k to less than 2M. The accompanying material of this paper is publicly available at https://github.com/apostovan21/BinarizedNeuralNetwork.

Result 2. **Benchmarking Local Robustness of High-Accuracy Binary Neural Networks for Enhanced Traffic Sign Recognition (Related to Activities 3.1, 3.3, 3.4; In account to Activities 2.4, 2.5).** Traffic signs play a critical role in road safety and traffic management for autonomous driving systems. Accurate traffic sign classification is essential but challenging due to real-world complexities like adversarial examples and occlusions. To address these issues, binary neural networks offer promise in constructing classifiers suitable for resource-constrained devices. In our previous work (see Result 1), we proposed high-accuracy BNN models for traffic sign recognition, focusing on compact size for limited computation and energy resources. To evaluate their local robustness, this paper introduces a set of benchmark problems featuring layers that challenge state-of-the-art verification tools. These layers include binarized convolutions, max pooling, batch normalization, fully connected. The difficulty of the verification problem is given by the high number of network parameters (905k - 1.7 M), of the input dimension (2.7k-12k), and of the number of regions (43) as well by the fact that the neural networks are not sparse. The proposed BNN models and local robustness properties can be checked at https://github.com/ChristopherBrix/vnncomp2023_benchmarks/tree/main/benchmarks/traffic_signs_recognition. The results of the 4th International Verification of Neural Networks Competition (VNN-COMP'23) revealed the fact that 4, out of 7, solvers can handle many of our benchmarks randomly selected (minimum is 6, maximum is 36, out of 45). Surprisingly, tools output also wrong results or missing counterexamples (ranging from 1 to 4). Currently, our focus lies in exploring the possibility of achieving a greater count of solved instances by extending the allotted time (previously set at 8 minutes). Furthermore, we are intrigued by the reasons behind the erroneous outcomes provided by the tools for certain benchmarks.

Result 3. **Benchmarking Verification of Neural Networks Tools on Binarized Neural Networks for Traffic Signs Classification (Related to Activities 3.1, 3.3, 3.4; In account to Activities 2.4, 2.5).** Self-driving cars heavily rely on understanding traffic signs to navigate safely and follow the rules of the road. To achieve this, binary neural networks (BNNs) can be used, as they are well-suited for devices with limited resources.. Deep neural networks in general, and BNNs in particular, exhibit safety and security risks in networks with excellent traditional evaluation performance. An example of such risk is susceptibility to the so-called adversarial examples. Previous work proposed: (1) high-accuracy BNN models for traffic sign recognition and (2) BNNs robustness checking wrt adversarial examples using dedicated formal verification tools. In this work, we attempt to interpret the adversarial examples obtained by these tools in the framework of VNN-COMP 2023. Additionally, a similar interpretation is performed on newer versions of two tools locally run by us. Our preliminary conclusions are that the adversarial examples generated by the formal verification tools need to be validated before using them to improve the quality of the BNN at design time (training). The tests performed and their summary are publicly available at https://github.com/andabranch/sage.

3.3 Non-technical Activities/Results

Besides the technical activities, the members of the project were also involved in activities supporting the formal methods and machine learning communities.

Mădălina Erașcu was serving:

- as **PC member** of The 15th Conference on Intelligent Computer Mathematics (CICM 2022), September 19 - 23, 2022, Tbilisi, Georgia and **Chair** of the PhD Symposium of the same conference; **PC member** of The 16th Conference on Intelligent Computer Mathematics (CICM 2023), September 4 - 8, 2023, Cambridge, UK.
- as the **Chair** of WG3 (Program Verification) of the COST action EuroProofNet - European research network on digital proofs (2022 - 2023) and **Vice-Chair** since 2023.
- **PC member** of 30th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS) 2024 April 6-13, 2024, Luxembourg Ville, Luxembourg.
- **PC member** of 32nd International Conference on Artificial Neural Networks (ICANN 2023), School of Engineering of Democritus University of Thrace, Greece; **PC member** of 33rd International Conference on Artificial Neural Networks (ICANN 2024), organized by Dalle Molle Institute for Artificial Intelligence Research (IDSIA USI-SUPSI) in Lugano, Switzerland in collaboration with AIDD and AiChemist Horizon MSCA projects; USI-SUPSI Campus Est, Via la Santa 1, 6962 Lugano-Viganello, Switzerland
- **PC member** of 25th International Symposium on Symbolic and Numeric Algorithms for Scientific Computing (SYNASC 2023), LORIA, Nancy, France, for Logic Programming and Symbolic Computation Tracks and the Workshop on Theory of Smart Contracts and Applications (TOSCA); **PC member** of 26th International

Symposium on Symbolic and Numeric Algorithms for Scientific Computing (SYNASC 2024), Timisoara, Romania, for Logic Programming track.

- **subreviewer** for The 14th International Symposium on Frontiers of Combining Systems (FroCoS 2023), Czech Institute of Informatics, Robotics and Cybernetics (CIIRC) of the Czech Technical University in Prague (CTU), Czech Republic, September 20-22, 2023.
- **PC member** for 19th European Dependable Computing Conference, Student Forum, KU Leuven, April 8-11 2024, Leuven, Belgium.
- **PC member** for the 20th Artificial Intelligence Applications and Innovations (AIAI 2024), Ionian University, Corfu, Greece; June 27-30, 2024.
- **PC member** of Formal Techniques for Java-like Programs (FTfJP 2024), co-located with ISSTA/ECOOP, 16 - 20 September 2024 Vienna, Austria.
- **Co-Chair** of the PhD Symposium of the Integrated Formal Methods (iFM) 2024, November 12, 2024, Manchester, UK.
- **PC member** of Best Romanian AI Thesis Awards, part of Romanian AI Days, Bucharest, September 26-27, 2024

Vlad Luca was serving in the **Artifact Evaluation Committee** of 30th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS) 2024 April 6-13, 2024, Luxembourg Ville, Luxembourg.

Four **master theses** related to the activities of the project were defended in an excellent fashion (July 2023):

- Marcus Ilisie. *A Symbiosis of Constraint Optimization, Symmetries and Symmetry Breaking for Scalable Cloud Deployment Problems*
- Eduard Laitin. *Speeding Up the Deployment in the Cloud of Component-based Applications using Graph Neural Networks and SMT solving*
- Vlad Luca. *SAGE - A Tool for Optimal Deployments in Kubernetes Clusters*
- Andreea Postovan. *Binarized Neural Networks for Traffic Sign Recognition: Training and Verification*

Mădălina Erașcu defended (April 2024) the **habilitation thesis** *Formal Methods Supported by Symbolic Computation for Engineering Applications in Cloud Computing and Artificial Intelligence.*

4. Dissemination and Exploitation

4.1 Dissemination

The project has an **up-to-date webpage**: https://merascu.github.io/links/SAGE.html.

Project results have been disseminated in 2 international CORE **conferences** (ICANN 2023 and IJCNN 2024) with proceedings, 1 conference (FROM 2023) indexed in Scopus, 1 **tutorial** (FROM 2024). These papers were also presented face-to-face at the respective venues. In addition, we contributed with **benchmarks** in the VNN-COMP 2023 (binarized

neural networks for traffic signs classification), Minizinc Challenge 2023 (Wordpress application) and CSPLib - a repository with constraint satisfaction problems (Wordpress application). All benchmarks are publicly available.

Participants of the **lecture Formal Verification** in the Winter Semester 2023-2024 held in Romanian to master specializations CyberSecurity and Software Engineering at West University of Timisoara, Department of Computer Science, were given to reproduce the results to VNN-COMP 2023. Some of them chose the benchmark proposed by us.

Mădălina Erașcu and Andreea presented a survey on the verification of binarized neural networks in the **departamental scientific seminar**, Department of Computer Science, West University of Timişsoara, Romania (December 7th, 2022).

Mădălina Erașcu participated at **Dagstuhl Seminar** 23401 on Automated mathematics: integrating proofs, algorithms and data, October 1-6, 2023, Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik in Germany. The talk she gave and interaction with other participants was around understanding the road from symmetries to the symmetry breakers of the constraint optimization problems which appear in deployment in the Cloud of component-based applications.

Mădălina Erașcu gave a **contributed talk** at The Tenth Congress of Romanian Mathematicians June 30 - July 5, 2023, Pitesti, Romania at the *Special Session Logic and applications*. The congress was jointly organized by the Section of Mathematical Sciences of the Romanian Academy, the Romanian Mathematical Society, the Simion Stoilow Institute of Mathematics of the Romanian Academy, the Faculty of Mathematics and Computer Science of the University of Bucharest, and the University of Pitesti. The topic of the presentation was the symbiosis of constraint optimization, symmetries and symmetry breaking for scalable Cloud deployment problems.

Some notable project results have also been advertised on the **LinkedIn page** of the PI, Madalina Erascu.

4.2. Exploitation

In 2022, we participated in the ADRVest Accel program (**start-up accelerator**), the first accelerator backed by the West Regional Development Agency. Our aim was to explore the business potential of a SaaS solution designed for the automated planning and deployment of resources. This solution targets businesses seeking to migrate their component-based applications to the Cloud, with the goal of reducing costs, time, and errors associated with planning and deployment. This exploitation result was disseminated in a newspaper which publishes news about (Romanian) entrepreneurship and innovation landscape: https://start-up.ro/demoday-adrvest-accel-cele-mai-bune-startup-uri-din-vest-in-fata-investitorilor/, see presentation of MANeUveR.

5. Project Results

#	Planned KPI (from project proposal)	Realized KPI
1	We aim to publish at least 3 research papers published in international conferences/journals related to the project.	**Conference papers:** 1. Bogdan David, Madalina Erascu. Automatic Deployment of Component-based Applications in the Cloud (short paper). Proceedings of the 7th SC-Square Workshop co-located with the Federated Logic Conference 2022 (FLoC 2022) as a part of the 11th International Joint Conference on Automated Reasoning (IJCAR 2022), Haifa, Israel, August 12, 2022. The initial paper was sent in 2022, before the start of the project, but we had to do some updates for the proceedings which were published in 2023 (https://ceur-ws.org/Vol-3458/). 2. Postovan, A., Eraşcu, M. (2023). Architecturing Binarized Neural Networks for Traffic Sign Recognition. In: Iliadis, L., Papaleonidas, A., Angelov, P., Jayne, C. (eds) Artificial Neural Networks and Machine Learning – ICANN 2023. ICANN 2023. Lecture Notes in Computer Science, vol 14254. Springer, Cham. https://doi.org/10.1007/978-3-031-44207-0_8 3. Postovan, A., Eraşcu, M. Benchmarking Local Robustness of High-Accuracy Binary Neural Networks for Enhanced Traffic Sign Recognition. In Horaţiu Cheval, Laurenţiu Leuştean and Andrei Sipoş: Proceedings 7th Symposium on *Working Formal Methods* (FROM 2023), Bucharest, Romania, 21-22 September 2023, Electronic Proceedings in Theoretical Computer Science 389, pp. 120–130. Published: 22nd September 2023. https://dx.doi.org/10.4204/EPTCS.389.10 4. Luca, Vlad-Ioan, and Mădălina Eraşcu. "SAGE-A Tool for Optimal Deployments in Kubernetes Clusters." *2023 IEEE International Conference on Cloud Computing Technology and Science (CloudCom)*. IEEE, 2023 5. Eduard Laitin and Mădălina Eraşcu. Fast and Exact Synthesis of Application Deployment Plans using Graph Neural Networks and Satisfiability Modulo Theory. To appear in the Proceedings of the International Joint Conference on Neural Networks 2024 (IJCNN 2024), part of IEEE WCCI 2024 (IEEE Proceedings). **Benchmarks** 1. We proposed benchmarks for traffic signs classification using binarized neural networks (https://github.com/apostovan21/vnncomp2023) at the Verification of Neural Networks Competition (VNN-COMP) 2023 (https://github.com/apostovan21/vnncomp2023) which received the outstanding benchmark award (https://merascu.github.io/links/SAGEResources/vnncomp2023_certificate_traffic-signs-recognition.pdf) 2. Wordpress application benchmark was selected in the Minizinc challenge 2022 https://www.minizinc.org/challenge2022/results2022.html. 3. Wordpress application is part of the CSPLib https://github.com/csplib/csplib/tree/master/Problems/prob090 a library of constrained satisfaction problems.

2	Moreover, all the implementations of our algorithms will be released as open-source code.	https://github.com/SAGE-Project
3	Dissemination will also take place through: (1) project website, and (2) the participation at local events gathering IT industry to promote our tool and how it can assist the business and technical needs of the company.	(1) Project website: https://merascu.github.io/links/SAGE.html (2) In 2022, we applied for participation in the ADRVest Accel, the first accelerator supported by West Regional Development Agency - West RDA. Our goal was to check the business opportunity of a SaaS solution for the automated planning/deployment of resources for businesses which want to move their component-based applications in the Cloud in order to reduce their costs, time and the faults of the planning/deployment. We were selected to pitch at Demo Day of ADRVest Accel (https://start-up.ro/demoday-adrvest-accel-cele-mai-bune-startup-uri-din-vest-in-fata-investitorilor/ -> MANeUveR), on November 11th. The main feedback was that we need to find our market and to define our competitive advantage.
4	We also plan to host online/offline the SC-square workshop which is held yearly (http://www.sc-square.org/workshops.html) and Machine Learning workshops/meetups.	We, instead, contributed to the organization of FROM 2024 (Working Formal Methods 2024), both in the organizing committee (https://from2024.uvt.ro/commitees/) as well as in the technical program with the tutorial *Optimization Modulo Theory: A Tutorial Using Z3 and Practical Case Studies* (https://from2024.uvt.ro/madalina-erascu/). Moreover, we hosted the EuroProofNet WG3 Program Verification meeting, 8-9 February, 2023: https://europroofnet.github.io/wg3-timisoara/.

6. Estimated Impact of the Results Obtained

The indicators for measuring impact are related to dissemination results, collaborations with other teams and knowledge transfer to younger generations of researchers which we presented in previous sections. From our point of view, the most important result is the one related to the combination of Graph Neural Networks and Satisfiability Modulo Theory which appeared in IJCNN 2024.

7. Conclusions and Future Work

All planned objectives were entirely fulfilled. The prototype implementations are available on Github: https://github.com/SAGE-Project.

Activities related to the project continue after its finalization:

- We will try to overcome the scalability issues of the methods and algorithms related to abstraction techniques for symmetries and symmetry breaking as well as the theoretical framework for symmetry breaking techniques for both case studies.
- Conclude the work related to Result 3 of the topic on verifying the properties of binary neural networks

- Extend the results obtained in IJCNN 2024 and prepare a manuscript for journal publication.
- Apply the algorithm developed for IJCNN 2024 to also other case studies, for example Traveling Salesman Problem and compare the results obtained with the ones from Joshi, Chaitanya K., Thomas Laurent, and Xavier Bresson. "An efficient graph convolutional network technique for the traveling salesman problem." *arXiv preprint arXiv:1906.01227* (2019).
- Using Large Language Models (LLMs) to find symmetry breakers for constrained optimization/satisfaction problems.
- Extend/modify the Cloud Deployment problem to such ensure sustainable deployment over the Cloud-Edge Continuum

Director Proiect,
(*Nume, Prenume, Semnatura*)
Erașcu Mădălina

Madalina Erascu
Digitally signed by Madalina Erascu
Date: 2024.08.27 13:21:10 +03'00'