***Report***

*on the Progress of the **MuVeT** project between January 2012 and December 2016*

The MuVeT project aims to develop a modelling approach, focused on multi-scale systems, based on a combination of membrane systems and X-machines. This strengthens both these formalisms, by using their existing capabilities and their existing tools, and also by addressing (some of) their limitations with regard to modelling complex multi-scale systems and phenomena. By considering several case studies from different areas (biology, economics, engineering), the project develops domain-specific high-level specification languages, based on membrane systems and X-machines, that enable complex systems and multi-scale phenomena to be expressed in a natural manner. These languages are accompanied by model checking and test generation techniques for such systems and phenomena, which provide the necessary means for formally verifying and validating the obtained models. Furthermore, all modelling, verification and testing methods emerging from the project are accompanied by powerful simulators and a toolkit that integrates all these techniques. The expressive power of the specification languages, the effectiveness of the verification and testing methods, as well as the efficiency of the simulators is also proven on the aforementioned case studies.

## Main results achieved

To achieve the above objectives, in the period January 2012 - December 2016, important achievements in the following directions have been made:

- Carrying out investigations on using P systems and X-machines for modelling complex systems through case studies in various fields.
- Development of case studies of qualitative and quantitative analysis based on P systems and model checking tools.
- Definition of a new class of P systems (called kernel P systems or KP systems) and an associated modelling language (called KP-lingua) that integrates in a natural way the main modelling features of P systems, adding to them a mechanism for rule application from X-machines.
- Development of new testing techniques and tools for state-based formalisms (X-machines)
- Extension to P systems of the developed testing techniques.

- Development of an integrated methodology for modelling, simulation and formal verification for the new kP systems language.
- Development of tools for automated verification of models created using KP-lingua language.
- Development of a powerful parallel simulator for P systems.

Each of the directions above will be reviewed in what follows, highlighting the major achievements.

## 1. Investigations on using P systems and X-machines for modelling complex systems through case studies in various fields

These include: a hybrid approach based on differential evolution and tissue membrane systems for solving constrained manufacturing parameter optimization problems [1]; the application of membrane algorithms to broadcasting problems, which are regarded as NP-hard combinatorial optimization problems [4]; realistic models of the Escherichia coli (E.coli) bacteria using X-machines and membrane systems and the extraction and formal verification of properties [8]; studies of models from the synchronization processes area in service orientate architecture [2]; the use of objects for a high level programming with P systems [28].

## 2. Development of case studies of qualitative and quantitative analysis based on P systems and model checking tools

The MuVeT team has made a significant contribution to the development of the Infobiotics Workbench (IFW) tool suite, based on stochastic P systems, and its use for system analysis in many case studies. In [34] and [35] we show how formal verification is used in system biology and synthetic biology through qualitative and quantitative analysis in several case studies.

## 3. Kernel P systems (kP systems)

A new class of P systems, called kernel P systems (kP systems for short), that covers many features of existing P systems successfully used in modelling, but also adds a rule control mechanism inspired from X-machines, is defined and discussed in [22]. The expressive power of kP systems is studied in [3, 10, 18]. The paper [20] studies the link between kP systems and generalized communicating P systems. In [37] it is shown that a kP systems with only rewriting rules can be simulated by communicating X-machines and a FLAME implementation is also provided.

### 4. Development of new testing techniques and tools for state-based formalisms (X-machines) and extensions to P systems

One of the main strengths of the X-machine model is its associated testing technique. This guarantees, under well defined condition that all functional errors of the implementation under test are revealed. The paper [12] presents JSXM, an X-machine based testing tool, developed by colleagues from the University of Sheffield with support form the MuVeT team. The paper [6] proposes an approach that, having a transition based model of a system, constructs an approximate automaton and a test suite for the system. In parallel with theoretical methods for testing, heuristic methods, based on genetic algorithms have also been developed [11].

### 5. Extension to P systems of the developed testing techniques

The paper [47] represents a significant advance on the issue of testing for implementations specified by P systems with transformation and communicating rules. Using the X-machine framework and the concept of cover automaton, it devises a testing approach for such systems, that, under well defined conditions, it ensures that the implementation conforms to the specification. It also investigates the issue of identifiability for P systems, that is an essential prerequisite for testing implementations based on such specifications and establishes a fundamental set of properties for identifiable P systems.

### 6. Integrated methodology for modelling, simulation and formal verification for the kP system language

The paper [24] illustrates the modelling power of kP systems by using a well-known NP-complete problem, the 3-colouring (3-Col) problem. It also presents an integrated modelling, simulation, property extraction and formal verification approach for P systems, illustrated by a tissue P system for the 3-Col problem. This approach is continued in [26], producing the kpWorkbench integrated framework.

### 7. Development of tools for automated verification of models created using KP-lingua language

kP systems are supported by a framework called kPWorkbench [26, 40], that integrates a set of tools for the simulation and verification through model checking of kP systems. In [26], the SPIN model checker is used for verification of properties of kP systems. KP Workbench also contains a native simulator for the execution of kP system models. In [38] two extensions of KPWorkbench are presented: a formal verification tool based on the NuSMV model checker and a large scale simulation environment using FLAME (Flexible Large-Scale Agent Modelling Environment).

## 8. Development of a powerful parallel simulator for P systems

Besides the kpWorkbench framework and the other tools and plugins for extraction and formal verification of KP/P systems mentioned above, we also report the development of a powerful parallel simulator using Hadoop technology, exploiting the scalability offered by Map Reduce and Big Data [27]. This simulator is also used for test data generation. The evaluation on a benchmark of automatically generated P systems confirm the scalability of this approach.

# Bibliography:


1. G. Zhang, J. Cheng, M. Gheorghe, Q. Meng. A hybrid approach based on differential evolution and tissue membrane systems for solving constrained manufacturing parameter optimization problems. Applied Soft Computing, 13 (3), 1528 - 1542, 2013. http://dx.doi.org/10.1016/j.asoc.2012.05.032. **ISI-indexed journal, IF 2.810, categ. A.**
2. A. Stefanescu, S. Wieczorek, M. Schur. Message Choreography Modeling - A Domain-Specific Language for Consistent Enterprise Service Integration. Software and Systems Modeling (SoSyM), 13 (1), 9-33 http://dx.doi.org/10.1007/s10270-012-0272-x**. ISI-indexed journal, IF 1.408, categ. A.**
3. M. Gheorghe, F. Ipate, R. Lefticaru, M. J. Pérez-Jiménez, A. Turcanu, L. Valencia Cabrera, M. García-Quismondo, L. Mierla. 3-Col problem modelling using simple kernel P systems. International Journal of Computer Mathematics, 90 (4): 816 - 830, 2013. http://dx.doi.org/10.1080/00207160.2012.743712. **ISI-indexed journal, IF 0.825, categ. C.**
4. G. Zhang, F. Zhou, X. Huang, J. Cheng, M. Gheorghe, F. Ipate, R. Lefticaru. A Novel Membrane Algorithm Based on Particle Swarm Optimization for Solving Broadcasting Problems. Journal of Universal Computer Science. 18 (13): 1821 – 1841, 2012. http://dx.doi.org/10.3217/jucs-018-13-1821. **ISI-indexed journal, IF 0.401, categ. B.**
5. M. Gheorghe, G. Paun, M. Perez-Jimenez, G. Rozenberg. Research Frontiers of Membrane Computing: Open Problems and Research Topics. International Journal of Foundations of Computer Science. 24(5): 547-624, 2013. **ISI-indexed journal, IF 0.326, categ. B.**
6. F. Ipate, A. Stefanescu, I. Dinca. Model Learning and Test Generation using Cover Automata. Computer Journal, 58(5), pp. 1140-1159, Oxford University Press, 2015. **ISI-indexed journal, IF 0.787, categ. B**.
7. P. Frisco, M. Gheorghe, M.J. Perez-Jimenez (eds.) Applications of Membrane Computing in Systems and Synthetic Biology. Springer, 266 pp, 2014.
8. A. Turcanu, L. Mierla, F. Ipate, A. Stefanescu, H. Bai, M. Holcombe, S. Coakley. Modeling and analysis of E. coli respiratory chain. Book chapter in P. Frisco, M. Gheorghe, M. J. Pérez-Jiménez (Eds), Applications of Membrane Computing in Systems and Synthetic Biology, Emergence, Complexity and Computation series, vol. 7, pp. 247-266, Springer, 2014.
9. J. Blakes, J. Twycross, S. Konur, F. J. Romero-Campero, N. Krasnogor, M. Gheorghe. Infobiotics workbench - A P system based tool for systems and synthetic biology. Book chapter in Applications of Membrane Computing in Systems and Synthetic Biology, Springer, 2014.
10. F. Ipate, R. Lefticaru, L. Mierla, L. Valencia Cabrera, H. Han, G. Zhang, C. Dragomir, M. J. Pérez Jiménez, M. Gheorghe. Kernel P Systems: Applications and Implementations. The 8th International Conference on Bio-Inspired Computing: Theory and Applicatons (BIC-TA 2013), Advances in Intelligent Systems and Computing, vol. 202, pp. 1081-1089. Springer, 2013. **ISI Proceedings.**

11. R. Lefticaru, F. Ipate. An Improved Test Generation Approach from Extended Finite State Machines Using Genetic Algorithms. 10th International Conference on Software Engineering and Formal Methods (SEFM 2012), Lecture Notes in Computer Science, vol. 7504, pp. 293-307. Springer, 2012. **ISI Proceedings, categ. B.**
12. D. Dranidis, K. Bratanis, F. Ipate. JSXM: A Tool for Automated Test Generation. 10th International Conference on Software Engineering and Formal Methods (SEFM 2012), Lecture Notes in Computer Science, vol. 7504, pp. 352-366. Springer, 2012. **ISI Proceedings, categ. B.**
13. E. Csuhaj-Varjú, M. Gheorghe, M. Stannett. P Systems Controlled by General Topologies. 11th International Conference on Unconventional Computation and Natural Computation (UCNC 2012), Lecture Notes in Computer Science, vol. 7445, pp. 70-81. Springer, 2012. **ISI Proceedings, categ. C.**
14. I. Dinca, F. Ipate, L. Mierla, A. Stefanescu: Learn and Test for Event-B - A Rodin Plugin. Third International Conference on Abstract State Machines, Alloy, B, VDM, and Z (ABZ 2012), Lecture Notes in Computer Science, vol. 7316, pp. 361-364. Springer, 2012. **ISI Proceedings, categ. C.**
15. I. Dinca, F. Ipate, A. Stefanescu. Model Learning and Test Generation for Event-B decomposition. 5th International Symposium On Leveraging Applications of Formal Methods, Verification and Validation (ISoLA 2012), Lecture Notes in Computer Science, vol. 7609, pp. 539-553. Springer, 2012. **ISI Proceedings, categ. C.**
16. L. Lin, R. Su, A. Stefanescu. Remarks on the Difficulty of Top-Down Supervisor Synthesis. 12th International Conference on Control, Automation, Robotics and Vision (ICARCV 2012), pp. 270-275. IEEE Computer Society, 2012. **ISI Proceedings, categ. A.**
17. A. Turcanu, F. Ipate. Computational properties of two P systems solving the 3-colouring problem. 14th International Symposium on Symbolic and Numeric Algorithms for Scientific Computing (SYNASC 2012), pp. 62-69, IEEE Computer Society, 2012**, categ. C**.
18. F. Ipate, C. Dragomir, R. Lefticaru, L. Mierla, M. J. Pérez-Jiménez. Using a kernel P system to solve the 3-Col problem. 13th International Conference on Membrane Computing (CMC 2012), pp. 243-258. Computer and Automation Research Institute, Hungarian Academy of Sciences, 2012.
19. Turcanu, F. Ipate. Simplifying Event-B Models of P Systems Using Functions. 13th International Conference on Membrane Computing (CMC 2012), pp. 455 - 458. Computer and Automation Research Institute, Hungarian Academy of Sciences, 2012.
20. S. Krishna, M. Gheorghe, C. Dragomir. Some Classes of Generalised Communicating P Systems and Simple Kernel P Systems. The Nature of Computation, 9th Conference on Computability in Europe (CiE 2013), Lecture Notes in Computer Science, vol. 7921, pp. 284-293, Springer, 2013. (**best paper award** in Natural Computation). **ISI Proceedings, categ. C.**
21. E. Csuhaj-Varjú, M. Gheorghe, M. Stannett. General Topologies and P Systems. Tenth Brainstorming Week on Membrane Computing. Vol 1, pp. 79 - 90. Fénix Editora, 2012.
22. M. Gheorghe, F. Ipate, C. Dragomir. A Kernel P system. Tenth Brainstorming Week on Membrane Computing. Vol 1, pp. 153 - 170. Fénix Editora, 2012.
23. M. Gheorghe, G. Paun, M. J. Pérez-Jiménez (Editors). Frontiers of Membrane Computing: Open Problems and Research Topics. Tenth Brainstorming Week on Membrane Computing. Vol 1, pp. 171-250. Fénix Editora, 2012.
24. R. Lefticaru, F. Ipate, L. Valencia Cabrera, A. Turcanu, C. Tudose, M. Gheorghe, M. J. Pérez Jiménez, I. M. Niculescu, C. Dragomir. Towards an integrated approach for model simulation, property extraction and verification of P systems. Tenth Brainstorming Week on Membrane Computing. Vol 1, pp. 291-318. Fénix Editora, 2012.
25. G. Zhang, M. A. Gutiérrez-Naranjo, Y. Qin, M. Gheorghe. A Membrane-Inspired Evolutionary Algorithm with a Population P System and its Application to Distribution System Reconfiguration. Tenth Brainstorming Week on Membrane Computing. Vol 2, pp. 277-292. Fénix Editora, 2012.

26. C. Dragomir, F. Ipate, S. Konur, R. Lefticaru, L. Mierla. Model checking Kernel P systems. 14th International Conference on Membrane Computing (CMC 2013). Lecture Notes in Computer Science, 8340: 151-172, Springer, 2013. **ISI Proceedings, categ. C.**
27. A. Ciobanu, F. Ipate. Using Big Data technologies with P systems. 14th International Conference on Membrane Computing (CMC 2013). Lecture Notes in Computer Science 8340: 117-137, Springer, 2013. **ISI Proceedings, categ. C.**
28. R. Nicolescu, F. Ipate, H. Wu. Towards High-level P Systems Programming using Complex Objects. 14th International Conference on Membrane Computing (CMC 2013). Lecture Notes in Computer Science 8340: 280-300, Springer, 2013. To appear. **ISI Proceedings, categ. C.**
29. M. Gheorghe, F. Ipate. Kernel P Systems - A Survey. 14th International Conference on Membrane Computing (CMC 2013). Lecture Notes in Computer Science 8340: 1-9, Springer, 2013. **ISI Proceedings, categ. C.**
30. S. Akshay, I. Dinca, B. Genest, A. Stefanescu. Implementing Realistic Asynchronous Automata. 33rd Conference on the Foundations of Software Technology and Theoretical Computer Science (FSTTCS 2013). Leibniz International Proceedings in Informatics (LIPIcs). volume 24, pp. 213-224. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2013. **ISI Proceedings, categ. B.**
31. A. Ciobanu, F. Ipate. P System Testing with Parallel Simulators - a Survey, Scalable Computing: Practice and Experience 14(3), 2013**.**
32. L. Lin, A. Stefanescu, R. Su, W. Wang, A.R. Shehabinia. Towards Decentralized Synthesis: Decomposable Sublanguage and Joint Observability Problems. In Proc. of 55th American Control Conference (ACC 2014), pp. 2047-2052. IEEE Computer Society, 2014. **ISI Proceedings**.
33. M. Gheorghe, F. Ipate, C. Dragomir, L. Mierla, L. Valencia Cabrera, M. García-Quismondo, M. J. Pérez Jiménez. Kernel P Systems - Version 1. Proceedings of the Eleventh Brainstorming Week on Membrane Computing, pp. 97-124. Fénix Editora, Seville, 2013.
34. S. Konur, M. Gheorghe, C. Dragomir, L. Mierla, F. Ipate, N Krasnogor: Qualitative and Quantitative Analysis of Systems and Synthetic Biology Constructs using P Systems, ACS Synthetic Biology, 4(1), 83-92, 2015. **ISI-indexed journal, IF 4.978, categ. C**.
35. S. Konur, M. Gheorghe, C. Dragomir, F. Ipate, N. Krasnogor: Conventional Verification for Unconventional Computing: a Genetic XOR Gate Example, Fundamenta Informaticae. Accepted. **ISI-indexed journal, IF 0.479, categ. B**.
36. G. Zhang, C. Liu, M. Gheorghe, F. Ipate, X. Wang: QEAM: An Approximate Algorithm Using P Systems with Active Membranes, International Journal of Computers, Communications and Control, 10(2), 263-279, 2015. **ISI-indexed journal, IF 0.746, categ. B**.
37. I. M. Niculescu, M. Gheorghe, F. Ipate, A. Stefanescu: From Kernel P Systems to X-Machines and FLAME, Journal of Automata, Languages and Combinatorics, 19(1-4), 239-250, 2014.
38. M. E. Bakir, F. Ipate, S. Konur, L. Mierla, I. Niculescu: Extended Simulation and Verification Platform for Kernel P Systems, Int. Conf. on Membrane Computing 2014, LNCS, 158-178, 2014. **ISI Proceedings, categ. C.**
39. I. Sakellariou, O. Kurdi, M. Gheorghe, D. Romano, P. Kefalas, F. Ipate, I.M. Niculescu: Crowd formal modelling and simulation: The Sa'yee ritual, UKCI 2014, 1-8, 2014.
40. M. E. Bakir, S. Konur, M. Gheorghe, I. Niculescu, F. Ipate: High Performance Simulations of Kernel P Systems, 2014 IEEE International Conference on High Performance Computing and Communications (HPCC), 409-412, 2014. **ISI Proceedings, categ. B.**
41. G. Ciobanu, T. S. Hoang, A. Stefanescu. From TiMo to Event-B: event-driven timed mobility. In Proc. of 19th IEEE Int. Conf. on Engineering of Complex Computer Systems (ICECCS'14), pp. 1-10, IEEE Computer Society, 2014. (**best paper award**) **ISI Proceedings, categ. A.**
42. L. Lin, A. Stefanescu, R. Su. On Distributed and Parameterized Supervisor Synthesis Problems. IEEE

Transactions on Automatic Control 61(3), 777-782, 2016. **ISI-indexed journal, IF 2.779, categ. A.**

43. F. Ipate, D. Dranidis: A unified integration and component testing approach from deterministic stream X-machine specifications, Formal Aspects of Computing 28(1), 1-20, 2016. **ISI-indexed journal, IF 0.806, categ. B.**
44. X. Wang, G. Zhang, F. Neri, T. Jiang, J. Zhao, M. Gheorghe, F. Ipate, R. Lefticaru: Design and implementation of membrane controllers for trajectory tracking of nonholonomic wheeled mobile robots, Integrated Computer-Aided Engineering 23(1), 15-30, 2016. **ISI-indexed journal, IF 4.698, categ. B.**
45. M. Gheorghe, S. Konur, F. Ipate, L. Mierla, M. E. Bakir, M. Stannett: An Integrated Model Checking Toolset for Kernel P Systems, Int. Conf. on Membrane Computing 2015, LNCS, 153-170, 2015. **ISI Proceedings, categ. C.**
46. L. Lin, A. Stefanescu, W. Wang, R. Su. Symbolic Reachability Analysis of Globally Synchronized Templates. Submitted to Automatica, 2015. **ISI-indexed journal, IF 3.020.**
47. M. Gheorghe, F. Ipate and S. Konur: Testing Identifiable P Systems Using Cover Automata and X-Machines. Information Sciences, 372, 565-578, 2015. **ISI-indexed journal, IF 4.038, categ. A.**
48. M. Gheorghe, R. Ceterchi, F. Ipate, S. Konur: Kernel P Systems Modelling, Testing and Verification - Sorting Case Study, Int. Conf. on Membrane Computing 2016, LNCS, to appear, 2016. **ISI Proceedings, categ. C.**
49. T. Stoenescu, A. Stefanescu, S. Predut, F. Ipate: RIVER: A Binary Analysis Framework using Symbolic Execution and Reversible x86 Instructions, 21st International Symposium on Formal Methods (FM 2016), LNCS, Springer, 779-785, 2016. **ISI Proceedings, categ. A.**
50. R. Lefticaru, L. F. Macias-Ramos, I. M. Niculescu, L. Mierla. Agent-Based Simulation of Kernel P Systems with Division Rules Using FLAME. Int. Conf. on Membrane Computing 2016, LNCS, to appear, 2016. **ISI Proceedings, categ. C.**
51. R. Lefticaru, L. F. Macias-Ramos, I. M. Niculescu, L. Mierla. Towards Agent-Based Simulation of Kernel P Systems using FLAME and FLAME GPU. Proceedings of the Workshop on Membrane Computing (WMC 2016), Manchester (UK), 11-15 July 2016. Technical Report – UB-20160819-1, University of Bradford, pages 58-61, 2016.
52. M. Gheorghe, R. Ceterchi, F. Ipate, S. Konur, R. Lefticaru: Kernel P Systems: From Modelling to Verification and Testing. Submitted to Theoretical Computer Science. **ISI-indexed journal, categ. B.**
53. S. N. Krishna, M. Gheorghe, F. Ipate, E. Csuhaj-Varju, R. Ceterchi: Further Results on Generalised Communicating P Systems. Submitted to Theoretical Computer Science. **ISI-indexed journal, categ. B.**
54. T. Stoenescu, A. Stefanescu, S. Predut, F. Ipate. RIVER: A Binary Analysis Framework using Symbolic Execution and Reversible x86 Instructions, Submitted to Fundamenta Informaticae, 2016. **ISI-indexed journal, categ. B.**