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Faculty of Computer Science and Automation

HABILITATION THESIS

in Computer Science and Information Technology

EFFICIENT MANAGEMENT OF RESOURCES IN LARGE SCALE DISTRIBUTED SYSTEMS

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DSRL
Distributed Systems
Research Laboratory

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Acknowledgement

My work presented in this habilitation is the result of my collaboration with many colleagues.

First and foremost, I owe my deepest gratitude to Professor Ioan Salomie, who has supported and advise me in my activity from a young and restless research assistant and PhD student up to a mature associated professor and research project director. This habilitation would not have been possible without his dedication, motivation, and guidance.

Second, I would like to thank Ionut Anghel, my colleague, and my friend. As if it were yesterday we have started to work together to our license thesis and now 12 years later, I can't believe that we had accomplished so much.

Third, I would like to express my gratitude to the members of the Distributed Systems Research Laboratory for their support and help in all the academic and research work that had led to this habilitation thesis. Also, I want to thank all my colleagues from the Department of Computer Science, of the Automation and Computer Science Faculty for wonderful and successful collaborations, also for their support.

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Finally, I would like to thank my family: my wife Oana, my children Andrada and Alexandru, my parents Voicu and Camelia. I dedicate this Habilitation thesis to them.

Summary

This habilitation thesis presents the main scientific, professional and academic work in which I had been involved after my PhD defense as a member of Computer Science Department part of Faculty of Automation and Computer Science, Technical University of Cluj-Napoca. The main subject of this habilitation is the management of resources in large scale distributed systems with the objective of optimizing their run-time operation and to increase their energy efficiency.

From the academic perspective, I am a member of Computer Science Department since 2007 and my career path had taken all the steps from assistant professor up to associate professor my current position. I currently teach Programming Techniques and Distributed Systems to bachelor students and Context Aware Software Design to master students. I had contributed to the definition of courses for new disciplines and to the updating of existing ones trying to combine the didactic activity with the research activity efficiently facilitating the knowledge transfer to students. I have co-authored 6 books which are leveraging on state of the art techniques and tools I had worked for research projects implementation and they are used as support materials for different bachelor and master level disciplines. I have coordinated students for their license or master thesis, and I have worked with them, to find solutions for open research problems, to validate and publish them in papers. I participate to: (i) activities related students license thesis, I am a secretary of license evaluation committee, (ii) elaboration of paper work and reports for ARACIS accreditation, and (iii) tutoring of students in relation with their 3rd year internship activities.

My scientific and professional work had been driven by the research projects implemented by the Distributed Systems Research Laboratory[1] team in which I had participated and under the supervision and guidance of Professor Ioan Salomie. During the reported period I conducted as project director 2 European H2020 projects, 1 national PN-III project and 1 research project with industry. Additional I was the Consortium Level Scientific and Technical Manager in one H2020 Ambient Assistive Living project and had the role of outreach coordinator in a COST action on nature inspired optimization heuristics. At the same time, I have participated as a team member in other 5 national and European projects in which I had the role of workpackage leader. Working in research projects I have been able to define and develop new techniques, algorithms, models, and to implement them in different tools and frameworks. I have published the research and scientific results of my work in 8 ISI journal articles (4 articles in the red zone) with a cumulative impact factor of 26.93 and 26 scientific papers in international or national conferences (ISI proceedings and BDI) or book chapters. After 2013 the papers which I co-authored had over 250 citations and I have impact factors h-index of 11 and i10-index of 13[2]. I have disseminated my results during scientific events by oral presentations and posters and have participated at over 10 project review meetings conducted by the European Commission in which I have represented the Technical University of Cluj-Napoca and I have presented the work done by DSRL in European projects.

[1] Distributed Systems Research Laboratory, http://dsrl.coned.utcluj.ro/

[2] According to Google Scholar

The detailed presentation of my relevant contributions selected to be the focus of this habilitation thesis is organized in three sections according to the objectives, use-cases, and requirements of the European and National projects that I am coordinating. Section 2 presents the main contributions in relation to the energy efficient management of Data Centers (DCs) the work being done in the context of H2020 CATALYST and FP7 GEYSER projects. During my PhD studies, my main research focus was on lowering the electrical energy consumption of DCs. After my PhD defense, I have been working on developing solutions to allow DCs to use their flexible electrical energy loads to voluntary participate in Demand Response (DR) programs contributing to the grid reliability and sustainability. In my work, I have considered other flavors of energy such as thermal and proposed techniques to allow DCs to effectively re-use their otherwise waste heat in nearby neighborhoods. Also, I have considered the workload relocation in other DCs a potential source of flexibility and proposed strategies for maximizing the use of renewable energy (i.e. follow the sun). My research contributes to the transformation of DCs in active energy players in their local grid thus I have defined novel business scenarios allowing DCs to capitalize on their new role and gain new revenue streams not foreseen before. Section 3 details my main contributions in relation with smart grid decentralized management and efficient integration of small scale prosumers using the blockchain technology and smart self-enforcing contracts. The work has been carried out in the context of H2020 eDREAM project that I lead. I have contributed to the definition of an innovative and decentralized approach to DR programs allowing smart grid actors such as aggregators and DSO to request, track and use the prosumers energy flexibility to address grid level problems such as congestion control. I have defined a blockchain based peer to peer energy marketplace implemented at micro-grid level promoting the local consumption of renewable energy and the implementation of dynamic coalitions of prosumers on the generation side to assure a more stable supply and to obtain increase revenue by selling the aggregated generation on national level energy markets. Section 4 presents my main contributions in relation to the management of manufacturing processes in smart factories using cyber physical systems, the work being done in the context of PN-III OptiPlan project that I lead. In this direction, I had proposed a two level control one global addressing the factory and reduction process integration with upstream suppliers and downstream distribution and one local at the level of each machine at shop floor level. I had defined agent based abstractions for transforming production line machines in Cyber Physical Systems (CPS) and choreography abstraction for addressing their integration in complex processes as Cyber Physical Systems of Systems (CPSoS). Also, I had proposed the use of big data analytics to aggregate and construct the global snapshot, to identify those un optimal situations which may generate emergent behaviors at CPSoS level and nature inspired heuristics to optimize the choreographies of CSPs.

Leveraging on existing work and achievements I have proposed in Section 5 a career development plan targeting as high level goal to become a well-established professor of computer science. To reach my goal I have proposed development plans for academic and scientific and professional aspects of my career aiming to improve the impact of my scientific work and the teaching and academic management abilities. By implementing the proposed actions with perseverance, I will be able to contribute at maintaining a high-quality quality threshold of the learning process in the Computer Science Department and to the preservation of the top-ranked positions in national research rankings.

Chapter I - Scientific, professional, and academic achievements

1. Summary of Achievements

In this chapter, my main achievements and contribution are presented organized on two different plans: scientific and professional achievements and academic achievements. I will start with a summary of my major achievements on both plans (obtained after my PhD defense) and I will provide detailed insights on the work conducted in the following areas: DCs electrical and thermal energy flexibility management, decentralized management of smart energy grids and management of manufacturing processes using complex cyber physical production systems in smart factories.

1.1. Scientific and Professional Achievements

After my PhD defense in 2012, the primary focus of my research activities was the resource management in large scale distributed systems aiming at optimizing their operation, especially in terms of energy efficiency and lower carbon footprint. In particular, I had considered the Data Centers (DCs), smart energy grids and the smart factories as targets in the main use-cases driven by the requirements of European and National research projects that I have lead in behalf of Technical University of Cluj-Napoca (see Figure 1). The work conducted in the area of ambient active living technologies will not be addressed in detail in this thesis.

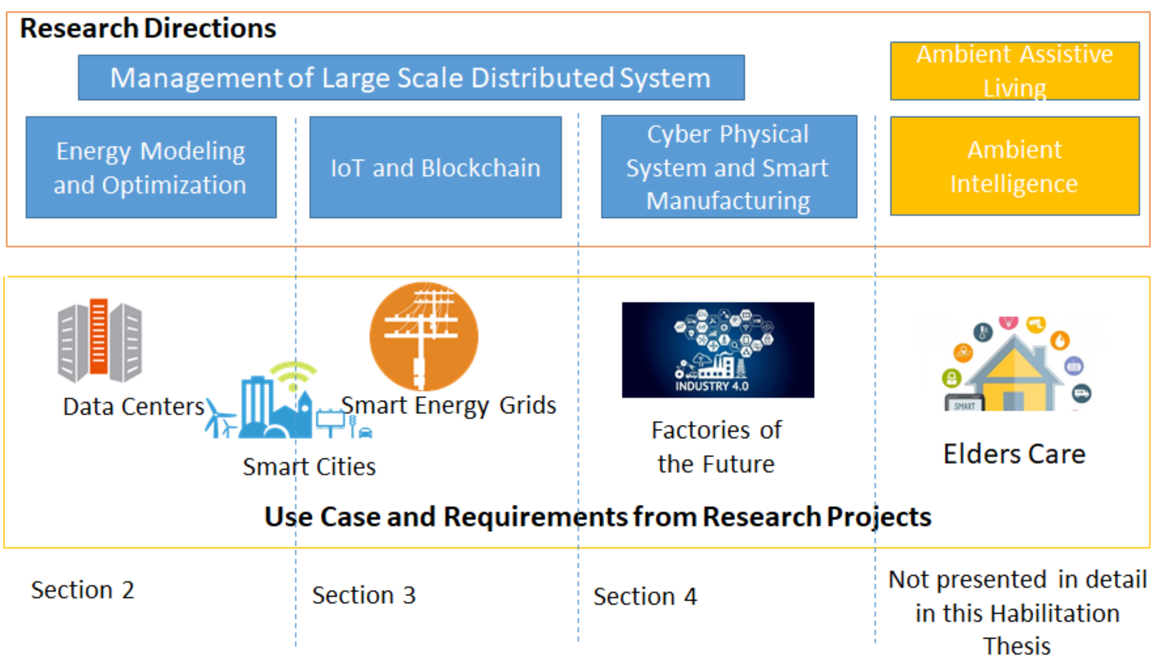


Figure 1. My research directions and their mapping on use-cases

In the area of DCs operation management the work achievements of this period had built on top of the work carried out during my PhD studies, but following a radically new perspective. While the research of my PhD was mainly focused on energy efficiency of DCs considering only their internal operation in isolation, after PhD my work was focusing on transforming the DCs in active energy players in their local smart energy grids ecosystems. Thus, their operation management optimization is no more addressed in isolation but considering their integration with the smart energy grids transforming DCs from a source of instability as large consumers putting a lot of pressure onto grid operation into a contributor to the grid stability, reliability, and sustainability. In particular, I had been investigating the potential latent energy flexibility of such prosumers with a view of developing the necessary technological infrastructure to use that flexibility (either by shifting or shedding) to meet various grid level optimization objectives. The publications in this area summarize my research achievements in a wide range of fundamental techniques and approaches such as system of system modeling and simulation, linear and non-linear optimizations, constrained resource scheduling, etc. As result, my work contributed to the ongoing efforts of transforming the DCs in technological flexible resources that can provide flexibility services such as congestion management, heat re-use in the local neighborhood, relocate workload in a follow a renewable energy approach. These scientific and technical achievements allow the new generation of green DCs to gain new revenue streams unforeseen before, outside their core business of running the workload of their clients.

In the area of smart energy grids management my work had been focusing on developing novel technologies for prosumers engagement in demand response (DR) programs. On demand side management one of the major obstacles in prosumers engagement in DR programs is data privacy and security, which I have innovatively addressed by considering the use of blockchain technology. This also overlaps the ongoing efforts for the decentralization of smart grid management which nowadays is moving from the “Edison Era” to the “Internet Era”. In this research area in my reference publications, I have proposed blockchain based techniques for the decentralized control of prosumers energy demand and enacting them to offer their energy flexibility for aggregators and peer to peer energy marketplace promoting the consumption of renewable energy closed to the point of its generation. On the energy generation side, my interest is going on the development of optimization and decentralized cooperation techniques allowing the small scale producers to aggregate in coalitions (i.e. Virtua Power Plants) for the provisioning of a steadier and reliable supply or for selling of an aggregated amount of energy in the national capacity market.

In the area of smart factories management, I had been working on the direction of digitalization and optimization of the manufacturing processes through the development and integration of Cyber Physical Systems (CPS) enhanced machines. In my publications, I have proposed a whole range of innovative ICT technologies for increasing the degree of adaptation and reactivity of manufacturing processes to the stimuli outside and inside the factory. They are leveraging on autonomic cyber-enhanced control of machines, context awareness through big data analytics, the definition of agent based abstraction as digital twins and integration of CPS enhanced machines in manufacturing processes. In terms of the impact they have the potential of increasing the factory economic, societal and environmental sustainability supporting the implementation of new business models such as production re-shoring and mass-customization.

In the three main research areas presented above I have published, after my PhD defense, 6 articles in ISI journals with impact factor, 3 of them being in the red zone (numbers 1, 2 and 4 in Table 1) and 3 of them being in the yellow zone (3, 5 and 6). The cumulated impact factor is 20.49 and for five of them, I was the first author or the corresponding author. In the same period, I have contributed and published 14 scientific papers in international or national conferences (ISI proceedings and BDI) or book chapters. Table 1 below presents my main contributions in terms of publications in the research areas presented in detail in this Habilitation Thesis.

Table 1. List of publications (personal contributions) after PhD Defence in research areas (covered in this thesis)

No	Publication Description
	Papers Published in ISI Journals
1	**Tudor Cioara**, Ionut Anghel, Ioan Salomie, Marcel Antal, Claudia Pop, Massimo Bertoncini, Diego Arnone, Florin Pop, Exploiting data centres energy flexibility in smart cities: Business scenarios, Information Sciences, 2018, ISSN 0020-0255 ***IF: 4.378*** DOI
2	**Tudor Cioara**, Ionut Anghel, Massimo Bertoncini, Ioan Salomie, Diego Arnone, Marzia Mammina, Terpsi Velivassaki, Marcel Antal, Optimized Flexibility Management enacting Data Centres Participation în Smart Demand Response Programs, Future Generation Computer Systems, Volume 78, Part 1, January 2018, Pages 330-342 ***IF:4.968*** DOI
3	**Tudor Cioara**, Ionut Anghel, Ioan Salomie, Methodology for Energy Aware Adaptive Management of Virtualized Data Centers, in Energy Efficiency, April 2017, Volume 10, Issue 2, pp 475–498 ***IF:1.634***, DOI
4	Marcel Antal, Claudia Pop, **Tudor Cioara**, Ionut Anghel, Ioan Salomie, Florin Pop, A system of systems approach for data centers optimization and integration into smart energy grids, Future Generation Computer Systems, Available online 24 May 2017, ISSN 0167-739X. ***IF:4.968*** DOI
5	Marcel Antal, **Tudor Cioara**, Ionut Anghel, Claudia Pop and Ioan Salomie, Transforming Data Centers in Active Thermal Energy Players in Nearby Neighborhoods, Sustainability 2018, 10, 939. ***IF:2.075*** DOI
6	Claudia Pop, **Tudor Cioara**, Marcel Antal, Ionut Anghel, Ioan Salomie and Massimo Bertoncini, Blockchain Based Decentralized Management of Demand Response Programs in Smart Energy Grids, Sensors 2018, 18(1), 162. ***IF:2.475*** DOI
	Papers Published in International Conferences (ISI Procesdings and BDI) or Book Chapters
7	**Tudor Cioara**, Terpsi Velivassaki, Massimo Bertoncini, Artemis Voulkidis, Ariel Oleksiak, Nicolas Saintherant, Vasiliki Georgiadou, Ionut Anghel, Maria Adele Paglia, Claudia Pop, Converting Data Centres in Energy Flexibility Ecosystems, IEEE 18th International Conference on Environment and Electrical Engineering and 2nd Industrial and Commercial Power Systems Europe 2018
8	**Tudor Cioara**, Ionut Anghel, Claudia Pop, Massimo Bertoncini, Vincenzo Croce, Dimosthenis Ioannidis, et. al, Enabling New Tehnologies for Demand Response Descentralized Validation using Blockchain, IEEE 18th International Conference on Environment and Electrical Engineering and 2nd Industrial and Commercial Power Systems Europe 2018.
9	**Tudor Cioara**, Ionut Anghel, Ioan Salomie, Marcel Antal, Massimo Bertoncini, Diego Arnone, Optimizing the Power Factor of Data Centers Connected to the Smart Grid, 5th International workshop on energy-efficient data centres, E2DC 2016 June 21 Waterloo, Canada, DOI
10	**Tudor Cioara**, Ionut Anghel, Marcel Antal, Sebastian Crisan, Ioan Salomie, Data center optimization methodology to maximize the usage of locally produced renewable energy. SustainIT 2015: 1-8 DOI

11	Cristian Pintea, Eugen Pintea, Marcel Antal, Claudia Pop, **Cioara Tudor**, Ionut Anghel and Ioan Salomie, CoolCloudSim: Integrating Cooling System Models in CloudSim, ICCP 2018.
12	Claudia Pop, Marcel Antal, Cristian Pop, Andreea Valeria Vesa, **Cioara Tudor**, Ionut Anghel, Ioan Salomie and Teodor Petrican Descentralizing the Stock Exchange using Blockchain: An Ethereum-based implementation of the Bucharest Stock Exchange, ICCP 2018
13	Teodor Petrican, Andreea Valeria Vesa, Marcel Antal, Claudia Pop, **Tudor Cioara**, Ionut Anghel and Ioan Salomie Evaluating Forecasting Techniques for Integrating Household Energy Prosumers into Smart Grids, ICCP 2018.
14	Marcel Antal, **Tudor Cioara**, Ionut Anghel, Claudia Pop, Ioan Salomie, Massimo Bertoncini, and Diego Arnone. 2017. DC Thermal Energy Flexibility Model for Waste Heat Reuse in Nearby Neighborhoods. In Proceedings of the Eighth International Conference on Future Energy Systems (e-Energy '17). ACM, New York, NY, USA, 278-283 DOI
15	Marcel Antal, Cristina Pop, **Tudor Cioara**, Ionut Anghel, Ionut Tamas and Ioan Salomie, Proactive day-ahead data center operation scheduling for energy efficiency: Solving a MIOCP using a multi-gene genetic algorithm, 2017 13th IEEE International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, 2017, pp. 527-534. ISBN: 978-1-5386-3368-7
16	Marcel Antal, Adelina Burnete, Claudia Pop, **Tudor Cioara**, Ionut Anghel and Ioan Salomie, Self-adaptive task scheduler for dynamic allocation in energy efficient data centers, 2017 13th IEEE International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, Romania, 2017, pp. 535-541. ISBN: 978-1-5386-3368-7
17	Ionut Anghel, **Tudor Cioara**, and Ioan Salomie, Context Aware and Reinforcement Learning based Load Balancing System for Green Clouds, Resource Management for Big Data Platforms, Springer, pp. 129-144, ISBN 978-3-319-44881-7, 2016, DOI
18	Marcel Antal, Cristian Pintea, Eugen Pintea, Claudia Daniela Pop, **Tudor Cioara**, Ionut Anghel, Ioan Salomie, Thermal Aware Workload Consolidation in Cloud Data Centers, ICCP2016, DOI
19	Massimo Bertoncini, Diego Arnone, **Tudor Cioara**, Ionut Anghel, Ioan Salomie, Terpsichori Helen Velivassaki, Next Generation Data Centers Business Models Enabling Multi-Resource Integration for Smart City Optimized Energy Efficiency. e-Energy 2015: 247-252 DOI
20	Marcel Antal, Claudia Pop, Dan Valea, **Tudor Cioara**, Ionut Anghel, Ioan Salomie, Optimizing Data Centres Operation to Provide Ancillary Services On-demand, GECON 2015, Cluj-Napoca, Romania. DOI
21	Ionut Anghel, Massimo Bertoncini, **Tudor Cioara**, Marco Cupelli, Vasiliki Georgiadou, Pooyan Jahangiri, Antonello Monti, Seán Murphy, Anthony Schoofs, Terpsi Velivassaki, GEYSER: Enabling Green Data Centres in Smart Cities, E2DC 2014, DOI

After my PhD defense, in my work, I have addressed other research areas such as the development of ambient assistive living systems for elders’ care (this work is not covered in detail in the next sections of this Habilitation Thesis). In this filed I have contributed to the publication of 2 journal papers one in the red zone and one in the yellow zone having a cumulated impact factor of 6.44 and 12 papers in national and international conferences. Table 2 below presents my main achievements in this research area in terms of published papers in journals and conferences.

Table 2. List of publications (personal contributions) after PhD Defence in connected research areas (not covered in this thesis)

No	Publication Description
	Papers Published in ISI Journals
1	**Tudor Cioara**, Ionut Anghel, Ioan Salomie, Lina Barakat, Simon Miles, Dianne Reidlinger, Adel Taweel, Ciprian Dobre, Florin Pop, Expert system for nutrition care process of older adults, Future Generation Computer Systems, Volume 80, March 2018, Pages 368-383, ISSN 0167-739X. ***IF:4.968*** DOI
2	Adel Taweel, Lina Barakat, Simon Miles, **Tudor Cioara**, Ionut Anghel, Abdel-Rahman H. Tawil, Ioan Salomie, A service-based system for malnutrition prevention and self-management, in Computer Standards & Interfaces, 2016. ***IF:1.479*** DOI
	Papers Published in International Conferences (ISI Procesdings and BDI) or Book Chapters
3	**Tudor Cioara**, Ionut Anghel, Dan Valea, Ioan Salomie, Victor Sanchez Martin, Alejandro Marchena, Elisa Jimeno and Martijn Vastenburg, Adaptive Workspace Interface for Facilitating the Knowledge Transfer from Retired Elders to Start-up Companies, Ambient Assisted Living and Enhanced Living Environments: Principles, Technologies and Control, Butterworth-Heinemann, Elsevier, pp. 287-309, ISBN: 978-0-12-805195-5, 2017, DOI
4	Roxana Jurca, **Tudor Cioara**, Ionut Anghel, Marcel Antal, Claudia Pop, Dorin Moldovan, Activities of Daily Living Classification using Recurrent Neural Networks, RoEduNet Conference 2018.
5	Dorin Moldovan, Adrian Olosutean, Viorica Chifu, Cristina Pop, **Tudor Cioara**, Ionut Anghel, Ioan Salomie,Big Data Analytics for the Daily Living Activities of the People with Dementia, ICCP 2018.
6	Viorica Rozina Chifu, Cristina Bianca Pop, **Tudor Cioara**, Ionut Anghel and Ioan Salomie, Identifying the Polypharmacy Side-Effects in Daily Life Activities of Elders with Dementia, Volume 798 of the Studies in Computational Intelligence series, ISSN 978-3-319-99625-7, IDC 2018.
7	Dorin Moldovan, Marcel Antal, Claudia Pop, Adrian Olosutean, **Tudor Cioara**, Ionut Anghel, and Ioan Salomie, Spark-Based Classification Algorithms for Daily Living Activities. In: Silhavy R. (eds) Artificial Intelligence and Algorithms in Intelligent Systems. CSOC2018. Advances in Intelligent Systems and Computing, vol 764. Springer, DOI
8	Teodor Petrican, Ciprian Stan, Marcel Antal, Ioan Salomie, **Tudor Cioara** and Ionut Anghel, Ontology-based skill matching algorithms, 2017, 13th IEEE International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, Romania, 2017, pp. 205-211. ISBN: 978-1-5386-3368-7
9	Claudia Pop, Alexandra Craciun, Carla Knoblau, Marcel Antal, Dorin Moldovan, **Tudor Cioara**, Ionut Anghel and Ioan Salomie, "Semantic data factory: A framework for using domain knowledge in software application development," 2017 13th IEEE International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, 2017, pp. 21-28. ISBN: 978-1-5386-3368-7
10	Dorin Moldovan, P. Stefan, C. Vuscan, Viorica Chifu, Ionut Anghel, **Tudor Cioara**, Ioan Salomie, Diet Generator for Elders using Cat Swarm Optimization and Wolf Search, International Conference on Advancements of Medicine and Health Care through Technology; 12th - 15th October 2016, Cluj-Napoca, IFMBE Proceedings, vol 59. Springer, pp 238-243, 2017, DOI

11	Dorin Moldovan, Claudia Pop, Marcel Antal, **Tudor Cioara**, Ionut Anghel, Ioan Salomie, Semantic Web Application Generator – A Library for Using Ontologies as Web Services, ICCP2016, DOI
12	Dorin Moldovan, Marcel Antal, Dan Valea, Claudia Pop, **Tudor Cioara**, Ionut Anghel, Ioan Salomie, Tools for Mapping Ontologies to Relational Databases: A Comparative Evaluation, ICCP 2015, DOI
13	Claudia Pop, Dorin Moldovan, Marcel Antal, Dan Valea, **Tudor Cioara**, Ionut Anghel, Ioan Salomie, M2O: A Library for Using Ontologies in Software Engineering, ICCP 2015, DOI
14	Ionut Anghel, **Tudor Cioara**, Ioan Salomie, ICT architecture for supporting elder employees to make conscious decisions under time pressure, The 2nd International Conference on Smart Learning Environments, September 2015, DOI
15	Adel Taweel, Simon Miles, Lina Barakat, Ioan Salomie, **Tudor Cioara**, Ionut Anghel, Thomas Sanders, Jim Charvill, DIET4Elders: a service-oriented architecture for the prevention and self-management of malnutrition, Broader, Bigger, Better – AAL solutions for Europe, Proceedings of the AAL Forum 2014 Bucharest Romania.

The above presented publications together with the ones published during my PhD studies had brought many citations is books, magazines, and volumes of scientific manifestations ISI or BDI. My profile as a researcher is visible in different public digital libraries such as Google Scholar[3], Researchgate[4], etc.

I act as a quality reviewer of several international ISI journals, dealing with the assessment of scientific works in order for them to be published. Some of those journals are listed below:

- Sustainable Computing, http://www.journals.elsevier.com/sustainable-computing
- Journal of Parallel and Distributed Computing, http://www.journals.elsevier.com/journal-of-parallel-and-distributed-computing/
- Computer Journal, http://comjnl.oxfordjournals.org/
- Future Generation Computer Systems, https://www.journals.elsevier.com/future-generation-computer-systems/
- Journal of Systems and Software, https://www.journals.elsevier.com/journal-of-systems-and-software/
- Information Sciences, https://www.journals.elsevier.com/information-sciences/
- Sustainability, http://www.mdpi.com/journal/sustainability/

Also, I have served as a PC member in national and international conferences such as:

- IEEE International Conference on Intelligent Computer Communication and Processing, http://www.iccp.ro/iccp2018/
- The Ninth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing, http://voyager.ce.fit.ac.jp/conf/imis/2015/committee.html#context
- IEEE International Conference on Computational Science and Engineering, https://cse2018.hpc.pub.ro/

[3] Tudor Cioara, Google Scholar, https://scholar.google.com/citations?user=nWTSIBwAAAAJ&hl=en

[4] Tudor Cioara, Researchgate profile, https://www.researchgate.net/profile/Tudor_Cioara

- IEEE International Conference on INnovations in Intelligent SysTems and Applications, http://inista.org/enbis2018.html

Since the beginning of my research career, after graduation, I have been involved as a member of Distributed Systems Research Laboratory in research activities and research projects. After my PhD defense, I have participated in the writing of many research project proposals. I have contributed the writing and submission of over 20 European project proposals (in the FP7 and H2020 frameworks) involving at least 4 partners from 3 different European countries per project and to the writing of over 10 national research project proposals. Some of those were successfully evaluated and have been materialized in research projects that are conducted and implemented by the DSRL team members.

In this period, I had won and lead as project coordinator on behalf of the Technical University of Cluj-Napoca 4 research projects 3 European projects and 1 national. For one of these projects I am the Scientific and Technical Manager of the consortium. Also, in one EU COST (European Cooperation in Science and Technology) action, I have the role of outreach coordinator. These projects are summarized in Table 3 below.

Table 3. List of research projects that I am coordinating

Period	Project Identity Card	Role	Scientific and Management Activity
2018-2021	**H2020 LCE-01-2017**, **eDREAM** - enabling new Demand REsponse Advanced, Market oriented and secure technologies, solutions and business models URL: http://edream-h2020.eu/ Consortium of 10 Partners from 5 countries: - Engineering S.p.A., Emotion s.r.l., Energy@Work, ASM Terni - Italy - Centre for Research & Technology Hellas - Greece, - University of Teeside, KiWi Power ltd - UK, - Atos Spain S.A. - Spain, - Technical University of Cluj-Napoca and Servlet SRL - Romania **Project Budget: 3.822.125 Euro** **TUCN Budget: 390.000 Euro**	**Project Director**	Management of scientific activity on behalf of the Technical University of Cluj-Napoca. Leader of WP3 on Techniques for DR and Energy Flexibility Assessment. Implementation of forecasting techniques for energy consumption, production and flexibility using Lambda architectures and deep learning. Developing blockchain technologies for decentralized management of smart grid by peer to peer trading of energy and flexibility potential offering for energy aggregators. Use of swarm inspired heuristics for the creation of prosumers collations in VPPs.
2017-2020	**H2020-EE-2016-2017, CATALYST** - Converting DCs in Energy Flexibility Ecosystems	**Project Director**	Management of scientific activity on behalf of Technical University of Cluj-Napoca.

Period	Project Identity Card	Role	Scientific and Management Activity
	URL: http://project-catalyst.eu/ Consortium of 10 Partners from 6 countries: - Engineering S.p.A., ENEL - Italy - SingularLogic S.A. – Greece - Aliander, Green IT Amsterdam, Schuberg Philis – Netherlands - QARNOT Computing - France - Power Operations Limited – UK - Poznan Supercomputing and Networking Centre – Poland - Technical University of Cluj-Napoca - Romania **Project Budget: 2.299.103 Euro** **TUCN: 263.750 Euro**		Leader of WP4 on DC flexibility prediction and optimization; Development of models for energy flexibility assessment of a DC (both electrical and thermal); Development of techniques for flexibility potential estimation and forecasting used to construct the overall DC energy budget; Implementation of an optimization tool to allow the integration of the DC in the energy grid by offering its flexibility to aggregators and participating in energy markets or ancillary services markets.
2017-2019	**H2020 AAL 36, MEDGUIDE** – ICT Integrated System for Coordinated Polypharmacy Management in Dementia Patients URL: http://medguide-aal.eu/ Consortium of 7 partners from 5 countries: - ConnectedCare Services b.v., Hogeschool Utrecht, Dutch Institute for Rational Use of Medicine – Netherlands - Karde AS – Novery - Vigisense SA – Switerland - Materia Group – AgeCare – Cyprus - Technical University of Cluj-Napoca – Romania **Project Budget: 2.039.024 Euro** **TUCN Budget: 199.200 Euro**	**Scientific and Technical Manager**	Responsible for ensuring that the conduction of the work will follow the plan; Coordination of the overall scientific and technical operational activities of the project; Ensuring the high scientific and technical quality of reports and deliverables submitted to the EU Commission; Consortium level coordination of knowledge management and innovation-related activities; Reporting and monitoring of the progress of work packages covering scientific and technical issues to the Steering Committee; Leader of WP2 on the development of services that offer personalized support for dementia care and polypharmacy management; Machine learning for daily life activities assessment and deviations registration.

Period	Project Identity Card	Role	Scientific and Management Activity
2016-2018	**PN-III-P2-2.1-BG-2016-37, OPTIPLAN** - Technologies for Digitalization, Analysis and Optimization of Manufacturing of Flow Regulators and Monitors at Emerson Factory URL: http://coned.utcluj.ro/OptiPlan/ Bridge Grant Project Between: TUCN and Emerson S.A. **Total Budget TUCN: 460.000 RON**	**Project Director**	Management of scientific activity on behalf of Technical University of Cluj-Napoca; Digitalization of discrete manufacturing processes of Emerson Factory; Use of big data analytics to increase the awareness on production efficiency; Implementation of semi-automatic tools to take optimization decisions in terms of reconfiguring the manufacturing process parameters.
2016-2019	**TUCN – Montran Labs Bilateral Research Project** - Blockchain distributed systems technology and services for electronic registration, transacting and processing of assets URL: http://dsrl.coned.utcluj.ro/ **Total Budget TUCN: 45.000 USD**	**Project Director**	Management of scientific activity on behalf of Technical University of Cluj-Napoca; Development of models and techniques for digital assets registration, tracking and distributed process using the blockchain technology; Development of smart contracts for tracking financial assets.
2016-2020	**COST Action CA15140** - Improving Applicability of Nature-Inspired Optimisation by Joining Theory and Practice (ImAppNIO) URL: http://imappnio.dcs.aber.ac.uk/	**Outreach Coordinator**	Address the gap between theory and practice and improve the applicability of all kinds of nature-inspired optimisation methods; Development of novel practice-driven theoretical frameworks and paradigms; Use nature inspired heuristics to solve distributed optimization, control and coordination problems.

At the same time, I was a member of other national and European research projects developed in DSRL. Table 4 below presents the main projects in which I had been involved in having at least the role of Workpackage Leader.

Table 4. List of research projects in which was/am a member and had the role of WP leader

Period	Project Identity Card	Role	Scientific Activity
2018-2021	**H2020 AAL REMIND** - Robotic ePartner for Multitarget INnovative activation of people with Dementia URL: http://dsrl.coned.utcluj.ro/ Consortium of 7 partners from 3 countries: • Zora Robotic NV, Ghent University – Belgium • University of Medicin and Pharmacy "Victor Babes" Timisoara, Technical University of Cluj-Napoca – Romania • Ovos Media GMBH, FH Campus Wien, MEDIZISCHE UNIVERSITÄT WIEN – Austria **Project Budget: 2.049.464 Euro** **TUCN Budget: 218.750 Euro**	Senior Researcher / Workpackage Leader	Management of WP2 on requirements elicitation, system user centric design, user journeys definition; Design of robot based monitoring system for acquiring data regarding the health and well-being of people with dementia; Development of techniques and tools for integrating robots in social activities aiming to stimulate the physical and cognitive functions of people with dementia; Development of big data analytics and machine learning algorithms for determining the behavioural profiles of people with dementia allowing for implementing proactive and personalized interventions using coaching systems.
2016-2018	**PN-III-P2-2.1-BG-2016-36, ECO2CLOUD** - Technologies for efficient management and scheduling of cloud resources in cloud for reducing Alpis data centre energy consumption URL: http://coned.utcluj.ro/Eco2Cloud Bridge Grant Project Between: TUCN and Alpis Data Centre **Total Budget TUCN: 460.000 RON**	Senior Researcher	Implementation of techniques and tools for efficient resources allocation in DCs; Development of a thermal aware workload scheduling algorithms targeting to increase the amount of heat to be re-used; Transfer of green data centres related knowledge such as the setting and monitoring of energy efficiency performance indicators.
2014-2017	**FP7 AAL Elders-UP! -** Adaptive system for enabling the elderly collaborative knowledge transference to small companies URL: http://www.eldersup-aal.eu/ Consortium of 7 partners from 5 countries: • ISOIN, IDENER – Spain	Senior Researcher / Workpackage Leader	Management and implementation of WP3 on personalized multimodal adaptive interfaces; Development of algorithms for automatic adaptation of web interfaces to the cognitive capabilities of elders;

	• Geoimaiging, Elderly Care Center "Agia Marina" - Cyprus • Stockport City Council - UK • Technical University of Cluj-Napoca – Romania • Connectedcare services b.v. - Netherlands **Project Budget: 2.050.656 Euro** **TUCN Budget: 291.600 Euro**		Development of algorithms for skills discovery and automatic composition into workgroups targeting the implementation of a specific task.
2013-2016	**FP7-ICT-2013.6, GEYSER** - Green nEtworked Data Centres as EnergY ProSumErs in smaRt city environments URL: http://www.geyser-project.eu/ Consortium of 7 partners from 5 countries: • Engineering Informatica SpA, ASM Terni – Italy; • Green IT Amsterdam, Alticom Datacenters – Netherlands • ABB, Wattics – Ireland • Zurich University of Applied Sciences – Switzerland • SingularLogic S.A. – Greece • RWTH Aachen University – Germany • Technical University of Cluj-Napoca – Romania **Project Budget: 4.980.512 Euro** **TUCN Budget: 297.600 Euro**	Senior Researcher / Workpackage Leader	Management of WP4 on data centre energy efficiency optimization; Design of an energy aware semantic model for defining the common vocabulary for defining the DC energy efficiency problem; Development of techniques for monitoring and estimating the energy budget of a DC; Implementation of a multi-criteria energy efficiency optimizer considering the participation in DR programs and workload federation among partner DCs.
2013-2016	**FP7 AAL DIET4Elders** - Dynamic Nutrition Behaviour Awareness System for the Elders URL: http://www.diet4elders.eu/ Consortium of 7 partners from 5 countries: • ISOIN, Coesco Deza S.L. – Spain • Tunstall Healthcare LTD, Kings College London – UK • Technical University of Cluj-Napoca – Romania	Senior Researcher / Workpackage Leader	Management and implementation of workpackage on personalized food ordering according the elders recommended diet; Implementation of a nutrition care process knowledgebase as an ontology providing the base for implementing a food recommender; Development of techniques for detecting unhealthy self-feeding behaviours of elders which may lead to malnutrition.

	Project Budget: 2.005.433 Euro **TUCN Budget: 357.600 Euro**		

1.2. Academic Achievements

The development of my academic and teaching career was accomplished in close cooperation with the members of DSRL and Computer Science Department and under the supervision of Professors Ioan Salomie. Since 2006 I joined the DSRL first as a Research Assistant and afterwards in 2007 as s Teaching Assistant within the Computer Science Department.

Table 5 below presents my educational path in the area of Computer Science and Information Technology, showing the relevant steps and accumulated competencies, mainly in the areas related to distributed systems. As it can be seen there is a continuity in my activity and also a correlation between the educational, teaching and research activities.

Table 5. My educational path

Period	**Institution**	**Degree**	**Acquired Competences**
2007-2012	Technical University of Cluj-Napoca	PhD in Computer Science	My PhD thesis subject was about the development of context aware adaptive systems and their applicability for increasing the energy efficiency of DCs.
2006-2007	Technical University of Cluj-Napoca	Master in Distributed Systems and Computer Networks	My Master Thesis subject was about the development of context aware ubiquitous systems as well as autonomic system featuring self-* properties.
2001-2007	Technical University of Cluj-Napoca	Computer Science engineer	My License thesis subject was on the modelling and execution of industrial business processes enacting products traceability with use case in the food industry

As result my academic development activities were centred on three main discipline in closed correlation with the distributed system area: distributed informational systems, web programming for large scale distributed streams and big data analytics and programming techniques.

For the laboratory teaching activities, I have considered and used modern, state-of-the-art technologies that are commonly used in the IT companies in Cluj-Napoca and also for the development of our research projects in the DSRL. This approach implied a continuous process of improvement and updating of the taught subjects. Also, within each laboratory, I have tried to correlate in an efficient way the didactic activity with the research activity. During my years of teaching activity, I have contributed to the writing of one distributed systems book:

- ✓ Ioan Salomie, Tudor Cioara, Ionut Anghel, Tudor Salomie - Distributed Computing and Systems, Editura Albastra, Cluj-Napoca, 2008, ISBN 978-973-650-234-7, 367 pages

Since 2007 I have been guiding students in elaboration of their license thesis, first as a consultant under the supervision of Professor Ioan Salomie afterward independent. Since 2012 I started to guide students in their master license elaboration. I have guided more than 50 undergraduate students and 15 master students and I can proudly emphasis that many of my papers contributions have been achieved in cooperation with my students. Table 6 below summarize my academic path highlighting the didactic, teaching activities that I have been conducted.

Table 6. My academic (teaching) path

Period	**Institution**	**Function**	**Teaching Activity**
2018-present	Technical University of Cluj-Napoca	Associated Professor	• Distributed Systems 4th year – Course; • Programming Techniques 2nd year – Course and Laboratory;
2014-2018	Technical University of Cluj-Napoca	Lecturer	• Distributed Informational Systems 4th year – Course and Laboratory; • Programming Techniques 2nd year – Laboratory;
2013- 2014	Technical University of Cluj-Napoca	Assistant Professor	• Distributed Systems 4th year – Laboratory; • Programming Techniques 2nd year – Laboratory; • Development of Web Applications - 4th year – Laboratory;
2007-2013	Technical University of Cluj-Napoca	Preparator	• Distributed Systems 4th year – Laboratory; • Programming Techniques 2nd year – Laboratory;

I had been involved in activities regarding the updating of the master courses agenda and thematic. In particular, I had updated the course on Context Aware Software Design by focusing it in the direction of context aware distributed processing of large scale distributed data streams, where I have introduced novel state of the art topics such as: (i) the implementation of scalable data models and architectures, (iii) the management of sensors based data streams and (iii) the development of real time views and processing of micro-batches. For the associated applications, I have proposed seminar works centred on state of the art technologies such as: Apache ZooKeeper[5], Apache Kafka[6], Apache Flume[7], Apache Spark[8] and Cassandra Database[9].

Together with my colleagues and under the coordination of Professor Ioan Salomie, I have published after my PhD defence 4 books (see Table 7). They are also recommended as support material for license or masters disciplines. Also, I have co-authored 1 laboratory guide book which had been used as a support teaching material:

- ✓ Marcel Antal Claudia Pop, Dorin Moldovan, Teodor Petrican, Ciprian Stan, Ioan Salomie, Tudor Cioara, Ionut Anghel, Distributed Systems Laboratory Guide, UTPRESS 2018, ISBN 978-606-737-329-5

Table 7. Books published after my PhD defence

No	Publication Description
1	Tudor Cioara, Ionut Anghel - *Distributed Frameworks for Managing Cyber Physical Production Systems in Smart Factories*, UT Press, 2018, ISBN: 978-606-737-296-0, 105 pages
2	Tudor Cioara, Ioan Salomie, Ionut Anghel, Dorin Moldovan, Georgiana Copil - *Context aware adaptive systems with applicability in green service centres*, UT Press, 2013, ISBN 978-973-662-851-1, 174 pages.
3	Ionut Anghel, Tudor Cioara - *Ambient Intelligence for Elders Care*, UT Press, 2018, ISBN: 978-606-737-297-7, 85 pages.
4	Ionut Anghel, Ioan Salomie, Tudor Cioara, G. Copil, D. Moldovan - *Autonomic computing techniques for pervasive systems and energy efficient data centres*, U.T. Press, 2013, ISBN 978-973-662-850-4, 140 pages

I have participated in some projects oriented towards the enhancing of teaching and practice activities. From 2012 I have participated in the PACT project (The National Partnership for the implementation of the company-university projects for the transition from school to the active life) as student tutor offering advice and evaluating their activity during summer practice placement in IT companies.

Also, I have been actively involved in the department's actions related to the teaching activity being involved with my department colleagues to the assessment and accreditation procedures for the BSc studies. Also, I am a member of the board for the evaluation of license thesis of the bachelor students and member of the students' enrolment commission.

[5] Apache ZooKeeper, https://zookeeper.apache.org/

[6] Kafka, A distributed streaming platfrom, https://kafka.apache.org/

[7] Apache Flume, https://flume.apache.org/

[8] Apache Spark, Lightning-fast unified analytics engine, https://spark.apache.org/

[9] Apache, Cassandra, http://cassandra.apache.org/

2. Management of Data Centers Energy Flexibility

Nowadays the operational expenses of Data Centres (DCs) are of great concerns for their owners and operators; thus, they are continuously seeking energy efficient and cost-effective solutions. As their offered business services are blooming the DCs demand of energy increases putting, as a result, a lot of pressure on the local energy grids (i.e. severe risk of supply shortage and instability in the electricity network) and also on the environment and society as a whole. All these factors are putting DC business in a risky position and creating higher pressure on the DC operators on cutting down the energy bills. Until recently these problems had been addressed only considering the internal optimization of DC operation with a view of lowering the overall energy consumption. In my PhD thesis we had investigated and proposed novel techniques for: (i) enacting the DC internal energy awareness [Pernici, 2012], [Copil, 2012], [Salomie, 2011], [Cioara, 2010], (ii) workload scheduling [Kipp, 2013], [Cioara, 2011b], [Copil, 2011], (iii) servers' consolidation [Pop, 2012], [Cioara, 2011a], [Anghel 2010], (iv) energy aware adaptions of workload distribution [Moldovan, 2012], [Cosinschi, 2012], [Cioara, 2011e] and (v) server usage optimization [Cioara, 2011c], [Anghel, 2011], [Cioara, 2011d].

Lately, it has been noticed that the DCs are characterized by large and yet flexible electrical energy load profiles which enact as a potential solution for cost reduction their voluntary participation in Demand Response (DR) programs of smart grids [Cioara, 2015], [Anghel, 2014], [Bertoncini, 2015]. Moreover, from a thermal energy perspective, DCs are significant producers of waste heat which can be effectively re-used either internally for space heating or in the nearby neighbourhoods [Cioara, 2018b], [Antal, 2016]. Thus, our work has been concentrating on addressing the DCs energy efficiency, not in isolation but from the perspective of managing their operation considering the optimal integration into the local energy grids [Cioara 2018a], [Antal, 2018], [Cioara, 2018c]. DCs have enormous, yet mostly unexploited, potential regarding their energy demand flexibility and thus we proposed innovative techniques allowing them to use this flexibility and to contribute to the ongoing efforts for more efficiently managing the energy in smart cities [Cioara, 2016], [Antal, 2015], [Antal, 2017a], [Cioara, 2018a]. Accordingly, using our proposed techniques DCs are expected to be transformed into such flexible energy players providing different levels and types of flexibility to the interested stakeholders such as Distribution System Operator (DSO) or District Heating Operator (DHO), with a view to become adjustable and adaptive energy prosumers [Antal, 2017b], [Cioara, 2018b], [Cioara, 2018c]. This work contributes to the process of creating the necessary technological infrastructure for establishing active links which are missing in the current situation, between DCs and, in general, ICT networks, on the one hand, and utility networks (heat and electrical), on the other side. This new vision paves the way towards defining new business models and the identification of new business streams unforeseen before [Cioara 2018a], [Bertoncini, 2015].

To address such energy integration concerns, within the FP7 GEYSER (Green Networked Data centers as energy prosumers in smart city environments) European R&D project [GEYSER] and H2020 CATALYST (Converting data centers in energy flexibility ecosystems) European R&D project [CATALYST] we have proposed the innovative approach of considering DCs as conceptual and technological hubs at the crossroad of energy (electricity, thermal, or a combination of the two) and data networks thus enacting the exploitation of their latent flexibility for achieving synergies and integration with other grid energy resources (see Figure 2). In the context of the smart grid, the DCs may act as *energy prosumers*, being both energy providers, exploiting on-site green or brown energy resources, and consumers with significant energy needs. In [Antal, 2017a], [Cioara, 2018a], [Cioara, 2018b] we have defined *mechanisms for eliciting DC internal latent thermal and electrical energy flexibility* by considering non-electrical cooling devices such as thermal storage, IT workload temporal and spatial migration through data networks, and dynamic usage of electrical storage devices or diesel generators.

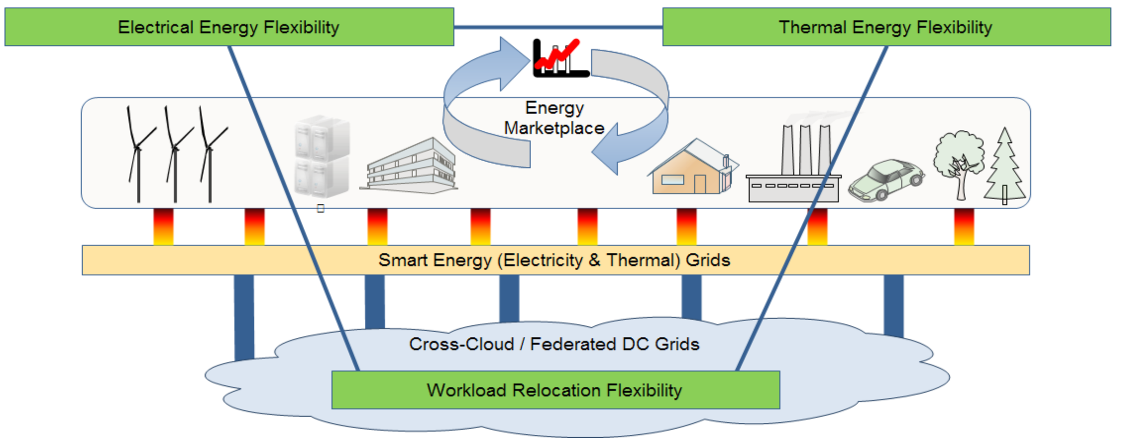


Figure 2. DCs as technological hubs at the crossroads of utility networks [Cioara, 2018a]

We consider the use the DCs as technological hubs operated at the crossroads of data, electrical energy and thermal energy networks enabling them, through the latent, potential flexibility as the main facilitator, to trade electricity, heat and IT Load as commodities (see Table 8).

Table 8. DC trading electricity, heat and IT Load as commodities

Utility Network	**Electrical Energy**	**Thermal Energy**	**IT Network**
Commodity	Electrical Energy and Flexibility	Heat	IT Load
CENTRALIZED or FULLY DESCENTRALIZED DCs			
Optimization Cases Considered	✓		
		✓	
			✓
	✓	✓	
	✓		✓
		✓	✓
	✓	✓	✓

The DC operator should be able to deal with potentially conflicting or complementary objectives which are defined by the operators of utility networks to maximize the DC revenues on one side and to lower the environmental impact on the other side (see relation 1). As a major contribution, on top of the proposed flexibility elicitation mechanism, we had proposed a set of complex business scenarios allowing DCs to capitalize on their latent flexibility [Cioara, 2018a].

2.1. DC Optimal Flexibility Management

We had defined a thermal and electrical energy flexibility optimization process which aims to adapt the DC's energy demand to meet various goals established at local smart grid level by taking advantage of potential workload relocation in other DCs as potential source of flexibility (e.g. a follow the renewable energy and maximize its usage in DCs operation [Cioara, 2015]).

$$\langle w_e * Obj_{Electricity} | w_t * Obj_{Thermal} | w_r * Obj_{Relocation} \rangle \xrightarrow{yields} DC^{MAX_{Revenue}}_{Min_{CarbonFootprint}} \quad (1)$$

The optimization problem had been addressed in detail in [Cioara 2018a] and [Cioara 2018b]. The optimization objectives are relying on the potential flexibility services (electrical and thermal flexibility) that a DC may offer to other energy stakeholders such as flexibility aggregators. The interactions among various actors for the provisioning of such services is depicted in Figure 3.

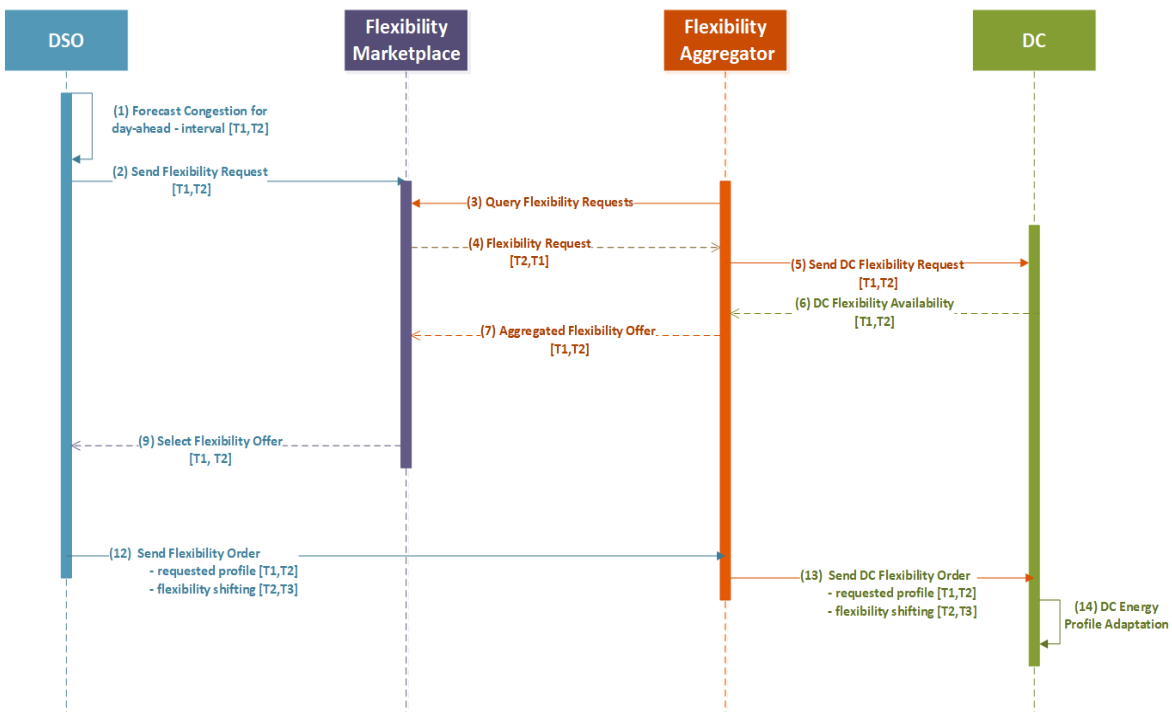


Figure 3. Energy flexibility services provisioning by a DC

As it can be seen the DC should address a potential flexibility request from an aggregator in a specific time interval $[T_1, T_2]$ by adapting its energy profile ($E_{DC}^{Adapted}(t)$) having as starting point its baseline energy profile ($E_{DC}^{Baseline}(t)$) to match the request provided in a form of a goal energy curve ($Flex_{Request}(t)$). The moment in time when the energy needs to be shifted can be before or after the $[T_1, T_2]$ of request (i.e. within the intervals $[T_0, T_1)$ or $(T_2, T_3]$).

Figure 4 presents the main classes of flexibility services a DC may provide by using our defined techniques:

- Congestion Management - implies the reduction of DC energy demand profile during the service time interval by managing its operation so that a specific amount of flexible energy is shifted later in time;
- Load Scheduling - implies the increase of DC energy profile during the service time interval by postponing the execution of some tasks and altering its profile prior to the service time.

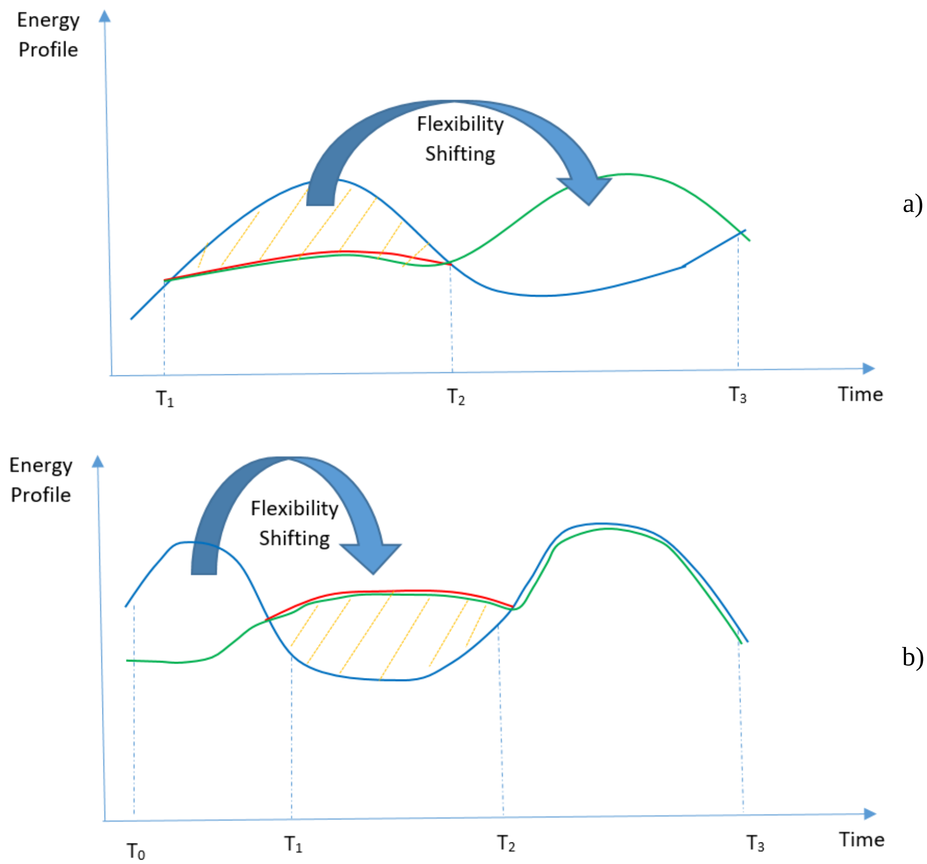


Figure 4. Flexibility services provided by a DC: (top) congestion management, (bottom) load scheduling service. Legend: blue – DC baseline energy profile, red – flexibility request and green – adapted DC energy profile

We had approached the flexibility management problem by modelling the DC as a discrete system and defining the energy demand of each DC's component (and of the entire DC as a whole) at timestamp t as a function of previous power demand states at timestamps $t-1, t-2, \ldots, t-k$, where $k < t$. At each timestamp t the optimal operation of the DC's components needs to be determined together with the amount of aggregated energy to be shifted in time such that the DC adapted energy profile matches the flexibility request curve provided as goal. Thus the optimization objective is to determine the amount of flexible energy of each DC component to be shifted in time such that the DC adapted energy consumption curve ($E_{DC}^{Adapted}(t)$) follows as close as possible the flexibility request curve ($Flex_{Request}(t)$):

$$Minimize\ \left(\sqrt{\sum_{t=T_1}^{t=T_2}\left(E_{DC}^{Adapted}(t) - Flex_{Request}(t)\right)^2}\right) \quad (2)$$

where

$$E_{DC}^{Adapted}(t) = \sum_{Comp \in DC_{FlexComponents}} E_{Comp}^{Adapted}(t) \quad (3)$$

To estimate the potential energy flexibility, the operation of each DC component is modeled using time-dependent transfer functions that estimate the thermal and electrical energy based on their inputs and an internal state. The inputs of each transfer function are bounded as to meet the constraints of DC safe operation thus the flexibility potential of each component is also bound:

$$E_{Comp}^{MIN}(t) < E_{Comp}^{Adapted}(t) < E_{Comp}^{MAX}(t) \quad (4)$$

In this case, the optimization decision is a complex process involving linear and/or nonlinear behavior of DC subsystems, the time to resolution of the associated solvers affetcting in some situations the quality of the flexibility optimization action plan. This is actually a Mixed-integer Nonlinear Programming (MINLP) optimization problem [Cioara, 2018b], [Antal, 2017a] for determining the optimal combination of energy flexibility variables for each DC component such that the defined optimization function is minimized. The combinatorial problem is addressed using complex branch-and-bound algorithms that enumerate all possible combinations of integer variables to determine the best feasible solution. The combinatorial search space is reduced using with a series of range bounding techniques (e.g. interval analysis and convex analysis), range reduction techniques (e.g. constraint propagation) and several relaxations techniques (e.g. NLP relaxation, NLP sub-problem for fixed integer variables and feasibility sub-problem).

Considering the potential requests of flexibility services form aggregators, the objective function is detailed as follows:

$$Obj_{Electricity}, Obj_{Thermal}, Obj_{Relocation} = \frac{1}{T_2 - T_1} * \sum_{t=T_1}^{t=T_2}\left[E_{DC}^{Adapted}(t) - Flex_{Request}(t)\right]^2 + \frac{1}{T_1-(T_0+1)} * \sum_{t=T_0}^{t=T_1-1}\left[E_{DC}^{Adapted}(t) - E_{DC}^{Baseline}(t)\right]^2 * (T_1 - t - 1) + \frac{1}{T_3-(T_2+1)} * \sum_{t=T_2}^{t=T_3-1}\left[E_{DC}^{Adapted}(t) - E_{DC}^{Baseline}(t)\right]^2 * [t - (T_2 + 1)] \quad (5)$$

The objective function aims at activating and shifting latent energy flexibility so that the DC energy profile is adapted to match the flexibility request signal during $[T_1, T_2]$ in the time intervals signalled by the aggregator: before the interval of request (i.e. $[T_0, T_1)$) or after the interval of request (i.e. $[T_2, T_3)$). To minimize the DC energy profile variations from the initial baseline, the differences outside the flexibility request interval $[T_1, T_2]$ are weighted by a factor which increases with the distance from the interval. As a result, changes in the DC energy profile, compared to the initial baseline, are imposed within or close to the demand response period, to the extent possible.

To calculate the amount of flexibility enacted by the DC we have leveraged on the work we had carried out in the context of the Smart Cities Cluster [SMARTCITY][10] in the direction of defining new metrics and KPIs. The flexibility offered is calculated on the basis of how much the DC energy profile is modified or adapted as result of the flexibility shifting:

$$Adapt_{Flex} = \frac{E_{DC}^{Adapted}(t) - E_{DC}^{Baseline}(t)}{E_{DC}^{Baseline}(t)} \quad (6)$$

Electrical Energy Flexibility

To evaluate the DC electrical energy flexibility potential which might be made available to different stakeholders from the local energy ecosystem we had started by analysing the operation of various DC components that are typically installed in a DC. The goal is to identify the main sources of electrical energy flexibility and to define a mathematical model for assessing this flexibility in various operational contexts. In several papers [Cioara, 2017], [Antal, 2017c], [Cioara, 2018b] we have identified the main flexible energy resources such as (see relation 7): (i) IT Servers and the associated workload [Antal, 2017d], [Anghel, 2016], (ii) electrical cooling system together with Thermal Storage Tanks (TES) [Pintea, 2018] and (iii) Electrical Storage Device (ESD) (i.e. batteries):

$$DC_{FlexComponents} = \{IT\ Workload, Electrical\ Cooling\&TES, ESD\} \quad (7)$$

In this case the total DC energy demand at each timestamp t can aggregated from its main components as:

$$E_{DC}^{Adapted}(t) = E_{Workload}^{Adapted}(t) + E_{Cooling}^{Adapted}(t) + E_{ESD}^{Adapted}(t) \quad (8)$$

For these components we have defined techniques for exploiting their energy flexibility summarized in Table 9.

Table 9. Electrical energy flexibility techniques – brief outline [Cioara, 2018a]

Component	Energy Flexibility Technique	Adapted Electrical Energy Demand Estimation
Servers and IT Workload	*Time shifting of delay tolerant workload (in the same DC).* We differentiate between real-time workload (i.e. *Workload-RT*), which has stringent requirements on real-time execution, and delay-tolerant workload (*Workload-DT*), which can be executed anytime until a given deadline. The DC energy demand is reduced at timestamp t with the amount of energy needed to execute the delay-tolerant load that is shifted at timestamp $t+u,\ u \in [1, T-t]$	$E_{Workload-DT}^{Adapted}(t) = \sum_{i=1}^{j=t} (s_{ij}) * E_{Workload-DT}^{Baseline}(i)$ • s_{ij} represents the percentage of energy consumed by the delay-tolerant workload scheduled at timestamp i, and shifted for execution at timestamp j, • $E_{Workload-DT}^{Baseline}(i)\ i \in 1..j$, is the estimated amount of energy required for executing the baseline delay-tolerant workload planed for execution at timestamp j (i.e. $i = j$), summed

[10] The Cluster is currently formed by seven EU projects (DC4Cities, RenewIT, Dolfin, GENiC, GreenDataNet, GEYSER and EURECA) and over 50 researchers. We had lead Task 1, on investigating existing DCs metrics and KPIs and we had contributed to the development of new ones.

	while the DC energy demand at timestamp $t + u$ is increased with the amount of energy needed to execute the delay-tolerant load shifted from timestamp t.	with the additional delay-tolerant workload shifted from previous timestamps i (i.e. $i < j$) $$E_{Workload}^{Adapted}(t) = E_{Workload-DT}^{Adapted}(t) + E_{Workload-RT}(t)$$
Electrical Cooling and Thermal Aware Storage	*Dynamic usage of non-electrical cooling systems (i.e. TES) to precool the DC and to compensate the electrical one.* At timestamp t the TES is charged, its coolant (i.e. water based thermal tanks) is overcooled by using the electrical cooling at higher capacity resulting in an increased energy demand. At timestamp $t+u$, $u \in [1, T-t]$ the TES is discharged, the DC is cooled down using the precooled coolant and the electrical cooling is used at low intensity resulting in a decrease of DC energy demand.	$$E_{Cooling}^{Adapted}(t) = E_{Cooling}^{Baseline}(t) + E_{TES}^{C}(t) - E_{TES}^{D}(t)$$ • $E_{TES}^{C}(t)$ and $E_{TES}^{D}(t)$ represent the amount of energy charged/discharged into/from TES at a specific timestamp. • $E_{Cooling}^{Baseline}(t)$ – is the energy used by the electrical cooling system
Electrical Storage Devices	The DC energy demand is reduced at timestamp t by the amount of energy discharged from batteries and increased at timestamp $t+u$, $u \in [1, T-t]$ by the amount of energy charged in batteries.	$$E_{ESD}^{Adapted}(t) = E_{ESD}^{D}(t) - E_{ESD}^{C}(t)$$ • $E_{ESD}^{C}(t)$ and $E_{ESD}^{D}(t)$ represent the energy charged and discharged into/from batteries.

Thermal Energy Flexibility

We had proposed techniques and models for allowing DCs to exploit the thermal energy flexibility as to meet the heat demand levels of nearby neighbourhoods [Antal, 2018], [Antal, 2017b], [Cioara, 2018a].

The execution of DC clients' workload on the IT servers generate heat that accumulates in the server room. Usually the DC incorporate an electrical cooling system that has the role of maintaining the temperature inside the server room under predefined set points. As the IT servers design is continuously improved for operating at higher temperatures and the server room density continues to rise, the DCs will be transformed in large producers of waste heat. However, there are two big issues with the reuse of DCs waste heat in the local thermal grid: its relatively low temperature in comparison with the ones needed to heat up a building and the difficulty of efficiently transporting it over long distances. This is why the current development trend is to install and use heat pumps to capture the waste heat and to increase its quality (i.e. temperature) for making the thermal energy more valuable and marketable.

Figure 5 presents such a heat pump based installation for allowing the server room to be cooled down using thermo-electrical processes. The basic hardware infrastructure upon which our model for thermal flexibility shifting for heat re-use in nearby neighbourhoods is built. The heat pump transfers the heat absorbed from the DC server room to the thermal grid by using a refrigerant based cycle and two water tanks:

- Cold water tank contains water at low temperatures which is circulated through the radiator pipe system to cool the radiator.
- Hot water tank contains water at higher temperatures feasible to be distributed and re-used in local neighbourhoods.
- A compressor is used to to increase the quality of heat while being transferred from the cold water tank to the hot water tank.

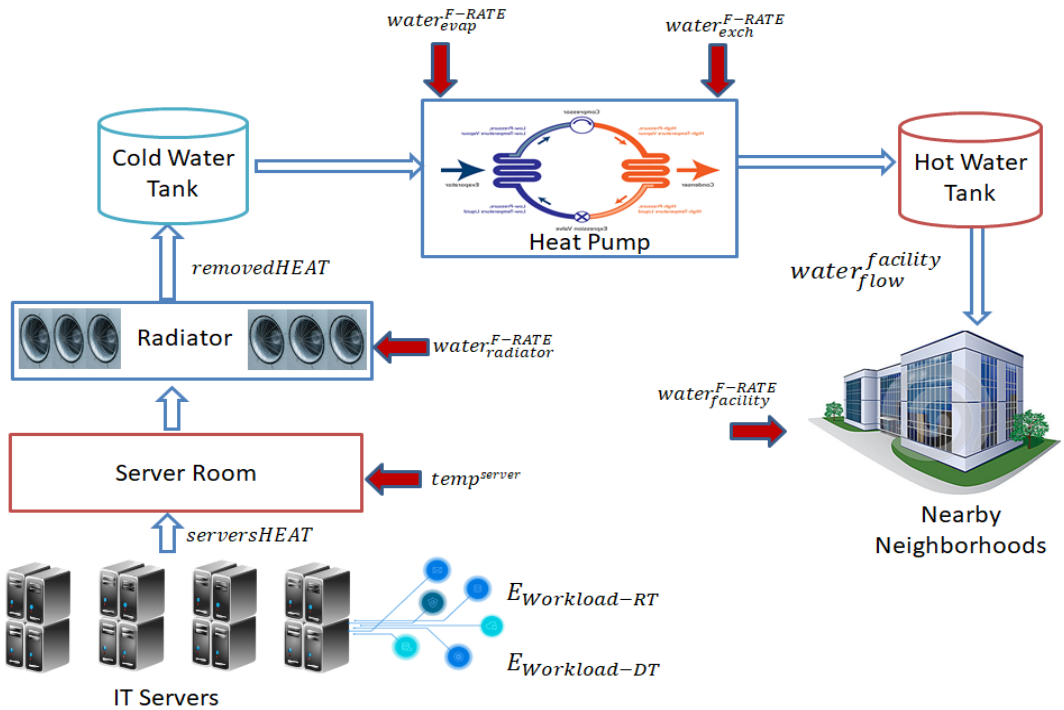


Figure 5. DC waste heat recovery and reuse in local thermal grid [Cioara, 2018a], [Antal, 2018]

The cooling system's radiators are used to chill the hot air from the server room by transferring the heat generated by servers from the server room to the water that flows through their pipes and then to the cold water tank.

The heat pump has two coefficients of performance indicators (COP), one defined for the water cooling process in the cold water tank and one defined for water heating process in the hot water tank:

$$COP_{Cooling} = \frac{Heat\ Removed\ From\ Server\ Room}{E_{Compressor}} \tag{9}$$

$$COP_{Heating} = \frac{Heat\ Supplied\ to\ the\ Local\ Grid}{E_{Compressor}} + 1 \tag{10}$$

where $E_{Compressor}$ is the energy consumed by the heat pump compressor. In other words $COP_{cooling}$ characterize the process done by the pump to remove that heat from the server room in the cold water tank using the radiators system pipes, while $COP_{Heating}$ characterize the process done by the heat pump to transfer the heat from the cold water tank to the hot water tank and to increase temperature of supplied heat.

Thus, the adapted DC thermal profile $E_{DC-heat}^{adapted}(t)$ representing the amount of heat re-used and transferred by the heat pump is calculated using relation (11).

$$E_{DC-heat}^{adapted}(t) = \left(COP_{heating} - 1\right) * \left\{\frac{E_{Workload}^{Adapted}(t)}{COP_{cooling}} - [TES_{cold}(t) - TES_{hot}(t)]\right\} \quad (11)$$

In relation (11), considering the law of energy conservation, we have assumed that all electrical energy consumed by the IT servers, $E_{Workload}^{Adapted}(t)$, is transformed into heat that needs to be removed. The electrical energy consumed by the cooling system to remove this heat is computed as the ratio between the electrical energy consumed by the IT servers and the coefficient of performance of the system, $COP_{cooling}$. Table 10 below summarize the defined models and techniques for re-using the waste heat in the nearby neighbourhoods.

Table 10. Thermal energy flexibility techniques – brief outline adapted from [Cioara, 2018a], [Antal, 2017b]

Component	Energy Flexibility Technique	Heat Re-used Estimation
Servers and IT Workload	Plan the delay tolerant workload execution to obtain a high servers utilization ratio allowing to increase for limited time interval the temperature set points in the server room while being careful not to endanger the proper operation of IT equipment. In result the heat is accumulating in the server room.	$E_{Workload}^{Adapted}(t) = E_{Workload-DT}^{Adapted}(t) + E_{Workload-RT}(t)$ $serversHEAT(t) \approx E_{Workload}^{Adapted}(t)$ • Delay tolerant workload consisting of the original baseline scheduled a timestamp t and the workload shifted for execution at t from previous timestamps $t - k$ while meeting the constraints defined for workload execution. • Servers generated heat is proportional with the workload they have to execute. $\int_{t_0}^{t} removedHEAT(x)dx =$ $\int_{t_0}^{t} serversHEAT(x)dx - accumulatedHEAT(t)$ • $accumulatedHEAT$ – the heat exhaust of servers which accumulates inside the server room; • $accumulatedHEAT$ - heat removed from the server room to balance the heat gain leading to a constant temperature equal to the defined set point.

		$$accumulatedHEAT(t) = m * c * (temp^{server}(t) - temp^{server}_{reference}(t_0))$$ • heat accumulated in the server room is determined in relation with the actual temperature value inside the server room at moment t compared with an initial baseline reference temperature at t_0 where m and c are the mass, respectively the heat absorption capacity of the substance (i.e. air).
Cooling System Radiators and the Cold Water Tank	Increase/decrease water flow rate between radiators and the cold water tank. Varying the flow rate of the water circulating through the radiator pipe system it can compensate / adjust the usage intensity of the electrical cooling system from the server room.	$$water^{F-RATE}_{radiator}(t) = \frac{removedHEAT(t)}{water_{heat-capacity} * \Delta T_{radiator}}$$ • $removedHEAT$ is the instantaneous value of heat transferred by the radiator at timestamp t from the server room; • $\Delta T_{radiator}$ the temperature gained by the water circulating through the radiator from the cold water tank. It is proportional to the heat that must be transferred to the tank, leading to a constant rise of water temperature inside the tank, due to heat absorption process; • $water^{F-RATE}_{radiator}(t)$ is the water flow rate through the radiator and cold water tank. $$TES_{cold}(t) = TES_{cold}(t_0) + \int_{t_0}^{t} water^{F-RATE}_{radiator}(x) * water_{heat-capacity} * \Delta T_{radiator}\, dx$$ • $TES_{cold}(t)$ the amount of thermal energy stored inside the cold water tank at timestamp t; • $TES_{cold}(t) < TES_{MAX}$ - by circulating the water through the radiator pipe system, the overall thermal energy inside the water tank increases while accumulated thermal energy inside the tank cannot be above a limit over which the efficiency of the cooling system dramatically decades.
Heat Pump with Cold and Hot Water Tanks	Vary the water flow rate between the heat pump and the cold and hot water tanks. As a result, the thermal energy is transferred between the cold water tank and hot water tank while a refrigerant cycle	$$TES_{cold}(t) = TES_{cold}(t_0) - \int_{t_0}^{t} water^{F-RATE}_{evap}(x) * water_{heat-capacity} * \Delta T_{evap}\, dx$$ • $water^{F-RATE}_{evap}$ rate of water circulated from the cold water tank to the heat pump. Varying the rate of water, the quality of the heat inside the tank is transferred and controlled;

	is used to increase/decrease the water temperature while consuming electrical energy. Using electrical energy the quality of the thermal energy stored in the hot water tank is increased (e.g. hot water to be re-used at around 70-80 degrees Celsius).	• $TES_{cold}(t)$ the thermal energy inside the cold water tank; • $TES_{cold}(t) > TES_{MIN}$ the thermal energy inside the tank cannot decrease under a specified limit. $TES_{hot}(t) = TES_{hot}(t_0) +$ $\int_{t_0}^{t} water_{exch}^{F-RATE}(x) * water_{heat-capacity} * \Delta T_{exch}\, dx$ • ΔT_{exch} the temperature with which the water is heated in the hot water tank by the heat pump compressor; • $water_{exch}^{F-RATE}$ the flow rate of water through heat pump's hot water circuit is used to control the amount of thermal energy stored in the hot tank • $TES_{hot}(t)$ the total amount of thermal energy stored inside the hot tank

IT Workload Flexibility

In our approach the IT network connection may provide a new source of flexibility to DCs: the workload spatial relocation to / from other DCs. In this context we have defined models allowing a DC to exploit migration of traceable ICT-load between federated DCs or leveraging on a IT Load Marketplace for increasing its thermal or electrical energy flexibility [Cioara, 2017], [Cioara, 2015], [Antal, 2017d], [Anghel, 2016].

This will allow a DC to increase its energy profile by relocating and executing workload from other DCs matching it with:

- time-varying on-site or local grid renewable energy availability (follow the renewable energy strategy);
- heat demand on the thermal energy grid;
- low prices of energy in the local energy marketplace;

At the same time the DC may decrease its energy profile relocating some of its workload to other DCs allowing it to provide congestion management services to flexibility aggregators when requested.

The amount of flexible energy to be relocated from the source DC, DC_{Source}, is considered as a percentage of the delay-tolerable workload and leads to a decrease of the source DC energy profile. Thus the workload adapted energy demand value of the source DC, $E_{Workload-DT}^{Adapted}(t)$, is calculated considering the workload to be relocated, $E_{Workload}^{Relocated}(t, DC_{Source})$, as follows:

$$E_{Workload}^{Adapted}(t) = \left(\sum_{i=1}^{j=t}(s_{ij}) * E_{Workload-DT}^{Baseline}(i)\right) + E_{Workload-RT}(t) - E_{Workload}^{Relocated}(t, DC_{Source}) \qquad (12)$$

At the destination DC, DC_{Dest}, the relocated workload need to be accommodated and executed on servers thus will lead to an increase of destination DC energy profile:

$$E_{Workload}^{Adapted}(t) = \left(\sum_{i=1}^{j=t}(s_{ij}) * E_{Workload-DT}^{Baseline}(i)\right) + E_{Workload-RT}(t) + E_{Workload}^{Relocated}(t, DC_{Dest}) \quad (13)$$

To compute the amount of flexible energy to be relocated and to select the appropriate destination DCs, we had defined a matrix $RelocationScheduling[DC][Interval]$ that is constructed for the source DC to represent all the potential workload relocation solutions in the available destination DCs. In this matrix each line is associated to a potential destination DC and each column is associated to a time interval over which the workload relocation is performed. The matrix has a number of lines equal to the number of potential destination DCs considered and a number of columns equal to the time intervals for which the migration occurs. A matrix element $RelocationScheduling[i][j]$ represents the percentage of the delay-tolerant workload from the source DC to be migrated into the destination DC i during the time interval j. Thus, the amount of energy associated with the delay-tolerant workload to be relocated in each partner DC is determined as:

$$E_{Workload}^{Relocated}(t, DC_{Source}) = E_{Workload-DT}^{Baseline}(t) * \sum_{\substack{k=1, \\ k!=Source}}^{\#DCs} RelocationScheduling[k][t] \quad (14)$$

We consider the minimization of workload relocation cost from the source DC to potential destination DCs, where the relocation cost is defined, for each interval t as a sum of the products between the percentage of relocated workload at that time interval to each destination DC k (as defined by the $RelocationScheduling(k, t)$) and the cost for relocation as defined by $RelocCost(DC_{Source}, DC_k)$. In this case the flexibility shifting decisions will take into consideration various cost factors as shown in Table 11 below.

Table 11. Workload relocation flexibility techniques – brief outline [Cioara, 2018a]

Component	IT Workload Flexibility Technique	Adapted Energy Demand Estimation
Relocated Workload Between DCs	Relocated workload to the DC with lowest network overhead	$O(Network) = \begin{cases} O(Bandwidth) \\ O(Latency) \end{cases}$ • The *Network overhead* for workload relocation between a source DC and a destination DC is determined considering the latency (i.e. delay in communication of messages between DCs) and throughput [Gb/s] (i.e. amount of data successfully transferred between DCs).
	Relocate workload to the DC with lowest energy price in local marketplace	$O(Price) = \frac{\lvert Energy_{Price}(DC_{Dest}) - Energy_{Price}(DC_{Source})\rvert}{MAX(Energy_{Price}(DC_{Dest}),\ Energy_{Price}(DC_{Source}))}$ • The *Price overhead* of relocation is calculated considering the variations of energy prices in local energy marketplaces
	Relocate workload to the DC with highest	$O(CO_2) = MIN_{CO_2}(Energy_{MIX}(DC_{Dest}), Energy_{MIX}(DC_{Source}))$

	availability of renewable energy	• The carbon footprint overhead is calculated based on the energy MIX used to power up and operate the DC. DCs with high usage of renewable energy will have a lower carbon footprint.

2.2. Novel DCs Business Scenarios

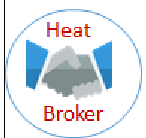
The flexibility model defined by us in the previous sections enact DCs to build their energy flexibility offers to interested stakeholders by: uniquely combining and optimizing internal generation capability, along with energy storage (either thermal or electric), smart cooling system usage, and computational workload time shifting / spatial relocation (in other DCs). In particular, thermal storage combined smart cooling and workload management have a significant potential to shed the peak load and reduce energy costs, provided that adaptation, responsiveness, and latency will match the time requirements from local utility operators. Optimal combination of optimization strategies allows the DCs to become active stakeholders in various energy related markets and in the smart energy grids optimization affairs.

We had defined three novel business scenarios [Cioara, 2018a] highlighting the importance of various commodities in gaining new revenue stream and decreasing carbon footprint. Table 12 lists all actors identified in the energy ecosystem which may benefit on DC flexibility.

Table 12. Energy ecosystem actors involved in the novel business scenarios ([CATALYST] D2.1)

	The Data Centre Operator is responsible for maintaining a secure, scalable, and efficient DC facility. The duties of the DC Operator entail oversight of the hardware infrastructure, network infrastructure, provisioning and maintenance practices, security practices, disaster recovery planning and execution, as well as general oversight of daily operations. The DC Operator is also in charge of analysing and optimizing the energy balance of the DC
	The Prosumers have controllable assets and are thereby capable of offering flexibility. A Prosumer can be regarded as an end user that no longer only consumes energy, but also produces energy. We do not distinguish between residential end users, small and medium-sized enterprises, or industrial users; they are all referred to as Prosumers. The DC itself is seen as a prosumer. [11]
	The Flexibility Aggregator role is to accumulate flexibility from Prosumers and sell it to the DSO. The Aggregator is also responsible for the invoicing process associated with the delivery of flexibility. The Aggregator and its Prosumers agree on commercial terms and conditions for the procurement and control of flexibility.[1]
	The DSO is responsible for the active management of the distribution grid and for the cost-effective distribution of energy while maintaining grid stability in a given region. To this end the DSO may use flexibility from Aggregators to manage congestion points and can check whether Demand Response (DR) activation within its network can be safely executed.[1]

[11] As defined by the Universal Smart Energy Framework, https://www.usef.energy/

	Marketplace Operator (Flavours: Electricity, Flexibility, Thermal and IT Load) role is the management, facilitation and operation of the marketplace.
	The Heat Grid Operator (HGO) is responsible for the management of the heat distribution and delivery system for both residential and commercial heating needs such as space heating and water heating
	The Heat Broker acts as an intermediator between the HGO(s) and heat producers who wish to provide their residual heat to the local heating system. The Heat Broker is a transitional role that combines the responsibilities of a heat aggregator and a supplier in the case of decentralized heat networks.
	This actor is a special electricity market participant responsible to bundle or aggregate clients in an effort of gaining additional leverage over the buyers and suppliers when it comes to negotiate offers and bids, and thus reaching agreements with more profitable prices.

The scenarios had been defined the context of CATALYST project highlight the importance of various commodities in gaining new revenue stream and decreasing carbon footprint, the network connections providing the necessary infrastructure is achieving these features. Using our defined flexibility management techniques, the DCs are empowered to provide the following services to different stakeholders by actively participating into various marketplaces (see Table 13).

Table 13. Markets on which DCs may use its flexibility (adapted and extended from [Cioara, 2017])

Commodity / Market		**DC Provided Services**	**Description**	**Interested Stakeholders**
Electrical Energy	Local Energy Market	Energy Trading	Sell the on-site generated energy	Energy Aggregators, other prosumers
	Flexibility Marketplace	Congestion Management	Shift flexible energy to decrease energy demand and avoid congestion point	Flexibility Aggregators, DSO
		Scheduling	Increase energy demand to match high availability of RES in the local grid	
	Ancillary Services Marketplace	Spinning Reserve	Provide fast ramping power	DSO
		Reactive Power Compensation	Modify the DC Power Factor to compensate voltage fluctuation in the Smart Grid	
Thermal Energy	Heat Marketplace	Sell heat re-used	Inject waste heat in the local grids	HGO, heat prosumers

IT Load	IT Load Marketplace	IT workload trading	Buy / sell workload to be relocated	Other DCs

Scenario 1: Single DC Providing Energy Flexibility
The objective is to manage and optimize the DC operation to **deliver energy flexibility services** to the surrounding electrical energy grids ecosystems to create new income source and reduce DC energy costs.

The DC is a prosumer (both consumer and producer) of electrical energy that has established a flexibility purchase contract with a Flexibility Aggregator as indicated in the Universal Smart Energy Framework (USEF) being in charge of '*acquiring flexibility from Prosumers, aggregating it into a portfolio, creating services that draw on the accumulated flexibility, and offering these flexibility services to different markets, serving different market players*'[12]. The contract includes the operating conditions for the flexibility service executed by the Flexibility Aggregator as well as the details on the settlement of the flexibility provided by the DC (see Figure 6).

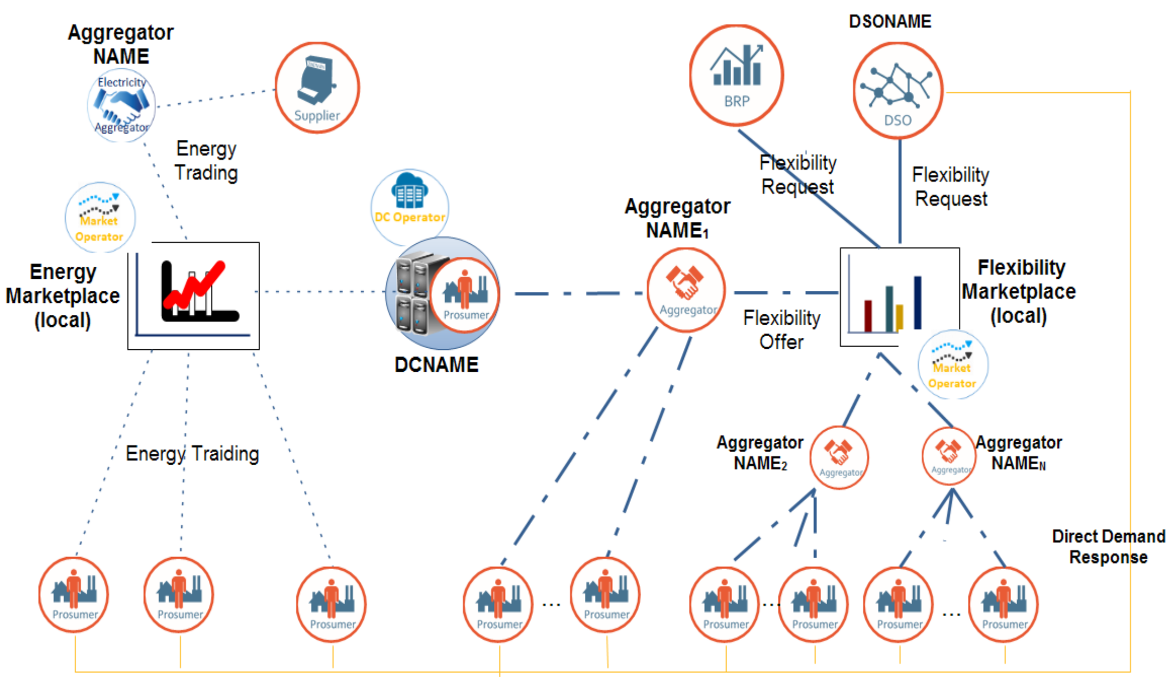


Figure 6. DC providing flexibility services to a flexibility energy aggregator

It is assumed that Flexibility Aggregator has implicitly established a flexibility service contract (through the Flexibility Marketplace) with the local Distribution System Operator (DSO) and that is registered in the Common Reference, which contains the list of each Congestion Areas published by the DSO. This repository can be accessed by Flexibility Aggregator to check whether it has enough

[12] Universal Smart Energy Framework, https://www.usef.energy/

aggregated flexibility from its customers in the congested area to be able to offer to the DSO (see Figure 6).

The day-ahead trading of flexibility could be achieved on daily basis as following:

- AGREGATORNAME$_1$ creates and sends a forecast of energy demand of all its clients to de DSO;
- DSONAME uses these forecasts to create a forecast of the total load on the congestion points
- In case congestion is forecasted:
    a. DSONAME places a request of flexibility in the Flexibility Marketplace with an associated financial reward;
    b. AGGREGATORNAME$_1$ checks the flexibility potential of the prosumers from its portfolio to see if it can address the DSO request;
    c. AGGREGATORNAME$_1$ responds to this flexibility request by placing a flexibility offer in the Flexibility Marketplace;
    d. DSONAME can accept one or multiple flexibility offers and if so, the DSONAME sends a flexibility order;
    e. AGGREGATORNAME$_1$ will send the flexibility request to prosumers from its portofolio (DCNAME is one of them) to adjust their load and fulfil the flexibility need of the DSO.

For the intraday trading of flexibility, the above steps are repeated considering the 4 hours ahead time frame.

DCNAME Gain: AGGREGATORNAME$_1$ will pay DCNAME for the flexibility provision based on the previously agreed flexibility contract.

At the same time the DC may act as a prosumer participant on the Local Electrical Energy Marketplace by buying or selling energy directly to/from other energy prosumers or from an Energy Aggregator. During the next operational day due to weather conditions there is an increased demand of energy and the energy price is high. DCNAME is able to shift is energy flexibility to decrease its energy consumption during intraday.

DCNAME Gain: DCNAME will make additional profits by selling through the Electrical Energy Marketplace the on-site electrical energy generated (diesel generators or renewable energy).

Scenario 2: Single DC Providing Heat and / or Flexibility Services

The objective is to manage the DC operation to:

- ✓ **deliver heat to the local heat grid**. Recover, redistribute and reuse DC residual heat for building space heating (residential and non-residential buildings such hospitals, hotels, greenhouses and pools), service hot water and industrial processes.
- ✓ **deliver both electrical energy flexibility services and heat** to the surrounding energy grids (power and heat) ecosystems. In this case the DC will act as a convertor between electrical and thermal energy and vice versa to gain extra revenue on top of normal operation.

The DC is assumed to be located in an urban agglomeration benefiting from policies, operations and infrastructure that enable recovery, redistribution and reuse of residual heat. The DC is fully monitored in terms of energy consumption, heat generation and actual IT loads. Also, the DC is able to evaluate and forecast its actual IT load capability and energy demand on daily basis. Additionally, the DC cooling infrastructure should allow for the recovery of its residual heat and its subsequent delivery to the local heat grid.

Depending on the cooling technology in use, the DC may harvest heat at the desirable temperature level to be re-used in local neighbourhoods. In case of the water based cooling the re-used heat might be used in the following cases:

- Processor level hot water at 60 ℃ could be re-used for space heating;
- Server level hot water at 45 ℃ could be re-used as tap water;
- Server room hot air at 25 ℃ could be used for house heating, etc.

As we have seen in our modelling approach a heat pump is needed to increase the low calorific heat generated by the DC before its delivery to the local heat grid. As heat flexibility the DC may adjust its server room temperature set points for limited time periods to increase the quality of the heat to be reused. Also the DC may capitalize on the use of a heat storage, such as a thermal energy storage system, to store heat and deliver it to the heat grid in addition to the direct heat normally supplied, thus increasing its heat capacity.

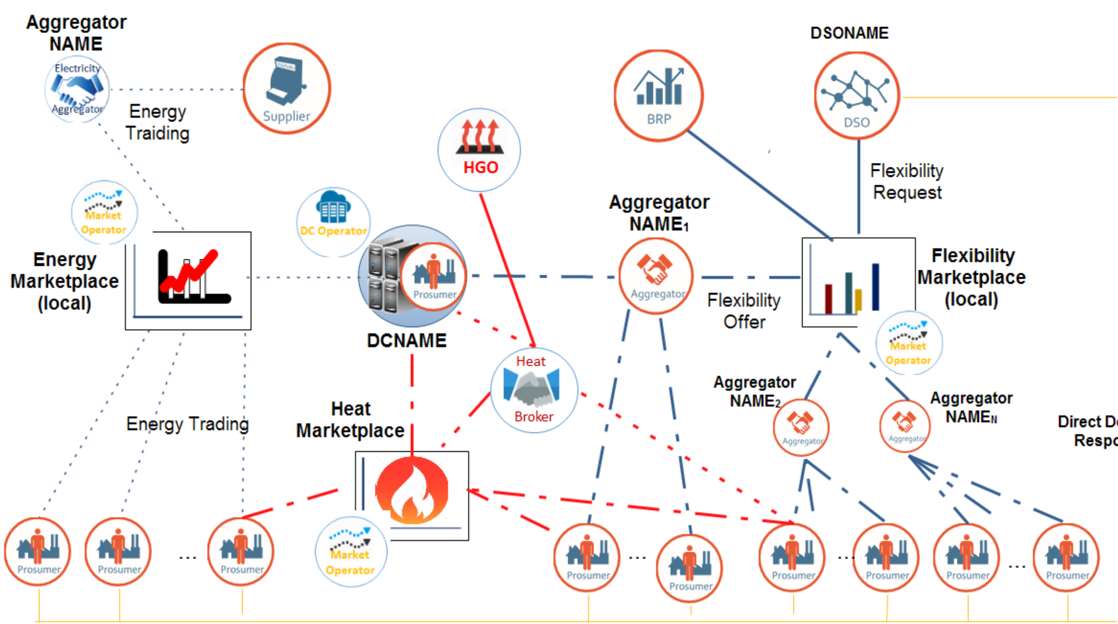


Figure 7. DC providing both energy flexibility and heat re-use services in its local energy ecosystem

We assume that the DC has a contractual agreement with the Heat Grid Operator to provide residual heat to the local heat grid. The Heat Grid Operator is the one responsible for the transportation and distribution of the heat to end consumers. Also the DC may capitalize on its re-used heat flexibility by participating as a heat prosumer on the local Heat Marketplace where it can trade its residual heat with other prosumers directly or with a Heat Broker (see Figure 7). The Heat Broker has the responsibility to supply heat at all times and as such guarantees its continuous supply by taking up some of the risks from DC side allowing them not to endanger their usual business activity (i.e. successful execution of clients' workload and delivery of high availability rates).

If a cold snap is forecasted for the next day, there people will need more heat for heating building space. In this case the local Heat Grid Operator would like to reduce its heat production costs by replacing more expensive peak load production that will be generated by the cold snap. Thus it sends a heat request to the DCNAME to buy its residual heat for the next day at the contractual stated quality.

DCNAME Gain: By leveraging on its heat flexibility DCNAME will gain the financial benefits stipulated in the Heat Grid Operator contractual offer for heat delivery. Additional it will contribute to the reduction of emissions by substituting the peak load production of heat which is typically produced by using fossil fuels.

At the same time there is a high demand of hot tap water in the morning and a Heat Broker has published a bid accordingly to the Heat Marketplace. DCNAME operator realizes the opportunity for making extra profits and decides to act as a prosumer participant to the Heat Marketplace. To increase the amount and quality of heat to be traded as hot water the DC operator decides to define higher temperature set points in the server room for a limited time period and places an offer to the Heat Marketplace. All valid supply offers are put in the increasing price order on an aggregate supply curve and all valid demand bids are put in decreasing price order on an aggregate demand curve, the clearing price at which the offers are being remunerated being determined at the intersection of the two curves.

DCNAME Gain: DCNAME also gain additional benefits for selling hot tap water.

Even though a cold day it is forecasted for tomorrow, it will be also sunny, thus an increased amount of solar energy will be produced that to be consumed. To avoid a congestion point in the local grid previously declared in the Common Reference, the DSONAME publish a request for flexibility in the Local Flexibility Marketplace. $AGGREGATORNAME_1$ and other flexibility aggregators become active and send their flexibility offers using the marketplace services. Considering that the flexibility offered by the $AGGREGATORNAME_1$ was accepted by DSONAME the $AGGREGATORNAME_1$ sends during the day a flexibility order to DCNAME (enrolled with the $AGGREGATORNAME_1$) to increase its load profile during the renewable energy production peak. DCNAME see this as potential new revenue complementary with the one offered for heat re-use. Thus it may leverage on its internal sources of energy flexibility delivering the desired levels of flexibility in terms of an increased energy demand. Thus, DCNAME schedules the execution of some delay tolerant workload to the time interval when the renewable energy peak is forecasted.

DCNAME Gain: DCNAME is being paid by $AGGREGATORNAME_1$ according to the agreed flexibility contract.

Scenario 3: Workload Federated DCs Providing Heat and Flexibility Services

The objective is to manage and exploit the migration of traceable ICT workload between DCs:

- *to match the IT load demands with time-varying on-site RES availability* (including Utility/non-Utility owned legacy assets) thus reducing the operational costs and increasing the share of renewable energy used.
- *to deliver energy flexibility services* to the surrounding power grids ecosystems aiming to increase DC income for trading flexibility.

- *to deliver heat* to their local heat grids aiming to increase the revenue for the reuse of their residual heat.

NETWORKEDCSNAME is a Networked Cloud provider, owning $DCNAME_1$ located in $CITYNAME_1$ and $DCNAME_2$ located in $CITYNAME_2$. $DCNAME_1$ has photovoltaic panels deployed on-site, while $DCNAME_2$ has wind turbines. They can also opt for workload relocation based on bilateral agreements if they have previously signed such an agreement and at the same time they are aiming to increase the amount of renewable energy used for their operation. $DCNAME_3$ is located in $CITYNAME_3$ having no renewable energy generation deployed on site. All three data centres are registered as participants to the IT Load Marketplace through which they are able to relocate IT workload among each other using the marketplace interaction mechanism (see Figure 8).

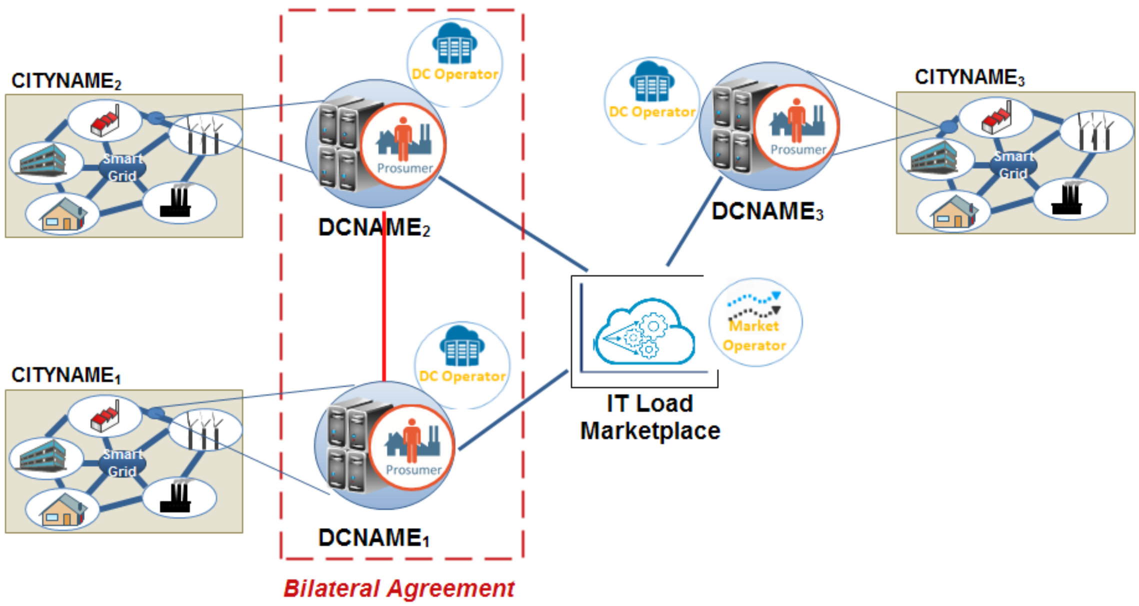


Figure 8. Workload relocation to increase the usage of on-site RES using partnership agreements or the IT Load Marketplace as facilitators

Today is a sunny day in $CITYNAME_1$; thus, a lot of solar energy is available at $DCNAME_1$. In consequence, on the basis of the bilateral agreement between $DCNAME_1$ and $DCNAME_2$, it is decided to temporary shift some non-critical load from $DCNAME_2$ and to relocate it to $DCNAME_1$. As result the energy demand of $DCNAME_1$ is increased being able to exploit the solar energy peak. As the performance of the services/applications associated to the workload relocated in $DCNAME_1$ may get worse for some customers, $DCNAME_2$ may have to renegotiate (decrease) some indicators of their contracted Service Level Agreements (SLAs) for limited period of time.

DCNAME Gain: Leveraging on their partnership for workload federation the DCs will be able to use for a larger extent the renewable energy produced in their site.

For the afternoon, weather forecasts show that the wind will start to blow hard in $CITYNAME_2$, thus there will be a peak of wind energy production. To exploit renewable energy generation to the largest possible extent, some workload will be relocated back from $DCNAME_1$ to $DCNAME_2$. As it can serve more IT load, $DCNAME_2$ uses the IT Load Marketplace to place a bid in the current market session for workload relocation so it can match the wind energy production peak. $DCNAME_3$ has some load available to be temporary relocated so it answers to the $DCNAME_2$ bid with a workload relocation offer. At the end of the session the bid and offers are matched and the workload from $DCNAME_3$ will be relocated to $DCNAME_2$.

DCNAME Gain: $DCNAME_3$ will be financially rewarded considering the calculated market session clearing price, while $DCNAME_2$ will decrease its CO_2 footprint as a result of using (when available) wind energy as much as possible.

$CITYNAME_1$ experiences a series of especially cold days with low temperatures thus the needs for building space heating are high, stressing the current capacity of the local heat grids. The Heat Grid Operator sends a request for heat to $HEATBROKER_1$ with which it has a contractual agreement for heat delivery. In response the $HEATBROKER_1$ submits a bid to the local Heat Marketplace as to cover the missing amounts for the coming day without having to operate the back-up fossil fuels or gas production units. $DCNAME_1$, with the support of the thermal energy flexibility, can respond to the offer by increasing the amount of heat generated, recovered and delivered to the heat grid. $DCNAME_1$ responds with an offer in the Heat Marketplace for the amount that it is able to cover. $HEATBROKER_1$ will ensure that the full amount is supplied thus capitalizing on its entire portfolio of local heat producers.

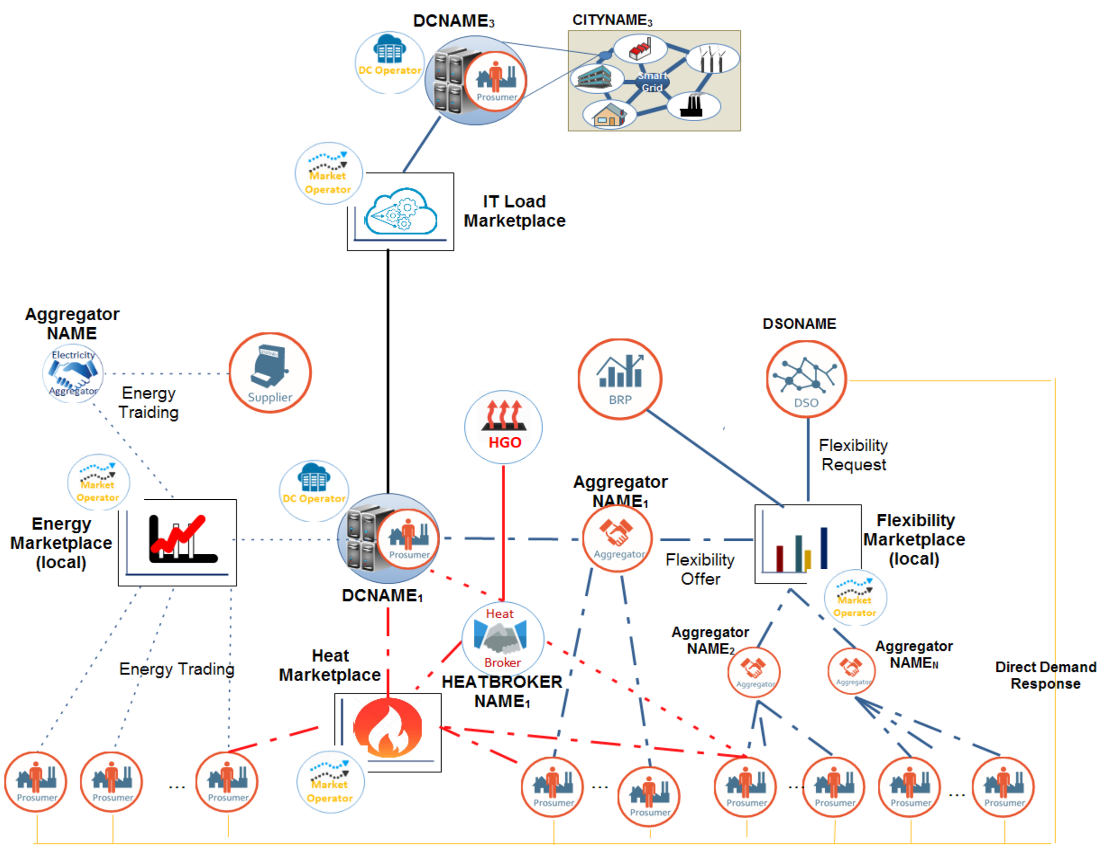


Figure 9. Workload relocation to increase the share of thermal and electrical flexibility provided by a DC

$DCNAME_1$ places a bid in the IT Load Marketplace for additional workload to be relocated and executed so it may generate more heat. $DCNAME_1$ requests for additional IT load to match the increased heat demand on their side, since the cost benefit for such an exchange (buy extra data to sell extra heat) is substantial. $DCNAME_3$ located at $CITYNAME_3$ has workload to be relocated and place its offer. $DCNAME_3$ in turn responds to the offer by migrating the necessary load, after also obtaining the approval from the end-users associated to the IT loads, since SLAs will be invariably affected (network latency).

In addition, $DCNAME_3$ decides to reduce temporarily the amount of heat delivered to their own local grid since using the defined models it is indicated that the gain from selling the IT load is higher than the one coming from selling the heat locally, assuming no penalty is enacted in this case. In any case, the Heat Broker from $CITYNAME_3$ guarantees the heat supply to the local heat grid by capitalizing on the other heat producers from its portfolio.

DCNAME Gain: $DCNAME_1$ gains revenues from selling more heat at better quality, while $DCNAME_3$ gain financial benefits from selling its IT workload.

It is a cold but sunny day in $CITYNAME_1$, which leads to an increase of the on-site energy generation in $DCNAME_1$. $DCNAME_1$ uses the green energy for energy-heavy operations, such as IT cooling, while executing both delay-tolerant and time-critical loads. $DCNAME_1$ may benefit from the excess energy via selling the energy in the Energy Marketplace, to an energy aggregator (i.e. AGGREGATORNAME) or other prosumers. Also it may accept IT loads to be relocated from other DCs by participating to the IT Load Marketplace. Due to the low energy prices in the Energy Marketplace, $DCNAME_1$ prefers to participate in the IT Load Marketplace.

As there is low green energy generation in $CITYNAME_2$, $DCNAME_2$ finds using the IT Load Marketplace that it is beneficial to offload some non-critical tasks to $DCNAME_1$. Also, $DCNAME_2$ has already chosen to use free-air or water cooling to avoid energy-consuming electrical cooling for executing critical IT loads. Both $DCNAME_1$ and $DCNAME_2$ negotiate SLAs for the load under relocation, if there is such a need.

At the same time, $DSONAME_1$ forecast that the increased energy generation in $CITYNAME_1$ will result in unbalances between production and consumption at local grid level which will be addressed by the flexibility aggregator $AGGREGATORNAME_1$. Since $DCNAME_1$ is heavily using both energy and IT resources, it cannot offer its energy flexibility to $AGGREGATORNAME_1$. On the other hand, $DCNAME_3$ being also located in $CITYNAME_1$ it has already bought energy at low prices from the Energy Marketplace (from $AGGREGATORNAME_1$), and it still has computing resources not running workload. So, $DCNAME_3$ can combine a flexibility offer (i.e. increase energy demand to cover RES peak) to the $AGGREGATORNAME_1$ with an offer in the IT Load Marketplace for buying workload to relocate. So, $DCNAME_3$, although having no on-site RES, it still gains cost benefits from increasing green energy generation as to cover the existing operations and undertaking remote loads.

Also, the execution of extra workload leads to heavy utilization of IT infrastructure increasing the amount of heat generation. Both $DCNAME_1$ and $DCNAME_3$ are using the heat reuse infrastructure available, to inject the otherwise wasted heat in offices or for pre-heating dynamic rotating UPS systems, if possible. Moreover, both of them may provide the excess heat to a Heat Broker for domestic heating through the Heat Marketplace. Although heat is sold now at lower prices than usual, it is still offers an additional source of revenue for the DCs.

DCNAME Gain: $DCNAME_1$ is able to lower its operational costs by buying energy at lower prices, $DCNAME_2$ gains financial incentives by offering non-critical workload to $DCNAME_1$, while $DCNAME_3$ gains revenues from offering congestion management flexibility service and additionally by selling re-used heat.

3. Decentralized Management of Smart Energy Grids

The energy grid is moving from the "Edison Era" to the "Google Era" offering new opportunities for a more secured, resilient and efficient distribution. Traditionally, the energy grid is constructed around centralized broadcast-like mono-directional energy systems, where electricity is remotely generated by power plants and transported over complex energy networks and infrastructures to the consumption points, with significant costs for interconnecting remote areas. The advent of intermittent decentralized renewable energy sources (RES) are completely changing the way in which the grids are managed to provide electricity to consumers, while preserving continuity and security of supply at affordable costs supporting the shift to more decentralized smart energy systems. If the locally generated renewable energy is not self-consumed locally problems such as overvoltage, losses and lifetime decay for the transformers and electric equipment may appear at local micro-grid level and could be escaladed to higher management levels [Cioara, 2016], [Cioara, 2015]. A micro-grid represents a "*localized group of prosumers that may operate connected to and synchronous with the main grid or disconnect in island mode*"[13]. Studies have shown[14] that a significant share of decarbonization potential from the deployment of distributed RES systems is going to be offset by the additional costs to properly manage and integrate them in the smart grids.

At consumption side due to the rapid growth in the deployment of Distributed Energy Prosumers (DEP) the smart grid management problems can no longer be efficiently addressed by using centralized approaches the need for visionary decentralized approaches and architectures being widely recognized. The development of IoT smart metering devices has increased the potential adoption level of decentralized energy networks where due to the lack of grid-scale energy storage capacity, electrical energy must be used as it is generated. Variations in energy production, either surplus or deficit, may threaten the security of supply, the lack of energy storage capabilities, leading to energy distribution systems overload and culminating with power outage or service disruptions, forcing the DEPs to shed or shift their energy demand to deal with peak load periods [Pop, 2018a], [Cioara, 2018d], [Antal, 2015]. The centralized energy systems take limited account of local conditions, are difficult to be optimized and offer no incentives for consumers to manage and adjust their consumption according to the generation profiles.

From an ICT perspective the research and industry have gained a lot of interest in the blockchain technology and its potential in decentralizing the management of complex energy systems. P2P trading platforms have recently emerged in a range of sectors as effective ways for reducing transaction costs and allowing small size suppliers to compete with large traditional suppliers. In particular, P2P energy trading, may be conveniently used for those markets characterized by high demand variability and diversity and low production economies of scale [Pop, 2018b], which occur in power network/energy markets aligned with the rise of energy prosumers. P2P trading systems include centralized P2P systems, with a central authority in the middle between supplier and procurers of service (such as Uber and Airbnb), to fully decentralized P2P systems, with no middle-

[13] About Microgrids, https://building-microgrid.lbl.gov/about-microgrids

[14] Decarbonizing the European Electric Power Sector by 2050: A tale guided by different studies, https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/WPEN2010-11

man in charge for managing transactions. P2P energy trading platforms offer three distinct value-streams [Cioara, 2018a]: (i) energy matching for the coordination of complementary flexibility assets where a market mechanism can incorporate prosumers' individual preferences and resource characteristics, (ii) uncertainty reduction due to the aggregation of flexibility and (iii) better capturing of satisfaction in using associated services. Along this landscape, mechanisms for creating dynamic coalition of prosumers are envisaged as being highly automated, and are the subject of current research, including bilateral contract networks and ex-post profit sharing from coalition game theory.

To address this urgent need of redesigning and decentralizing the energy distribution grid we have investigated and proposed the use of blockchain technology as driving force. In our vision the blockchain technology has the potential to provide a disruptive innovative approach to Demand Response (DR) programs, flexibility services provisioning and energy trading paving the way for secured cryptography based decentralized management of smart energy grids [Cioara, 2018a]. In several papers we had proposed blockchain based distributed models and architectures [Cioara, 2018d], [Pop, 2018a], [Petrican, 2018], [Cioara, 2018b] supporting the transition towards a more diverse, low-carbon, co-operative system, where energy management may effectively take place at local level, while simultaneously offering valuable services for avoiding grid reinforcement and facilitating voltage management and energy balancing.

In the context of H2020 eDREAM project we are contributing to the transfiguration of traditional energy market approaches and smart grid operations into novel decentralized and community-driven energy systems fully exploring local capacities and constraints (see Figure 10). eDREAM will conduct pioneer research for implementation and adoption of blockchain based verification assessment mechanisms allowing DSOs (Distribution System Operators) to know promptly, in a secure non-modifiable way the effective amount of service delivered and to activate accordingly the appropriate financial settlement to the flexibility providers.

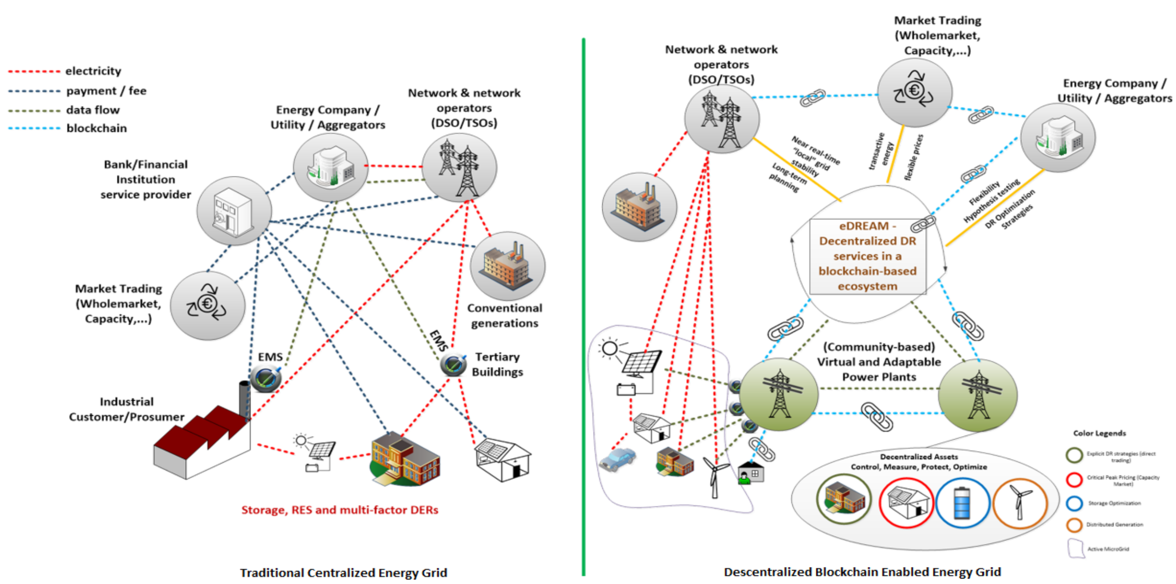


Figure 10. Centralized versus decentralized energy grid [EDREAM]

At the same time in the context of collaborative research project with US Montran Labs [MONTRAN] we had investigated and proposed models and techniques for registering, tracking and processing of digital assets [Pop, 2018b] that have a great level of applicability in the context of energy grid by considering the energy in various forms (consumption, generation or even flexibility) as the digital asset to be tracked.

The adoption of the blockchain concepts will transform the smart grid into a democratic community that no longer relies on a central authority, but can take any decision through smart contracts rules enforced and verified by each DEP of the grid. Also the traditional centralized management of the smart grid that is prone to single point of failure vulnerabilities is replaced with a decentralized approach, where the statistics, transactions, control services and payment settlements are all computed and verified in a distributed manner by each node in the network.

3.1. Architecture and Decentralized Management Scenarios

We propose a blockchain based architecture for distributed management, control and validation of flexibility services and associated DR programs in low voltage smart grids (see Figure 11) with a view of assuring high reliability and decentralized operation by implementing traceable and tamper-proof energy transactions and near real time financial validation [Pop, 2018a].

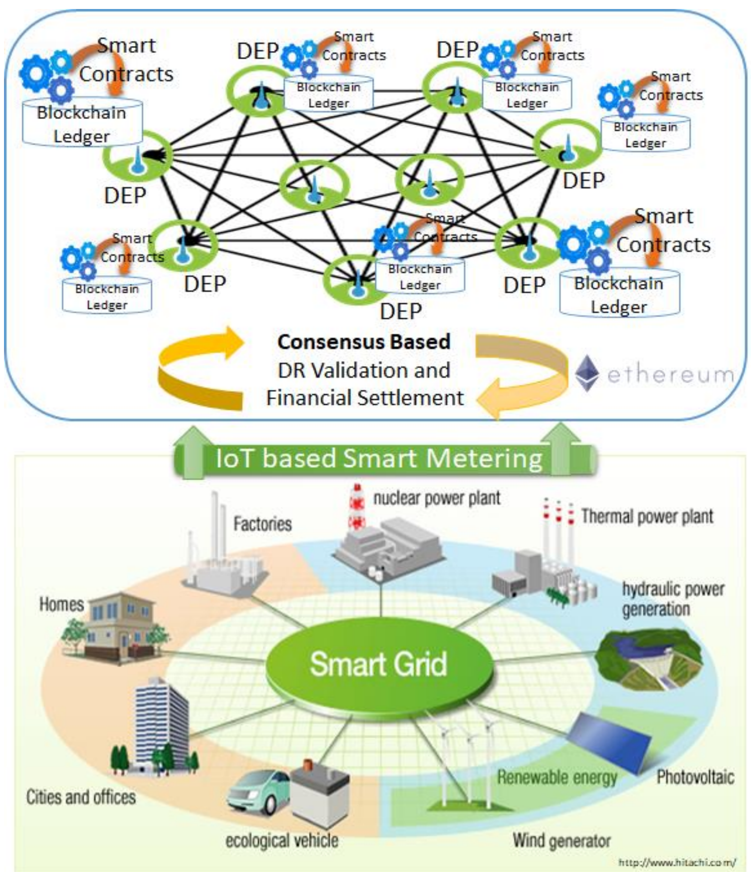


Figure 11. Blockchain based architecture for decentralized management of energy grids [Pop, 2018a]

We model the grid as a collection of distributed energy prosumption (DEP) (consumption, production or both) resources able to coordinate and support fully decentralized demand–supply matching and stable grid operation through a blockchain based infrastructure. DEPs can be involved directly with the Distribution System Operator using DR programs and distinct control of the deployed assets or via enabling aggregators by offering their flexibility availability. The DEPs have the option of trading energy among each other in a peer to peer fashion thus achieving a better management of consumption and production at the micro-grid level and contributing to the whole grid stability by not escalading the localized un-balances.

The architecture is featuring the following main components:

- A *distributed ledger* for storing DEPs energy data at the micro-grid level. All energy monitored data registered at the level of a DEP will be registered and stored as immutable transactions. As a result, the individual energy production or energy consumption values will be aggregated in blocks which will be replicated in the ledger.
- A set of *self-enforcing smart contracts* for decentralized energy management and control. Through specific mechanisms will enable the peer to peer trading of energy among DEPs and offer-demand matching and decentralized coordinated control for energy stakeholders such as the DSO which will be able to assess and trace the share of contracted flexibility services, actually activated in real time by the aggregators.
- *Consensus based* transactions validation and financial settlement. The main goal is to implement a novel blockchain-based validation protocol featuring increased reliability of the smart grid system operation, better energy incentives for DEPs and increased usage of renewable energy.

DR and Flexibility Services Management

In this case, prosumers are able to offer and trade their flexibility in terms of loads modulation. Prosumers can be involved via enabling aggregators or directly with the DSO via direct DR and control of DEP's energy assets (see Figure 12). This flexibility management case can be seen as an extension of the DC flexibility management by innovatively considering the DC as an aggregator of its own resources [Cioara, 2018a], [Cioara, 2018b].

Through self-enforcing smart contracts enabling both demand-offer matching and decentralized coordinated control, the energy stakeholders such as the DSO will be able to assess and trace the share of contracted flexibility services, actually activated in real time by the aggregators. This will impact the energy grid management by:

- maintaining the balance of supply and demand in a decentralized environment,
- achieving the final goal of reducing the overloading and
- reaching the power network stability by means of the flexibility provided by the active micro-grids.

The micro-grid can work in both grid-connected or island mode and can be registered to the DR programs being able to sign/accept smart contracts, each of their DEPs making available their energy flexibility.

The balance between energy demand and energy production is managed by the corresponding DSO who can analyse the actual state of the distribution grid and forecast the needs for energy flexibility to deal with potential distribution grid level congestion problems targeting to identify grid issues and actors that can solve them by providing the required flexibility. In this case the DSO aims to access micro-grid DEPs taking advantages of the micro-grid flexibility as to guarantee smart grid stability by making available *flexibility-as-a-service* through smart contracts.

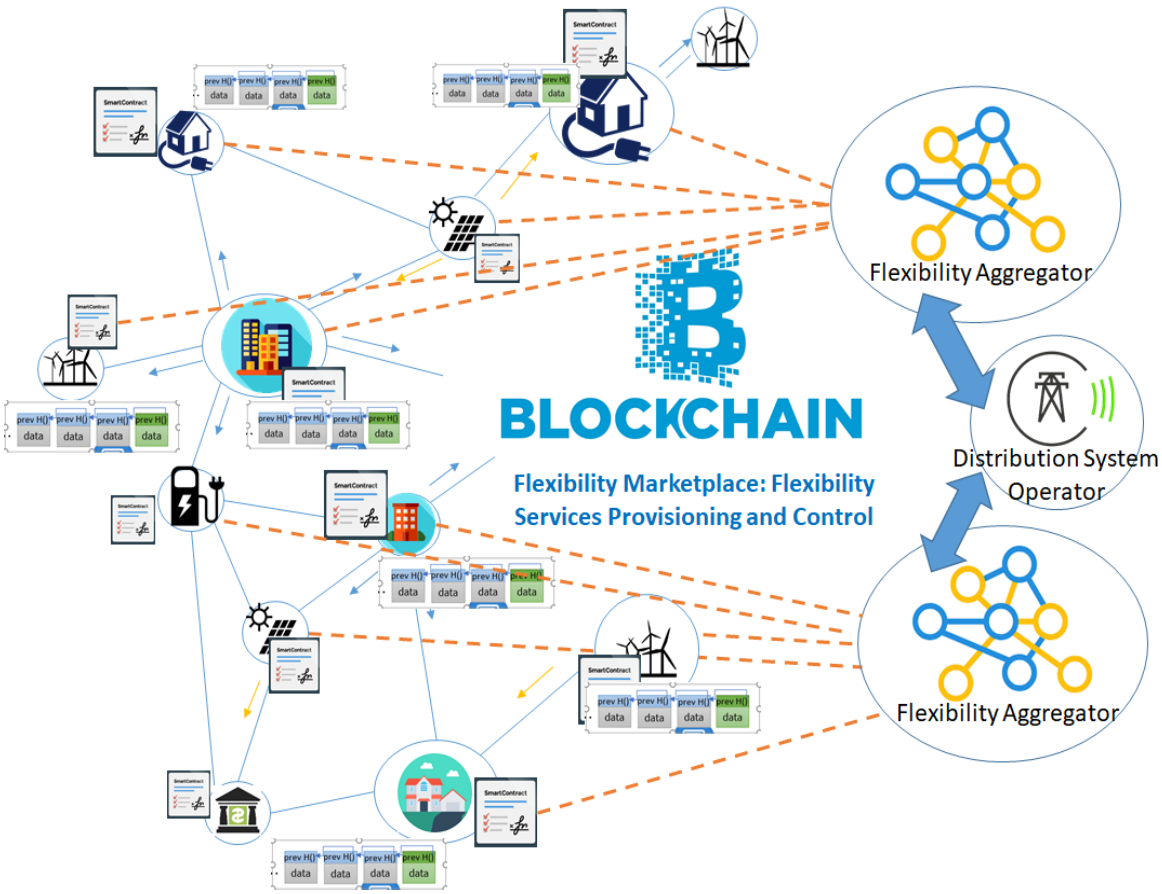


Figure 12. Blockchain based flexibility trading and control

Each DEP of the micro-grid has been enabled to offer via smart contracts his flexibility to specific aggregators to which it is enrolled. Using our prosumer level forecasting techniques [Petrican, 2018] the Aggregator creates and sends a forecast of the aggregated energy demand of all its registered DEPs to the DSO, who uses these forecasts to estimate the total load and detect potential congestion points [Cioara, 2018c], [Cioara, 2018d]. When the DSO identifies a congestion point and the associated grid connections and it has to declare it in the Common Reference Operator (CRO) registry and the aggregators in that micro-grid are activated and contract prosumers connected to this congestion point to offer flexibility. More specifically the DSO sends a flexibility request and aggregators respond to this flexibility request with a flexibility offer. The DSO can accept one or multiple flexibility offers and then sends a flexibility order to selected aggregators who will adjust the load of their registered DEPs as to fulfil the flexibility need.

The self-enforcing smart contracts will be defined to manage the levels of energy demand flexibility (i.e. from aggregators and their enrolled prosumers on one side and from aggregators to the DSO on the other side), associating incentive and penalties rates. The corresponding smart contracts evaluate the difference between the requested energy flexibility (i.e. a DR signal) and the flexibility actual delivered (as relived by monitored energy values registered in the distributed ledger). If relevant deviations are identified, specific actions will be taken to rebalance the energy demand with the energy production, thus, the smart contracts act as a decentralized control mechanism.

The smart contract defines the DEPs energy baseline profile and expected adjustments in terms of the amount of energy flexibility to be shifted during DR event time intervals. The power baseline profile is a regular energy profile of an DEP determined as the average of past measured energy values; it reflects how much energy the prosumers may have consumed in the absence of DR event.

The aggregators will inject individual control signals (i.e. upon the DSO request) in the smart contracts regulating individual DEPs flexibility thus requesting them to adapt their energy profile by shifting flexible energy. Aggregators will evaluate the difference between the total amount of flexible energy actual activated, normalized to the baseline energy consumption of each distributed energy prosumer.

The flexibility requests received by a DEP is recorded in the ledger, thus, the smart contract verifies in near real time the monitored energy consumption data against the associated DR signal to detect any significant deviations and notifies the aggregator. In case of notable positive or negative deviations the smart contract calculates the associated penalties for prosumer. Otherwise the prosumer is rewarded considering the DR revenue rates and how much of the prosumer energy demand profile has been adapted during a DR event. The total incentives for a DEP for its adaptation during a DR event is calculated by the aggregator based on the flat rate provided by the DSO for the aggregated flexibility (i.e. a daily revenue rate for each kW of energy shifted or a discount rate on the regular electricity bill).

Peer to Peer Energy Trading

We defined an energy marketplace that will enact any prosumer to directly participate in the market auction. This is of utterly importance in the context of integrating many small scale distributed energy prosumers providing opportunities for competitive or cooperative procurement models [Cioara, 2018b], [Cioara, 2018d], [EDREAM-D2.2]. The market will match consumers with energy producers and will rely on green energy tokens for rewarding the consumption of renewable energy when it is available. For creating energy tokens we propose the use of ERC-721 open standard[15] which allows to represent the energy asset as a non-fungible token in the blockchain system. The tokens will be generated at a rate proportional with the forecasted renewable energy production at local system level [Petrican, 2018], transforming the energy in a transactable digital asset. The producers and consumers will then use tokens to participate in the electricity market sessions leveraging on self-enforcing smart contracts. The market will leverage on the self-enforcing smart

[15] ERC-721 open standard, http://erc721.org/

contracts to implement in a programmatic manner the potential P2P energy trading between the energy prosumers (see Figure 13).

Self-enforcing smart contracts are distributed at the level of each peer prosumer voluntarily enrolled with the marketplace and will stipulate the expected energy production/demand levels, energy price in tokens or the associated token-based incentives for rewarding the prosumers consuming the renewable energy when available, etc. During a market session each prosumer will submit bids and offers (i.e. from their contracts) representing the amount of energy they are willing to buy or sell. The use of smart contracts will allow the participants to automatically submit bids and offers, the validity checks ensuring that market session rules are not violated being also evaluated by the smart contracts themselves.

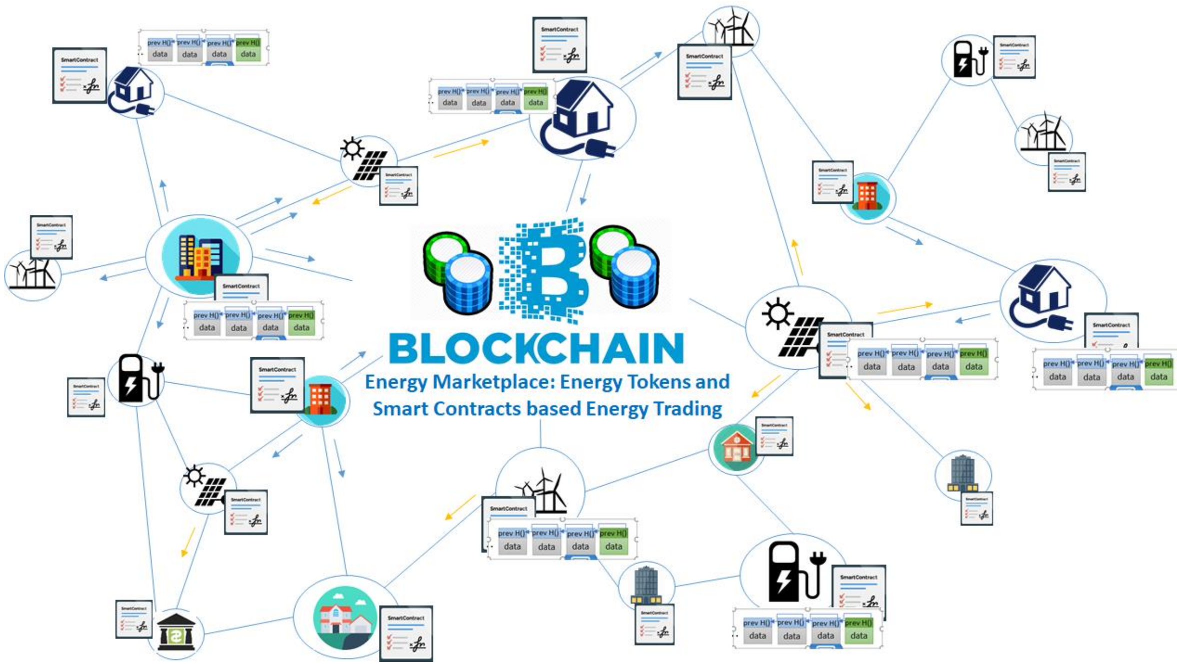


Figure 13. Blockchain based P2P energy market

A market level smart contract will programmatically deal with market operation processes such as matching bids and offers and calculating per session the energy clearing price. For clearing price calculation, the market level smart contract aggregates and sort the energy supply offers in ascending order and the energy demand bids in descending order. The intersection point between the two curves gives the market-clearing price. The offers (supply) having the price lower than the clearing price will be matched with the bids (demand) having a price higher than the clearing price. Prosumers may accept or reject the matched offers/bids. The acceptance of an offer/bid implies the market participant's commitment to inject/withdraw the quantity of energy specified in the offer/bid, or, in case of partial acceptance of the offer/bid, the corresponding share, in a prefixed time frame. In result energy transactions are generated, replicated in all the nodes and validated but they are not fully confirmed until a new block containing them will added to the blockchain.

The market financial settlement is set up on the consensus-based validation. Once issued, the energy transactions are registered and replicated in future blockchain blocks across all the nodes in the network. The consensus mechanisms implemented in the blockchain system, keeps track of all these changes and validate at each point the corresponding state updates. Thus, instead of having one authority for keeping all centralized energy transactions, like the DSO, the responsibility is equally shared among every peer node of the network. Each transaction is tracked and validated locally by each peer before unanimously accepting it in the history. The market implements a completely replicated and highly reliable decentralized validation process, where each node is responsible to validate the integrity of the registered market actions: tokens issued, bids and offers, market clearing price computation, monitored values, settled price, green energy consumer rewards and brown energy consumer penalties. The results of each prosumer node computation will determine whether the actions contained in the block are valid and whether the block will be added as a valid one in the chain history. As a result, the decision on the actual share of green energy which has been effectively delivered / consumed by each peer and associated financial incentives in form of tokens will be unanimously agreed upon through consensus by all the other network peers.

Virtual Power Plants (VPP) Management

This distributed management scenario addresses the increasing need to optimize the output from multiple local generation assets (i.e. wind-turbines, small hydro, photovoltaic, back-up generators, etc.) that primarily serve local communities, but also have export connections to power distribution network [EDREAM-D2.2]. The goal is to provide the technological means for considering in near real time fashion the distributed generation of electricity of multiple types with a view of creating optimal coalitions of DEPs (also called Virtual Power Plants) to provide a reliable aggregated power supply. The benefits behind creating such coalitions is that a mix of different energy generation resources which have different energy generation models and scale may be interested to cooperate in a convenient way, with a view to achieve pre-defined smart grid sustainability objectives. At the same time, this will increase the participation in DR programs of small renewable energy producers by supporting any household which has as little as 1 kW capacity generation. Being built on top of the peer to peer local energy trading and flexibility provisioning this scenario will allow a set of DEPs to be aggregated and ultimately participate as a player on higher level energy markets [Cioara, 2018] such as a flexibility service provider to TSO (Transmission system operator) or a wholesale capacity provider on the wholesale or capacity market (see Figure 14). The VPP will be able to maximise utilisation and revenues from RES and classic generation sources through accessing different markets as an aggregated portfolio, by continuously adapting its capacity to the optimum paying service.

In this context, the use of self-enforcing smart contracts for the distributed aggregation of the combined output of the generation assets as a VPP is the best way to improve on maximizing/minimizing the overall specific objective functions. This is due to the heterogeneous nature of the generation assets having different production profiles throughout the day and different response times to control signals thus allowing their operation to be optimal distributed and tracked by using the smart contracts. At the same time, leveraging on their amount of energy generation by grouping the distributed energy sources in a single portfolio may generate benefits. The resulting curve will have different profile from that of any of its individual components and therefore may be used in a new way – depending also on how fast and within what bandwidth the assets can respond to external signals. The desired objective would be a VPP that is active on the wholesale market by operating on a profit maximizing function and providing services to the TSO while supporting the need of local prosumers and consumers.

In a similar manner the VPP could leverage on the aggregated flexibility profiling of its individual peers to provide flexibility services for a DSO. This is leveraging on the smart contract for tacking and regulating the baseline of individual prosumers to estimate DR potential for turn-down services of generation assets (e.g. start and sync time for CHP or diesel generator, output baselining for PV and wind mills in certain weather conditions). This will allow for automatic and decentralized assignment of new sites/assets to a particular type of outbound service based on the assets particularities such as response time, sync times and maximum dispatch period (i.e. offering power factor regulation services [Cioara, 2016]). In this context prosumers segmentation on the generation side is crucial for the process of maximising revenues as each type of service/markets served by the VPP has specific requirements for the measurement and verification of the power capacity and energy exported to the main grid.

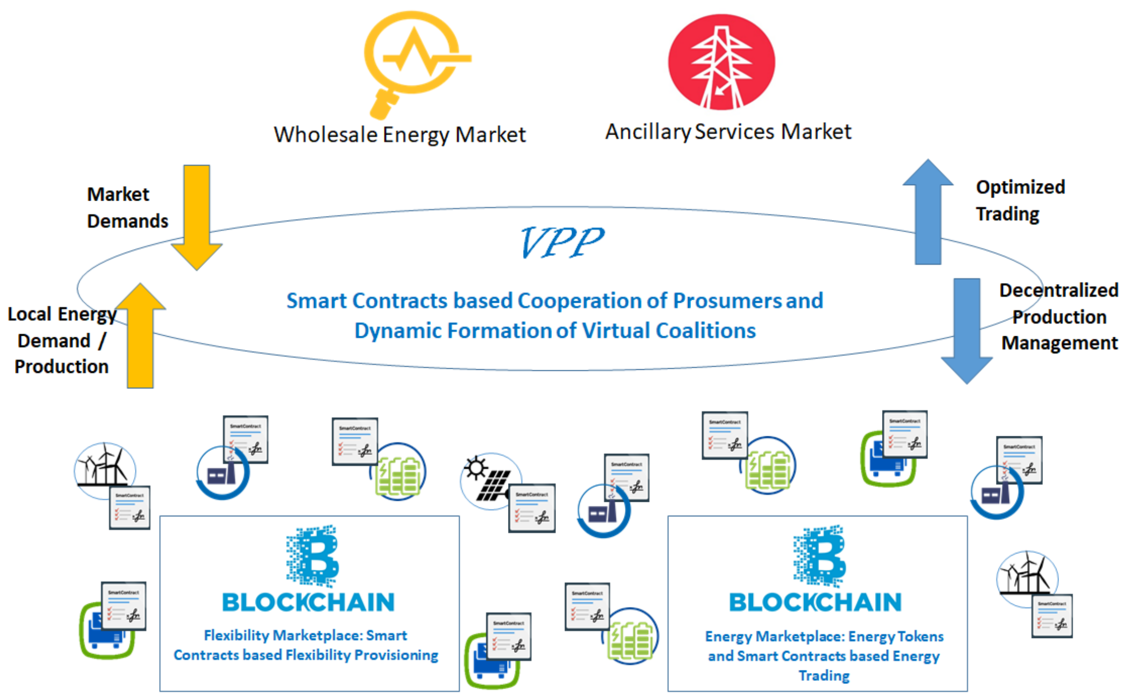


Figure 14. Virtual Power Plants management

3.2 Distributed Ledger for Energy Transactions

We had proposed the implementation of a blockchain distributed ledger at the micro-grid level in which all energy monitored data registered at the level of a DEP will be registered and stored as immutable energy transactions. Thus, the individual energy production or energy consumption values will be aggregated in blocks which will be replicated in the ledger (see Figure 14). A DEP will be modeled as a node of the peer to peer distributed energy network (i.e. a graph of peer nodes) and will maintain a copy of the ledger which will be automatically updated when new data are being registered. Other energy players such as the energy aggregators or the DSO that are interested in micro-grid management are also registered as peers.

Whenever a new DEP joins the blockchain network, a new node (i.e. light or full) is created and will be connected to a predefined list of seed nodes. The seed nodes will provide the new jointed node with information about all the DEP peers they know about, the process being repeated with the new discovered peers, until the new node builds its own list of peers. The nodes can be *light* or *full*, depending on the amount of information they store. The most common nodes are full nodes which keep the entire blockchain locally (i.e. replicated) and can build blocks and make transaction validations on their own, without relying on any other instance of the network. Moreover, they are nodes that actively participate to consistency and the integrity validations of the blockchain by participating in the consensus algorithms. The light nodes come into the scene due to the fact that the entire blockchain requires a very large memory space. The light nodes (also called Simplified Payment Verification nodes) do not hold the entire blocks (e.g. Node 5 in Figure 15), but only their headers thus reducing the storage space by 1000 times.

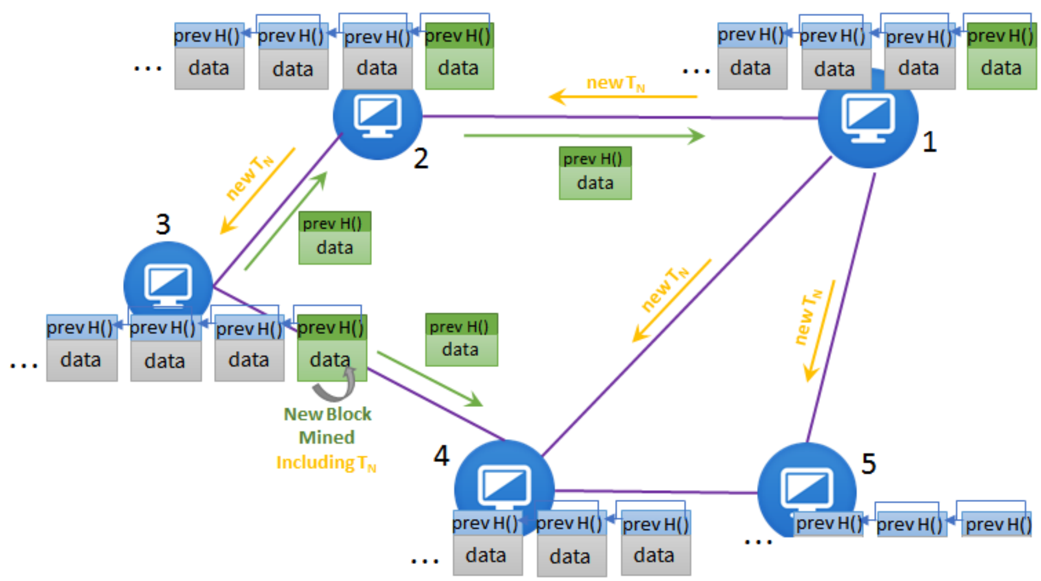


Figure 15. Blockchain blocks distribution among peers [Pop, 2018a]

When a new energy transaction is registered, the issuer node (e.g. Node 3 in Figure 15) will propagate it to all its peers (Node 2, Node 4, and Node 5 in Figure 15). In turn, the nodes receiving the energy transaction will validate and forward it to their own peers, and so on until the transaction is known by all the nodes in the network. In a similar way, when a node manages to mine a block of energy transactions (e.g. Node 1) will propagate it to its peers (e.g. Node 2, Node 4) and each receiving node will validate it, before sending it further to other nodes. To avoid loops in the network, a node will also decide not to forward an event or transaction if it was already previously registered.

Energy Provenance and Immutability

The data structures used to create the proposed energy transaction blockchain based ledger assures the provenance property by enacting the tracking back the energy transactions until the moment of its creation in the blockchain. The distributed ledger is a collection of blocks, linked back using hash pointers, each block storing a set of valid transactions on the registered digital assets (see Figure 16). The linked list is an append-only data structure. Any changes that would appear in previous registered nodes would lead to inconsistencies, because the hash pointer of that block would change. If one needs to change the content of a previous node, all the following nodes will need to be rehashed and re-linked to obtain a consistent updated data structure. The advantage brought by this structure is the tamper proof log on all the transactional information contained in the blocks. Also, being an append-only type of data structure (new blocks are always added at the head of the chain) this structure offers reliable historical information and also prevails the order in which the energy transactions are registered. The probability of changing the value of the transacted energy asset in a block by an attacker decreases with the number of blocks following that block in the append-only linked list.

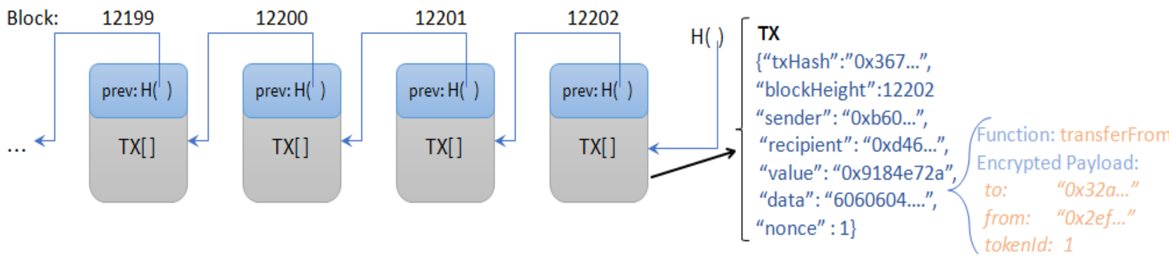


Figure 16. Energy transactions registered in blockchain

In our proposed approach each DEP which generates energy can register energy assets in the distributed ledger, based on the information provided by the associated power meter, by signing a registration transaction having as a receiver the address of the asset managing smart contract [Pop, 2018a], [Cioara, 2018d]. The flow of energy between DEPs will be then represented in blockchain as energy transactions between two DEPs accounts. To make an energy transaction, the contract managing the producer's account will issue an operation of type transfer and specify the producer's address, the energy to be transferred and the receiving counterpart, which is the consumer's address. To prove the ownership of the energy the DEP provides the hash pointer to previous energy transactions showing that the energy asset belongs to him and signs the current transactions, to validate the transfer.

Three main features make the hash functions suitable to be used for storing the energy transactions data securely and in a tamper proof manner in the distributed ledger:

- *Collision-free property* - for any two input energy transactions T_X and T_Y there is a very high probability to have two different hash values $H(T_X) \neq H(T_Y)$. Collisions are possible, due to the fact that the size of the input data is longer than the size of the output data. However, a good hashing function is designed such that, by knowing the hash code there are no better ways to find the input value, other than trying all the possibilities. This property has a very important consequence for the security of the stored data on energy transactions. Considering that an attacker has knowledge of the hash code of an energy transaction, $H(T_X)$, the probability of determining the actual transactional information T_X is extremely low due to the fact that it would take an unfeasible long time to try all the possibilities.

- *Data concealing property* - allow any DEP to hide its energy transactions data by providing a hash of that data (considering that it is improbable for an attacker to provide another piece of data to have exactly the same hash).
- *Data binding property* - between the hash code and the input data on energy transactions allows the DEP entity to prove the origin and the ownership of the energy data at any time in the future by applying the hash function on the original piece of data. Hash values can be further used to identify and verify the integrity of data. When retrieving the data based on a specified hash pointer one can check that the data has not changed since the creation.

The micro-grid may feature a large number of energy transactions that may occur over a short period of time. Thus, to increase the performance and decrease the length for the chain we had used Merkle Trees featuring hash pointers to aggregate multiple transactions in a single block [Pop, 2018a] (see Figure 17). To build such a tree, all energy transactions in the block are paired two-by-two and the Merkle Tree is built form bottom to the top based on the hashes of these transactions. The tree leafs will contain the energy transactions while the upper levels will be incrementally constructed by pairing and combing the hashes of two elements from an inferior level until the root is reached. If the total number of transactions considered is odd, then the last transaction will be duplicated. In this way, a binary hash tree is built up to the root. The result is a 32-byte string encoding an entire set of data. Due to its structure, any change that occurs at leaf level, due to tampering with data, will trigger modification up to the root of the Merkle Tree.

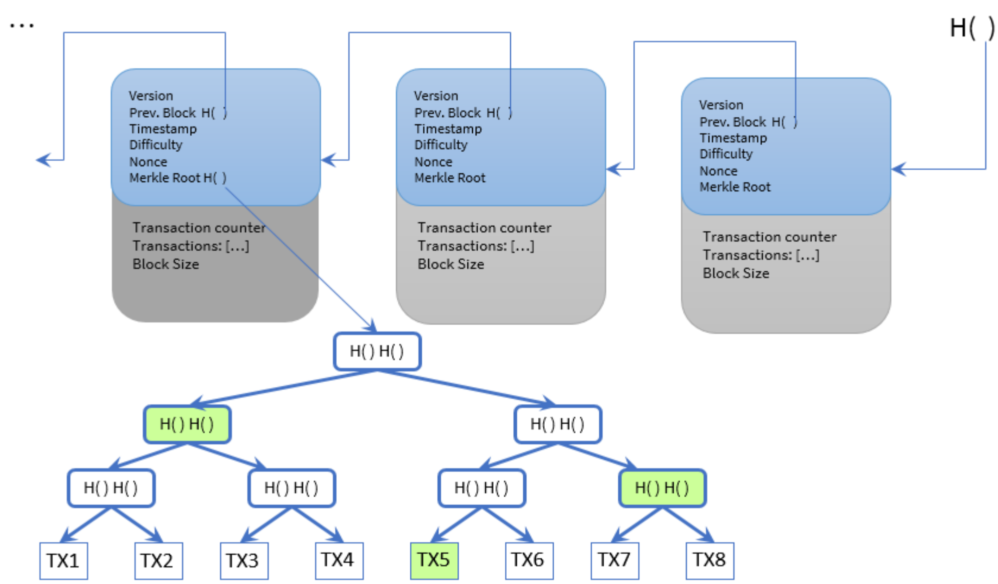


Figure 17. Merkle Tree for storing multiple energy transactions in a block and Merkle path example

The Merkle Tree Root hash encodes the entire collection of energy transactions that are aggregated in the current block. This hash value is of important significance because it is responsible to ensure the validity and the integrity of the recorded transactions in time. The Merkle Tree Root hash is added in the header of the block and, together with all the other fields in the header, is used to generate the hash of the block. The block hash is further used to identify a block in the entire blockchain. It is never stored in the block structure or in the blockchain storage; instead, it is always computed by each node based on the information contained in the header. The hash of the tree root provides a smaller footprint, an important advantage for the DEP nodes that do not have enough storage capabilities (i.e. light nodes). This is extremely important for small scale DEPs which may not have large computing capabilities deployed on site. Thus, the DEP associated light nodes will store only the header of the blocks while the actual energy transactions will be stored remotely. The Merkle Tree root will provide enough information for the light prosumer nodes to be able to check the consistency of the chain. At the same time, the light prosumer nodes may interrogate other network full nodes for information to verify if an energy transaction was mined and to identify the block that stores the actual transaction.

Since the network may contain both honest and dishonest nodes, a light node cannot rely on simple positive answers, but it will request a proof that energy transaction is mined in a specific block. The simplest way to prove that an energy transaction is stored in a block is to rehash the entire Merkle Tree to obtain the root node hash. If the root node hash obtained is the same with the one stored in the header of light prosumer node block, it would lead to the conclusion that the specific energy transaction was successfully mined. However, since a large number of energy transactions can be included in the block, the verification process can be significantly improved by providing only a Merkle Path instead of the entire set of transactions. For example, consider that the light prosumer node needs to find if energy transaction TX6 was mined or not. It will request for a Merkle Path that proves the membership of this transaction in a specific block. This path will contain the hash roots of the subtrees that are not influenced by the hash of the TX6 transaction, marked by green nodes in Figure 16. In this sense, the first hash of the path is the hash of the transaction that was paired with TX6. The hash of the two transactions will be then paired with the second hash from the Merkle Path, and so on until reaching the Merkle Root of the tree. The performance improvement of this approach is considerable, since the light node will need to compute only Log(N) hashes to prove the membership of an energy transaction.

Energy Transactions Privacy

Considering that in the blockchain all energy transactions are duplicated and shared across the network peer nodes, it is imperative to provide solid ways for preserving the privacy of market registered DEPs. Their energy production / consumption patterns should not be visible to other peers in the network. The privacy of the energy profiles and transactions is utterly important, since they are considered personal data that can further be used to extract information regarding different daily patterns of the prosumer. The Public-key cryptography plays a crucial role for assuring the ownership over the energy data, the security of all energy transactions as well as the authentication and authorization. DEPs will use their private key to sign their own energy transactions which will be addressable on the blockchain network only via their public key. Being based on mathematical functions that make it easy to compute the public keys, but infeasible to compute the private key given the public key, the cryptographic signature of transactions will ensure non-repudiation in the blockchain based management platform.

To enforce energy asset ownership, each entry of an energy transaction is linked to the identity of a DEP which must own at least one pair of public-private keys. By applying several hashing and encoding algorithms over the public key the prosumers identity is generated as a 34 characters string.

Since the energy transaction is guarded with cryptographically locking scripts, the only way to prove energy ownership, unlock the assets and perform a transaction is to own the paired private key.

The private-public keys help build an authentication and authorization mechanism in distributed ledger. The traded energy tokens part of a transaction is not sent directly to the address of the receiving DEP but rather to a locking script / smart contract which contains the public key of the recipient. The locking script / smart contract contains a set of rules that must be enforced whenever the energy token is transitioned again in the future. In this way the energy tokens are locked and next energy transactions involving them will need to provide the required signature generated using the private key through an unlocking script. The transactions' energy tokens are locked with locking scripts using public keys of the corresponding DEP recipients and to unlock them, it is required a cryptographic signature that can only be provided by a DEP peer holding the paired private key. Once the transaction is mined, the recipient DEP is given ownership over the energy assets.

Technically all the information stored as energy transactions on the distributed ledger is public thus privacy preservation methods such as zero knowledge proofs can be adapted to ensure the privacy of transactions on energy tokens. This kind of methods allow one party, named the verifier to check if the other party, named the prover, has a secret information without the prover to divulge the information. In this scope we had advocate the use of Zero knowledge proofs[16] which had been successfully used by digital currencies to create anonymous transactions without the need of third parties by unlinking transactions from the origin of the payment.

3.2. Smart Contracts for Micro-Grid Management

In this section we present our ongoing work in the area of defining and using smart contracts for distributed control and for implementing peer to peer local energy and flexibility marketplaces [Cioara, 2018d], [Pop, 2018a], [Pop, 2018b].

Prosumers Registration and Permission Control

Two types of blockchain infrastructure deployments can be considered for the micro-grid decentralized management implementation: public blockchain or private blockchain. The main difference among them lies on the access right and control of new DEP joining a micro-grid and on the reading / writing rights they may be empowered (see Table 14).

Table 14. Public vs private blockchain for micro-grid energy management

	Public		**Private**	
	Permission less	**Permissioned**	**Consortium**	**Enterprise**
Access	Any Prosumer	Any Prosumer based on Prior Validation	Based on Owners Group Validation	Based on Administrator Validation

[16] Zero Knowledge Proofs of Identity, https://www.fi.muni.cz/~xslaby/kr/9/p210-fiege.pdf

Transactions	Any Prosumer	Owners and Validated Prosumers	Owners and Validated Prosumers	Administrator
Commit to Chain	Any Prosumer	Owners and Subset of Validated Prosumers	Owners and Subset of Validated Prosumers	Administrator

The DSO's desire is to keep some degree of control on new DEPs registration to the grid and this limits the potential blockchain deployments suitable for micro-grid management.

The first alternative we propose is regarding permission control to consider private blockchain deployments as solution to manage the access rights of DEPs and to restrict some of them to a group of owners (e.g. group of energy aggregators or even the DSO in specific cases). In this case the energy micro-grid can be managed by a group of big DEPs, retailers or aggregators having an important stake in the market operation or by a single entity such as the DSO. It is important that the DEPs are known and vetted before given access this decision having a great impact upon the micro-grid operation, both in terms of security and consensus. Since the DEPs are known and could be hold accountable for their actions, the need for highly energy consuming consensus algorithms for transactions validation and financial settlement such as Proof-of-Work is not necessary justified. In such a private ecosystem, the validators are legally accountable, thus a certain level of trust between the nodes can be considered. Thus, more energy efficiency consensus algorithms can be suitable for private blockchain ecosystems (i.e. Proof of Authority[17] or Practical Byzantine Fault Tolerance[18]). However, a private blockchain requires to have trusted entities at least for validating new DEPs and issuing new blocks on the chain.

The second alternative we propose is to use a public permissioned deployment and to manage the new DEPs registration validation using smart contracts. Prior to their validation the DEPs will be able to read data from the chain but they will not be able to write new energy transactions and to mine/validate the chain blocks. The permissions management is achieved in the public blockchain system, by either validating the DEPs before their registration to the micro-grid blockchain based energy management, or by establishing some permissions rules at the level of each decentralized application, by keeping a registry of all the validated DEPs in the smart contracts. Since our aim is to change the current micro-grid management one of the main requirements is to eliminate the control of the central entities such the DSOs. As result the energy management processes will be decentralized and governed by the decisions and consensus achieved through the collaboration of all the DEPs registered. In this regard the proposed solution considers a public blockchain network, whose robustness and security is intrinsic without requiring a trusted entity to ensure the well-functioning of the system. However, the openness of the system rendered the public chain maybe considered as unsuitable for many institutions and enterprises rising governance and the privacy concerns.

[17] https://medium.com/poa-network/proof-of-authority-consensus-model-with-identity-at-stake-d5bd15463256

[18] http://pmg.csail.mit.edu/papers/osdi99.pdf

Such smart contract for DEPs registration and access control should:

- Enforce that every new DEP that access the micro-grid has its blockchain platform account validated by several reputable accounts already registered before being tracked by the account registry function of the smart contract;
- Keep track of all the DEPs accounts from the micro-grid and register information about their actions and accounts reputation;
- Decrease the DEP account reputation in case it is not respecting the bids or offers it makes regarding the energy production/consumption or does not provide the agreed flexibility services;
- Consider reputation regarding the DEP's rights and for enforcing of each new action initiated by the DEP.

Smart Contracts for Flexibility Services

We had defined and used self-enforcing smart contracts for management of flexibility services at micro-grid level and control in low voltage grids [Pop, 2018a]. They address the demand side management of the micro-grid being associated with individual DEPs, aggregators and DSO.

The *DEP smart contracts* are defined in distributed fashion at the level of each DEP part of the micro-grid, enrolled with an aggregator and participating to DR based flexibility services. It will specify (see Figure 18) for each DEP the baseline energy consumption profile as an energy curve as well as the actual energy values captured by the associated smart meter and stored as transactions in the blockchain.

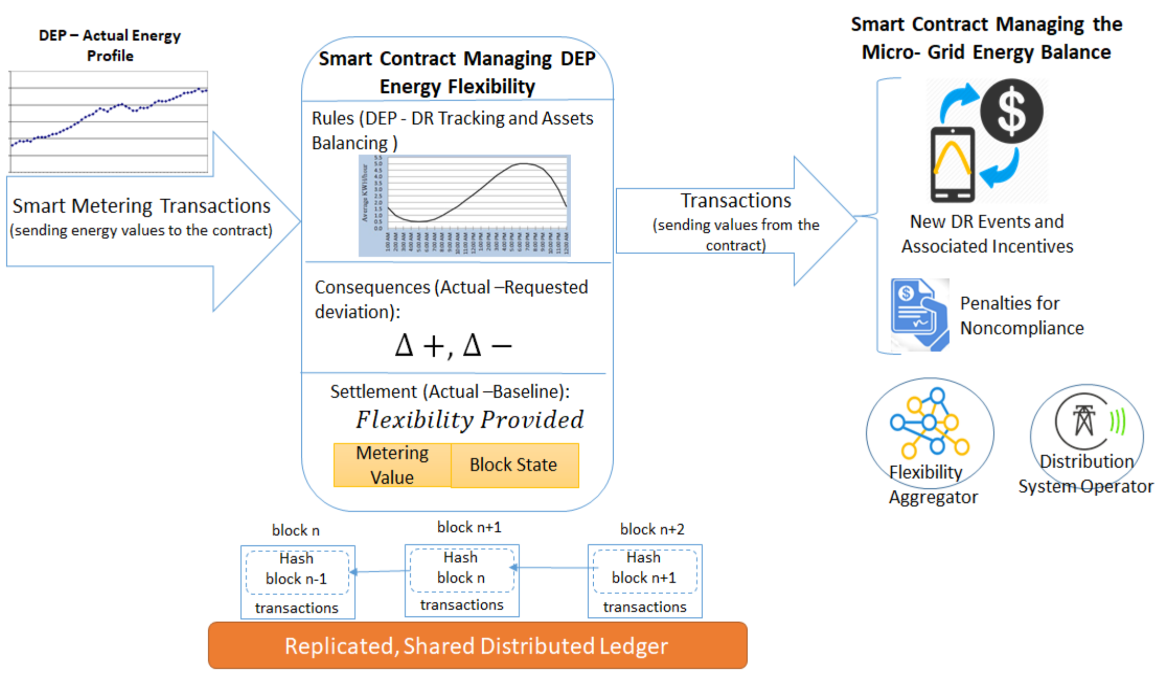


Figure 18. Self-enforcing smart contracts for flexibility services management and decentralized control [Pop, 2018a]

The aggregator will inject flexibility requests as a DR signal in the smart contract of specific DEPs. Afterwards the contract will automatically evaluate for each value provided and stored to a specific block by the IoT smart metering device associated with the DEP, the difference between the requested energy demand curve and actual sampled energy values. If significant deviations are found actions are taken to rebalance and match the energy demand with the energy supply thus the smart contract will act as a decentralized control mechanism and energy assets balancing towards the DSO. Based on the registered deviations in the micro-grid new DR flexibility services are defined in a decentralized manner as well as the financial incentives for penalizing the prosumer that violates the smart contract and for rewarding the one that will address the new DR flexibility service defined.

To determine the flexibility levels actually provided by each DEP the DEP's smart contract will also evaluate the difference between the baseline energy demand profile of a DEP and the energy consumption values registered by the smart meter. The calculated value will be used to determine the incentives for rewarding the DEP for its provided flexibility.

In our approach the DEP smart contract is a piece of code that defines the rules for DEP participation in DR flexibility services which need to be verified and agreed upon all interested actors (i.e. prosumer, aggregator, DSO). The rules may describe the behavior of DEPs during the flexibility related demand response events or may even address various constraints for maintain the grid stability and reliability. These contracts are registered in the blockchain similarly with the energy transactions. They can be triggered by new energy transactions (i.e. registering new energy data from the IoT smart meters), which will determine each blockchain node to update its state based on the results obtained after running the smart contract. However, even if the term is "contract" the smart contract should be seen as an agent that has *state variables* and enforcing *associated rules* and whose execution can be triggered at any point after its successful deployment.

Table 8 presents the main state variables defined in a smart contract regulating a DEP participation in a flexibility demand response service.

Table 15. DEP's smart contract state variables [Pop, 2018a]

State Variable	Description
Baseline Energy Profile $E_{Baseline}$	Regular energy profile of a DEP determined based on minimum of 12 months of measured energy values;
Current Energy Profile E_{Actual}	Monitored energy consumption values acquired by the IoT smart energy metering devices consumption;
Flexibility Request Profile $Flex_{Request}$	Energy profile requested through the flexibility service. Injected by the aggregator into the DEP smart contract

The data acquired by each energy metering device associated with DEP is stored in blockchain and triggers the DEP smart contract execution. The new monitored energy values are added to the energy curve describing the Current Energy Profile of the DEP considering a time interval T:

$$E_{Actual}^{DEP} = \{P_{Monitored}^{DEP}(t) \big| \ t \in T\} \tag{15}$$

Being enrolled with the aggregator to provide flexibility services the DEP are provided with a flexibility request signal $Flex_{Request}$ and financial incentives to adjust their energy demand during DR events (i.e. $Flex_{Rate}^{kW}$ the rate for each kW of energy shifted established by the DSO and distributed by aggregator to DEPs). The provisioning of a flexibility request signal by a DEP will be registered in the ledger, thus the DEP smart contract will check in near real time the monitored energy consumption data against the requested curve signal to detect any significant deviations and notifies the DSO accordingly. The deviations are determined as:

$$\Delta_{E_{Actual}^{DEP} - Flex_{Request}^{DEP}} = \sum_{t_{start}}^{t_{end}} | \ P_{Actual}^{DEP}(t) - Flex_{Request}^{DEP}(t)| \tag{16}$$

where t_{start}, t_{end} represents the interval of the flexibility service. A positive value $(\Delta +)$ signals that the DEP has not reduced its energy demand as requested while a negative value $(\Delta +)$ signals that the DEP has decreased too much its energy demand.

In case of significant positive or negative deviations (over 10% of the flexibility request signal) the DEP smart contract will calculate the associated penalties for DEP. Otherwise the DEP will be rewarded by the aggregator considering the flexibility service incentives established by the DSO and how much of the DEP energy demand profile has been adapted during the DR event.

To determine how much energy a DEP has shifted the difference between the actual energy demand values and the established baseline profile is calculated for the flexibility service time interval:

$$Flex_{Provided}^{DEP} = \sum_{t_{start}}^{t_{end}} | \ P_{Actual}^{DEP}(t) - P_{Baseline}^{DEP}(t)| \tag{17}$$

The total incentives for a DEP for its adaptation during a DR event is calculated using formula:

$$Flex_{Reward}^{DEP} = \ Flex_{Request}^{DEP} * Flex_{Rate}^{kW} \tag{18}$$

We have defined the *aggregator smart contract,* a new type of smart contract associated with the energy aggregator that defines the rules for making available and aggregating the flexibility provided by individual DEPs. Being a smart contract it is replicated and enforced in each DEP of the smart grid network. In other words it aims to track and aggregate the $\Delta \pm$ registered at the level of each DEP with the overall goal of matching and balancing the total energy production and consumption at grid level. In case of detecting imbalances between production and consumption the aggregator smart contract will initiate new flexibility request services and communicates to the interested DEPs the $Flex_{Request}$ and associated incentives and penalties. At the same time, it will aggregate the individual flexibility levels provided by individual DEPs to determine the overall flexibility made available by its portfolio to the DSO. Table 16 presents the state variables controlled by the aggregator level smart contract.

Table 16. Aggregator smart contract state variables (adapted and enhanced from [Pop, 2018a])

State Variables		Description
Aggregated Energy Flexibility provided by DEPs, $Flex_{Provided}^{Aggregator}$		Aggregated energy flexibility provided by aggregators enrolled DEPs during a flexibility DR service time interval
Micro-grid Energy Flexibility State, $\Delta_{Micro-Grid}$		The energy flexibility state at the level of aggregators and its DEP portfolio
New DR Programs	Flexibility request profiles for DEPs	New flexibility request signals for bringing the smart grid in balanced energy state
	Flexibility service incentives and penalties	The incentive offered as a reward for making available the flexibility. The penalties imposed for noncompliance.

Relation (18) presents the mathematical formalism for determining the overall micro-grid energy flexibility state as a balance between the total energy consumption of DEPs and the expected aggregated energy demand by the DSO. It is calculated by aggregating the $\Delta \pm$ imbalances registered at the level of each DEP enrolled with the aggregator and participating to the flexibility service:

$$\Delta_{Micro-Grid} = \sum_{i=1}^{N} \Delta_{E_{Actual}^{DEP^i} - E_{Actual}^{DEP^i}} \tag{19}$$

where N represents the number of DEP enrolled with the aggregator.

The micro-grid energy flexibility state will aggregate both positive and negative values. The positive value represents a deficit of energy flexibility in the micro-grid (i.e. the DEP consumes more than instructed through the flexibility request signal), and the negative value represents a surplus of energy flexibility in the micro-grid (i.e. the DEP consumes less than instructed through the flexibility signal). If such imbalances are determined the aggregator smart contract will construct new flexibility requests signal allowing other DEPs in its portfolio to address them and as result re-balance the energy state of the grid.

The total energy flexibility made available by an aggregator to the DSO using its DEPs portfolio is calculated as:

$$Flex_{Provided}^{Aggregator} = \sum_{i=1}^{N} Flex_{Provided}^{DEP^i} \tag{20}$$

In a similar fashion we had defined *DSO smart contract* for regulating the DSO behavior towards assuring the right balance of the energy state at the overall grid and enforcing its stability (see Table 17). The DSO smart contract evaluates at grid level the balance between the energy production and consumption and if unbalances are determined (i.e. load congestion point or surplus of renewable) it contacts the aggregator asking to provide the difference by shifting a certain amount of flexible energy in its portfolio.

$$Flex_{Request}^{Aggregator} = \Delta_{Grid} = E_{Production} - E_{Consumption} \tag{21}$$

For an aggregator to be rewarded and receive the financial incentives its total energy flexibility should match the amount requested by the DSO:

$$Flex_{Request}^{Aggregator} = Flex_{Provided}^{Aggregator} \tag{22}$$

Table 17. DSO smart contract state variables

State Variables	Description	
Energy Grid State, Δ_{Grid}	Grid level balance between production and consumption. It is used to request flexibility from aggregators being injected by the DSO into the aggregators' smart contracts.	$\Delta_{Grid} > 0$ Decrease energy demand by shifting baseline energy profile to avoid peak load
		$\Delta_{Grid} < 0$ Increase energy demand by scheduling energy flexibility to match an energy generation peak

Smart Contracts for Energy Trading Management

In this case, the micro-grid management is achieved by implementing a democratic, open, peer to peer energy market thus offering the possibility to any DEP to participate in the market auction. The DEP will be able to sell its surplus of renewable energy to other DEPs and / or acquire the energy at lower prices than the ones provided by an energy retailer. This is of utterly importance, since in the past few years the distributed renewable energy resources have multiplied, opening challenges and opportunities for competitive procurement models. At the same time, by matching the small scale energy producers with consumers in a localized fashion it will contributed to the micro-grid energy balance allowing the renewable energy to be consumed as much as possible in the area in which it was produced without involving extra transport costs.

To develop such a peer to peer market we have defined the energy as a non-tangible and non-fungible asset. The fungibility is the property that describes an asset as being indistinguishable from another asset (i.e. interchangeable without any detectable differences). For a given quantity of energy there are several aspects that make it distinguishable from another. For example, the source of energy (solar, wind, fuel, etc.) is an aspect that clearly differentiates future tokens. Furthermore, the timeframe and the micro-grid region of energy generation can also be used to differentiate between energy tokens. Nowadays there are defined several standards regarding the representation of real life assets using blockchain and specific rules for issuance, tracking, transfer and destruction. However, only one of these standards addresses the non-fungible assets. Thus, we have proposed the adoption of ERC-721[19] for representing the energy asset as a non-fungible energy token in our blockchain based energy marketplace (see Figure 19).

[19] ERC- 721, http://erc721.org/

```
pragma solidity ^0.4.24;
contract EnergyToken is  ERC721 {
   string internal name;
   string internal symbol;
   uint256 internal marketTotalTokens;

   mapping (address => uint256) internal ownedTokensCount;
   mapping (address => uint256[]) internal ownedTokens;
   mapping (uint256 => address) internal tokenApprovals;

   event Transfer (address indexed _from, address indexd _to, uint256 _value)
   event Transfer (address indexed _seller, address indexd _buyer, uint256 _value)

   function balanceOf (address _DEP) public view returns (uint256) {...}
   function acquireTakens (address _DEP, uint256 _value) public view returns (bool) {...}
   function transferFrom (address indexed _from, address indexd _to, uint256 _value) public returns (bool)
   ...
}
```

Figure 19. Energy tokenization using smart contracts and ERC721 standard

The ERC-721 based energy token smart contract allows the specification and configuration of token properties, by providing for each token instance a description through the tokens URI. At the same time the metadata for each energy token is consisting on information regarding the type of energy produced, generation time as well as the producer's location. In our implementation each token will correspond to 1 kWh of energy thus allowing the accommodation and operation on the marketplace for small size DEPs.

Furthermore, the energy token smart contract will act as a depository keeping track of the energy token balances of each DEP. The contract defines the basic functionality, exposing methods for interrogating the balance of an DEP account, transferring energy tokens from one DEP account to another, or giving rights to third party accounts to act as representatives and initiate energy tokens transfers instead of the actual owner of the tokens.

Nowadays energy markets are based on two types timeframes: short-term contracts for day-ahead or intraday markets and long-term contracts. Our peer to peer energy market is focusing on the short term contracts and relies on self-enforcing smart contracts for defining the DEPs actions in the energy market sessions.

The main actors in this case are the DEPs which may buy or sell energy and the market operator. Their behavior is implementing via smart contracts thus their associated actions are stored in the blockchain and subject to validation of all registered peers.

The smart contract defining the DEP actions in case of selling energy implement the following functionality (see Figure 20):

- Expected production tokenization - Before a market session is opened each DEP has to acquire several energy tokens proportionally with their expected (i.e. forecasted) energy production they want to sell (if any). The tokens will be deposited in their accounts and will act as an obligation for energy production. Also, the price paid for the tokens is set as a guarantee (i.e. stake) in case that the obligation is not fulfilled by the DEP.
- Energy offer publication – during the market session the DEPs will publish offers for selling energy by specifying the unit price required for energy sold and proving ownership over the energy tokens.

The smart contract defining DEP actions in case of buying energy will be defining the functionality associated with placing bids on a specified amount of energy and the price willing to pay for each energy token unit.

```
pragma solidity 0.4.24;
contract DEPEnergyBid {
   address private consumer;
   address private energyTokenContract;
   string private marketSession;

   mapping(uint => uint) public hourlyEnergyBid;
   mapping(uint => uint) public  hourlyEnergyPrice;
}
```

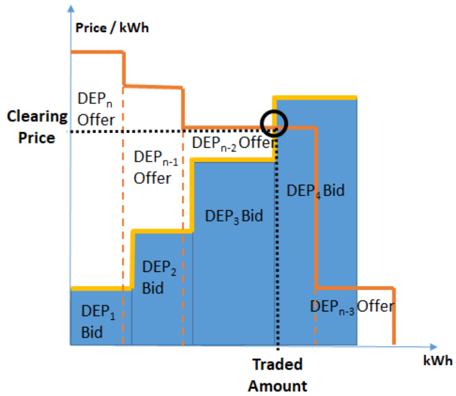
```
pragma solidity 0.4.24;
contract DEPEnergyOffer {
   address private producer;
   address private energyTokenContract;
   string private marketSession;

   mapping(uint => uint[]) public  hourlyEnergyTokenOffered;
   mapping(uint => uint) public  hourlyEnergyPrice;

   function getEnergyTokens(uint h) public view returns (uint[]){
      return hourlyEnergyTokenOffered[h]; }
}
```

Figure 20. Smart contracts skeletons for buying selling energy by DEPs in the energy market

The market operator smart contracts will model and automatize the following market level functionalities: market session management, energy bids – offers marching and session financial settlement.

- The market session management smart contracts define the trading rules during the session. According to the individual forecasted energy production of all DEPs registered during a market session, the energy tokens corresponding to the production amount will be mapped to the corresponding forecasted time of generation. During the market session, the using personalized smart contracts, each market registered prosumer will be able to submit energy offers or bids specifying price-quantity pairs for each timeslot defined by the session type (24 hours for day-ahead and 4 hours for intraday). The market session smart contract validates that all submitted bids and offers matching the defined requirements. All the energy offers / bids a DEP registers in a market session is modeled as a smart contract deployed on the blockchain and tracked by the blockchain.
- The energy bids – offers matching smart contract collects all the bids / offers submitted. Two mappings are defined. The first mapping keeps track all energy bids registered in the chain for each hour, while the second one does the same actions on energy offers. Whenever a new DEP energy bid is registered in the energy market session it is required to deposit an amount of energy tokens proportional to the quantity willing to buy and the price willing to pay. The tokens will be locked in the smart contracts until the end of the market session. Before the session end, each bid must be validated against the market rules and an algorithm for determining the energy clearing price is run. The energy supply offers are sorted in ascending order and the energy demand bids are stored in descending order. The intersection point between the two curves gives the market session clearing price. This is the price at which all the matching actions will be traded. The bids / offers matching consider the energy offers (supply) with the price lower than the clearing price and the energy bids (demand) with the price higher than the clearing price (see Figure 21). For every energy bid or offer not matched in the current market session the deposit energy tokens are un-locked and returned to the corresponding prosumer. For the matched ones, only the difference between the energy tokens deposit and the transacted energy cost at the establish clearing price will be returned,

the rest being safeguarded by the contract until the transactions settlement moment (i.e. until the actual energy is produced / delivered and the proof is registered in the blockchain).




```
pragma solidity 0.4.24;
contract MarketSessionBidsOffersMatching {

   string private marketSession;
   mapping(uint => EnergyBidEntry[]) private hourlyEnergyBids;
   mapping(uint => EnergyOfferEntry[]) private hourlyEnergyOffers;

   function registerBuyOrder(DEPEnergyBid _energyBid) public payable{
      for(uint h=0;h<24;h++){
         uint quantity = _energyBid.hourlyEnergyBid(h);
         uint price = _energyBid.hourlyEnergyPrice(h);
         hourlyEnergyBids[h].push(EnergyBidEntry(msg.sender,quantity, price));}
   }
   function registerSellOrder(DEPEnergyOffer _energyOffer) public{
      for(uint h=0;h<24;h++){
         uint256[] memory  tokenIds =_energyOffer.getEnergyTokens(h);
         uint price = _energyOffer.hourlyEnergyPrice(h);
         hourlyEnergyOffers[h].push(EnergyOfferEntry(msg.sender,tokenIds, price));}
   }
   function matchOrdersAndUpdateMarketSettlement()  public{ }
   ...
}
```

Figure 21. Smart contract for bids offers matching and clearing price calculation [Cioara, 2017a]

- The smart contract for market session settlement is responsible to verify that the promises are held and the energy transactions are conducted accordingly. The producer proves that it holds the locked energy asset agreed to be produced by providing the specific token ids and the consumer address is required as a recipient of energy tokens transfer. On successful energy monitoring and registration in the blockchain, the consumers' tokens will be delivered to the producer as payment for the delivered energy. The consumed tokens will remain as proof for the prosumers activity for future evaluation and validation. However, for any deviation from the values promised for bids and offers, the prosumer will be penalized and required to pay additional fees for the imbalance caused.

Consensus based Validation

Blockchain distributed consensus is used for energy transactions verification, validation and near real time financial settlement of DEP accounts. It relies on the information gathered from the network of DEPs describing energy transactions and flexibility shifted, aggregators describing the defined flexibility services and DSO. The information will be aggregated in future blocks, permanently registered and replicated across the distributed ledger. Since the data structures offered by blockchain are based on hash pointers, the resulting benefit is that the entire ledger becomes a tamper proof log that can be modified only by re-computing the hashes for all the following blocks, which is infeasible. Thus, an important operation in the blockchain approach is that the network should collectively agree on the contents of the ledger which in our case will reflect the state of the micro-grid and the flexibility services effectively provided. As a result, instead of one authority for keeping all energy transactions centralized, like the DSO, with the new approach it is shared amongst every network participant. Each time new energy transactions are registered, these values will be locally checked at the level of each peer by the self-enforcing smart contract using the energy market session regulations and flexibility services rules and agreements. Since the smart contracts will be deployed in the network, every rule will be enforced by each peer and validated in near real time across all the peers. As result the decision on the share of energy or contracted flexibility which has been effectively delivered by each peer and associated financial settlement will be unanimously agreed upon by all the other network peers through consensus. They collectively verify the entire blockchain, and energy transactions are not considered to be fully ‘confirmed’ until a new blockchain blocks have been added.

We will use the participant stake (Proof of Stake) to determine the likelihood of network peer to add the next block of energy transactions to the blockchain and to confirm and validate all energy transactions involved and the associated financial settlement. The Proof-of-Stake algorithms for mining the next valid block and validating associated transactions/services in the blockchain (we want a unique chain) could be extended to the specific case of micro-grid energy management with a view of providing increased reliability of the grid operation. Each DEP part of the grid, could take the role of flexibility services or transactions validator. Each validator should own some stake in the electricity network, in our case the total rewarded incentives received so far, or the number of energy tokens owned could be used as a guarantee of blocks validity. To avoid a centralized decision in which only the richest member takes the validation decision some degree of randomization should be provided. Solutions similar to the one provided PPCoin cryptocurrency[20] which combines flip coin randomization with the energy token age as an arbitrary factor (or incentives age) could be adopted. Thanks to the blockchain based approach the DSO knows in near real time the actual share of activated energy flexibility services as well as the validated energy transactions and figure out accordingly the potential solutions to deal with the occurred unplanned situations.

In short, the distributed consensus validation for energy micro-grid management works as follows [Pop, 2018a]:

- the transactions are registered by each DEP and shared with the network in order to be mined in future blocks;
- the blocks are replicated to all the other DEPs and the distributed ledger is updated to reflect the state of the grid;
- for each DEP self-enforcing smart contracts will track the accomplishment of energy transactions and flexibility services;
- all DEPs collectively verify the entire blockchain, and the energy transactions are not considered to be fully ‘confirmed’ until they are validated and aggregated in new blocks which is added to the ledger;
- the share of energy or contracted flexibility effectively delivered, and the financial settlement are calculated using ledger information.

[20] PPCoin cryptocurrency, https://peercoin.net/

4. Management of Cyber Physical Production Systems

In a period of significant economic pressure, it is unanimously acknowledged that optimizing manufacturing processes in terms of productivity, efficiency, and quality of service delivery is a top priority of nowadays factories. As the business and manufacturing processes are becoming more complex, their digitization and management become a pressing issue. Being exposed to the rapid changes inside the factories as well as to the market conditions and customer changing requirements manufacturing processes management demands flexibility on the fly coordination and adaptation.

These days the manufacturing systems are upgraded from industrial to the digital information age and this trend is common to other sectors such as the energy sector. This is driven by technological advancements in the areas of sensors networks, IoT and mobile cloud computing which led to the development of Cyber Physical Systems (CPS) for managing processes featuring sensors and actuators and agents (humans or software) which may interact and collaborate. In this context, we had identified an industry need for new advanced techniques for integrating systems in more complex distributed ones by coordinating their execution to implement new business processes. Thus, we had proposed the development of Cyber Physical Systems of Systems (CPSoS) as large scale entities that monitor and control organizational and cross organizational processes in real-time, requiring a high degree of autonomy and dependability, and aggregating different autonomous CPS in various application domains [Cioara, 2018f], [Anghel, 2018]. In our vision, the CPS have the potential to provide the foundation and backbone of Europe future economic infrastructure, supporting the development of new smart cyber driven services, and improve our quality of life in many areas.

The systematic structured design of CPS and their integration and networking into CPSoS is rather challenging. In factory automation, the new CPS developed and used for production control are deployed in isolation without any connection with the factories business environment thus being unable to automatically adapt the production parameters in a near-real time fashion considering factors such as product properties, costs, logistics, time, and sustainability.

The use of conventional integration techniques for the development of complex CPSoS is not possible due to their heterogeneous and large scale distributed nature making their engineering, management and horizontal integration extremely expensive. Our vision and work carried out in this field [Cioara, 2018f] is for new networked service oriented CPS delivery and business models, which are less linked to the ownership of fully proprietary, yet fully vertical integrated CPS and will pave the way for a service based innovation within networked marketplaces ecosystems where different technology enabling companies will be motivated to cooperate with standardized integrator or CPSoS middleware providers and with service providers to define a proper innovative positioning along the CPSoS value chain. In this context we had proposed the development and novels models, techniques and tools allowing for enacting the distributed and automatic management of CPS enhanced machines and processes both at (see Figure 22) (such decentralized hierarchical control we had used in other contexts as well [Cioara, 2017], [Salomie, 2007a], [Salomie 2007b]):

- local machine level (i.e. shop floor level) considering machine operation and production related data acquired using sensors;

- global level (factory coordination level) considering factory external business stimuli and CPS distributed integration in cross organizational processes.

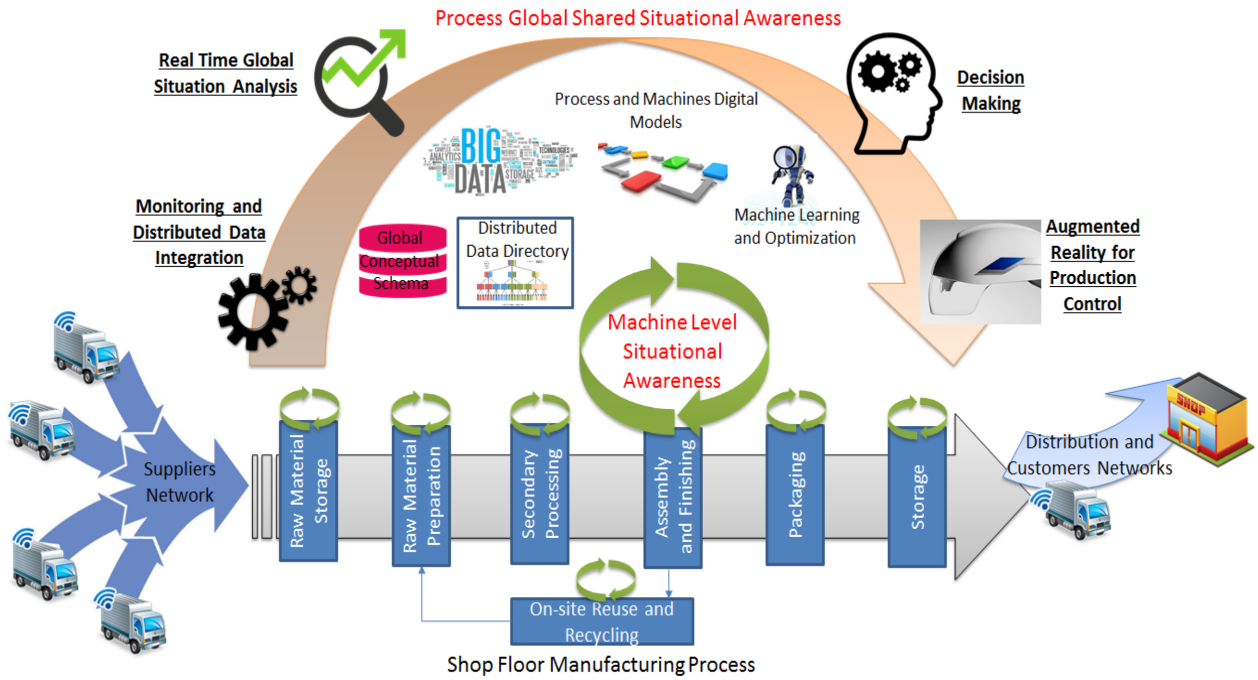


Figure 22. CPSoS integration and distributed coordination (vision of OptiPlan bridge grant project)

Due to its ability to feedback and adapt production operation parameters by considering both the local machine level operation awareness and global manufacturing process level shared awareness (including production external upstream and downstream stimuli) the technological approach we propose may provide the necessary support for increased flexibility and reactivity of production processes driving the paradigm shift to plug-and-produce. This has the potential to reduce production costs supporting European factories to re-shore manufacturing plants or to deploy new ones in Europe.

This will drive the innovation of existing manufacturing business models which need to be updated and improved to take full advantage of the enacted factories supply and customer network awareness and increased production agility aiming to identify new revenue stream for factories. We had proposed new business models that are based on open horizontal integration across the entire socio economic ecosystem of the factory (see Figure 23), in which all the interested (possibly competing) stakeholders along the production chain will digitally cooperate at the cyber level to take advantage of factories' flexible production systems. Our proposed business models will aim to exploit factories digital global awareness of both suppliers and customers' network to allow them to provide unique selling propositions and compete based on their increased reactivity to deliver new customized products through adaptable and flexible manufacturing processes [Cioara, 2018f].

The envisioned business models will bring added value to the entire production chain:

- **Factories** will feature a CPS enhanced machines at shop floor level digitally integrated into CPSoS production process aware on non-optimal situations outside and inside the factory and able to automatically adapt the production parameters in a near-real time fashion considering factors such as product properties, costs, logistics, time, and sustainability.

- **Supply network** added value will be driven by the better and optimized integration of suppliers with manufacturing companies at digital cyber level thus making them more aware on the final customer needs. The suppliers will become more reactive and will have the opportunity to increase the flexibility of their distribution models targeting their integration into global chain networks.
- **Customer network** will benefit on better quality products customized to their specific and chaining requirements, thus supporting the mass customization trend. The customers will be able to track and provide feedback on the products manufacturing through the digital cyber level integration that will be propagated down to shop floor level to adapt the production process.

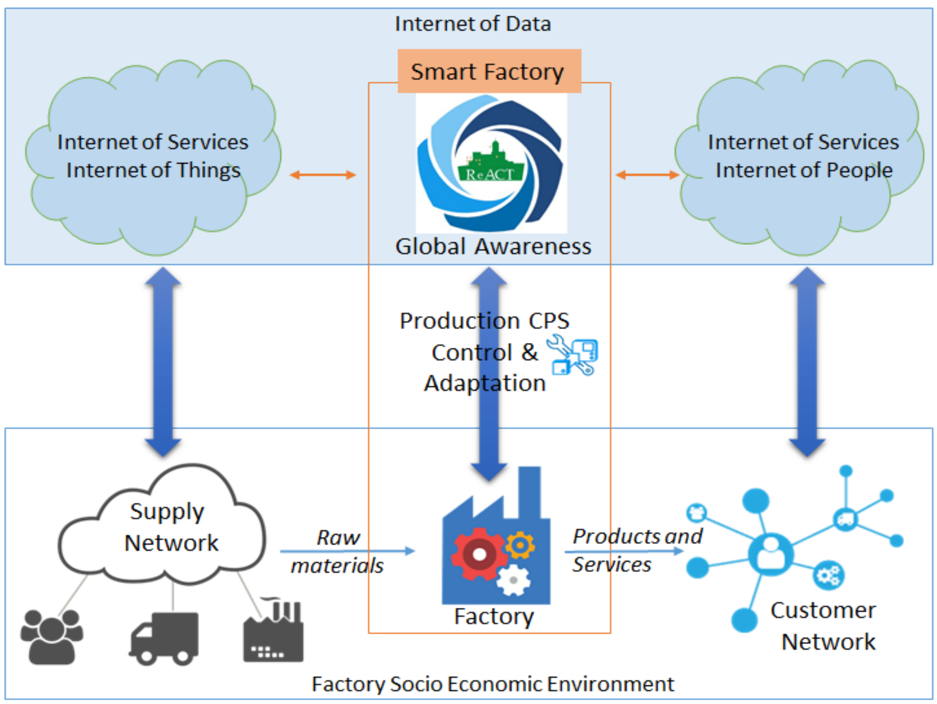


Figure 23. New business models supported using advanced distributed systems and technologies [Cioara, 2018f]

The work carried out in this area was conducted in the context of the CNCS/CCCDI UEFISCDI Bridge Grant Project OptiPlan which was aiming at implementing and transferring novel technologies for digitization, analytics and optimization for the discrete manufacturing process of gas meters and regulators in Emerson Factory. The results of the continuous research efforts in the area of factories of the future had been published in scientific papers such as [Moldovan, 2018], [Moldovan, 2017], [Pop, 2017], [Anghel, 2018], etc. Also, the proposed architectures, techniques, and models had been presented in details in a book on “Distributed Frameworks for Managing Cyber Physical Production Systems in Smart Factories” [Cioara, 2018f].

4.1. Local Management of CPS Enhanced Machines

We propose the transformation of a production line machine in a CPS by adding self-managing capabilities to conventional shop floor level machines and resources targeting their efficiency optimization and the decrease of configuration and maintenance time. Thus, it will aim at:

- Optimizing the production line machine operation efficiency by detecting those circumstances in which the machines are less productive due to improper preventive maintenance and resources allocation;
- Providing support to human workers for their re-configuration considering new production or batch characteristics so that their setup time will be shorter targeting to achieve some degree of self-configuration.

We are leveraging on machine level operation sensed data, the digital model of the physical machine and operation flexibility mechanism to enact the local situation awareness on machine operation efficiency, production configuration settings and constraints satisfaction algorithms to take optimization decisions [Cioara, 2018f], [Cioara, 2013]. The decisions could be automatically enforced using actuators or communicated to human workers by means of the smart helmets which will enforce them (see Figure 23).

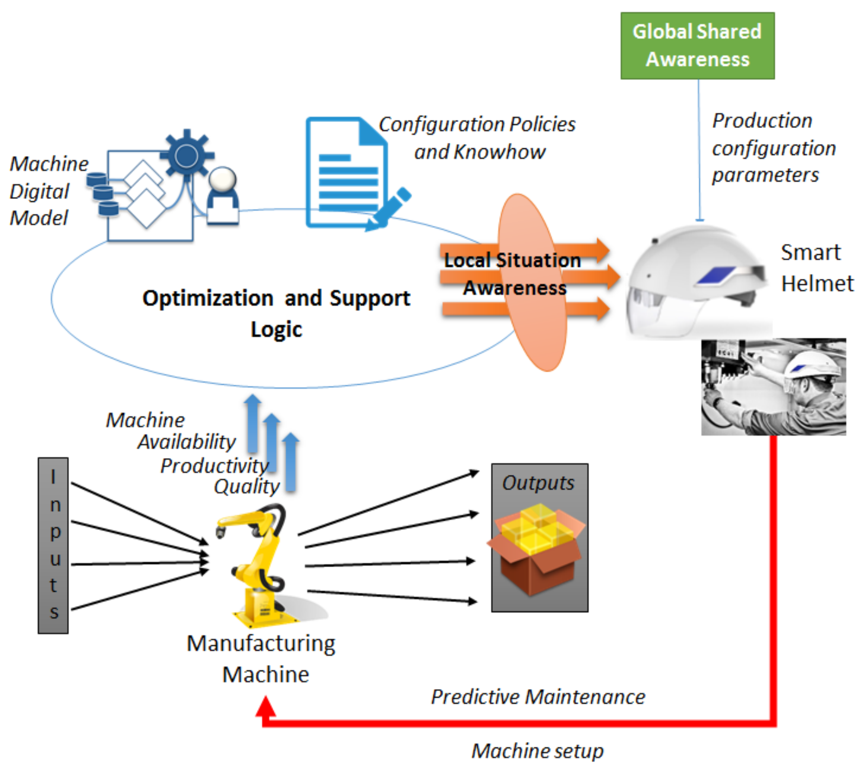


Figure 24. Machine level CPS management and control [Cioara 2018f]

The machine level cyber management and control is blind to the overall manufacturing process states and more over on the business context on which the factory is operating. Thus, by itself, it can lead to sub-optimal behavior and operation of the manufacturing process. The global control and shared awareness instead manages the behavior of the overall production process by integrating all machine levels CPS and considering stimuli outside the factory from upstream suppliers' network and downstream distribution (including customer requirements) to infer the shared situational knowledge that will drive the manufacturing, adaptations, and configurations.

At the shop floor level information regarding machines availability (i.e. actual and planned operation time) performance ration and speed loops, quality (good or bad pieces produced) are collected and used to ensure an optimal distribution of resources to physical machines and preventive maintenance. Also providing support for human workers for machine setup based on the production and batch configuration parameters provided by global awareness control is critical for reducing their setup time as much as possible to improve production flexibility. Policy based configuration mechanism will be provided targeting self-configuration thus supporting the factories trade-off between manufacturing batches as large as possible and maximizing the production and doing small batches and deliver products quicker to the customers.

We provide the technological means for detecting those localized circumstances in which the machines are less productive due to improper preventive maintenance and resources allocation and self-configuration policies to ease their setup for implementing new production parameters provided by the global shared awareness control. The developed techniques will provide to CPS enhanced machines a certain degree of independence in deciding on configuration and optimization actions leveraging at first on human support by means of augment reality devices for actions execution paving the way for the development of "plug and play" CPS enhanced machines.

The machine level awareness and management is organized in three phases (see Figure 23):

- Observation phase - the context in which the CPSs are operating is sensed using sensors to construct local system's snapshots. These snapshots are only taken once a significant change has been made to the status of the monitored machine. The change can be defined as a variation in machine operation, a maintenance action or a change in the working regime.
- Decision phase - use optimization algorithms to take decisions regarding machines local re-configuration and control aiming to optimize its operation. The decision phase will have the ability to seamlessly take into account the positive and negative feedback parameters from the distributed coordination and self-adaptation level to adjust the CPS visible behavior in terms of operational parameters (which may be fine-tuned) and interactions with other neighboring CPS which may be adjusted.
- Acting phase - does the actual adjustment of local management behavior by means of actuator driven actions (when available) or with the help of human specialists who are seamlessly placed as mobile CPS in the feedback loop using the augmented reality device. The smart helmets enact the anytime and everywhere awareness of humans' coordination as mobile CPS within manufacturing CPSoS operation. Using smart helmet humans will be able to visualize on-site projections of defined choreographic models, patterns reviling their integration into CPSoS and will get real time support for to fine tune the CPS operational parameters and their interactions.

Agent based Digital Twins

We had proposed the use of software agents' abstractions for modeling and implementing the digital twins of shop floor machines transforming them in CPS [Cioara 2018f]. Their main advantage is that the agent based abstractions enable rigorous and systematized development of choreographies of various time and spatial decupled CPS that autonomously execute their task in manufacturing processes. Moreover, it enacts the usage of choreography based collaboration patterns for representing CPS integration into manufacturing and business processes as CPSoS being easy to understand by human decision makers (even without software skills), but at the same time sufficiently expressive to be efficiently mapped to executable code. Thus, our agent based approach assures the required levels of independence for the CPS local operational, while the agent choreography patterns will assure their collaboration, coordination, and integration in time and space decoupled processes.

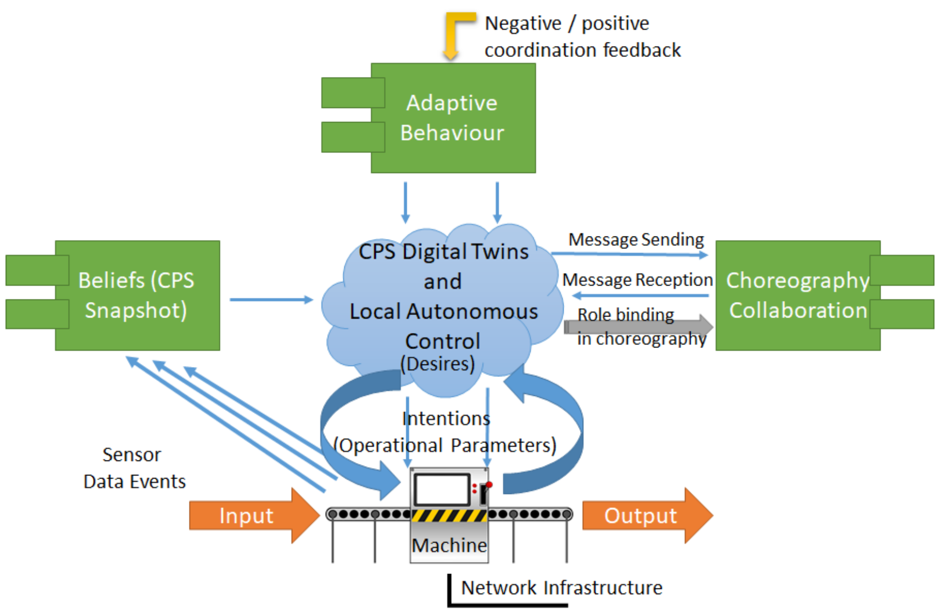


Figure 25. BDI agent as digital twin of CPS enhanced manufacturing machines

The CPS digital twin agent abstraction (see Figure 25) follows the Belief-Desire-Intention model for development and programming of intelligent agents and it is using the Foundation for Intelligent Physical Agents (FIPA) IEEE standard[21] for interoperability between various implementations of multi-agent technology and Agent Communication Language (FIPA-ACL) for message exchange protocols (i.e. choreography expected messaging collaboration). The agent believes will represent events snapshots collected by the CPS sensing infrastructure and potential interactions and collaborations with other agents. Desires are the motivational state of the CPS in terms of hybrid discrete-continuous models and optimization objectives while intentions are tasks/behavior control actions to be executed. The availability of a well-defined, open, consistent and complete set of agent based smart CPS models and interfaces is a prerequisite for their re-usage and integration as plug and

[21] http://www.fipa.org/

play components and viewing the networked CPS through a sort of interacting goal-driven agent's paradigm.

We had proposed the abstraction of choreography of agents to represent from the global CPSoS perspective the interactions between CPS deployed at factory shop floor level [Cioara, 2018f]. The choreographies are based on interconnected interfaces paradigm in which the choreography logic is split across its constituent CPS agents using the expected message exchange behavior. Three different aspects are desired in choreography specification: the constituent CPS agent's individual behavior, the choreography topology specified in terms of CPS agent's neighbors and the CPS physical groundings, (i.e. concrete configuration, data formats, inputs/outputs, etc.). Due to CPS geographical distribution, independent management and operation, it is of vital importance to ensure the reliability (robustness and correctness) of agents' interactions and messages exchanged. This will be achieved by defining reusable abstract choreography based conversational models for coordinating the conversation and interactions of multiple agents. The abstract choreographies will represent various potential topologies of the coordination candidate solutions. The defined abstractions will provide the basis to enable non-IT domain experts to develop decentralized CPSoS composed on CPS twin agents that may further adapted by means of swarm heuristics for decentralized control.

4.2. Manufacturing Process Level Management and Integration

We had proposed the development of a manufacturing process integration level that coordinates the execution of CPSoS choreographies that shares a global situational awareness at digital level and manages the dynamicity and flexibility of manufacturing processes by adapting and adjusting the operation of CPS enhanced machines to the changes that may appear in their execution context (raw materials procurement, shop floor level production and product distribution). It decides on adaptation actions that will optimize:

- the usage of factories resources and physical machines in process execution and will help avoiding non-optimal or faulty context situations such as CPS enhanced machines starvation, resources bottleneck, energy leakage, etc.,
- factory CPSoS manufacturing processes integration into the whole production chain considering the suppliers and distribution networks and
- the adaptation and re-configuration of CPSoS manufacturing processes to changing requirements of customer requirements with a view of supporting the paradigm shift to mass customization.

Layered Architecture for CPSoS Optimization

To support our vision techniques, we had proposed new technologies for developing and executing scalable choreography of CPSoS manufacturing processes targeting their decentralized management and coordination. They are built upon and integrated into a broader agent based platform extending its capabilities for modelling CPS digital twins' agents, creating new collaboration patterns among them, forecasting collaborative emergent behavior prior to execution and self-adapting their run-time operation using swarm intelligence based coordination [Cioara, 2018f], [Moldovan, 2018].

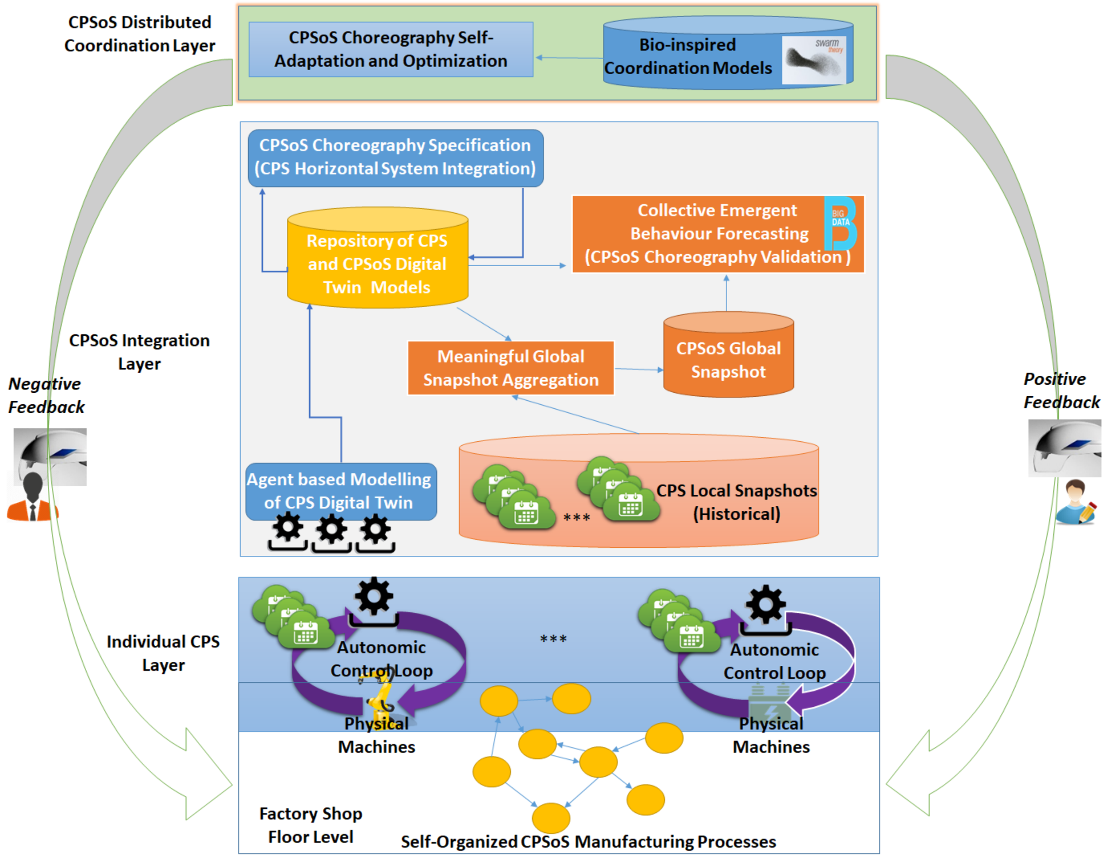


Figure 26. Layered Architecture for CPSoS integration and distributed coordination

The proposed techniques and models are organized according to a layered agent-based architecture which provides a high degree of modularity, scalability, and re-utilization having the following hierarchical layers (see Figure 26):

- *Individual CPS Layer* – set of agent based CPS autonomously executing specific defined tasks and featuring the following abilities: (1) sense the context in which they are operating using wireless sensors and construct local system's snapshots, (2) control their local operation leveraging on sensed data, digital twin models and optimization algorithms thus adding self-managing capabilities to physical machines and resources (3) adjust their local behavior by means of actuators driven actions.
- *CPSoS Integration Layer* – provides agent-based abstractions, techniques, and tools for constructing CPS agent digital twin models from the layer below, horizontal integration in more complex CPSoS using flexible agents' choreography techniques and emergent behavior forecasting leveraging on big data analytics on historical traces of snapshot data. Event ordering and big data integration techniques will be used to construct in a meaningful manner the CPSoS snapshots under the absence of a global unifying time reference.
- *CPSoS Distributed Coordination Layer* - uses bio-inspired models and meta-heuristics for the self-adaptation and optimization of CPSoS processes operation following a goal driven approach. The distributed coordination techniques will be defined aiming to organize and fine tune the operation and interaction of the individual CPS in a seamless manner without

disturbing their task execution. Simple positive or negative feedback mechanisms will be used to determine new operational parameters of constituent CPS.

Global Snapshot and Emergent Behavior Assessment

The manufacturing processes choreographies of individual and autonomous CPS enhanced machines may give rise to complex emergent behaviors as a result of the roles played by constituents, interaction among them and interaction of outside manufacturing process business stimuli. Due to the complexity of the interaction space, these kinds of behaviors/situations can't be inferred by domain experts when the manufacturing process choreography digital model is constructed, adapted or optimized.

The agent based software models offer new views on the operation of CPS enhanced machines providing efficient abstractions to understand also the CPSoS behavior and to generate automatically executable code. Since the autonomous and already deployed and vertically integrated CPS are exposed to uncertainties in their operation context generating disturbances in their tasks execution, their combination and horizontal integration in CPSoS at the digital level will potentially give rise to un-optimal collective behavior featuring emergent properties. The challenge for the systems engineers is to predict and analyses such emergent undesired behavior before the CPSoS actual deployment and execution. The management of these kinds of problems is exacerbating when we have to deal with combinations of heterogeneous autonomous CPS operating at different time scales and inside the same organization or even across different organizational contexts.

There is an evident need for providing techniques and tools for behavior assessment of CPSoS choreographies modeling manufacturing processes [Anghel, 2018], [Moldovan, 2015], [Moldovan, 2015], [Cioara, 2018f]. Such complex behavior is neither linear (stable, periodic) nor uncorrelated (chaotic), but formed by self-organization of CPS in a long transient period and found at the border of stability and chaos. Our approach is that most state transitions in individual CPS constituents of a CPSoS will affect only its local neighborhood, but once in a while, entire avalanches of propagating state transitions can lead to major faults requiring reconfiguration of the whole CPSoS manufacturing process.

The *first step* in assessing potential emergent undesired behaviors is to ensure a total or partial order of the events triggered autonomously by individual CPS machines with the goal of constructing a causally consistent global snapshot of the state of the CPSoS (see Figure 27). To obtain such a global state the local snapshot taking actions of individual CPS need to be coordinated in the absence of a global time and in a distributed manner. We had proposed the use of the Chandy and Lamport 'snapshot' algorithm [Chandy, 1985] to determine global states of CPSoS by constructing meaningful global snapshots. It will make use of a special type of control event called marker which has the role of determining which type of events to be included in the global CPSoS snapshot. The snapshot taking procedure can be concurrently started by each CPS as long as their marker events can be distinguished. Each CPS after registering its local state snapshot is obliged to send a marker event to its neighbors. Each CPS receiving such as marker event is obliged to register its snapshot if it has not recorded its state yet. When a CPS that has already saved its state receives a marker event it updates the snapshot with events unsaved since the last snapshot.

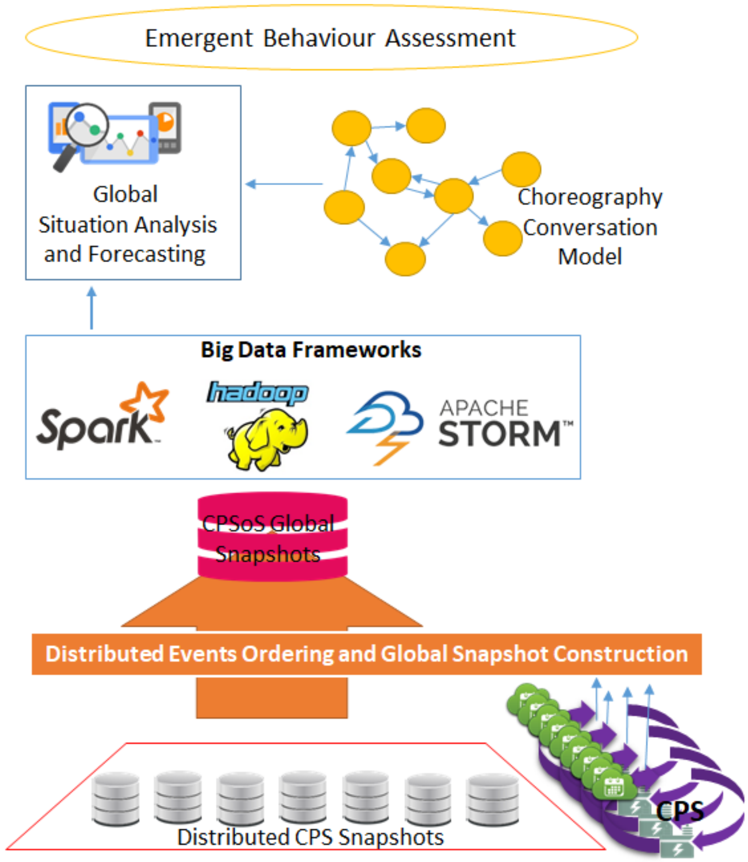


Figure 27. Global snapshot and emergent behaviour assessment in a CPSoS manufacturing process

The *second step* is the data integration in which from these local snapshots, a complete global snapshot is constructed by saving and aggregating the state for each CPS in a coordinated manner. The history of global snapshots states of the CPSoS will be subjected to big data analytics techniques with the goal of validating the defined choreographies and conversation models by determining those CPS individual state transitions that have the potential to trigger avalanche effects which may generate un-optimal behaviors with emergent properties. On-line, real-time analysis will be conducted to identify anomalies in CPS normal patterns or behaviors that can affect the outcome of the entire choreography and stability of the CPSoS. The defined choreographic conversational models will be kept synchronized with physical world data and used to define and perform queries to analyses the distributed integration of constituent CPS providing insights about their local operation impact at the global system level.

Thus, the distributed global snapshot at manufacturing process level will integrate both: (i) the contextual data and events are gathered from factory shop flow level installed sensors and made available to the higher level digital control and (ii) data distributed cross various organizations from the factory's upstream suppliers and downstream distribution networks is integrated at digital level (internet of data).

The contextual data is generated by the shop floor deployed sensors (i.e. factory internal stimuli). The data is referring to the CPS enhanced machines individual operation as well as to the overall CPSoS manufacturing process integration. The context data are usually collected from various heterogeneous entities (i.e. physical machines, advanced sensors or smart components), therefore, in order to be analyzed and processed at runtime such data must be pre-processed and represented in a semantically integrated manner at digital global level. Thus, we had defined semantic integration techniques to aggregate factory internal context data taken from sensors and with data sources distributed across partner organizations [Pop, 2017], [Pop, 2015], [Moldovan, 2015]. We will use them to assess the global awareness of the business situation outside the factory correlated with the state of CPSoS production processes. The external business stimuli are referring to the socio-economic environment in which the factory operates and includes information regarding the changing distribution market conditions and raw materials supply chain, time-to-market requirements, social responsibility of the factory, the impact on the environment and carbon footprint, legislation, etc. We propose to follow a schema integration method (Figure 28) in which a collection of existing conceptual data model schemas (i.e. Local Conceptual Schema at individual CPS level inside the factory), are merged with data model schema exported by upstream production ERPs and by the downstream production CRM to generate a semantically integrated model (a single schema). Along with the globally integrated schema, a Distributed Data Dictionary is having information about the location of the data fragments identifying the remote sites location and providing location transparency.

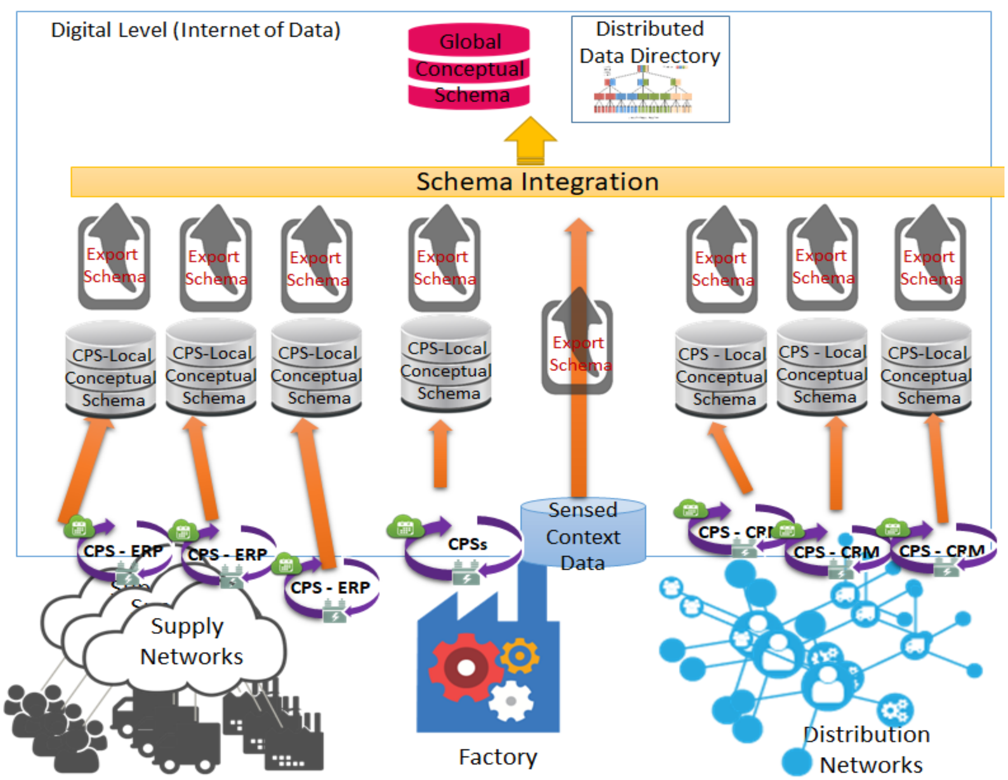


Figure 28. Distributed data integration and global snapshot construction [Cioara, 2018f]

On the of the global snapshot big data processing techniques are employed to detect those un-optimal context situations / behaviors and CPS configurations which may generate emergent behaviors [Anghel, 2018], [Moldovan, 2017]. It considers the manufacturing process operation, factory integration with upstream and downstream networks and implementation of customer requirements. Real-time analysis is conducted to identify these kinds of anomalies in normal patterns or behaviors (e.g. potential patterns that may affect the steady flow of components from suppliers that may delay the production process) that can affect the outcome of a factory business or manufacturing process using Apache Spark[22]. When using machine learning algorithms on sensor data from discrete manufacturing line challenges such as the missing or out of scale data, the noise, the large number of features, etc. need to be addressed.

Figure 29 presents the sequence of steps we have defined to deal with the above presented issues [Moldovan, 2017]:

- Data pre-processing and cleaning – aims to prepare the data to be programmatically processed conforming to a well-defined global conceptual schema. The following data transformations may be also undertaken: eliminating missing values, replacing undefined or out of scale values and data normalization or discretization. The problems are usually generated by sensors heterogeneity and lack of standardization, different rate of data sampling, errors in data transmission (i.e. lost messages).
- Feature selection – aims at collapsing the characteristics considered in the learning algorithms by eliminating the ones which have no influence on the final results. Thus the search space is reduced and the performance of the machine learning algorithm improved. Algorithms such as Boruta[23], Support Vector Machines[24] or Principal Component Analysis[25] could be used in this step to determine features influence scores.
- Cross Validation – aims at splitting the data set in two part: one for training the machine learning algorithms and one for estimating the performance of the algorithms. For Cross Validation a 5-fold approach could be used. The data set in split randomly in 5 subsets that having the equal number of samples. The machine learning algorithms are repeatedly applied on 4 folds of the data set while the remaining fold will represent the testing data set.
- Classification step – aims at applying machine learning algorithms on the training data with the goal of learning a classification model. Algorithms such as Logistic Regression or Random Forest can be used.
- Model Evaluation - classification results are evaluated based on the test data set, i.e. the system must be able to correctly classify data with which it has not interacted, or in other words data that was not part of the training data set. The obtained model may be evaluated

[22] Apache Spark, https://spark.apache.org/

[23] Boruta: Wrapper Algorithm for All Relevant Feature Selection, https://cran.r-project.org/web/packages/Boruta/index.html

[24] Support Vector Machines, http://scikit-learn.org/stable/modules/svm.html

[25] Pricipal Component Analysis, http://setosa.io/ev/principal-component-analysis/

using metrics such as: the accuracy, the F-measure, the recall, the precision and the False Positive Rate.

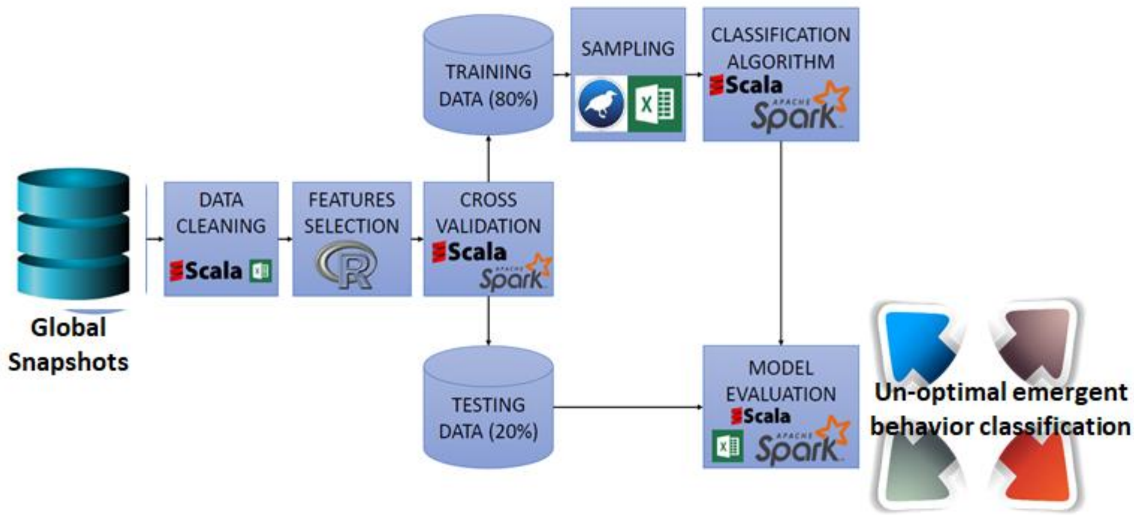


Figure 29. Big data analytics global snapshot analysis and un-optimal behaviors classification [Moldovan, 2017]

CPSoS Construction, Distributed Coordination and Adaptation

Modeling tools are needed on the of the defined abstractions to enable rigorous and systematic development of CPSoS manufacturing process using distributed choreographies of autonomous CPS enhanced machines as well as specification of requirements and goals. This kind of tools needs to be expressive enough to be used also by non-IT professionals and to provide support for faster model development and better model reuse. Of significant importance is to provide support for CPSoS design space exploration to determine the required capabilities, accuracies, number of CPS enhanced machines to achieve the overall functional and non-functional goals of manufacturing processes and desired quality, performance, reliability, scalability and robustness. This will not start from scratch, but we propose to build upon the results provided by ongoing initiatives in the Future Internet Society such as the software outcomes of the H2020 project CHOReVOLUTION[26] which aims at providing choreographic tools for future internet services composition. We will extend the service choreographies abstractions for CPS agent while leveraging on composition execution support provided by agents' platforms such as JADE[27]. Of a particular interest is the quality for BPMN visual design language allowing to directly annotate the BPMN[28] Choreography Diagram with quality requirements that the CPS twin agents need to follow. Extensions could be defined to allow different levels of control for agents' defined interactions (i.e. "loose" or more "tight" control) and to enable domain experts to develop decentralized large scale CPSoS composed of heterogeneous networked CPS at digital level by defining choreographies of digital twin agents. The domain experts will

[26] H2020 project CHOReVOLUTION, http://www.chorevolution.eu/bin/view/Main/

[27] Java Agent DEvelopment Framework: Jade Site, http://jade.tilab.com/

[28] BPMN, Business Process Modeling Notation, http://www.bpmn.org/

specify the agents’ choreography's roles in terms of expected messaging behavior of the participants that will play and the sequencing and timing of the messages that they can consume and produce. This will support the decision makers’ activity of exploring CPSoS manufacturing process choreography design alternatives (i.e. candidate solutions) before deployment and execution while the defined abstract conversational models will be kept for later use. The choreography of CPS digital twin agents is run when its participants execute their defined roles using the deployment and execution support provided by the agent based platforms.

The CPSoS chorographical models construction could be automatized by looking at the events logs of manufacturing processes execution prior to their digitization. In particular, the process mining techniques are relevant in this case. Their aim is to identify and extract process patterns from data logs (hosted by an enterprise information system) to reconstruct an overall process model and components interaction flow. One of the major drivers behind the rise of business process mining is the need of factories to learn more about how their processes operate in real environments and context but their limitation lies in the fact that modeling problem parameters need to be selected in advance. Event logs are one of the primary sources of big data in factories and mining this data is critical for improving manufacturing process performance and for digitizing their operation (see Figure 30).

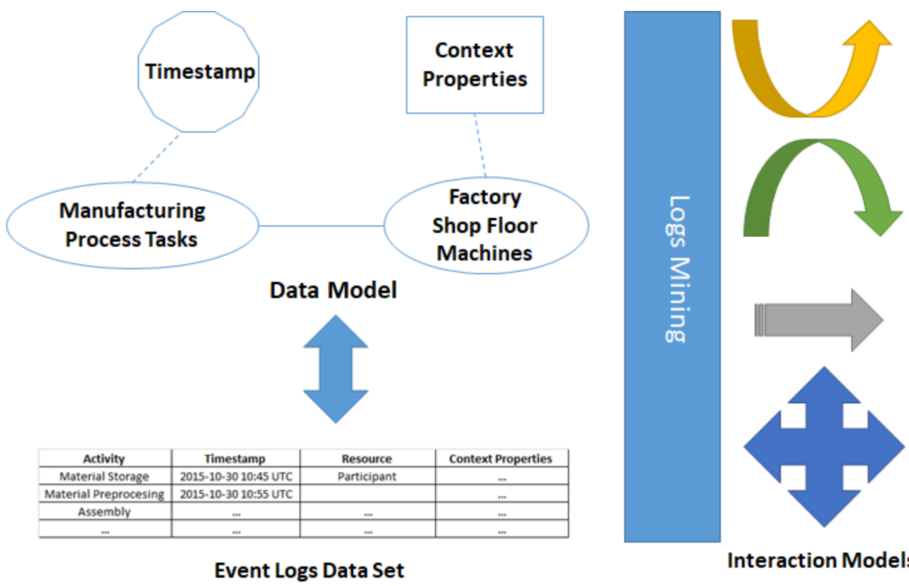


Figure 30. Mining the interaction traces among machines in manufacturing processes [Cioara, 2018f]

The minimum information that needs to be contained in such a data set is the process activity, the resource consumed by that activity, contextual properties and the event a combination of activity with properties and a timestamp. Algorithms are developed to extract ordering relations such as traces, causal, parallel, and unrelated out of event logs based on the ordering relations between the activities recorded in the log.

CPSoS management and adaptation can be implemented by leveraging on swarm inspired meta-heuristics with the goal of achieving the optimal coordination of local individual autonomous CPS based machines operation in the on the defined choreographic model.

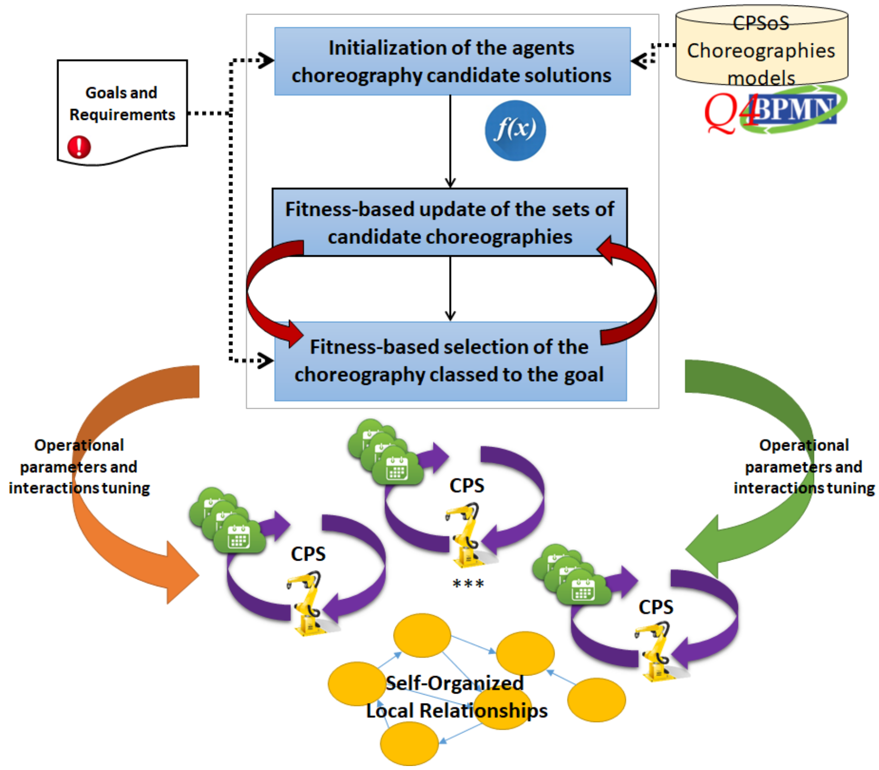


Figure 31. Swarm based distributed coordination feedback generation [Moldovan, 2018], [Cioara, 2018f]

The global CPSoS coordination problem is solved in four steps (see Figure 31):

- The first step aims at formally defining the search space leveraging on the interactions, behavioral and operational parameters of each individual constituent CPS, as defined by their agent based digital twin models. The various agent choreographies conversational models are considered and used to define the candidate solutions on the space assuring a high degree of diversity. On the search space, we will investigate and define a set of penalty-based fitness functions that consider the distance to the target specified goal –penalties are applied to solutions that do not have a high quality.
- The second step aims to map the concepts of the coordination problem to concepts of chosen meta-heuristic and to provide an appropriate formal representation of these concepts such that they enable a low processing overhead. For example, if the Particle Swarm Optimization meta-heuristic is considered, we will have a number of intelligent digital twin agents (i.e. implementing the particles behavior) that cooperate with each other to identify the optimal or a near-optimal combination of coordination features. Each agent will have a position and a velocity associated, where the position is represented as a set of interactions with other CPS digital agents, and the velocity is given by the operational parameters variation.
- The third step deals with the adaptation/enhancement of the meta-heuristics algorithm and its specialization according to the problem being solved and additionally include some supplementary processing steps to provide a balance between exploration and exploitation. For example, in the case of Particle Swarm Optimization, a Simulated Annealing-based

strategy that aims to search for the best solution in the neighborhood of a current processed chorographical solution can be used to improve its exploitation component.

- The fourth step aims at running the defined meta-heuristics, selects the candidate solution with the smaller distance to the goal (as determined using the fitness function) and transmits the new fine-tuned operational parameters and interactions to the local individual CPSs by means of simple feedback mechanism: (i) positive feedback - the CPSoS responds to the perturbation in the same direction as the change (i.e. towards amplification of the perturbation), and (ii) negative feedback - the system responds to the perturbation in the opposite direction (i.e. towards the rejection of the perturbation).

Table 10 below summarizes the main advantages brought by our proposed technical approach to manufacturing process digitization through the development CPS enhanced machines and their integration and coordination at cyber level into CPSoS using choreographies or digital twin agents.

Table 18. Main advantages of our proposed approach

Approach Advantage	**How it is achieved**
High degree of autonomy	The set of autonomous CPSs is operating independently at the physical level to fulfil defined their tasks and goals are virtually represented at digital levels by intelligent agents as digital twins. Constituent CPS are separately modelled and integrated, but maintain a continuing operational existence at the physical level independent of their choreography conversational model integration in CPSoS.
Adaptability	Distributed coordination of autonomous CPS using nature inspired meta-heuristics targeting their self-organization on defined CPSoS choreographic models and self-adaption and optimization associated manufacturing processes behavior. Positive and negative swarm level feedback is given for adapting the individual CPS operation. Complex behaviors of CPSoS which are not specific to any of its CPS will emerge as a result of choreography integration and operational coordination.
Scalability	Due to swarm intelligence inspiration, there will be no need to train new individual CPS agents or to refine the rules of their interaction in choreographies. Thus increasing the number of individuals CPS does not proportionally increase the number of agents' interactions in the digital world.
Complexity Management	Big data analytics and forecasting techniques for undesired emergent behavior assessment on the historical data snapshot traces. CPSoS model validation and usage of agent based model for simulating the behavior and interactions of the CPS integrating into a more complex CPSoS.
Seamless Management of Both Stationary and Mobile CPSs	Virtualization of both stationary and mobile CPS (e.g. humans with smart helmets), including smart location-based management and optimization of CPS while-on-the-move, will be enabled, with a view to manage and coordinate anytime, anywhere, anyplace CPSs, and to pave the way for a service-based networked value chain, enabling service-based delivery of CPS (CPS as a service).
Humans as CPS in coordination loop	Smart helmet augmented reality supporting humans to turn into mobile CPS enriched yet active stakeholders within the CPSoS coordination loops.

Chapter 2 – Scientific, professional and academic career development

5. Career development plan

My career development plan is based on the principle of continuity in academic, research and professional activities by leveraging on the previous expertise and achievements and on combining and correlating didactic activities with the research and university management activities. As a model of development, I have used the self-oriented and self-assessment model in which I will set my career development course and objectives and I will be primarily responsible for their implementation, control, and evaluation.

Considering the actual state of my career development reported in Chapter 1, I have defined objectives for my career development considering each specific type of activity (see Table 19).

Table 19. Development objectives per type of activity

Type of activity	Career development objectives
Scientific and Professional	Further, increase the impact of my research by identifying and addressing new and challenging problems in the area of resources management in large scale distributed systems both in research projects and in scientific papers.
Academic	Improve the teaching abilities, and propose new BSc and MSc courses in which the research and technological results will be transferred and used. Example of such technologies: distributed control using blockchain, green computing and data centre management, industrial processes and cyber physical systems.
	Contribute to the academic management activities specific for the Computer Science Department as well as to the research and innovation management activities in the Technical University of Cluj-Napoca

The career development plan contains the set of actions that I will take in the future so that the development goals defined are met. Thus I have structured it into two main directions:

- actions for the development of academic activity;
- actions for the development of scientific and professional activity.

5.1. Academic development plan

The academic development it is divided into two main action plans, one addressing the teaching development and one addressing the academic management development (see Table 20).

The ***teaching activity development plan*** is centred around the implementation of good practices in the processes of knowledge transfer and student learning. At the same time, my aim is to continuously improve the quality of the academic process by updating the teaching act to the highest Academic standards and harmonizing it with the latest methods within the disciplines I teach.

The ***development plan in relation with academic management*** is focused on continuing the management activities that I already carry out at the level of Computer Science Department and implementing new ones aiming for a proactive involvement in the research management activities of the Technical University of Cluj-Napoca.

All the academic development actions defined will allow me to contribute at maintaining a high-quality quality threshold of the learning process in the Computer Science Department and to the preservation of the Department and Faculty on the top-ranked positions in national academic rankings.

Table 20. List of actions for academic activity development

Defined Action	Implementation Details
Actions for teaching activity development	
Increase the quality of my courses (continuous activity)	Periodically update the contents of the courses in accordance with the evolution and the trends of the national and international research and technology. I will study how similar courses are lectured in the world's top universities and I will update the information taught in accordingly. I will try to introduce in the information taught as far as possible references to the state of the art technologies and results obtained in the scientific research activities carried out in the DSRL laboratory.
Keep up to date the technologies used for implementing the practical activities	Improve the material taught at the laboratory to include the new technologies or relevant tools. Keep close contact with the software companies from Cluj-Napoca and use their feedback for specifying practical activities according to their needs (i.e. using the techniques and tools commonly used in software development). I will specify new laboratory themes to capture the theoretical concepts taught at the course and plan to introduce alternative technologies for the implementation of the proposed topics for the students, allowing them the possibility to choose. I plan to publish a new version of the laboratory support for distributed systems by introducing new technologies and presenting the concepts taught with examples of application in practice or research.
Use a student-centred teaching approached for improving the learning process	I plan to use teaching strategies, techniques, and resources to meet the needs of all students such as: • inquiry-based instructions to encourage the students to think for themselves and become more independent learners; • cooperative learning strategies to encourage students to work together by promoting small groups for projects implementation; • differentiation strategy by allocating practical activities based on the students' abilities. I will constantly ask the students for their feedback and will use it in the teaching process and content of the subject studied.

Defined Action	Implementation Details
Develop continuously the professional and teaching skills	Develop new abilities to communicate and present information through training and participation in specialized sessions about new educational technologies. Transform the teaching process in an interactive one focused on building competences in students leaving an open path for the students towards individual study. Keep up-to-date on new research on how students learn, emerging technology tools for the teaching, new curriculum resources, etc.
Improve students evaluation process making it more objective and transparent	The exams subjects will be organized in three main parts the theoretical part, problem solving part and the technologies part each of them having different ponders into the final grade. The difficulty of each subject will be established in such a way that each student will be capable to solve the problem according to his level of preparation, but only a relatively reduced number of students will be able to obtain the maximum score. The theoretical evaluation will not focus only on the reproduction of the concepts discussed during the course, but also on their application in practical concrete situations. I will continue to use the anti-plagiarism software infrastructure developed by DSRL team from evaluating the practical applications at programming techniques discipline and I plan to extend its usage also for practical applications at distributed systems discipline.
Transfer of research knowledge to the students	I plan to address this in two directions: • update the curricula of disciplines taught to incorporate new knowledge gained in the research project; • continue to involve the students in the research activity for the proposed license / dissertation projects. In this sense I will define specific themes in correlation with the tasks we are leading in national or international projects. I intend to increase the ratio and impact of students within the research activities, in the Computer Science Department, helping and teaching them to write scientific papers for conferences.
Consolidate and improve the teaching teams at each course	Identify top students capable of participating to academic teaching activities since year 2 and gradually involve them in both teaching and research activities. Facilitate the hiring of new teaching assistance that will help with the implementation of practical activities by offering them the opportunity to work at the same time in DSRL research projects.

Defined Action	Implementation Details
	Create and manage stable teams per courses formed of professor, teaching assistant, master and doctoral students and take care of potential modifications with no negative impact upon the students.
Actions for academic management development	
Participate to the promotion of Computer Science in research and academic fairs	Participate to the development of materials that describe the educational and research achievements of the Computer Science Department. Create presentations for different scientific academic events (e.g. International Exhibition of Research, Innovation and Inventions - ProInvent). Present the research activities of DSRL team to high school students during the university open days week.
Participate to the activities of evaluating license or master thesis	Continue the involvement in the evaluation of students' license thesis. I am already participating as a secretary of license committee but my short term goal is to become a full member of the evaluation committee. Get involved in the process of evaluating the master thesis. Currently I not a member of the evaluation committee but my short term goal is to become one. Increase the number of students that I guide for the fulfilment of their license and master thesis by offering opportunities to be part of research activities and to be integrated in the development of solutions to be used in practice.
Participate to the management activities of Computer Science Department	Continue the involvement in the department level activities of: • Participate to the process of admitting new students in Computer Science Department; • Participate in the preparation of the ARACIS accreditation; • Continue the activity of tutoring the student practice related activities. Become a member Automation and Computer Science faculty council and participate the decision making process.
Participate to the research and innovation management decision making in TUCN	Actively participate to the process of setting up the research and innovation priorities and short / long term strategies in TUCN. Participate in the process of defining and implementing the framework under which the research project are/will be managed in TUCN. Participate to the implementation of bi-directional dynamic learning process at TUCN level based on the interactions with different industry stakeholders targeting the transition of research to industry. This will be done leveraging on existing and future industry connections and networking.

Defined Action	Implementation Details
	Leveraging on the knowledge about project proposal writing and management gained during my research activity involvement in DSRL projects to provide advices and guidance to other member of Computer Science Department.

5.2. Scientific and professional development plan

The scientific and professional development plan is created having in mind the synergy with the research and innovation activities of DSRL and the same time the strategic objective of increasing the impact of my research (see Table 21).

Table 21 Actions set for scientific and professional development

Defined Action	Implementation Details
Continuous involvement in the research activities associated with ongoing projects within the DSRL laboratory	Work for the implementation of technical tasks assigned to us in new or ongoing national and international research projects. Plan and allocate the research and innovation work among DSRL team members in accordance with their capability and experience. Check and review the work conducted against the set objectives and provide feedback and guidance. Participate in the progress meetings on the ongoing projects in order to present the results of the laboratory and to establish bilateral contacts with the partners in the project. Write and contribute to the scientific and technical deliverables assigned to DSRL in research projects. Participate in project review meetings and provide reports regarding the work done by DSRL to European Commission. Investigate and accumulate specific competencies in new directions and technologies emerging in computer science such as: blockchain, analysis of large data sets, non-linear optimizations, etc. Increase the number master dissertations coordinated, as well as involvement in mentoring activities of doctoral students. Implementation and use of good practices in the scientific research activity conducted in DSRL.
Increase the quality of the scientific papers published	Identify new research directions and hot topics in the area of large scale distributed systems. Identify appropriate use-cases to objectively demonstrate and evaluate new techniques and methodologies proposed. Select conferences and journals the optimal match the topics of the papers allowing to increase the visibility and impact of my research.

Defined Action	Implementation Details
	Mostly target the conferences ranked A or B and phasing out to publish in the C conferences. Target the publication of articles in ISI journals in Q1 / Q2 area; Increase the number of papers evaluated for conferences indexed in international databases and the number of journals to which I act as a scientific reviewer.
Propose and participate in new national and European research projects;	Conduct a detailed analysis of the main research directions established by the European Commission in the Horizon2020 program (and beyond) and harmonizing and adapting the research work of the DSRL to them. Participation in launching calls for projects proposals on specific areas of the Horizon 2020 program and the next framework program. Identify important directions in research in my field of activity and analyse the projection of my results at an international and national level. Identify topics and open calls which match my research filed and DSRL competences. Construct new consortium by exploiting the synergies of competences among partners in our research network matching the open calls requirements. Effectively manage the project proposal writing phase by assigning tasks and requiring specific content from consortium partners.
Knowledge exploitation and transfer with the industry	Establish collaborations with companies from our country or abroad in order to carry out consultancy and technology transfer activities. Work in the direction of interconnecting the DSRL scientific expertise with the needs of economic sector identifying potential collaborations and synergies. Identify industry use-case and requirements that can be used to drive my research work. Improve the practical knowledge of master and doctoral students facilitating the implementation of internship programs with relevant companies.
Take-up consortium level management roles in European level projects	Monitor the compliance of the partners with their obligations and the implementation of corrective decisions. Verify consistency and submitting reports and other deliverables (including financial statements and related certifications) to the European Commission. Coordination of the overall scientific and technical operational activities of the project, ensuring the high scientific and technical quality of reports and deliverables submitted to the EU Commission.

Defined Action	Implementation Details
	Consortium level coordination of knowledge management and innovation-related activities. Report and monitor the progress of work packages covering scientific and technical issues to ensure the integration of scientific, technical, practical requirements into technical solutions. Meet regularly with the representative of each partner to define, coordinate and update a collaborative exploitation and dissemination plan. Identification of conferences, magazines, and journals for dissemination. Define the Intellectual Property Rights and data maintenance and harmonization of the consortium partners' policies and continuous evaluation and coordination of the effort required to develop marketable products.
National and European level dissemination of research DSRL projects results	Participate in conferences and call launching meetings to identify potential partners and ideas for future projects. Ensure the visibility and awareness of the DSRL and developed projects and to support the widest adoption of its results in industry, standardisation, and research. Acquire relevant feedback by engaging in dialogue with relevant stakeholders and use this feedback for constructing new innovative systems, refining existing ones and propose new projects. Create an effective communication strategy for making relevant stakeholders aware and understand the DSRL innovative technologies and support early adoption by the industry. The dissemination strategy for DSRL projects results that will: • Identify the target audiences and provide dissemination material and activities explicitly tailored to address the different audiences; • Define key messages of DSRL innovation and select the appropriate modes of communication; • Contact directly or indirectly the potential research partners to provide effective demonstration and evaluation of the DSRL research results; • Maximize the exposure of messages by exploiting the communication channels provided by the EU, national public bodies and TUCN.
Contribution to standards and participation in standardization bodies	Identify the representative standardization organization relevant for DSRL research and innovation activities. Define and use a two-way communication approach:

Defined Action	Implementation Details
	• Promote the DSRL projects results to the relevant standardization groups to increase the impact of the research; • Use relevant standards for the systems and technologies development in order to increase their adoption. Preliminary list of relevant standardization activities identified and synergy with the work reported in this habitation thesis: • <u>Green data centres</u>: TIA-942 Data Centre Standard on design and operational issues, Data Centre Site Infrastructure Tier Standard: Topology of Uptime Institute and Green Grid Association which had established metrics (as an example, the Power Usage Effectiveness) and the Data Centre Maturity Model; • <u>Smart grid, energy markets and blockchain</u>: The Expert Group 3 – Regulatory recommendations for smart grid deployment of the European Smart Grid Task Force, Smart Grids European Technology Platform, Integrated Energy Marketplace APIs and business models, European Blockchain Partnership, EU Blockchain Observatory and Forum • <u>Cyber physical systems and Industry 4.0</u> - IEC 62264 - Enterprise-control system integration, IEC/TR 62794 - Reference model for the digital factory, ISO/IEC 20140 - Energy efficiency, Cyber-Physical Systems Public Working Group, etc.

Conclusions

This habilitation thesis summarizes the scientific, professional and academic work in which I was involved after my PhD defense in 2012 and also presents a development plan which is based on the principle of activity and work continuity.

I have presented in detail my main achievements on three research direction that represented the main focus of my scientific and professional work: the energy efficient management of DCs, the management of smart energy grids and their decentralized control and finally the management of smart factories and production processes using complex cyber physical systems. All the techniques and model reported are closely related to, or motivated by, practical problems in nowadays operation of large scale distributed systems and can be directly mapped to the requirements and use-case of research projects I was/am coordinating.

My contributions led to significant results on topics related to the efficient management of DCs such as: the activation of latent electrical energy flexibility of DCs to achieve an optimal integration into the smart grid, optimization the thermal aware process for waste re-use in nearby neighborhoods and workload relocation among DCs to implement green optimization strategies such as follow the renewable energy. This work was reported in Section 2 and was conducted first in the FP7 GEYSER project in which I led the workpackage in DCs energy optimization and was continued in the H2020 CATALYST project which I am coordinating.

My significant contributions in the area of smart grid management are referring to the use of blockchain technology for registering and tracing energy as a digital asset, more specifically: the development of an innovative peer to peer energy marketplace at micro-grid level promoting the local consumption of renewable energy, the development of flexibility marketplace allowing the DSO and aggregators to track in real time fashion the actual share of flexibility activated by each individual prosumer and the implementation of dynamic coalitions of prosumers on the generation side allowing the provisioning of a more stable supply and to obtain increase revenue by selling the aggregated generation on national level marketplaces. The work was reported in Section 3 and was conducted in the context of a bilateral research collaboration project with Montran-Labs USA and H2020 eDREAM project which I am coordinating.

In the area of smart factories, my contributions were on the use of new and innovative ICT techniques for optimizing the production processes with a view of making them flexible and adaptable to the shop floor changes and also to the changes in supply and distribution networks. In more details I have proposed the development of Cyber Physical Systems of Systems as large scale entities that monitor and control the production processes, agent based abstractions for implementing the digital twins of shop floor machines and choreographies corresponding to complex production process and finally big data analytics and nature inspired heuristics for process optimizations which may take place up to lot size level and detection of suboptimal situations which may generate emergent unwanted behaviors. The work was reported in Section 4 and was conducted in the context of national PN III project OptiPlan that I was coordinating and partially in the framework of an EU COST project.

At the same time, I had significant contributions to other research areas which were not necessarily the main focus this habilitation such as Ambient Assistive Living. In this area, I was workpackage leader in about 5 finished or ongoing FP7 and H2002 projects targeting different aspects of the care of elders.

All my contributions go beyond the existing state of the art which can be demonstrated by looking at various criteria showing the impact of my work. After my PhD defense, I have published 8 ISI journal papers with a cumulative of 26.93 and 26 papers in well-established international and national conferences or book chapters. Science 2013 my research papers had received over 250 citations. They are published papers that contain both theoretical and applied results

On academic level, my teaching activity was focused around the disciplines of distributed systems and program techniques. In my teaching activities, I have considered and used modern, state-of-the-art technologies keeping a close connection with the research activates carried out in research projects but also with the software industry in Cluj. In this sense, I have published 7 books that are used as support for license and master disciplines one of them being used as support for practical application in distributed systems discipline.

For my career development, the strategic goal is to become a well-established professor of computer science and I have set support objectives on each plan of my career development: increase the impact of my scientific research, improve the teaching abilities and get involved in academic management activities. To reach my goal I have devised a management plan split on into two main directions: academic development and scientific and professional development. The academic development plan set specific actions for improving the teaching activity by implementing good practices in the knowledge transfer and student learning processes and for supporting the department level activities and involving in innovation management activities of TUCN. The scientific and professional development plan is focused on improving the synergy between my work and innovation activities of DSRL.

In a longer outlook, I would like to stay in the field of energy efficiency management of large scale distributed systems following a holistic approach by not focusing only run time optimization but also by conducting a whole lifecycle assessment of such systems from their conception until they are not used anymore and recycled.

Tudor Cioara,

Cluj-Napoca, November 2018

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