Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 176 (2020) 3636–3644

Procedia Computer Science

www.elsevier.com/locate/procedia

24th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems

Protecting the environment: a multi-agent approach to environmental monitoring

Matteo Cristani[a,*], Luca Pasetto[a], Claudio Tomazzoli[a]

[a] Dipartimento di Informatica, University of Verona, Italy

Abstract

In this paper we discuss a transition model from commonly adopted models of data gathering, transfer and management for environmental monitoring towards more sophisticated ones based on Artificial Intelligence and IoT. The transition model is based on the paradigm of multiple agent systems. The adoption of this transition model is motivated by the need to improve effectiveness, efficiency and interoperability of environmental monitoring by simultaneously guaranteeing its sustainability in economic terms.

Keywords: Environmental monitoring; Scada System; Intelligent Systems.

---

1. Introduction

Protecting the environment is one the most important issues of the modern Era. Historically, we shall consider the current period ascrucial for two reasons:

- It is the moment of history in which the environment has been mostly in danger for many different reasons, first of them is *pollution* in all its direct effects [22];
- It is also the first moment in the recent past in which *systematic monitoring* is introduced in the environment itself, that becomes a complex data gathering apparatus [25].

It has been proposed to use many different techniques to manage the enormous amount of data that come from sensors in the environment itself, many of which include the usage of machine learning, statistical learning or reinforcement learning as in, for instance [3].

However, a general viewpoint that looks at the environment as *a complex system of interlaced agents* exchanging information, that act partially autonomously and partly in orchestration, has not been a focus. Only a few, rather practical examples can be found that indeed correspond to the above mentioned model as in [18].

---

[*] CMatteo Cristani
E-mail address: matteo.cristani@univr.it

10.1016/j.procs.2020.09.336

In this paper we employ the experience obtained in a project aimed at assisting the Regional Agency for the Environment of the Regione Veneto (ARPAV) and some theoretical models that we have developed in this period to model a general architecture of a multi-agent system employed for environmental monitoring, devise the problems related to its implementation and maintenance, focus some difficulties related to the management of the Cloud Architecture in this context, and finally deploy a transition model that can be used to modernise these complex architectures, that are ubiquitous in the worldwide community of agencies for environmental protection. The paper therefore proposes a methodology for the transition towards an architecture that results more reliable and easy to manage, whose schema is also devised.

Section 2 describes the basic infrastructural level of environmental monitoring, and identifies common traits that regard these aspects by comparing monitoring high-level architecture descriptions of several existing monitoring networks. Section 3 identifies three major limits that are common in these architectures, and Section 4 provides a proposal for an architecture that overtakes these limits. Section 5 describes a methodology for transition to such an architecture from existing limited architectures. Section 6 discusses some related work and finally Section 7 takes some conclusions and sketches further work.

2. The infrastucture level of environmental monitoring

The structure of sensor networks for environment monitoring is strongly varying in different places and periods, depending on the evolution of technology and the political sensitivity about the nature of pollution and its impact. By a recognition on a few network systems [21, 26, 19], and some specific research investigations [1, 4, 32, 20] we provide here an abstract synthesis of the most general issues of data flow and system architecture for these technologies, to the best of our knowledge and at the state of the art of the development so far.

The environmental monitoring aims at a variety of purposes that we can summarise in three major groups:

- Establishing the impact of activities including industrial plants, breeding farms, extensive cultivation, urban settlements, waste collection, disposal and transformation, transportation;
- Identify the potentially illegal actions carried out on the monitored area by means of unauthorised activities or by activities in which the value of the produced pollution is illegal;
- Monitoring the weather status in order to provide weather forecasting, and also to provide weather alerts.

We can therefore identify the activities of monitoring in temporal paths:

1. Activities that are perfectly synchronous, that reveal a specific set of data from the environment and generate an alert or news;
2. Activities that are asynchronous, but on a continuous base provide information on the state of the environment from one specific view point;
3. Activities that aim at revealing something about the environment in a specific moment in a specific position.

Among activities of type 1 we count *weather nowcasting*, *pollution emergencies* or *environmental crisis*. Among activities of type 2 we count *weather forecasting* and *pollution monitoring* and finally the activities of type 3 are *environmental controls*.

Typically, the above described activities are carried out by means of a *survey apparatus* typically consisting in

- Specific *sensor networks* to monitor one or more than one specific environmental value, including *air pressure*, *air humidity*, *rain*, *snow height*, *presence of PM2 or PM5* pollution particles, *wind speed and direction*, *water speed*, *water pollution* and many other ones;
- *Local SCADA* systems that interpret data, provide packeting and send them to the network;
- *Antennas* devoted to transfer data from sensors onto gateways, in order to provide the archival activities needed to add data to data centres;
- Technologies for data archiving, that articulate in *gateways*, *data storage* (with *backup systems*);
- Software technologies that allow to interpret data in view of their usage in one of the above mentioned activities.

Schematically, we can describe the data flow of Environmental monitoring systems (EMS) as in Figure 1. A general architectural schema of EMS can be found instead in Figure 2.

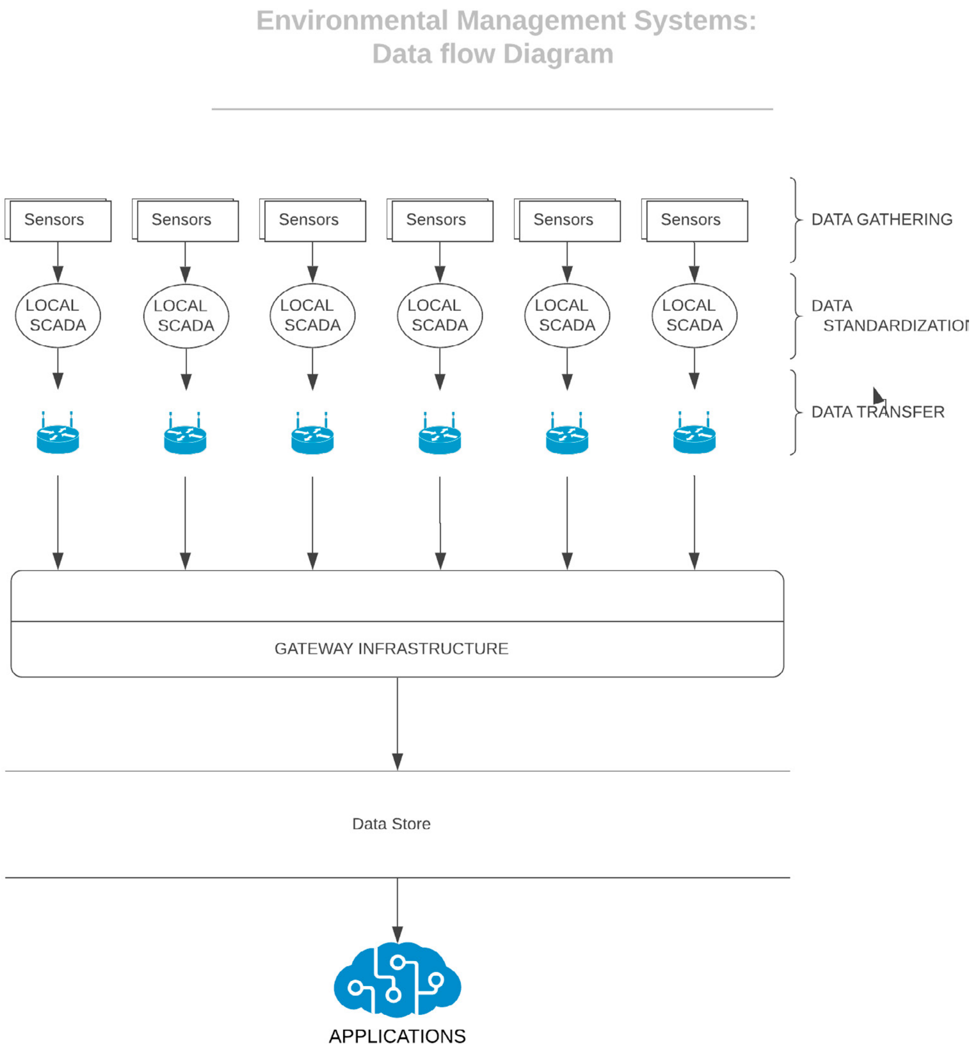

Fig. 1: The data flow of an EMS.

3. Three main drawbacks of current environment monitoring architecture

3.1. Analysis of the limits of the current architecture

We can summarise the limits of the architecture introduced in Section 2 as follows:

- The architecture is independent, typically, of the high-speed internet connection. This, though useful in several cases, including emergencies when the connection is dropped down, weather conditions making access to the internet difficult, and others, limits the speed or regular monitoring and makes it difficult to modify the behavioural protocol without an on-site maintenance that is expensive and time-consuming;
- Data are not standardised and therefore unification and comparison are effort-critical.
- Data processing is centralised and therefore the technologies are not able to make decisions on emergencies while data are collected but only at the end of the process itself. This is due to the adoption of the traditional PLC and Local SCADA technologies that are very common in sensor-intensive environments.

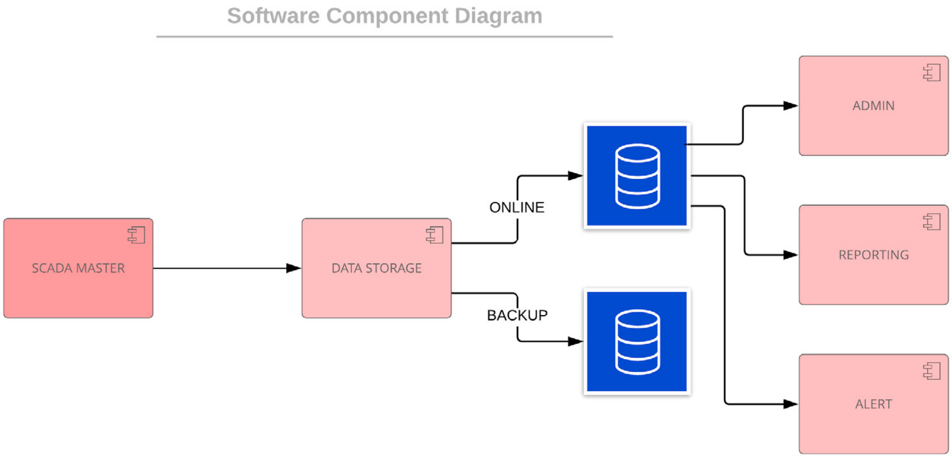

Fig. 2: The software components of an EMS.

To correct the above mentioned drawbacks we hypothesise the adoption of a *multiple agent integrated technology*, in which some simple changes to the basic technologies are performed and a scalable, multi-step integration methodology is devised in order to overwhelm the second and third drawbacks listed above during maintenance period. Before going to the drawbacks, let us specifically identify the nature of the mentioned problems.

Special purpose networking services. Speed is the first limit due to the adoption of this solution. Although connection may be quite complex to guarantee by means of current Internet infrastructure in some of the areas where sensors for environmental monitoring are located, in the proximity of the data gathering point, at a reasonable distance, it is rather simple to provide ad-hoc solutions. On the other hand, the usage of specific non-standard protocols on the large majority of communications for sensor data in the current most common configurations is reducing the controllability of data by means of ISO/OSI hierarchy of protocols that can be instead used easily in IoT.

Data standardisation. It would be very useful to introduce a universal standard in the description of the *environment state*, that is not yet on the horizon of environment analysis. As we shall show in Section 4 this shall allow to introduce a standard in data storage, exchange, comparison and in general in processing those data for document processing that can be used for workflow standardisation, beyond data standardisation.

Centralised architecture. No decision can be taken by a sensor or a group of sensors, though automation is often possible in many situations. Also communication of environmental state, emergencies or other conditions is impossible, when this architecture is adopted. We show how to avoid these limits by a Multiple-agent architecture in Section 4. In particular, this aspect interfere with the limits introduced above.

Which types of technologies are the collected data fed to? Is monitoring the only approach we can adopt?

Mainly we should look at the following technologies that receive data from environmental monitoring, some of which get those data from automation, some from a less automatable process.

- The *Laboratory Information Management Systems* that are conferred with data coming from the analysis of the monitored environment, usually *air, terrain, water*;
- The *Meteorological forecasting and nowcasting services* where data are conferred to confirm or disconfirm forecasting based on mathematical models;

- The *Environmental and weather emergency services* that are alerting and following the alert phase during an emergency;
- The *Documental and reporting* services, where data are synthesise in order to provide information on the state of the environment.

Therefore we need to consider that for every user of one of the above mentioned technologies, the currently provided services should migrate in the future solutions while preserving the same quality and access present so far, and introducing the identified upgrading. The problem with this perspective is economic sustainability. Changing simultaneously all the monitoring services in a specific area is impossible from a financial viewpoint for many reasons that we now provide in Subsection 3.2.

3.2. Economic barriers to moving forward in environmental monitoring

Environmental monitoring is usually seen as a *public service* and it is indeed typically provided by public bodies usually special purpose ones, though some countries adopt a *subsidiary* solution, where private subjects provide the data collection regarding the environment by a public service contract. It is however difficult to keep providing this level of service when the interest in environmental monitoring speeds up on a continuous basis as has happened in recent years. Citizens and local authorities require more and more to be informed on the state of the environment, and usually aim at obtaining those data in a more and more specific way. Therefore we need to figure out the correct social configuration, that is also typical of the evolution of many services of the same type including instruction and health, where sustainability is related to the combination of universality and adaptivity to the local needs.

From a *pure cost* viewpoint, we should guarantee that the transition between a configuration like the one we depicted in Section 2 (with the limits analysed in Section 3.1) can be overwhelmed by the solution identified in Section 4 taking into account two conflicting temporal properties:

- We need the solution to be *sustainable* on a *pure budget* perspective, as the possible income derived by the services offered as shown below, are economically ground on the completeness of the network in a specific subarea;
- We need the solution to be deployed in a reasonably short time for the above mentioned perspective of effectiveness of the income opportunity, but simultaneously to guarantee that the realisation interval does not exceed the lifetime of the blend of technologies, for this would re-introduce the mentioned drawbacks in the general picture.

4. Multi-agent paradigm in environment monitoring

We depict the technology structure in three levels, as shown in figure 3.

In Section 4.1 we shall discuss the technological level of the proposed solution, while Section 4.2 is devoted to introduce the ontological layer, where concepts on three layers are described, regarding *data standards*, *service standards* and *service level agreement negotiation*. Finally, Section 4.3 shows how the *service orchestration* and *service coordination* technologies are employed to solve the emerging problems of security, reliability and completeness of the standards introduced in Section 4.2.

4.1. The technological infrastructure: Iot and Internet everywhere

The infrastructure that is currently operating on the majority of deployed environmental monitoring technologies is formed as follows:

- Sensors on the field;
- PLC, that collects the field values;
- SCADA master that saves the field values read by the PLC on a local data storage;
- Special-purpose connection to a remote centralised database;
- Database technologies connected to applications;
- Applications, consisting mainly in documental systems and LIMS.

The target technology shall change only from the PLC level (included) onward:

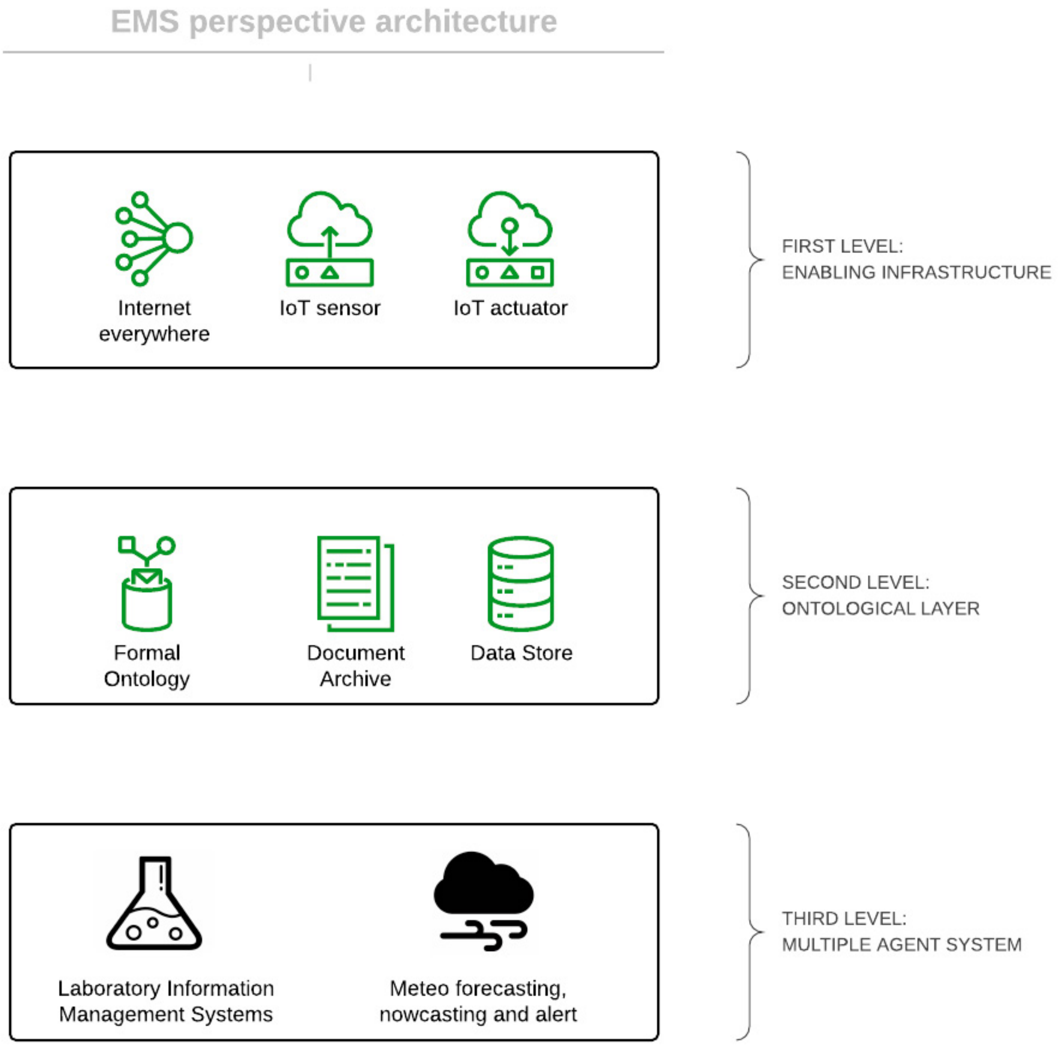

Fig. 3: The architecture of future EMS.

- IoT technologies connected to sensors (System on chip or Single Board Computer);
- High-speed internet connection;
- Alternative routing to high-speed internet, that forms, along with the regular connectivity, the known paradigm of *internet everywhere (IE)*;
- Alternative solution to the transmission of data by means of emergency connection services in case of internet fault;
- Remote data collection in unified database;
- Applications.

The introduction of the IoT enabling infrastructure makes it also easier to manage the faults of sensors or the interruption of the connection. In fact, the current architecture is generally *passive* in terms of PLC processing, for data transmission services, so that the antennas are managed usually as pure connection means. In a IoT with IE architecture the connectivity is managed in an active way, and faults are revealed locally and possibly corrected.

4.2. Ontologies for data, service and service level agreement

Data standardisation for laboratories has already been studied to some extent. Examples can be found in pharmacology [34, 33] and in biochemistry [29, 31]. However, a standard on the chemical and other types of measures is still to come. In this research we look for an ontology for *laboratory analyses of the environment* that identifies the following aspects:

- A taxonomy of analyses types, including in the properties methods of revelation, standard values, legal limits and other aspects of the test, including the ontological structure of the diagnostic process (see [14, 15]);
- A taxonomy of the services provided in the system, specifically the web services exposing data for the applications connected to them;
- A module of service level agreement negotiation, starting with the ontological layer proposed in [27], and employing the ontology agreement approach proposed in [7, 6, 5].

4.3. Adopting the multiple agent paradigm

Autonomous decision should be taken by single agents in a Multiple Agent System in order to avoid *systematic coordination* that is the commonly used approach to distributed computing. The scenarios in which these decisions are strongly useful in an EMS are four:

1. **Alert:** when a single element of the architecture on the field, namely a SoC or an SBC are revealing a situation that configures a situation in which there is an evidence for
    - ***A violation*** of law limits;
    - ***A danger*** for the proximal area;
    - ***A limit value*** for a forecasting model, configuring specific conditions for instance for meteorology;
2. **Local action:** when a SoC or SBC reveals a specific property that, along with other properties revealed in turn by other technologies in the proximity, corresponds to the need for a specific action. For instance, this happens when some sort of device is connected via actuators and a condition that triggers the usage of that apparel is revealed.

At the extreme of the architecture, we shall have the applicative components. These are typically *data intensive* technologies and specifically documental systems (to generate reports, or bulletins) and *Laboratory Information Management Systems (LIMS)*. In both these technologies we shall consider semantic aspects. Semantic perspective on documental systems, in particular for what concerns the management of cloud technologies has been introduced by the authors in [8]. The ontological layer shall ensure coverage of the semantic aspects for LIMS.

5. From limited monitoring technologies to multi-agent ones: some methodological issues

The transition between the current architectures and the one prospected in Section 4 is based on a nine-step approach. The steps are illustrated below.

- **Step 1: Update the sensors.** Sensors of new generation exist that need to substitute the existing ones in order to guarantee uniformity of signal processing, effectiveness in IoT connectivity, precision, recall and accuracy of the measures.
- **Step 2: Substitute the PLC.** Hybrid computing technologies are substituted with SoC or SBC connected to the sensors with a technology that can be programmed with high-level programming languages and does not need sophisticated interfaces to connect to the Internet;
- **Step 3: Adopt the *Internet everywhere* paradigm.** Proximity release of connections to the internet via direct, and substitutive overlapping technologies, in order to guarantee connection both when the systems are working appropriately and when the connection is dropped down;
- **Step 4: Introduce remote SCADA technologies.** Data are now on the Cloud (private or public) and can be thus accessed by any networked connection.
- **Step 5: Adopt the MAS paradigm.** SoC/SBC are equipped with *Decision support* software along with local intelligent interfaces. The transition at the enabling infrastructure level is driven by the ONTO-PLC methodology [9].

- **Step 6: Introduce actuators interfaces.** When actuators are available, connection to MAS locally are provided.
- **Step 7: Introduce the ontological layer.**
- **Step 8: Adopt the LIMS technology.**
- **Step 9: Adopt the Documental technology.**

The methodology defined above is applied as shown in Figure 4.

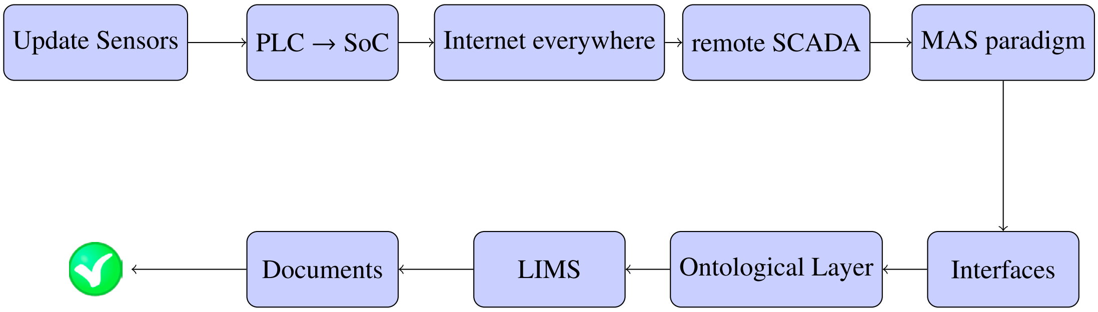

Fig. 4: Transition Methodology

6. Related work

The agent technologies that we propose to employ have been used by the authors in a line of research that aims at providing energy saving in smart environments [16, 30, 12, 11].

A similar application domain is the *ecological one*, where ontology has been applied in a successful way to provide unification frameworks for heterogeneous knowledge [24]. Knowledge sharing is one of the foundations of ontological layer design, as in the case of neuroscience [28].

A similar approach to the ontological layer has been also pursued by MacEachren et al. in their study on collaboration tools for geoscientists [23]. The concepts introduced in the ontological layer are founded on the theory of *domain metrization* discussed by Andreas in [2].

7. Conclusion and further work

In this paper we introduce a perspective on how monitoring the environment will be in a future when *multiple agent systems* along with *formal ontologies* as standardisation tools at data gathering, data storing, and document generation will be adopted. The enabling infrastructure is depicted by *IoT*, along with high-speed everywhere internet.

It is clear that the adoption of the MAS paradigm, the definition of the ontological layer and the development of a *proximity service* subsidiary economic model require a social innovation perspective, also managed by innovative methods of social network analysis [13, 17, 10], and possibly also legislation amendments. These themes will be the subject of studies by the research group in the future.

Acknowledgements

First author gratefully thanks ARPA Veneto (Agenzia regionale per la protezione ambientale del Veneto - The Regional Agency for Environment Protection of Veneto) for financial support under grant of *Technical-scientific support* with the Department of Computer Science of the University of Verona.

References

[1] J.M. Ahn, K.Y. Jung, D.S. Yang, and D.-S. Shin. Verification of water environment monitoring network representativeness under estuary backwater effects. *Environmental Monitoring and Assessment*, 190(8), 2018.

[2] H. Andreas. Ontological aspects of measurement. *Axiomathes*, 18(3):379–394, 2008.

[3] S.F. Ardabili, B. Najafi, S. Shamshirband, B.M. Bidgoli, R.C. Deo, and K.-W. Chau. Computational intelligence approach formodeling hydrogen production: A review. *Engineering Applications of Computational Fluid Mechanics*, 12(1):438–458, 2018.

[4] S.N. Behera, M. Sharma, P.K. Mishra, P. Nayak, B. Damez-Fontaine, and R. Tahon. Passive measurement of no2 and application of gis to generate spatially-distributed air monitoring network in urban environment. *Urban Climate*, 14:396–413, 2015.

[5] E. Burato and M. Cristani. Learning as meaning negotiation: A model based on english auction. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 5559 LNAI:60–69, 2009.

[6] E. Burato and M. Cristani. The process of reaching agreement in meaning negotiation. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 7270 LNCS:1–42, 2012.

[7] E. Burato, M. Cristani, and L. Viganó. A deduction system for meaning negotiation. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 6619 LNAI:78–95, 2011.

[8] M. Cristani, A. Bertolaso, S. Scannapieco, and C. Tomazzoli. Future paradigms of automated processing of business documents. *International Journal of Information Management*, 40:67–75, 2018.

[9] M. Cristani, F. Demrozi, and C. Tomazzoli. Onto-plc: An ontology-driven methodology for converting plc industrial plants to iot. volume 126, pages 527–536, 2018.

[10] M. Cristani, D. Fogoroasi, and C. Tomazzoli. Measuring homophily. volume 1748, 2016.

[11] M. Cristani, E. Karafili, and C. Tomazzoli. Energy saving by ambient intelligence techniques. pages 157–164, 2014.

[12] M. Cristani, E. Karafili, and C. Tomazzoli. Improving energy saving techniques by ambient intelligence scheduling. volume 2015-April, pages 324–331, 2015.

[13] M. Cristani, F. Olivieri, C. Tomazzoli, and G. Governatori. Sending messages in social networks. 96:123–133, 2018.

[14] M. Cristani, F. Olivieri, C. Tomazzoli, L. Viganó, and M. Zorzi. Diagnostics as a reasoning process: From logic structure to software design. *Journal of Computing and Information Technology*, 27 (Special Issue):43–57, 2019.

[15] M. Cristani, F. Olivieri, C. Tomazzoli, and M. Zorzi. Towards a logical framework for diagnostic reasoning. *Smart Innovation, Systems and Technologies*, 96:144–155, 2018.

[16] M. Cristani, C. Tomazzoli, E. Karafili, and F. Olivieri. Defeasible reasoning about electric consumptions. volume 2016-May, pages 885–892, 2016.

[17] M. Cristani, C. Tomazzoli, and F. Olivieri. Semantic social network analysis foresees message flows. volume 1, pages 296–303, 2016.

[18] C. Deng, H. Wang, W. Zhang, and Z. Jiao. Optimizing policy for balanced industrial profit and water pollution control under a complex socioecological system using a multiagent-based model. *Water (Switzerland)*, 10(9), 2018.

[19] Anna Maria Cicero et al. indirizzi per la progettazione delle reti di monitoraggio delle sostanze perfluoroalchiliche (pfas) nei corpi idrici superficiali e sotterranei. Technical report, 2019.

[20] M. Cristani and N. Gabrielli. Practical issues of description logics for spatial reasoning. volume SS-09-02, pages 5–10, 2009.

[21] L.Verdi et al. Integrazione delle reti di monitoraggio automatiche italiane: situazione attuale e prospettive future. Technical report, 2016.

[22] C.J. Foley, Z.S. Feiner, T.D. Malinich, and T.O. Höök. A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. *Science of the Total Environment*, 631-632:550–559, 2018.

[23] A.M. MacEachren, W. Pike, C. Yu, I. Brewer, M. Gahegan, S.D. Weaver, and B. Yarnal. Building a geocollaboratory: Supporting human-environment regional observatory (hero) collaborative science activities. *Computers, Environment and Urban Systems*, 30(2):201–225, 2006.

[24] J. Madin, S. Bowers, M. Schildhauer, S. Krivov, D. Pennington, and F. Villa. An ontology for describing and synthesizing ecological observation data. *Ecological Informatics*, 2(3 SPEC. ISS.):279–296, 2007.

[25] F.E. et al. Muller-Karger. Satellite sensor requirements for monitoring essential biodiversity variables of coastal ecosystems. *Ecological Applications*, 28(3):749–760, 2018.

[26] S.C. Nixon. European freshwater monitoring network design. Technical report, 1996.

[27] A. Paschke and M. Bichler. Knowledge representation concepts for automated sla management. *Decision Support Systems*, 46(1):187–205, 2008.

[28] M. Samwald, H. Chen, A. Ruttenberg, E. Lim, L. Marenco, P. Miller, G. Shepherd, and K.-H. Cheung. Semantic senselab: Implementing the vision of the semantic web in neuroscience. *Artificial Intelligence in Medicine*, 48(1):21–28, 2010.

[29] S. Schulz and L. Jansen. Formal ontologies in biomedical knowledge representation. *Yearbook of medical informatics*, 8:132–146, 2013.

[30] C. Tomazzoli, M. Cristani, E. Karafili, and F. Olivieri. Non-monotonic reasoning rules for energy efficiency. *Journal of Ambient Intelligence and Smart Environments*, 9(3):345–360, 2017.

[31] A. Wiesner, J. Morbach, and W. Marquardt. Information integration in chemical process engineering based on semantic technologies. *Computers and Chemical Engineering*, 35(4):692–708, 2011.

[32] K.R. Zhao, Q.Q. Ma, X.Y. Zheng, and K.C. Lu. Design for the heterogeneous environment monitoring network component-base management system. volume 2, pages 1525–1533, 2010.

[33] M. Zorzi, C. Combi, R. Lora, M. Pagliarini, and U. Moretti. Automagically encoding adverse drug reactions in meddra. pages 90–99, 2015.

[34] M. Zorzi, C. Combi, G. Pozzani, E. Arzenton, and U. Moretti. A co-occurrence based meddra terminology generation: Some preliminary results. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 10259 LNAI:215–220, 2017.