Modeling Complex Software Systems: A Case Study on Sustainable Water Supply Maintenance

Tihana Galinac Grbac[1,*], Dragan Sokolović[2], Jurica Kovač[2], Darko Etinger[1], Dalibor Fonović[1], Dario Kukuljan[1], Srđan Danijel Simić[1] and Nikola Tanković[1]

[1]*Juraj Dobrila University of Pula, Zagrebačka 30, Pula, HR-52100, Croatia*
[2]*Smart Aqua d.o.o, Radićeva 27, Pula, HR-52100, Croatia*

Abstract
Digitalization is introducing a virtual representation of the physical world. Such virtual or digital assets, interconnected via global communication network, open unbounded management opportunities that are realized in form of software. Nowadays, digitalization is not a matter of technology change, but is rather perceived as a prerequisite of modern and sustainable operation. Thus, proactive digitalization continuously increases the complexity of globally interconnected software systems and new emerging technologies may bring significant improvements in their management. Management and sustainable goals depend on sound and effective software system engineering solutions. In this paper, we discuss modeling complex software systems within a water supply case study, in which digitalization is introduced to accomplish sustainable goals. Our focus is on water leak report and repair process, for which we open interesting further research and development challenges, based on our previous experiences in modeling complex software systems and in modeling software failure report and repair process.

Keywords
Modeling complex systems, Water Supply System, Sustainability, Crack report and detection

1. Introduction

The complex software systems are not any more only present in the space mission software systems, as at the beginning of the software crisis [1]. As a result of wide digitalization, networks evolution, and integration of new technologies, the complex software systems became part of everyday life of any individual and any institution and in all domains of human activity. Digital transformation as a response to continuous innovation in digital technologies requires not only digital assets, but also development of capabilities related to digital agility, digital networking and big data analytics [2]. As a consequence, the appearance of software system complexity problems are experienced in various sectors. The main purpose of this paper is to

SQAMIA'22: 9th Workshop on Software Quality Analysis, Monitoring, Improvement, and Applications, September 11–14, 2022, Novi Sad, Serbia
*Corresponding author.
†These authors contributed equally.
tihana.galinac@unipu.hr (T. Galinac Grbac); dragan@smartaqua.hr (D. Sokolović); info@smartaqua.hr (J. Kovač); darko.etinger@unipu.hr (D. Etinger); dalibor.fonovic@unipu.hr (D. Fonović); dario.kukuljan@unipu.hr (D. Kukuljan); ssimic@unipu.hr (S. D. Simić); nikola.tankovic@unipu.hr (N. Tanković)
0000-0002-4351-4082 (T. Galinac Grbac)

stress the importance of extracting knowledge on **modeling complex software systems** and the possible generalization of this knowledge across various domains.

Sustainability is nowadays widely recognized as one of the main drivers for future evolution of society as a whole. The "sustainable development" has been recognized as the leading goal for future development and formulated in form of principles in the 2030 Agenda for Sustainable Development of United Nations, building on the previous strategies since the 1970's. It is one of the key priority tasks in all EU strategies, in particular, the latest European Green Deal, thus reflecting on various sectors (manufacturing, energy systems, tourism, healthcare, agriculture). Public infrastructure that provides services to individual and industrial users should bring the main advantage to sustainable societies. *Water Management Systems, WMS*, the case we study in this paper, is one of the great examples, in which a coordinated action may bring significant benefits to global sustainability goals.

At the Juraj Dobrila University of Pula, Croatia, a group of research and educational professionals in collaboration with experts from water systems domain is formed aiming to focus on developing and promoting sustainable goals based on emerging technologies in WMS. The outcome of this initiative would yield several contributions. Within WMS our research and may contribute to standards definition by application of new technologies and modeling approaches in water leakage repair practice. Conclusions regarding complex system practice and understanding theoretical foundations and generalizations of mathematical and empirical models in complex systems modeling would be obtained. The last, but not least, the contribution to the local society would be achieved by educating and engaging local industry, government and public sector in sustainable solutions development, and thus, enabling their efficient and effective alignment towards global sustainable goals fulfillment.

The paper is structured as follows. In Sect. 2 problems of digital transformation are introduced. The WMS initiative and the focus on the practice for repair of water leakage cracks of concrete structures is the subject of Sect. 3. In Sect. 4 a literature review on digitalization and application of new technologies on repair of water leakage cracks in WMS is provided. In Sect. 5 a case study on digitalization in the largest Croatian water management company is presented. Finally, Sect. 6 contains the discussion and opens new avenues for future work.

2. Modeling Complex Systems in Digital Transformation

One of the key prerequisites for the migration towards sustainable society is digitalization. The term digitalization does not cover only digitization process. It has the broader meaning and is related to adoption of digital technology by organizations or public [3]. Digitization is the process of converting analog information into digital. This means that every information about any physical artifact has its digital representative that can be managed by software and thus provide automation possibilities. As a consequence, progressive software service developments have occurred with appearance of big data challenges that need software processing. Here, it is important to stress that the way in which the knowledge is extracted and its abstract representation in the digital world is made, may have significant impact on effectiveness of digitalization. On the other hand, digitalization itself may not fully explain the complex mechanisms of a physical system and its underlying processes [4]. Therefore, additional efforts are required to examine modeling complex systems while digitalizing various domains, like for example the case of the WMS. The following list provides the key research and development topics and problems, which should be addressed during the digital transformation process, according to [2]:

- *Digital phases and digital growth strategies:* Any innovation, improvement introduction into an organization managing a complex software system needs systematical definition of digital phases, i.e., define how companies go through the phases of digital transformation, identify digital assets and capabilities. The complexity hinders numerous obstacles whereas easily can collapse into complex and unpredictable behavior and result in failed digital transformation [5]. Systematic digital transformation leadership and organizational agility positively influence digital transformation [6]. Therefore, Maturity Model for Digital Strategy Assessment (MMDSA) has been proposed as a guide and reference framework for digital transformation management within different industries and sectors [7]. Furthermore, digital growth strategies should identify potentials for further evolution and growth, how to evolve existing systems, understand the impact of evolution in relation to business advantage and system capabilities.
- *Digital resources:* In view of digitalization anything could be digitalized. However, the right approach is to digitalize all resources that needs coordinated actions, where there might occur waste of time, inefficient resource use or serious conflict situation that may harm quality of service or product delivered. These may include physical resources such as cables, channels, or routers that are virtualized in the telecommunication network (an example of virtual resource management platform is OpenStack), or documentation like for example software failure reports (an example of software failure report management platform is Bugzilla). The digital resources are the key for development of management platforms that would further enable future evolution.
- *Organizational structure:* Digital resources are interconnected and usually form a virtual view of the organizational structure. Such structure has a significant impact on management decisions. Therefore, an important aspect is the identification of effective structures which would best fit agility and sustainability goals. There exist well defined design principles for managing complex systems such as abstraction, modularity, hierarchy and layering. These principles are useful for introducing the standardization of procedures how the complex systems should be built. Therefore, for every new case study (complex software system, telecommunication network, energy network, water network etc.), clear structures which enable easier standardization and further management should be developed.
- *Metrics and Goals:* Coordinating improvement activities needs systematic methodology based on set of metrics to guide management decisions by measuring operational performance and directing towards global goal fulfillment. For example, International Water Association (IWA) has proposed a performance indication system for water professionals to enable internal project assessments and metric benchmarking based on standard metrics [8].

3. Water Management System as a Complex System

The water supply systems, according to some archaeological evidence, existed already around 2500 BC. The people of that time have already discovered the importance of irrigation system for public and development. An example is the Aflaj Irrigation Systems of Oman, dating back to AD 500, which is constructed using gravity to channel the water from underground sources or springs to support public needs such as agriculture and domestic use. The basic idea was to develop fair and effective distribution system for water share among geographically distributed groups of people, villages and towns. During the evolution of water supply systems, the WMS strategies were developed, and many aspects of the WMS services have been recognized. Similarly as many other complex systems, the WMS can be categorized as a complex system, because of its numerous users that require services from the common source (natural source water that is limited), and this common water source is one of the main Earth resources that is circulating in environment and thus securing the fundamental conditions for all living beings. It is hard to distinguish boundaries among variety of ecosystems, related groups of interested parties, companies, countries, etc.

European Commission has established in 2000 a framework for community action in the field of water policy [9] aiming to define policy for sustainable water management and protection of freshwater resource. The main objectives of the policy are to protect all forms of water (surface, ground, inland and transitional), to restore the ecosystems in and around these bodies of water, pollution reduction, and sustainable water use by individuals and businesses. Furthermore, there is an established network of water professionals called the International Water Association, IWS, with the common goal for wise, sustainable and equitable water management. Their main activities are related to lead and train professionals within the water sector towards digitalization. Their course of action actually identifies the concrete actions and procedures within digitalization topics listed in Sect. 2.

The focus of this paper is on the leakages in the water distribution system [10]. The leaks formed by the various contributing factors like pipes age, material quality, soil movements, pressure, etc. can cause significant water-leakage and water waste problems, and damages to other infrastructure assets like roads, buildings, other installations and in the end also the interface of the leaking water may be the subject of wetness and thus *increase humidity* in some indoor locations or even in some extreme cases may cause health problems to water system users and contamination of water due to infiltration of dirty water from the pipe surroundings in moments of pressure drop. Although there are several well defined practices, procedures and techniques defined for use in such water-leak conditions, these have shown high variation in results and therefore may not be fully effective in all circumstances. Note that these practices are difficult to apply and may require well skilled personnel. Furthermore, numerous environmental conditions in relation to human activity factors in the cracked location may have impact on results. As a consequence, these may lead to further increased maintenance cost. Standard [10] aims to trigger standardization practice for selecting appropriate leakage repair materials and methods for all cases of bursts and leakage due to the diversity of environmental degradation factors existing in the construction field. Digitalization of WMS with help of new emerging technologies, but also with meaningful modeling tools and techniques, may bring significant value to these standardization efforts.

4. Literature review on WMS

Recent WMS literature has addressed the problems of finding new and innovative technologies in water leak detection, digitalization of water leak reports and modeling approaches for better management of water distribution network and its equipment. Numerous technologies have been used, and we review them in Table 1 based on [11].

Digitalization of WMS involves the use of mobile phones, drones, networked computers and laptops as sensory devices to collect information used within various applications to accomplish water management tasks. These devices are controlled and used in interaction with humans, and human-computer applications have a dominant role. These are, for example, mobile applications that introduce real time repair reporting documented through images, or social network applications that enable efficient end user reporting on water leaks, or drone applications that enable remote leak location investigation, or electronic bill as source of identification of water leak, etc.

The classical approach to leak detection within water supply distribution system is based on a continuous water monitoring system, i.e., hourly flow and pressure measurements. The proposed solutions are implemented on the basis of combined GIS (Geographical Information System) and SCADA (Supervisory Control and Data Acquisition) systems. GIS system is used to locate and represent water distribution network within a geographical map. SCADA systems are used in water distribution networks to measure the pressures and flows of water in the water pipes and channels and to control network objects like pump stations or reservoirs based on these data [12]. The sensors are implemented across the distribution network and the data measured from sensors are continuous flows of time series measurements obtained from various measurement points within a water distribution network. The abnormal state is represented as significant outliers detected in time series data, and data mining techniques, like for example Artificial Neural Network, are used to optimize computing time needed to analyze all time series [13]. Various supervised algorithms have been proposed for this purpose [14]. These solutions are costly to implement due to numerous measurement devices that need to be installed. Moreover, this classical modeling approach, based on flow and pressure measurements, is not precisely detecting the location of the leak within the distributed network. Therefore, a subsequent number of papers have applied the idea of discretization of the water supply system to predefined areas, district metered areas (DMA) and identification of localized area within this discrete map [15, 16]. The case study in [17] presents the implementation of the real-time monitoring and data analytical Cloud based tools within two Chilean water supply systems. They report on the reduction of water losses due to smart selection process for prioritizing replacement of critical customer meters, better understanding of reported events and reduction of the response time of those events. Analytical tools used along with real-time monitoring system are used for categorization of bursts and evaluation of their impact on water loss volumes. Smart prioritization of repairs and reduced water leaks is obtained in this way.

Another approach to leak detection is the use of the hydraulic model and involves simulations of leaks in all nodes and pipes of the network aiming to match the flows and pressures measured within the real distributed network. The main drawback of this model is that it is very time and computing resource consuming process. The third approach presented in [12] combines monitoring system, hydraulic model with neural network classifier, and thus succeeds to reduce the computing time for simulations.

In parallel with SCADA systems, as a closed industrial standard technology, there is a growing body of research on new models and approaches in WMS systems based on Internet of Things (IoT). As an open standard technology, it brings much faster innovation cycle and better integration with other technologies. It is an emerging technology that introduce sensing environment into communication. A multi layer architecture consists of *Perception layer* consisting of sensory devices, *Network layer* that interconnects distributed sensory devices and enable reliable and secure communication in IoT using different communication methods such as ZigBee, Ethernet, GSM. At the *Service layer* numerous services are provided that use sensory network and provide services to the applications on the top of the layered architecture within the *Application layer* where various IoT tools, visualisation tools (e.g. Ubidots), modeling and prediction tools, etc., may be implemented. This architecture requires development of numerous functions like sensing, communication, data storage to Cloud, AI for knowledge extraction, etc. For these functions there is a vast amount of enabling technologies. A recent survey of new emerging technologies across the IoT architecture is provided in [18]. IoT based WMS is combined with other technologies like GIS, Internet, satellite maps, mobile phones, or human reports to report on water leaks. A solution for water leak detection based on IoT devices is presented in [19]. The water distribution system is abstracted and sensors are implemented across the smart home for water leak detection. Smart building example of real time monitor and control by smart water meters and data analytic is presented in [20]. Furthermore, in [21] an IoT based solution is presented for waste water management. A solution based on the wireless water pressure sensors to classify failures based on the pressure values is given in [22].

Digital transformation of water leak report and repair process has recently been addressed with Digital Twin (DT) technology. The core idea behind digital twin technology is to digitalize object of management, e.g. water distribution network, and perform real-time interaction among digital and real world, and thus, allow full integration of these two worlds. Hence, much more reliable and safer modeling system for prototyping and decision making process may be achieved. The main difference compared to simulations is that we can have real time and continuous calibration of the model [23]. The work on implementing digital twin within water management system is presented in [24]. The authors present their experiences while building a digital twin of the water distribution network of Valencia, Spain, and its metropolitan area. Derived from their experiences, they report on benefits the technology brings to the water distribution network and the key leanings on development of such a system. Efforts in digital twin based digital transformation of water distribution network have been presented in [25]. The paper reports on digital water services developed on top of digital twin to support real-life asset management design intended for analysis and customization of water distribution networks and for monitoring and leakage reduction through pressure control.

Modeling of WMS has largely been discussed in relation to modeling urban growth and digital transformation. Mainly in the context of cities which are complex systems, adaptive, self-organized complex structures, and thus interconnecting with various disciplines social, cultural, technical, ecological, physics and others [26]. The work presented is discussing solutions based on modeling dynamical systems with help of cellular automation. The socio–ecological aspect by using complex network analysis tools such as motifs and analytical methods such as density, reciprocity, and centrality are analyzed in [27]. This study presents how studying socio-technical

Table 1
Technologies used in Urban Water Management Systems

Technology	Acronym	Description
Information and Communication Technology	ICT	Applications for use on mobile phones, tablets, drones, networked computers and laptops based on GSM-GPRS, 3G and 4G long-term evolution (LTE)
Geographical Information System	GIS	Management system for managing geographical in relation to associated personal data
Content Management Systems	CMS	Computer software systems used to manage creation and modification of digital content
Decision Support System	DSS	Digital system used to support management decisions and guide further actions in organization or business
Recommender systems	–	A system used to predict the rating or popularity of item and recommend preference a user would give to an item.
Computer models and Simulations	–	Software abstraction of physical system used for simulation of physical system
Supervisory Control and Data Acquisition	SCADA	Remote real-time monitor and control of processes without human intervention used in industry automation, proprietary, wired communication
Internet of Things	IoT	Real-time remote monitor and control of processes without human intervention used in smart cities, based on IP and open standards
Digital Twins	DT	Software abstraction of physical system used as real-time digital counterpart of a physical object or process

relations in networked infrastructure systems may provide promising result in management such infrastructure.

The reported benefits of use of technologies that may provide real-time measurements are better and more effective system support in terms of waste management, predictive and effective system maintenance, long term real time monitor may influence the change of human habits and behavior by reducing costs. Others also reported benefits such as low energy consumption, easy installation and easy Cloud integration and data acquisition. All these solutions are reported for continuous monitoring and control purposes and visualization of such continuous data is one of the greatest benefits.

5. Study case

5.1. Case description

The case study is performed within Vodoopskrba i odvodnja d.o.o. Zagreb, the largest WMS company in Croatia. It is responsible for maintenance of water supply system, sewerage, water quality control, and water purification for the city of Zagreb, Samobor, Sveta Nedelja, and the municipality of Stupnik. The length of the water supply network is approximately 3,500 km, and about 310,000 m^3 of water are pumped daily. The public water supply system covers about 800 km^2, which supplies about 900,000 inhabitants with water.

This project is the first digitization phase of WMS in the Zagreb water utility aiming to improve water leakage management. Digitalization activities were performed on the process of leaks repair activities, from reporting until final repair works. The main task undertaken within this project was conversion of the existing (analog and paper based) water leak report registration process into a digital system.

5.2. Description of current state

The maintenance process implemented within Vodopskrba i odvodnja d.o.o. (Zagreb water utility) consists of Urgent interventions, Water leak detection and maintenance of hygienic conditions within distributed water supply system and Maintenance of water supply network. Water distribution network is divided into 12 organizational units that are responsible for services on distributed network infrastructure. Urgent interventions consist of the call center and operations field working teams. The processes were heavily based on human and paper based administration. The process of maintenance is as follows:

- Citizens (customers) and water utility employees reports the water leakage to the central call center
- Administrative person in the call center make formal written notifications in the "Report book" and checks location in the existing GIS
- Administrative person contacts by phone field teams for urgent interventions to check received notification on site
- If possible, urgent team repairs visible leaks. When leak is repaired or not, they call back personnel in the call center to inform them about the situation and also write down own report (working order documents)
- In case urgent intervention team was unable to repair the leak, administrative person in the call center prepares separate written document about the leaks informations collected and sends it by fax (in urgent cases notifies by phone) to leak detection manager or to the leaks repairs managers
- Leak detection teams conduct works following received information and at the end of the day prepare separate documents for each leak located that is later delivered to the administrative person in the call center
- Leak repair teams perform work orders following received documents from the call center and prepare their own final document that is later submitted to the call center
- Administrative person in the call center at the end of the procedure for each leak has to upend information in the "Report book" and also in separate PC Data base.

5.3. Description of new technologies employed

The implementation of the Smart Aqua solution includes the following technologies:

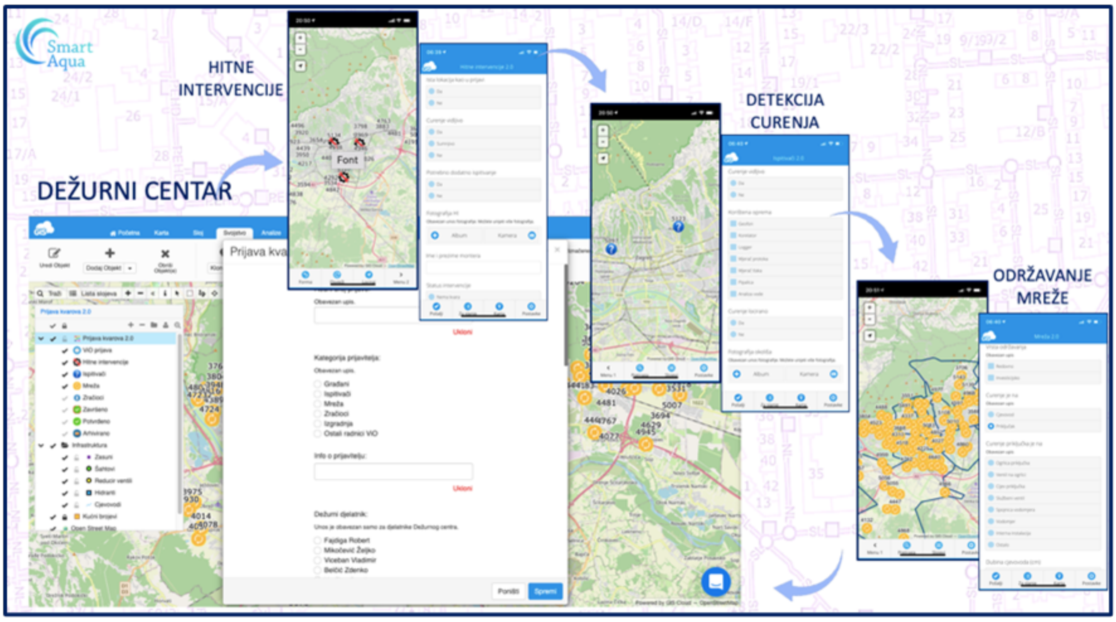

Figure 1: GIS based interface of Vodoopskrba Zagreb leak reports.

1. digitalization of reports from the citizen side to the Vodoopskrba i odvodnja d.o.o, as to enter the data of the fault report on the digital map in a simple and intuitive way with all associated information needed to field workers to carry out repairs
2. integration of the information collected from the citizens into central CMS database along with digital data about the infrastructure (pipelines, valves, hydrants, ...)
3. development of CMS with list of all internal operations and field working teams, where each field team sees its assigned tasks with a specification of needs
4. integration of company database CMS with GIS data,
5. introduction of DSS to appoint field workers to the water leak report
6. digitalization of water leak report closure with details about action performed
7. automatic synthesis of data and analytical display of the same on the dashboard in real time for the needs of managers

An example of visualization is presented in Figure 1. The paper based documentation is replaced with digital. The main digital asset introduced is the digital report on water leak. All communication with field workers is implemented through mobile applications in real time. Applications developed for urgent interventions have access to the company CMS and use overview over historical water leak reports in interaction with GIS and field worker data. Complete improvement process involved a number of training workshops for educating personnel on improved processes based on technologies use.

5.4. Reported benefits

The main benefit of this project was increased process efficiency, shorter lead time from report to problem solution. Also, each field worker becomes an active participant both in the creation of information and in the use of all available information. Simplicity and intuitiveness in the use of digital tools, which do not require previous IT experience, are essential. The rapid implementation of the system enables visible benefits in a short time, which contributes to the process of acceptance of digital technologies by employees. Furthermore, digitalization of information from the field operations enable continuous monitor of water leak report and repair process that improved quality of the whole process, improved coordination among organizational units, introduced standard reporting procedures that reflected on better monitoring and prediction. After all, the removal of paper based documents has also positively affected process costs, but also human need for paper reporting. The biggest benefit has been reported by field workers, because of simplicity of use with timely reporting procedures.

6. Conclusion, discussion and future work

Digitalization of public sector is not as easy as one may think. There are numerous obstacles, from people acceptance to technology change. The **structured leadership and improvement strategies** are the primary challenge to address. Digital transformation requires interdisciplinary approach [2] and is not one step process, but stepwise procedure of adoption of new technology, and in each step the overall increase in entropy should be minimized [28]. The availability of adequate **training tools** may speed up the adaptation process.

There has been relatively limited research on advancements that digitalization bring to sustainable WMS compared to other domains (e.g. health, transport, energy), [23]. The **predictability of system behavior** is the most important for sustainable WMS. Modeling WMS predictability is a complex issue, since it involves numerous factors like geographical distribution, numerous sensory data, real-time and continuous measurements from various points across distributed network. Furthermore, the applied new technologies that emerge toward digital twins solutions may require sophisticated software engineering skills due to progressive innovation of software services after digitalization, service integration problems, the side effects of service run-time versus static time compilation and engineering aspects across the system life-cycle. The similar requirements and problems we study in domain of telecommunication network and engineering software systems. Therefore, we want to consider **how transferable are empirical knowledge and mathematical models** collected from modeling software in other sectors across the various disciplines. Our research project [29] aims at understanding how the system structure affects the global system behavior [30, 31, 32, 33]. We see correlations to software structures that are present in complex software systems we have studied so far. We may transfer the knowledge from software and network management to WMS. More precisely, our previous study on topology of software structures to predict software smells may contribute to modeling WMS to predict water leaks.

Finally, the digitalization of WMS could be perceived as just one case study of global digitalization. There are common pitfalls while digitalizing all sectors. **Abstract knowledge from various case studies can be generalized to form sound theories for further evolution**

in computer and network science field with respect of abstraction, structure modeling and analysis and management in general.

7. Acknowledgments

We acknowledge the support of the Croatian Science Foundation research project no. HRZZ-IP-2019-04-4216 and the Erasmus+ Key Action 2 project No. 2020−1−PT01−KA203−078646.

The case study has been implemented by Smart Aqua d.o.o., Pula, Croatia, and carried out within Vodoopskrba i odvodnja d.o.o. Zagreb, Croatia.

References

[1] H. van Vliet, Software Engineering: Principles and Practice, John Wiley & Sons, Ltd., 2008.

[2] P. C. Verhoef et al., Digital transformation: A multidisciplinary reflection and research agenda, Journal of Business Research 122 (2021) 889–901.

[3] Oxford English Dictionary, Oxford University Press, Oxford, UK, 2022.

[4] N. Alsufyani, A. Q. Gill, Digitalisation performance assessment: A systematic review, Technology in Society 68 (2022) 101894.

[5] B. Rogers, Why 84% of companies fail at digital transformation, Accessed 20 July 2022. URL: https://www.forbes.com/sites/brucerogers/2016/01/07/why-84-of-companies-fail-at-digital-transformation/#526ea4e1397b.

[6] B. K. AlNuaimi et al., Mastering digital transformation: The nexus between leadership, agility, and digital strategy, Journal of Business Research 145 (2022) 636–648.

[7] Z. Korachi, B. Bounabat, Towards a maturity model for digital strategy assessment, in: M. Ezziyyani (Ed.), Advanced Intelligent Systems for Sustainable Development (AI2SD'2019), Springer International Publishing, Cham, 2020, pp. 456–470.

[8] H. Alegre et al., Performance Indicators for Water Supply Services – Second Edition, International Water Association Publishing, London and Seattle, 2013.

[9] European Commission, Water Framework Directive 2000/60/EC of the European Parliament and of the Council, 2000.

[10] ISO Central Secretary, General practices for the repair of water-leakage cracks in concrete structures, Standard ISO/IEC TR 29110-1:2016, International Organization for Standardization, Geneva, CH, 2020. URL: https://www.iso.org/obp/ui/#iso:std:iso:tr:16475:ed-2:v1:en.

[11] C. Banerjee, A. Bhaduri, C. Saraswat, Digitalization in urban water governance: Case study of Bengaluru and Singapore, Front. Environ. Sci. 10, Art. no. 816824, 12 pages (2022).

[12] I. Rojek, J. Studzinski, Detection and localization of water leaks in water nets supported by an ICT system with artificial intelligence methods as a way forward for smart cities, Sustainability 11, Art. no. 518, 13 pages (2019) 518.

[13] S. R. Mounce et al., Sensor-fusion of hydraulic data for burst detection and location in a treated water distribution system, Information Fusion 4 (2003) 217–229.

[14] A. Blázquez-García et al., Water leak detection using self-supervised time series classification, Information Sciences 574 (2021) 528–541.

[15] W. Moczulski et al., SysDetLok – a leakage detection and localization system for water distribution networks, IFAC-PapersOnLine 51 (2018) 521–528. 10th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes SAFEPROCESS 2018.
[16] D. Eliades, M. Polycarpou, Leakage fault detection in a district metered area of a water distribution system, Journal of Hydroinformatics 14 (2012) 992–1005.
[17] J. Cassidy et al., Taking water efficiency to the next level: digital tools to reduce non-revenue water., Journal of Hydroinformatics 23 (2021) 453–465.
[18] J. Lin et al., A survey on Internet of Things: Architecture, enabling technologies, security and privacy, and applications, IEEE Internet Things J. 4 (2017) 1125–1142.
[19] A. S. Ali et al., A solution for water management and leakage detection problems using IoTs based approach, Internet of Things 18 (2022) 100504.
[20] I. Andrić et al., IoT approach towards smart water usage, Journal of Cleaner Production 365 (2022) 132792.
[21] R. M. M. Salem, M. S. Saraya, A. M. T. Ali-Eldin, An industrial cloud-based IoT system for real-time monitoring and controlling of wastewater, IEEE Access 10 (2022) 6528–6540.
[22] J. Pérez-Padillo et al., IoT platform for failure management in water transmission systems, Expert Systems with Applications 199 (2022) 116974.
[23] Z. Wang et al., Cyber-physical systems for water sustainability: challenges and opportunities, IEEE Communications Magazine 53 (2015) 216–222.
[24] P. C. Fuertes, F. M. Alzamora, M. H. Carot, J. A. Campos, Building and exploiting a digital twin for the management of drinking water distribution networks, Urban Water Journal 17 (2020) 704–713.
[25] F. G. Ciliberti et al, Digital transformation paradigm for asset management in water distribution networks, in: 10th Int. Conf. on ENERGY and ENVIRONMENT (CIEM 2021), 2021, pp. 1–5.
[26] R. White, E. Guy, U. Inge, Modeling Cities and Regions as Complex Systems: From theory to planning applications, MIT Press, Cambridge, MA, 2015.
[27] L. Manny et al., Socio-technical networks of infrastructure management: Network concepts and motifs for studying digitalization, decentralization, and integrated management, Journal of Environmental Management 318 (2022) 115596.
[28] T. A. Larsen, W. Gujer, The concept of sustainable urban water management, Water Science and Technology 35 (1997) 3–10.
[29] T. Galinac Grbac, Reliable and safe complex software systems: From empirical principles to theoretical models in view of industrial applications, Accessed 20 July 2022. URL: https://croris.hr/projekti/projekt/4473?lang=en.
[30] T. Galinac Grbac, P. Runeson, D. Huljenić, A second replicated quantitative analysis of fault distributions in complex software systems, IEEE Trans. Soft. Eng. 39 (2013) 462–476.
[31] J. Petrić, T. Galinac Grbac, Software structure evolution and relation to system defectiveness, in: M. J. Shepperd, T. Hall, I. Myrtveit (Eds.), 18th Int. Conf. on Evaluation and Assessment in Software Engineering, EASE '14, ACM, 2014, pp. 34:1–34:10.
[32] N. Tanković et al., Transforming vertical web applications into elastic cloud applications, in: IEEE Int. Conf. on Cloud Eng., IC2E 2015, IEEE CS, 2015, pp. 135–144.
[33] A. Vranković, T. Galinac Grbac, Ž. Car, Software structure evolution and relation to subgraph defectiveness, IET Softw. 13 (2019) 355–367.