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Digital Transformation of Legionella-Safe Cooling Towers: An Ecosystem Design Approach

Purpose: Legionnaires' disease is a major threat to public health. Solutions to deal with this problem are usually siloed and not entirely effective. This paper models the information requirements of legionella-safe cooling towers in the era of Industry 4.0.

Approach: A year-long design science research was conducted in a cooling tower producer for heavy industries. The project started with a bibliometric analysis and literature review of legionella in cooling towers. Goal modeling techniques are then used to identify the requirements for digital transformation.

Findings: The improvement of legionella prevention, detection, and outbreak response in digitally enabled cooling tower should involve different stakeholders. Digital twins and blockchain are disruptive technologies that can transform the cooling tower industry.

Originality: For theory, this study revises the most recent advances in legionella protection. Legionella-safe systems must be prepared to anticipate, monitor, and immediate alert in case of an outbreak. For practice, this paper presents a distributed and digital architecture for cooling tower safety. However, technology is only a part of outbreak management solutions, requiring trustworthy conditions and real-time communication among stakeholders.

Keywords: Industry 4.0; Ecosystem design; Legionella pneumophila; Bibliometric analysis; Smart product-service system.

1. Introduction

Legionnaires' disease, also known as legionellosis, is a form of pneumonia caused by the exposure to legionella bacteria (Legionella pneumophila). The infection is normally transmitted through inhalation of contaminated aerosols and is the second most usual form of bacterial pneumonia in the United States (Orkis et al., 2018).

Cooling towers contamination is a key cause for the devastating legionnaires' disease outbreaks in industry (ECDC, 2019; Fitzhenry et al., 2017; Mouchtouri et al., 2010), being able to disperse the bacteria for miles around the industrial site. Traditional prevention measures include temperature control, copper and silver ionization, and effective maintenance procedures (Cloutman-Green et al., 2019; ESGLI, 2017; Orkis et al., 2018). Other proposals allow faster identification of the bacteria (Párraga-Niño et al., 2018) and innovative real-time surveillance of critical parameters (Whiley et al., 2019). However, current systems to monitor and control legionella are still expensive, not 100% effective, and "highlight the urgent need to shift from relying on the alarm bell of human disease to primary prevention strategies designed to limit Legionella colonization and dispersal" (Fitzhenry et al., 2017). Therefore, additional solutions are necessary to monitor, warn, and respond to legionella contamination in industry.

The fourth industrial revolution (Industry 4.0) promises radical changes in safety at work with the use of new technologies. Digital transformation in industry is a worldwide priority supported by the adoption of artificial intelligence, cloud computing, internet of things (IoT), augmented/virtual reality, simulation, or mobile technologies (Galati and Bigliardi, 2019). The technological portfolio is vast and aims to decentralize, individualize, and integrate manufacturing processes - horizontal, vertical, and end-to-end digital integration (Liao et al., 2017). The popularity of digital twins and blockchain has also increased in the past years. The concept of digital twin was introduced by NASA and includes a physical object, its digital version, and the connections between both (Glaessgen and Stargel, 2012). For example, General Electric implemented digital twins in multiple turbines using sensors, 3D visualization techniques, and advanced data analytics to monitor performance, assess failures, and predict maintenance interventions (GE, 2016). Blockchain is a disruptive technology to store immutable and encrypted data, improving trust and traceability in the users transactions (Gunasekara et al., 2021; Mendling et al., 2018). The potential of combining technologies to innovate is significant, but the transition can be challenging, and each companies should create a strategic roadmap (Ghobakhloo, 2018).

This research started after a meeting with the managers of a cooling tower manufacturer interested in creating more resilient systems to deal with legionella contamination. Accordingly, the following research objective is formulated:

- *RO1: Design a legionella-safe cooling tower system deploying Industry 4.0 technologies.*

Legionella prevention is a multidisciplinary effort requiring a thorough assessment of the scientific advances in the field. Consequently, a second research objective is:

- *RO2: Understand how the problem of legionella in cooling towers has been addressed in the literature.*

The remainder of this paper is organized as follows. Section 2 describes the selected design science research (DSR) approach (vom Brocke et al., 2020; Hevner et al., 2004; Peffers et al., 2007). The results are subsequently presented: (1) a review of key literature in legionella prevention and the potential of Industry 4.0 to contribute to a solution and (2) the ecosystem design (Tsujimoto et al., 2018) for legionella-safe cooling towers. The discussion follows, detailing the implications of digital transformation for legionella-safe cooling towers. The paper closes with a summary of the main conclusions, limitations, and opportunities for future work.

2. Design Science Research Approach

Design science research has its foundations in the work of Simon (1996) and enables the creation of artifacts to solve organizational problems, which can "be in the form of a construct, a model, a method, or an instantiation" (Hevner et al., 2004). Design knowledge accumulates and evolves in iterations (vom Brocke et al., 2020) that need to balance the artifacts and the theories produced (e.g., prescriptions to build the artifact) (Baskerville et al., 2018). The DSR process follows the following phases (Peffers et al., 2007):

1. Problem identification and motivation

Prevention of legionnaires' disease is a priority for the cooling tower industry (Iervolino et al., 2017; Orkis et al., 2018; Walser et al., 2014). Existing methods are not sufficient, and major outbreaks continue to occur (ECDC, 2019; Fitzhenry et al., 2017; Gonçalves et al., 2021; Russo et al., 2018). Digital transformation made possible by Industry 4.0 can contribute to the problem of legionella in cooling towers. Facilities management calls for new frameworks to promote sustainability and control of diseases (Falorca, 2020).

2. Definition of the objectives for a solution

Conceptual design of a blockchain-based ecosystem (Longo et al., 2019; Tsujimoto et al., 2018) that integrates cooling tower management with the concept of the "fleet" – similar assets sharing data and producing knowledge (GE, 2016). Blockchain is emerging as an important technology in the field of facilities management (Gunasekara et al., 2021).

3. Design and development

Literature review and bibliometric analysis (van Eck and Waltman, 2010) to evaluate how legionella protection has been addressed in the context of cooling towers. Conceptual model design.

4. Demonstration

Small-scale prototype using commercial off-the-shelf microcontrollers and low-cost sensors to evaluate the potential of the model in the case company.

5. Evaluation

Joint assessment by researchers and practitioners. A summative evaluation (Venable et al., 2016) was found sufficient because the case company was setting up a co-funded research project proposal.

6. Communication

Contacts with government entities and leading laboratories to ask for advice on legislation and emerging innovations for legionella prevention. Scientific publication.

Inspired by the work of Tsujimoto et al. (2018), this paper defines Industry 4.0 ecosystem of cooling towers as a community of human and non-human actors in permanent interactions with each other and with the environment, able to promote change using information technologies. The colling tower ecosystem must balance three goals: social (e.g., public health), technological (e.g., digital transformation: sensors, cloud servers, blockchain infrastructure), and organizational (e.g., regulatory compliance, information flows. and cooperation agreements).

The next section presents the research setting. Next, the literature review process is explained.

2.1. DSR Case Setting

The case company (CC)'s mission is to provide engineering services and technologies for paper and pulp, mining, and oil industries. Building and maintenance of large-scale cooling towers are key business activities, as illustrated in Figure 1.

Fig. 1: Cooling tower construction.

Cooling towers are common in industrial processes, removing energy from hot water in contact with cool air. This important equipment is also a common source of bacteria in water circuits. Legionella bacteria can multiply faster in water temperatures ranging from 20ºC and 50ºC (optimum growth 35ºC–45°C). There are other risk factors involved such as the water quality, age of the cooling tower, or the working periods (Mouchtouri et al., 2010). Outbreaks of legionnaires' disease caused by cooling towers have dramatic consequences, as revealed by several reports issued by the European Centre for Disease Prevention and Control. For example, "a cooling tower of a paper factory has been suspected of causing the outbreak (… and) [w]ater samples have been taken from the cooling towers of 17 companies, with two found to be highly contaminated" (ECDC, 2019). 32 confirmed cases and two deaths were confirmed in the Evergem area in Flanders, Belgium. More recently, in January 2021, Portuguese authorities declared the end of an outbreak in the North. A total of 88 cases were reported and, although sporadic, “outbreaks [and fatalities] occur, often in relation to cooling towers or other aerosol-generating installations” (ECDC, 2021).

The response to outbreaks is complex and the fast identification of contaminated sources is essential to public safety. Therefore, CC aims to ensure legionella safety by design. Their strategy includes the development of physical structures that also offer digital services in a layered architecture (Yoo et al., 2010) for a new generation of cooling towers.

2.2. Literature Review Process

The literature review included six main stages, namely “(1) defining the research question, (2) determining the characteristics of primary studies, (3) retrieving a sample of relevant literature, (4) selecting, (5) synthesizing, and (6) reporting the results” (Durach et al., 2017). The first stage included a general search in Google Scholar to identify recent trends in Legionella research (since 2015) using the keyword combination: "legionella" + "industrial cooling tower" (112 results since 2015), "cooling tower" + legionella + "real time monitoring" (77 results; no time restriction), and "internet of things" + legionella + "cooling tower" (21 results). Afterwards, the authors refined the search in Web of Science (WoS). A total of 303 papers were selected in this database for bibliometric analysis (last updated 02/03/2021) using the keywords “legionella” and “cooling tower” in topic search. VOSViewer (van Eck and Waltman, 2010) was used to create bibliometric networks and identify important concepts addressed in the field.

3. Results

Section 3.1. introduces the bibliometric analysis and review of foundational literature. Section 3.2 presents the conceptual model for legionella-safe cooling towers.

3.1. Making Sense of the Literature

Figure 2 depicts a citation analysis for the sample of papers indexed in WoS between 2010 and 2020.

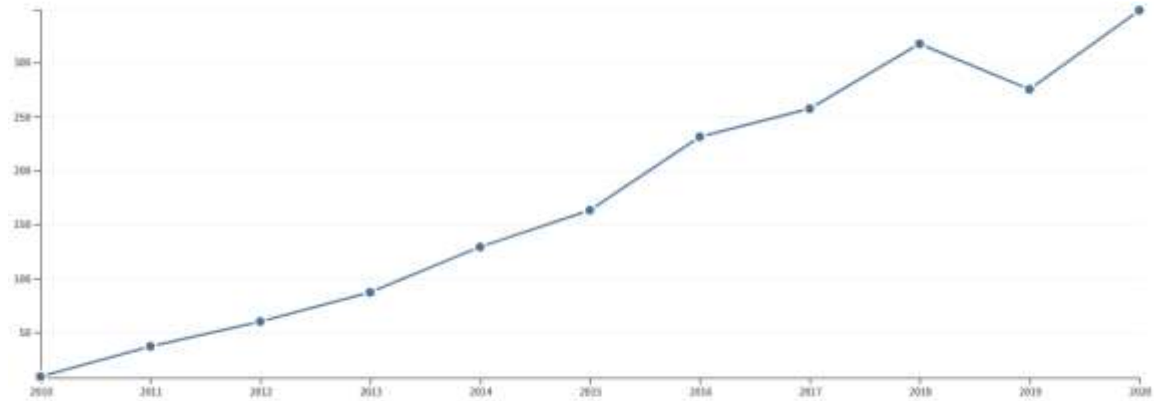

Fig. 2: Citation analysis in WoS: legionella and cooling towers (2010-2020).

There is a steady increase in the number of citations, reaching a pick in 2020. The 303 papers were cited 7310 times, h-index 44, and an impressive 24.12 average citations per item (March 2021; more than doubling the 10.63 citations per item of 3279 paper found using only "cooling tower" in the keywords). The VOSViewer tool (van Eck and Waltman, 2010) was applied to extract key topics in this sample (Figure 3).

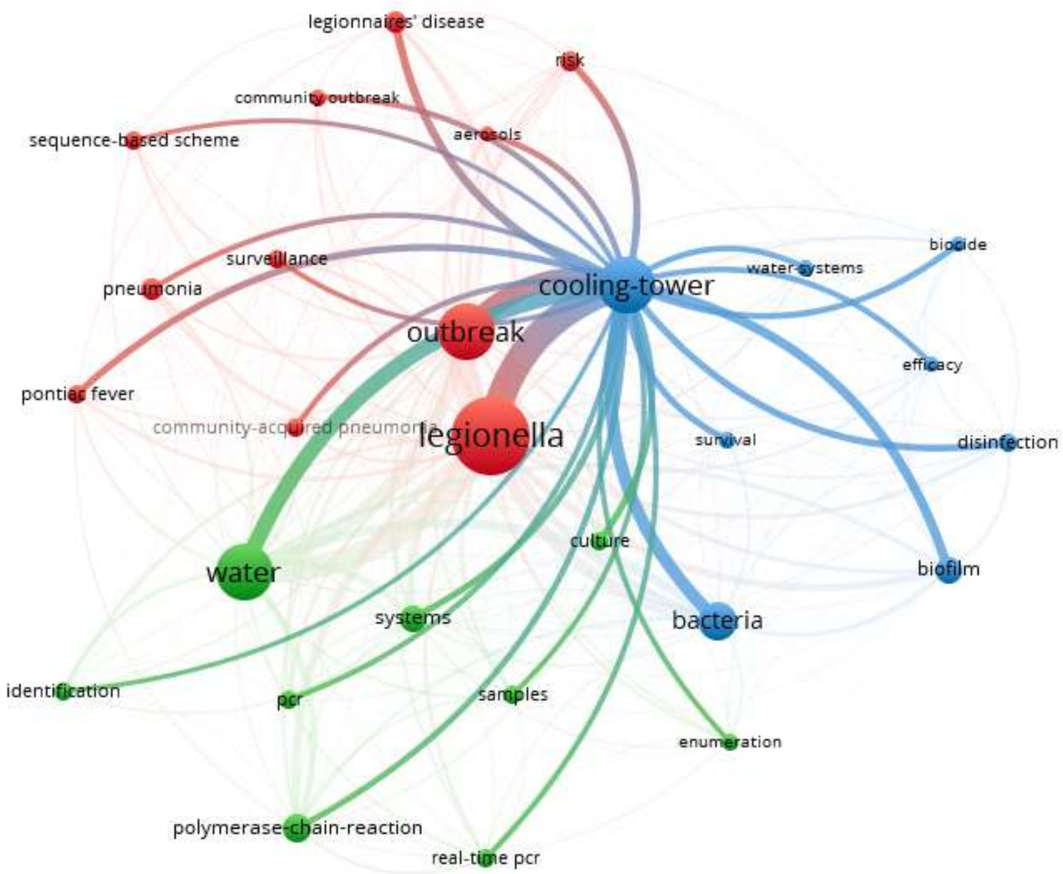

Fig. 3: Keyword analysis of legionella and cooling tower research in WoS.

Three main clusters of papers are identified in Figure 3 (co-occurrence of words using keyword plus; minimum cluster size: 8; thesaurus file aggregating similar terms): cooling tower (blue cluster); outbreak (red cluster); and analysis (green). It is surprising the lack of clusters addressing digital solutions. Two main clusters were identified for bibliographic coupling of countries: one more influenced by the United States (England, France, Australia, Canada, Turkey, Italy, and Netherlands), and the other leaded by Germany, Spain, and Japan, also including China and South Korea. Nevertheless, the problem of legionella is global and new technological solutions must address the cooling tower facility (section 3.1.1) and the outbreak management and bacterial analysis (section 3.1.2).

3.1.1. Legionella in cooling towers

Temperatures between 20 degrees C and 50 degrees C increase the risk of legionella development (Gonçalves et al., 2021). Therefore, one of the most usual methods to control the bacteria is to keep cold water below 20º and hot water stored at least at 60º, combining with the use of biocides (Cloutman-Green et al., 2019; Iervolino et al., 2017). Additional methods include membranes for monitoring, maintenance, and control in combination with sulfate and alkalinity (Sharma et al., 2020), and the continuous release of copper and silver ions into the water, showing positive results in the control of legionella at near 43º (Cloutman-Green et al., 2019). However, "[i]t is important that the functioning of the system and associated equipment is considered as a whole and not in isolation (e.g. considering a cooling tower without taking the supply water quality into account)" (ESGLI, 2017).

Poor maintenance of the cooling tower, limited routine sampling, and inadequate control measures of legionella are well-known causes of outbreaks (Mouchtouri et al., 2010; Türetgen et al., 2005; Walser et al., 2014). However, planning may not be enough to avoid the problem. A study presented by Orkis et al. (2018) found that despite proper maintenance, other factors such as age, frequency of use, type of organization (e.g. hospital, factory), and capacity (particularly above 422 tons) may increase the risks. These authors reported that almost half of the 56 cooling towers identified in the study was positive for legionella pneumophila. This significant proportion is aligned with the results presented by Mouchtouri et al. (2010), where "about half of the cooling towers examined were contaminated with Legionella spp, and 23% of the collected samples were highly contaminated with a concentration ≥ 104 cfu L−1". Moreover, in case of an outbreak, it is possible to have multiple sources of contamination and the causality is not always clear. This may hinder a timely response to contain the damage and the necessary legal, organizational, and environmental actions that must follow.

Automation is important, but not a silver bullet. For example, the report of an outbreak in Ohio concluded that the biocide automated system was a cause of the problem, particularly "during season changes, when cooler or warmer than expected temperatures can lead to variations in cooling demand, causing automated systems to turn on and off and creating environments more conducive to the growth of Legionella" (Quinn et al., 2015). Therefore, technological support to minimize risk of contaminations must be implemented in parallel with training of the staff, inspection, and testing (Health and Safety Executive, 2013a).

Regulations and guides are available to facilities managers (ASHRAE, 2020; ESGLI, 2017; Health and Safety Executive, 2013a). For example, the ANSI/ASHRAE Standard 188-2018 "Legionellosis: Risk Management for Building Water Systems" (ASHRAE, 2018), is an important tool to develop water management plans, providing the minimum requirement to ensure safety in cooling towers. Moreover, it is advised to (1) clean and test for legionella, quarterly (in year-round run) or once before, after, and during the cooling season, (2) make water tests, (3) routinely clean the basin/tank, and (4) thoroughly inspect and clean older cooling towers (Orkis et al., 2018). There are also European guidelines such as the European Working Group for Legionella Infections (2017) and Health and Safety Executive (2013a, 2013b). Nevertheless, industry's compliance to regulations is still lower than desired (Fitzhenry et al., 2017).

3.1.2. Outbreaks and Analysis of Legionella in Industry

There are different tests to evaluate legionella. For example, the polymerase chain reaction (PCR) usually made by experts (Sánchez-Parra et al., 2019) or Legiolert (Rech et al., 2018) that quantifies legionella pneumophila with high precision and produces results in seven days. Biosensors that convert biological identifications into electrical signals have already been tested, particularly, immunosensors and genosensors, but still have limitations for industrial applications (Mobed et al., 2019). Other proposals use microfilms to identify the bacteria in two hours (Párraga-Niño et al., 2018) or the recent DGGE method to monitor its evolution (Bayle et al., 2020). Nevertheless, multiple factors affect the growth of legionella in cooling towers, which include other microorganisms in the biological ecosystem (Paranjape et al., 2020).

Industry 4.0 technologies are also emerging in legionella detection. IoT offers a possible alternative to biosensors, monitoring the parameters that affect legionella growth, namely, liquid flow and temperature (Whiley et al., 2019). The data collected in real-time and the adoption of artificial intelligence (Armero et al., 2011) may be used for early warning of dangerous situations.

However, studies using information systems to achieve legionella-safe cooling towers are still scarce. One example is presented by Rudbeck et al. (2010) using a geographical information system. These authors assess the distribution of the infection cases and detect areas that require further surveillance. Interestingly, Racine et al. (2019) state that "drawing conclusions on the health of a system based on a snapshot in time is ill-advised [… conversely,] legionella positivity should be viewed through a storyline" revealing the importance of information systems to collect data. For example, equipment use, water quality, context of operation (e.g., temperature, specific events), and compliance with maintenance procedures.

Contextual information about the cooling tower is also important. For example, the meteorological conditions such as warm temperature, low winds, and high humidity (Russo et al., 2018), or storms that may increase the risk of legionella proliferation and diffusion, even if biocides are used (Brigmon et al., 2020). It is now clear that climate change will escalate the problem of legionnaires' disease and call for action from governments, academics, and private organizations (Walker, 2018).

Technologies will have a role to play in the cooling towers of the future. For example, using UV light-emitting diodes to inactivate the water pathogens (Oguma et al., 2019). Mobile technologies can be adopted to create legionella log books (e.g., Legionella Control, 2021; TEAMS, 2021). Schulze et al. (2019) propose a cyber-physical system for advanced management of cooling towers, revealing the potential of Industry 4.0 for the operation and data analysis of this important industrial facility. However, the literature does not yet integrate real-time legionella protection and contamination alert, promoting synergies between stakeholders.

Compliance evidence is mandatory to protect public health. The severity and growth rate of legionella outbreaks suggest that reliable maintenance records must be a priority to company inspectors, certification bodies, and health and safety assessors. Blockchain is a technology that can be used to store immutable data, offering an infrastructure for trustable and shared information (Mendling et al., 2018). For example, the information collected via IoT and (calibrated) sensors can be made available in real-time to third party entities (e.g., biocide levels and testing results that can be added to the blockchain by the laboratory). Therefore, the creation of a comprehensive cooling tower ecosystem will be crucial. This paper departs from the inspiring definition of ecosystem in the area of innovation and technology management proposed by Tsujimoto et al. (2018): “[t]o provide a product/service system, an historically self-organized or managerially designed multilayer social network consists of actors that have different attributes, decision principles, and beliefs”, contributing with a conceptual model for legionella-safe cooling tower, as presented in the next section.

3.2. Field Results: Designing a Smart Legionella-Safe Architecture for Cooling Towers

Several meetings were held with the company experts and health and safety assessors to evaluate the feasibility of a multi-stakeholder digital platform (e.g., manufacturer, maintenance team, assessors, health authorities). The research team also contacted a laboratory specializing in public health and the government health department to understand the opportunities and challenges for legionella-safe cooling towers. Eight experts were contacted in this three-week phase that served to confirm the lack of integrated solutions.

IoT sensing capabilities and reliable data sharing were two priorities identified for the design. Then, a survey of potential suppliers was carried out (e.g., water temperature sensors operating from -50°F to 250°F) for preparing the project. The stakeholders' requirements (Freeman, 1984) are represented in Figure 4 using a goal modeling language (ITU-T, 2012).

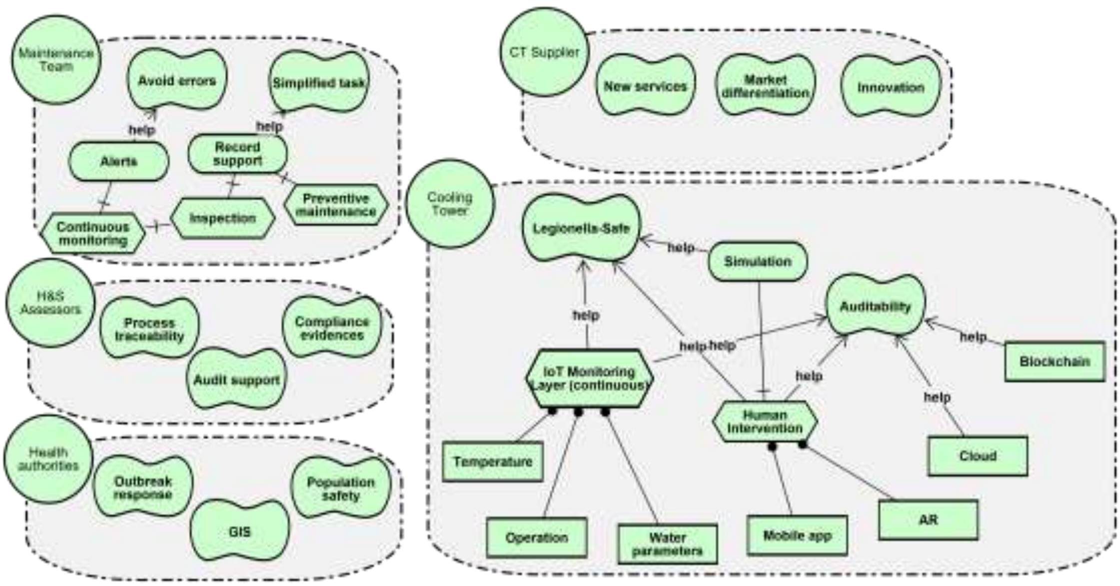

Figure 4: Legionella-safe cooling tower: ecosystem goal model.

For the sake of simplicity, only the soft goals (; high level system requirements) are represented for the H&S assessors, health authorities, and the cooling tower (CT) supplier (case company). The cooling tower structure (at the bottom-right of Figure 4) and the maintenance team (insourced or outsourced, on the top-left) include the goals (; what the actor wants), tasks (; how to do it), and resources (; with what).

The cooling tower digital twin is based in IoT (e.g., sensors and communication devices to manage temperature, time of operation, cycles, and water parameters), a mobile augmented reality app to assist the local users (e.g., maintenance team; auditors), a cloud infrastructure and a permissioned private blockchain (Iansiti and Lakhani, 2017) optimized for IoT (Novo, 2018). Contrasting with public blockchains, only authorized users can participate in the network and data transactions are restricted.

The cooling tower blockchain stores data needed by the assessors and health authorities in outbreak investigation. Moreover, the “digital twin fleet” (GE, 2016) aggregates data from multiple cooling towers. Although each stakeholder (e.g., company, maintenance team, assessor, and supplier) has restricted access to “their” cooling tower digital twin, manufacturers and health authorities can supervise cooling towers pertaining to a specific area. Some of the advantages of this configuration are: (1) faster detection of problematic cooling towers in an outbreak situation; (2) more accurate prioritization for inspections; and (3) increased visibility of maintenance activities.

According to the health and safety experts, most companies are aware of regulatory requirements for cooling towers, but government authorities have an important role in legionella prevention. A digital ledger may be used to prove that maintenance is executed as planned. A maintenance manager contacted during this research stated that “industry staff and service providers can be prosecuted for maintenance negligence in cooling towers. We are the most interested party (…) maintenance budgets are thinner, but compliance is not an option - and must be clear, when the consequences of failure are severe (…)”.

There are also weaknesses in blockchain-based solutions. Data processing costs are higher when compared to traditional cloud databases. Therefore, critical data (e.g., immutable data used for compliance evidence) can be stored in the blockchain, while a secure cloud-based platform is sufficient to store less critical operational data. The amount of IoT-related data can increase significantly and only a part is needed for historical analysis.

Figure 5 presents a small-scale prototype using an Arduino Mega microcontroller, low-cost sensors (e.g., temperature and humidity, water flow, alkalinity), communication devices (e.g., GSM shield and wi-fi) and operation tracking systems (e.g., engine state).

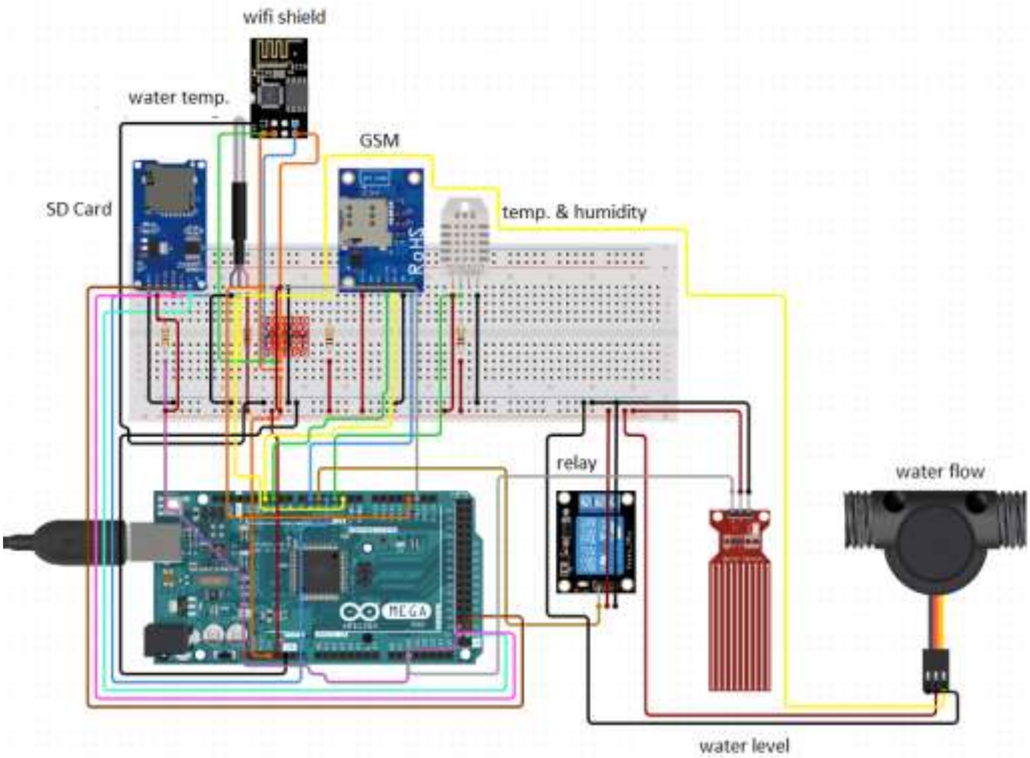

Fig. 5: Legionella-safe cooling tower: small scale IoT prototype.

The prototype helped in the discussion with company managers, illustrating the real-time communication requirements: wireless board (on the bottom-left of Figure 5); GSM GPRS shield to send notifications (e.g., temperature warnings); and an SD card for local data storing (simulating a local server used for non-critical data). Systems redundancy (crucial for industrial scale deployment) is omitted in this simplified model.

The cooling tower maintenance app was inspired in the popular electric scooters' QR code and GPS confirmation to ensure that the measurement is accountable and reliable (GPS coordinates stored in the blockchain). Figure 6 presents the overall architecture of the cooling tower ecosystem inspired by Guo et al. (2021)' three-layered proposal for smart production-logistics systems.

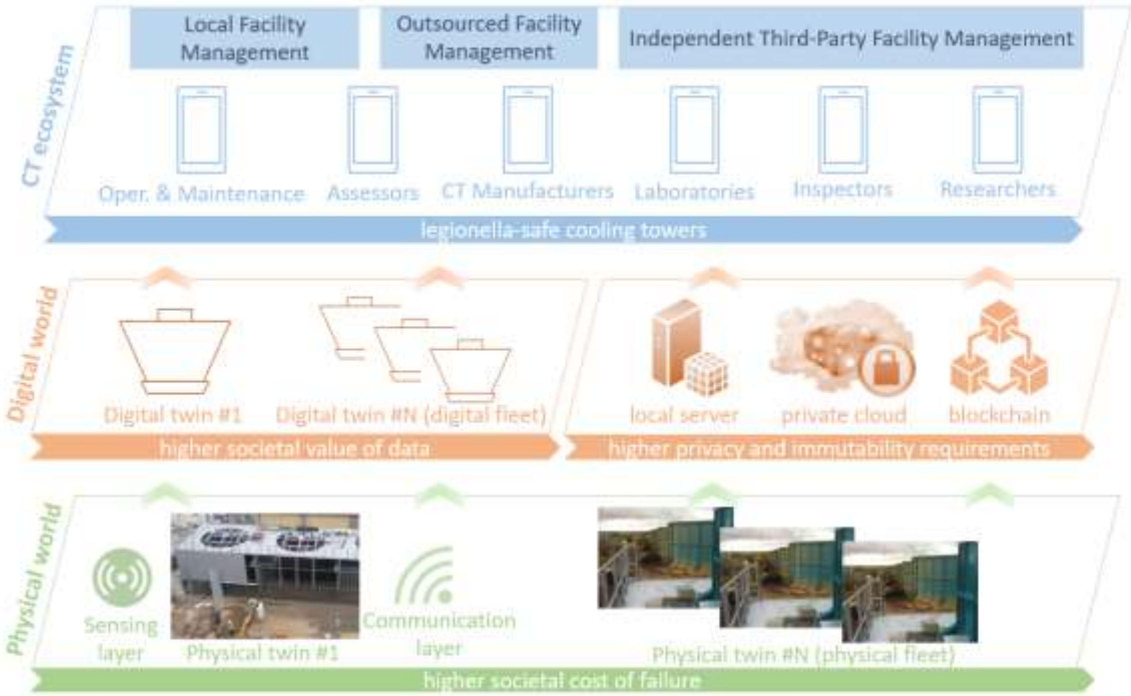

Fig. 6: Legionella-safe cooling tower: ecosystem design.

The layers of the proposed architecture are described in Table 1.

Table 1: Three-layered architecture for legionella-safe cooling towers.

Layer	**Description**
Cooling tower ecosystem	Different interfaces and permissions are needed according to the stakeholder's role: local, outsourced, and independent. For example, CT suppliers have read-only access to specific data of their cooling towers

	(fleet) for the purpose of product improvement and outsourced maintenance planning.
Digital world	Digital twin software and algorithms. Data can be stored (1) locally, (2) in private clouds (non-critical data sharing), or (3) in the permissioned blockchain infrastructure (evidence-based safety information).
Physical world	Cooling tower equipment. Smart devices. Sensors and communication systems.

According to CC, this solution is viable, but additional work is needed to incorporate advanced data analytics (Schulze et al., 2019) and artificial intelligence capabilities to forecast legionella threats. There are recent proposals to adopt predictive analytics in facilities management (Roskams and Haynes, 2019), strengthening the team's conviction that real-time monitoring and intelligent (shared) warning systems are key pillars for the future of cooling towers. CC plans to include laboratories in the business ecosystem, sharing their reports in the digital platform. The data market opportunities (e.g., insurance companies) are left unexplored at this stage of the research.

4. Discussion

Climate changes will increase the risk of pathogen infections (Walker, 2018) and will call for solutions to deal with this problem. Safety can be improved using new technologies but "[m]ore interdisciplinary research is needed in order to improve the integration of human labor with intelligent equipment (…) on improving the social responsibility of businesses, on workplace design and configuration and on the effective use of information technologies" (Badri et al., 2018). Moreover, the important contributions for cyber-physical cooling towers (Schulze et al., 2019) can be extended to the aspects of disinfection, maintenance, and outbreak response in business ecosystems (Tsujimoto et al., 2018):

- Assisting health authorities, producing reliable digital twins of cooling towers in multiple (georeferenced) locations. Potential sources of contamination are more visible in case of outbreaks. Moreover, health authorities' inspections can be planned more effectively, with real-time access to the results of certified auditors and laboratories. Older facilities, with dangerous temperature profiles or long periods of inactivity, and lack of adequate plans and maintenance records (Mouchtouri et al., 2010; Orkis et al., 2018; Walser et al., 2014) are on the top of the list.
- Implementing a fleet of cooling towers (GE, 2016; Glaessgen and Stargel, 2012), useful to monitor operation and evaluate opportunities for improvement.
- Integrating stakeholders from the service area: (1) maintenance service (users of the mobile app), (2) health and safety assessors, (3) biosensor suppliers, or (4) water laboratories.
- Protecting public health from environmental threats. Legionella warnings can be extended to the entire cooling tower ecosystem.
- Deploying a smart product-service system (Valencia et al., 2015) using Industry 4.0 technologies. Cooling towers are common in industry, but the service capabilities of this structure are very limited. The proposed model offers a possible solution to improve the societal value of cooling towers.

To the best of the authors knowledge this is the first proposal of an ecosystem architecture (Tsujimoto et al., 2018) for legionella-safe cooling towers. This paper presents an updated literature review and extends the work of Schulze et al. (2019) for the digital transformation of cooling towers, focusing health and safety. Moreover, the goal modeling language used for the ecosystem design was found accessible by the project participants with different backgrounds.

4.1. Implications for Ecosystem Design of Cooling Towers

Goal modeling can be an effective approach to model requirements of business ecosystems, representing the motivations of different stakeholders. Although the experts participating in this design were more familiar with flowcharts (e.g., ISO 9001 process models), they found the goal models interesting.

The fleet of digital twins (GE, 2016; Glaessgen and Stargel, 2012) is important to protect public health but also in the case of outbreak investigations. For example, confirming that cooling towers had regular maintenance and not only on the eve of inspections. Therefore, facility ecosystems must balance multiple stakeholders' goals and combine biological, technological, organizational, and societal concerns.

Business ecosystems are not new (Weill and Woerner, 2015), but there is a lack of design approaches to address sustainable goals such as the health of the population in industry settings. It is also necessary to ensure resilience and safety of the digital twins. Redundancy of calibrated sensors and blockchain-based infrastructure are envisioned, but other solutions may be tested.

5. Conclusions

This paper presents a literature review and a conceptual model of legionella-safe cooling towers. The project was launched by a cooling tower manufacturer aiming to create a “smarter” product-service system (Valencia et al., 2015). The recent COVID-19 pandemic makes evident that outbreaks require an effective communication among the main actors involved. Facilities of the future will need more investment in the development of “biographies” (Spring and Araujo, 2017) that can be supported by digital twins and distributed ledger technology.

There are also limitations to this study. First, the natural restriction of the databases and the keywords selected for the literature review. Second, several research projects for legionella are being developed, some of them involving health authorities and sensors producers. CC still does not have a confirmation of government authorities to allow a wide adoption of the platform, calling for more regulations. Third, at this stage, only a prototype is available. The instantiation of the proposed ecosystem will reveal more issues (e.g., measurement uncertainties, detailed cost-benefit analysis) that need to be addressed. Fourth, although confirming that Industry 4.0 research in legionella is scarce and gathering important insights from industry experts, more data is necessary to prove the value of the ecosystem proposal, when comparing to separate techniques of disinfection, tests, and maintenance. The final system must be tested in outbreaks and additional work will be necessary over the next years to turn cooling towers into smart-safe facilities.

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