# Design Analysis of Smart Water Meters: An Open Design Approach

Flávio Henrique Alves[1] [a], Maria Cecilia Calani Baranauskas[1] [b] and Alexandre L'Erario [2] [c]
[1] *Department of Information Technology, Federal University of Paraná, Curitiba-PR, Brazil*
[2] *Institute of Computing State University of Campinas, Campinas-SP, Brazil*
[3] *Department of Systems and Dep. of Computing, Federal Technological University of Paraná, Cornélio Procópio, Brazil*
*fl*

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Abstract: The control of water resources has become increasingly necessary due to population growth and climate questions. This control is so critical that it is related to the UN's Sustainable Development Goals (SDGs): SDG #6 is clean water and sanitation, which aims to ensure the availability and sustainable management of water and sanitation for all people. This study addresses the application of Information and Communication Technologies (ICT) as a solution to water management problems in smart cities, highlighting the importance of the participatory construction of smart water meters (SWMs) as a potential solution to monitor water consumption. The design and implementation of SWM provides significant technical and social challenges, but promises to improve efficiency in water control and consumption. The objective of this study is to investigate SWMs, analyzed using the open design methodology to identify problems, questions, solutions and ideas in their implementation. We understand how SWMs can benefit water management and propose more effective and participatory solutions. The methodology adopted involves three stages: analysis of the case of Company X, selection of cases from the literature, and analysis with Open Design. Analysis is performed using Open Design artifacts to identify stakeholders, questions and problems, and solutions and ideas related to SWMs. As a result, it is possible to identify open problems and questions that need to consider a more participatory and inclusive approach in developing SWM solutions. The use of Open Design is promising and makes stakeholder engagement more effective in creating sustainable and affordable solutions.



## 1 INTRODUCTION

The presence of treated fresh water is essential to the life of humanity and is intrinsically related to the way of life of all people on the planet. The world's cities seek to become smarter as the population grows and consumes more water resources, so these resources must be managed efficiently (Wang and Li, 2021).

Currently, sustainability issues have gained notoriety, such as the United Nations Sustainable Development Goals (SDGs): SDG #6 is Clean Water and Sanitation, which has Information and Communication Technologies (ICT) as allies to achieve its objectives (UN, 2015).

ICTs are used in experiments to automate the control and consumption of water in its various sectors of use (Nascimento, 2022). Challenges such as improving the data transmission rate, telecommunications standardization, sensors that detect quality and not just quantity, and maintainability, among others (Campisano et al., 2013), have not yet been overcome for SWM to be effectively installed and used. Furthermore, including stakeholders in this scenario adds a result with better applicability to development.

Therefore, this research aimed to investigate and apply the Open Design (OD) platform to understand the problem in the specific context of water availability and sustainable management. OD keeps the user as an active part throughout the solution design and development cycle, as an effective contributor with their vision of their real needs (Gonçalves et al., 2021; Reis et al., 2018).

This work applies the OD to selected literary works and also in the case of a company in the production sector. To this end, we analyzed SWM prototypes, raising relevant aspects for the evaluation of SWM products.

The methodology of this research followed three steps to achieve its objectives. In the first stage, we

[a] https://orcid.org/0000-0003-0806-9726
[b] https://orcid.org/0000-0002-4830-5298
[c] https://orcid.org/0000-0001-5233-7113



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investigated the case of Company X, using sources of evidence such as documentation, archival records, and direct observation of the participant. In the second stage, we selected cases from the literature, searching for articles related to Smart Water Meters (SWM) on the Web of Science, analyzing publication trends and collaborations between countries.

Finally, in the third step, we performed an analysis using the Open Design Platform, which included identifying stakeholders and developing an assessment framework to elicit stakeholder concerns and needs, as well as propose solutions and ideas. These steps provided a solid framework for understanding the context of smart water meters and identifying potential challenges and solutions to improve water management.

This article is organized as follows: in Section 2 we present some challenges and limitations present in the SWM design. In Section 3 we show how we selected articles from the literature and analyzed the case of the Company X prototype. In Section 4 we present the results of the analysis of the use of OD artifacts. In Section 5, we discuss solutions and ideas for problems and issues raised; in Section 6 we conclude our study.

## 2 BACKGROUND

Water scarcity is one of the critical SDGs (UN, 2015). According to goal number 6 among those listed in the SDGs, the intention is to guarantee the availability and sustainable management of water and sanitation for all, respecting an agenda that will last until 2030.

The SDGs propose the use of ICT for smarter cities, but the control and consumption of water pose challenges. Dawood et al. (2022) highlight the fragility of water networks in several regions, such as Latin America, the United States and Canada. They advocate the use of ICT to guide decisions on repairs and consumption control.

A study carried out by Beal and Flynn (2015) reveals various challenging and limiting issues, covering both economic and technical aspects in the planning phases. Among them are the positive return on investment, few studies with qualified results, limited experiences and meters that offer different technologies. Furthermore, they present implementation challenges, for example, developers with little experience, technology compatibility, implementation, acquisition, and installation time and communication variability between devices.

SWM solutions are intended to replace conventional mechanical water meters. A water meter is a device that measures and records the volume of water consumed in water supply networks. Mechanical recording mechanisms visibly display water consumption, displaying it in volume measurement units widely recognized throughout the world, such as cubic meters or their smallest parts. The modified SWM system uses this mechanical apparatus to perform the measurement and interpret the data without human intervention (Pimenta and Chaves, 2021).

Contributing to the problem of water control and consumption through smart IoT devices are solutions explored in academic and industrial contexts. However, despite several efforts, there are still difficulties in applying and using smart devices to control and consume water (Fuentes and Mauricio, 2020; Hemdan et al., 2023).

In this article, we filtered and selected reports from articles and a business case from several other researchers and technology professionals who believe that a possible solution is to employ smart devices to control and consume water. However, outstanding challenges impede the use and adoption of these technologies in residential meters on a significant population scale.

We use two OD artifacts, the Stakeholder Analysis (Interested Parties) and the Assessment Framework on the Open Design Platform, to investigate, understand and propose solutions to the problem of water control and consumption using smart devices in the meters of water distribution networks.

Open Design is a Platform that allows anyone to contribute ideas and feedback to the development of products and services, from the beginning of the process, and not just in the prototyping phase (Gonçalves et al., 2021). Designed based on Organizational Semiotics (OS) and Participatory Design (PD), (Pereira et al., 2013) OD was used in several scenarios such as: combating violence against children and adolescents (da Silva Júnior et al., 2022), mobile application (Buchdid et al., 2019), functionality research (Reis et al., 2018) among other applications.

The application of the OD principles that the Open Design Platform offers to produce promising results in addressing specific issues, relying on the involvement of interested parties and considering socioeconomic factors. It aims to achieve socially responsible, participatory and universally beneficial design, accessibility, transparency, sustainability, collaboration and others, both in the process and in the final product (Pereira et al., 2013).

# 3 WORK METHODOLOGY

The study is divided into 3 stages: the first stage is the transcription of the case of company X. The second stage is bibliometrics and visual analysis of the review of selected articles on SWMs. The third and final step is to analyze the perspective chosen in steps one and two. We insert the information extracted from both steps[1] into the Open Design Platform to analyze the relevant information by comparing Problems and Questions versus Solutions and Ideas, as shown in Figure 1.

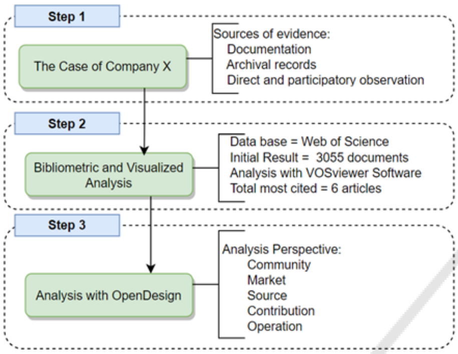


Figure 1: Steps of the methodology.

## 3.1 Step 1 – The Case of Company X

Our investigation used sources of evidence such as documentation, archive records, direct participant observation with the participation of the main researcher of this article, thus maintaining multiple sources of evidence.

We selected the audience for the investigation of the Company X case to feed the Stakeholders artefact on the Open Design Platform. In addition to the selected articles, the case of Company X was analysed from the perspective of the Evolution Frame artefact to list the Problems & Questions and Solutions & Ideas of Open Design. To maintain the anonymity of the company participating in the case study, for compliance reasons, we are using the fictitious name of the company, thus being called "Company X".

## 3.2 Step 2 - Cases Selected from Literature

To prepare this step, we considered some systematic mapping steps of Kitchenham et al. (2017). The selected papers were articles searched in the Web of Science [2] in October 2023.

The search criteria involved topics related to Smart Water Meter (Smart Water Meter OR Smart Water Consumption OR Connected Water Meter OR IoT Water Meter OR Automated Water Meter OR Advanced Water Meter OR State-of-the-Art Water Meter OR Electronic Water Meter OR Remote Reading Smart Water Meter OR Digitized Water Meter OR Next-Generation Water Meter), we made the search more flexible using only the "OR" operator because we aimed to expand the scope of the term SWM (Badke, 2021).

We used the start date of 2016, which was the year the Company X prototype was created, to select the articles, so we collected articles from 2016 to 2023.

The aim of the search was to identify the most cited articles in any language related to the creation of the Company X prototype analyzed on each continent. The Web of Science made possible to identify publication trends in research on SWM, its use in countries and regions, as well as the most cited articles in each continent. In addition, the VOS viewer software [3] (Van Eck and Waltman, Leiden University, Leiden, Netherlands) was used to perform data mining, mapping, and clustering of the retrieved articles (n=3055). Countries were labelled with colored circles, as shown in Figure 3.

The size of the circles was positively correlated with the occurrence of the countries in the title. Therefore, the size of an item's label and circle was determined by the weight of the item. The heavier the weight of an item, the larger the label and circle of the item.

Finally, the articles were organized by citation number and title, and abstract and keywords were analyzed. The exclusion criteria were: No focus on solutions in the context of SWM and non-accessible articles. The most cited articles from each of the 6 continents were filtered and no publications with affiliation from the continent of Antarctica were found.

## 3.3 Step 3 - Analysis with Open Design

We used artifacts from the Open Design Platform (da Silva et al., 2019) to analyze the Company X prototype and 6 other solutions reported in selected articles. We applied two OD artifacts, the first artifact is the Stakeholder Identification Diagram framework, which identifies who can affect or be affected by the solution and we map them into five categories (operation, contributions, source, market and community) that represent their influence on the design.

The second OD artifact is the Evaluation Framework, which makes it possible to survey the Problems

[1] Available in: https://prnt.sc/K94f0G1MD0Uz
[2] https://www.webofscience.com/
[3] https://www.vosviewer.com/

& Stakeholder Questions of interested parties and the possible Solutions & Ideas that may arise from this analysis. The Open Design Platform supported all analysis [4]. We try to explicitly identify the decisions made during the design process and the reasons why those decisions were made.

# 4 RESULTS

## 4.1 Step 1 – The Case of Company X

The study investigated the case of Company X in its real context that idealized the solution for reading and measuring residential water consumption in a SWM prototype in 2016. The objective was solving problems of measuring residential water meters that were done manually in a complex, repetitive process, prone to human and bureaucratic errors.

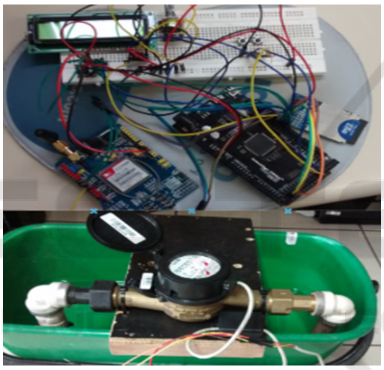

Figure 2: Company X prototype.

In the design process, the perspectives of two systems analysts, a supervisor of residential water meter reading and metering services, a general services assistant, and a commercial director were considered as stakeholders. Thus, there were a total of 6 participants (n =6) in the project, all members were senior in their roles and had high technical knowledge of the context in which they intended to solve the problem.

As presented in the Figure 2, Company X created the prototype that contained IoT hardware items such as flow sensors, Wi-Fi module, GSM module, SD storage card, LCD screen, power supply, wires, resistors, protoboard, and mechanical water consumption meter.

Another part of the solution had a communication software that recorded the flow through a text file on an SD card, marking the date/time when the measurement was made. All data was sent by message via 3G connection, to a server that made the information available to the Web and Mobile applications.

Data collected from Company X subsidized information used to understand the on-site design environment of an SWM, as well as the experiences of the participants, contributed to the completion of the Stakeholder Diagram.

[4] Available in: https://opendesign.ic.unicamp.br/p/flavio-halves/SWM/

## 4.2 Step 2 – Bibliometric and Visual Analysis

Three thousand and fifty-five articles on smart water meters published between 2016 and 2023 were retrieved from the Web of Science database. There was a tendency to increase the number of publications between 2016 and 2023, the aggregate increase for the period is approximately 81.08%.

The number of publications peaked (592 articles) in 2022. The publications came from 79 different countries. Among these countries, the People's Republic of China published the largest number of articles (702), followed by the United States (539) and England (239).

The VOS Viewer software was used to analyze the network visualization of co-authorship relationships between countries. Only countries with a minimum of 5 cited articles were included. Of the 79 countries that reached the threshold, the People's Republic of China was at the center of SWM research and was in closely collaborated with India, Iran, and South Korea (Figure 3).

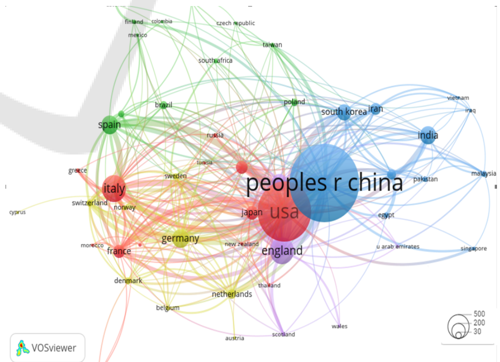


Figure 3: Network map showing the relationships between various countries in the SWM area.

Substantial research collaborations were also noted between the United States and other countries, including Italy, Japan, and France. Brazil has some expression with other countries, especially with Spain.

The terms stand out in large five clusters (Figure 4), with themes that were also concerns of those involved in the prototype of Company X, reported in the previous section (4.1 Step 1 – The Case of Company X), such as, for example, difficulty with the source of "energy" (yellow cluster) to keep the devices connected, how to "measure" (green cluster) the "flow" in case of power or "load" outage, how to solve the unavailability of the "network" (red cluster) to send data to the server and how to identify and process data with other water "properties" (blue cluster).

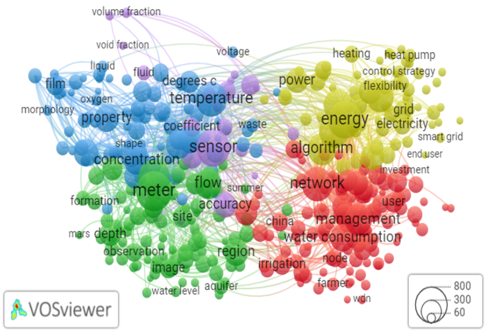


Figure 4: Most commonly used terms in titles and abstracts.

Among other related terms, characterizing the challenges present over the years, such as few studies with qualified results, limited experiences, and meters that offer different technologies, among others.

Table 1: Most cited articles on their continents.

| ID | DOI | Affiliation | Continent | Times Cited |
|---|---|---|---|---|
| 135 | 10.1016/j.compeleceng.2019.05.006 | Pakistan | Asia | 61 |
| 139 | 10.1016/j.envsoft.2017.12.015 | Australia | Oceania | 60 |
| 194 | 10.1016/j.watres.2018.11.035 | South African | Africa | 48 |
| 195 | 10.3390/su9040582 | Spain | Europe | 48 |
| 203 | 10.1016/j.envsoft.2020.104633 | North Carolina | North America | 16 |
| 480 | 10.1007/s10661-020-08535-4 | Peru | South America | 25 |

According to the above-mentioned criteria, the articles selected for the analysis step with the Open Design Platform are presented in order of highest citation in Table 1.

## 4.3 Step 3 – Analysis with Open Design

To start using the Open Design Platform, we collected the information provided by the Case of Company X, to select the elements that make up the Stakeholder Identification Diagram (Figure 5). The prototype was developed by the company in 2016 and unlike the cases identified in the literature, we had access to user feedback and interacted with the various stakeholders.

We obtained a total of 37 stakeholders allocated to the different layers of the artifact. The Company X's case made it possible to include elements that were cited and reported in the process of creating and developing SWMs.

### 4.3.1 Stakeholder Identification Diagram

In the 'Operation' layer, stakeholders considered technical were identified, such as system analysts and managers. They were directly involved in solving technical processes such as information integration, cost, business rules, communication, hardware, and software.

In the 'Contributions' layer, we identified parties that directly contribute with information to the creation of the SWM or were affected by it, i.e., Sanitation Company and Water Resources Managers, are those who have much information, by having involvement with consumers, suppliers, with technical parties such as chemists responsible for the analysis of water purity.

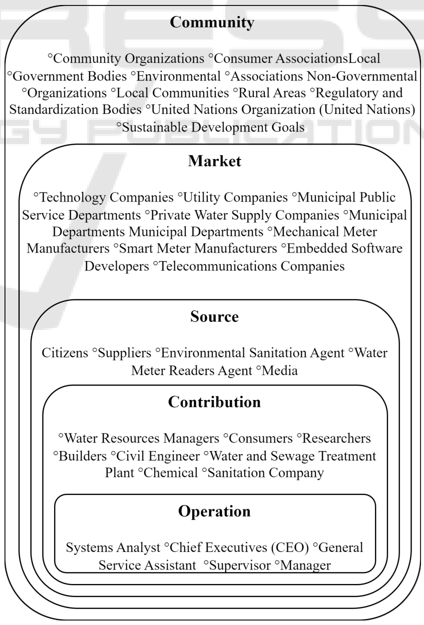


Figure 5: Stakeholder identification diagram, selected from the case of Company X.

In the 'Source' layer, sources of information, such as the media, consumers, and potential users of SWM, such as citizens of a region, were identified. The 'Market' layer was primarily composed of agencies and departments that offered and controlled water consumption.

Composing the 'Community' layer, we find representatives with concerns about the social context, about data security policies, such as the Regulatory and Standardization Bodies, or organizations and actions focused on sustainability, such as, for example, the United Nations Organization (United Nations) and Sustainable Development Goals (SDGs).

These community members play a significant role, as they can establish legal regulations and formal norms that direct strategy in raising awareness of the use of natural resources with water.

#### 4.3.2 Evaluation Framework

By classifying and organizing the stakeholders, it was possible to clarify the needs of each agent and raise their 'Problems & Questions' in a systemic way. We selected 43 problems and open questions identified in the case of the company and in the review of the selected articles.

We have separated some of the problems and questions raised and illustrated them in Figure 6. It is possible to access the data in full through the address provided . Figure 7 shows a part of the result of the artifact from the Open Design Platform 'Solutions & Ideas' selected in the artifacts 15 Ideas and Solutions were generated in a specific context of water availability and sustainable management.

#### 4.3.3 Problems & Stakeholder Questions

In the 'Operation' layer, 12 problems and questions related to the technical concerns were identified (Figure 6), the most cited topics are about energy (Company X - Energy) to keep SWM active, network availability (Company X - Network) for data traffic, lack of standardization of the proposed solutions (ID 195 - Lack of Standardization) hindering replicability and data security.

In addition to the variability of the data (ID 203 - Data Variability) in water consumption caused by factors such as different end users, seasonality and socioeconomic conditions of users. This variability makes it challenging to accurately predict water consumption.

Regarding the 'Contribution' layer, costs related to acquisition and installation (Company X - Acquisition Cost) in homes were a concern raised, as it was not defined who will bear this financial investment. Current degraded infrastructure can be an aggravating factor to more financial commitment (ID 139 - Outdated Infrastructure Design).

Emphasizing that current urban water system designs are often based on outdated data and assumptions about water consumption and billing patterns, leading sustainability to unnecessary oversizing of infrastructure (ID 480 - Monthly Billing and Lack of Awareness).

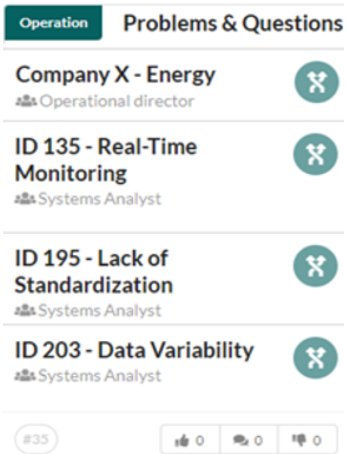


Figure 6: Fragment of the Evaluation Framework by selecting Problems & Questions.

In the category of 'Source', questions and problems that affect citizens due to sensationalist news are present (ID 194 - Disinformation); they can influence the exacerbated consumption of water.

SWM can influence the perception of water as a commodity and not as a common good, leading to a change in the subjectivities of citizens (ID 195 - Impact on Citizen Subjectivity that can add value when considering that water is private property, not a natural resource that must be accessible to everyone for consumption and survival.

Topics listed in the 'Market' category reflect topics such as excessive cost of implementation and maintenance (ID 195 - High Initial Cost), SWM compared to conventional meters, which can be a financial challenge. On the financialization of water companies (ID 195 - Financialization of Water) and the role of smart metering in increasing their revenue streams, which may have wider societal implications, in which water is primarily seen as an investment opportunity and source of profit.

The 'Community' layer has broad problems and questions that involve legislators and competent people that aim at the well-being of all. There are concerns about privacy issues related to the collection of water consumption data, especially about customer data (ID 195 - Privacy Concerns).

Sustainability issues such as water scarcity in many parts of the world, which affects agricultural processes (ID 135 - Water Scarcity) that use water indiscriminately, for example, existing drip irrigation systems are considered inefficient due to minimal water control. irrigation amounts. We can consider it, especially in varied conditions such as day and night times and different seasons (ID 135 - Inefficient Irrigation Systems).

The case of Company X highlights an imminent concern in the case of replacing mechanical meters with SWMs: what to do with the mechanical meters that are replaced is also an open problem. (Company X - Disposal of Replaced Meters).

## 5 DISCUSSION ON SOLUTIONS & IDEAS FOR PROBLEMS & QUESTIONS

Solutions & Ideas identified in the case of Company X and in the selected articles, accounted for 15 items. A fragment of the Solutions & Ideas from the Evaluation Frame artefact is represented in Figure 7. We can consider few Solutions & Ideas when we relate to the Problems and Questions listed.

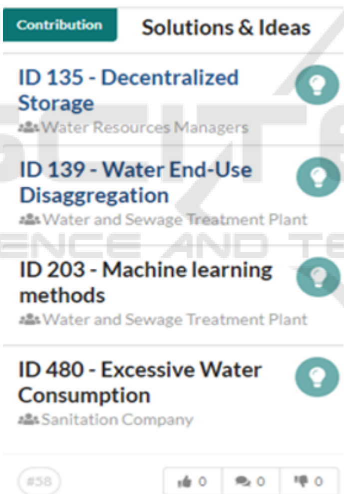


Figure 7: Fragment of the Evaluation Frame selecting Solutions & Ideas for Problems & Questions.

Company X did not resolve questions raised in the process of creating its prototype, which led to the discontinuation of the project. Other solutions proposed in the selected articles emphasized the analysis of data, which were collected in nations that have an elevated level of economic and social development.

The United States (ID 203 - Support Vector Regression (SVR) - ID 203 - Artificial Neural Networks (ANNs) - ID 203 - Random Forests (RFs)) and Australia (ID 139 - Water End-Use Disaggregation), which will already propose an analysis of the end use of water, how to autonomously categorize water consumption data into different categories, such as leaks, washing machine, shower, irrigation, etc. This differentiation helps both water service providers and customers understand how water is being used, enabling better insights into consumption patterns.

Other solutions and ideas match the local reality of regions, countries, and nations with less developed economies and lower living standards compared to developed countries that have failed to deploy SWM to use the data and information to improve their services, such as Cape Town on the African Continent (Booysen et al., 2019) which discusses the water crisis faced and consumer responses to the threat of rationing and shortages.

Solutions are proposed to understand the dissemination of information (ID 194 - Media's Role in Shaping Perceptions). The media's interpretation and discussion of the advertisements contribute to the public's perception of the crisis and play a significant role in driving behavioural change in the population.

Internet searches and social media activity were used to play a crucial role in informing the population, helping them to understand their vulnerability to the water crisis and their capacity to respond (ID 194 - Importance of Public Engagement).

Like Company X's prototype, the Peru project on the South American Continent (Fuentes and Mauricio, 2020) achieved related results, providing a comprehensive solution for real-time water consumption and billing measurement (ID 480 - Monthly Billing and Lack of Awareness), and leak detection, addressing the questions of inefficient water use and lack of timely data.

However, the solution was consolidated in only one bench prototype and was not applied in a real context. These advantages need to be balanced with challenges related to standards, costs, privacy, and impact on user behavior.

## 6 CONCLUSION

Water scarcity, combined with consumption control and efficiency challenges, is a concern. When investigating the case of Company X and analyzing the selected articles using the Open Design methodology, significant technical and social challenges associated with the implementation of SWMs become evident.

The prototype designed by Company X left problems and doubts opened in 2016 trying to solve the problem that remains current, despite adopting an innovative approach that uses IoT communication hardware and software to monitor residential water consumption.

By carrying out the bibliometric analysis it was possible to identify notable contributions from countries such as China, the United States and Brazil. There is evidence of collective effort to face water management challenges.

The open design methodology contributed by systematically identifying the perspectives of interested parties, highlighting different concerns and needs in different layers of society, bringing useful elements to the discussion for the participatory and effective construction of SWM.

The study contributes significantly to understanding and addressing critical issues related to water management in smart cities, offering relevant knowledge, innovative solutions and a collaborative methodology to address these challenges effectively and sustainably.

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