energies

MDPI

Article

Perspectives on the Advancement of Industry 4.0 Technologies Applied to Water Pumping Systems: Trends in Building Pumps

Danilo Ferreira de Souza [1,2,*], Emeli Lalesca Aparecida da Guarda [3], Welitom Ttatom Pereira da Silva [1], Ildo Luis Sauer [2] and Hédio Tatizawa [2]

1 Faculty of Architecture, Engineering and Technology—FAET, Campus Cuiaba, Federal University of Mato Grosso, Cuiabá 78060-900, Brazil; wttatom@gmail.com
2 Institute of Energy and Environment—IEE, University of Sao Paulo—USP, Sao Paulo 05508-010, Brazil; illsauer@iee.usp.br (I.L.S.); hedio@iee.usp.br (H.T.)
3 Environment Comfort Laboratory, Federal University of Santa Catarina, Florianopolis 88040-900, Brazil; emeliguarda@gmail.com
* Correspondence: danilo.souza@ufmt.br

Abstract: The rational use of energy systems is one of the main discussions in sustainability in the 21st century. Water pumping systems are one of the most significant consumers of electricity in urban systems, whether for urban water supply, sewage, or use in vertical buildings. Thus, this work aims to present Industry 4.0 (I4.0) technologies applied in buildings' water pumping systems, focusing on energy efficiency, supervision, and control of the pumping system. The work involves four steps: (i) identifying the existing I4.0 technologies and (ii) mapping the possibilities of applying Industry 4.0 technologies in building pumping systems. The study includes the analysis of (16) articles published in journals between 2018 and June 2021 to identify I4.0 technologies cited in the publications. It identified and grouped eighteen (18) technologies based on twenty-two (22) terms observed in the papers. The study classified the identified technologies into three possible applications in a building water pumping system. The applications include: (i) directly applicable, (ii) partially applicable, and (iii) application not yet identified. Therefore, the study presents the advantages of I4.0 technologies developed primarily for the industry sector, also applicable in residential building water pumping systems. These technologies' benefits include energy efficiency, user control, a reduction from periods of failure of the pumping system (maintenance), water quality, and moving towards Intelligent Pumping or Pumping 4.0.

Keywords: Intelligent Pumping; buildings; Internet of Things; sustainability

Citation: de Souza, D.F.; da Guarda, E.L.A.; da Silva, W.T.P.; Sauer, I.L.; Tatizawa, H. Perspectives on the Advancement of Industry 4.0 Technologies Applied to Water Pumping Systems: Trends in Building Pumps. *Energies* **2022**, *15*, 3319. https://doi.org/10.3390/en15093319

Academic Editor: Nikolaos P. Theodossiou

Received: 30 March 2022
Accepted: 29 April 2022
Published: 2 May 2022

1. Introduction

In ancient times, access to water was a limiting factor in human development and quality of life. The development of water pumps allowed humans to overcome this challenge [1]. From hunter-gatherers to early farmer-herders, energy sources for pumping power included human labour (manual pumping), animal labour, and forces of nature (wind and water, i.e., gravity). Thus, since ancient times, the quest for efficiency in water and energy use has been important for human development [2].

According to the United Nations (2019), 55% of the world's population concentration is in cities [3]. It is estimated that 2.5 billion people will be added to the urban population by 2050, leading to a greater than 50% increase in people living in urban areas. In this sense, society's need/energy demand will increase.

The building construction sectors combined are responsible for almost one-third of total global final energy consumption and nearly 15% of direct CO_2 emissions, and energy demand from buildings and building construction continues to rise [4]. Given this, it is observed that the need for infrastructure, such as water pumping in buildings, can intensify. For example, in vertical buildings, one of the sources of energy consumption is water pumping systems. Urban water supply systems consume between 1 and 4% of a municipality's electricity; they are usually the most significant single electricity consumer, and from capture to final use in homes, urban pumping systems can consume 3.3 kWh/m^3 [5].

In this context, continuous urban growth will lead to an increase in megacities with more than 10 million inhabitants and the number of vertical multifamily housing buildings, making this type of building an attractive option [6,7]. Therefore, high energy demand becomes one of the answers to the verticalization of buildings, as there is a direct relationship between the height of the building versus population density versus the pumping system. Thus, these systems must be efficient and have low amounts and frequencies of failures, to fit into essential equipment for residential buildings.

There are two indicators to advance pumping system energy efficiency—the minimum standard called the Minimum Energy Performance Standard (MEPS) and the equipment efficiency labels, which inform consumers about the equipment's energy efficiency level [8].

MEPS and labels are updated over the years according to improvements in materials and equipment designs, making it possible to manufacture on a commercial scale with increasing efficiency. Electric motors and hydraulic pumps are the equipment with the most significant reductions in energy losses in pumping systems [9]. However, the efficiency indicators of this equipment tend to stabilize due to the theoretical limits of the technologies [10,11]. Thus, in the short term, there is no prospect that new technologies for electric motors and pumps will present for a significant increase in efficiency [11].

In this way, the following performance gains are in the optimal dimensioning of the installation and the search for the pumping system operation in the best performance region [12]. Thus, the subsequent advances will be in process management and pre-identification of problems that cause a pumping system to stop.

Since 2011, the management of an industrial process has changed significantly from the technologies of Industry 4.0 (I4.0), with a strong tendency towards computerization of the manufacture and manufacture of products, concepts of safety, efficiency, and sustainability [13], in addition, to be in line with the need to improve efficiency in water pumping systems. I4.0 advances and trends point to cities and buildings becoming intelligent, efficient, and sustainable [14–17], with pumping systems becoming important.

The central question of this research is to answer the following question: What are the technologies to be implemented in building water pumping systems so that they are considered Intelligent Pumping? From this perspective, this work aims to map the application possibilities of I4.0 technologies, which can be applied to water pumping systems in buildings, and to propose a flexible architecture for the application.

2. Methodology

The proposed methodology includes: (i) identification of the leading technologies of I4.0 and (ii) mapping of application possibilities of the I4.0 technologies, as shown in Figure 1.

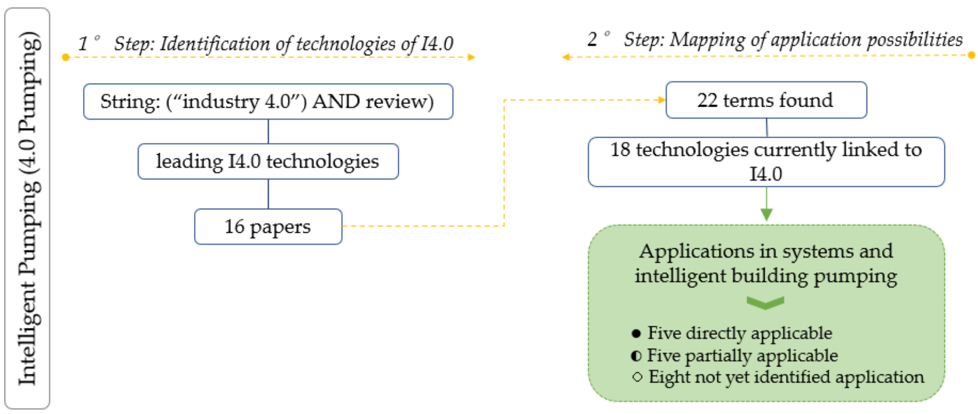

Figure 1. Flowchart of the methodological steps of the study.

A typical pumping arrangement in a building system is composed of an upper and lower reservoir, pump motor set, suction, and discharge pipes. The water originates from the public supply system and is then conducted to the reservoir units, and later flows by gravity to the housing units of the building. To see more details of the typical building pumping system considered in this study, consult the model available in [18].

Traditional pumping systems are activated based on two conditions: (i) the presence of water in the lower reservoir unit and (ii) a low level of water in the upper reservoir unit. With these conditions, a float switch in each reservoir interconnected in a series turns the pumping system on and off by an electromagnetic switch (contactor), as shown Figure 2. The system can be energized during the day and activated only by the two conditions.

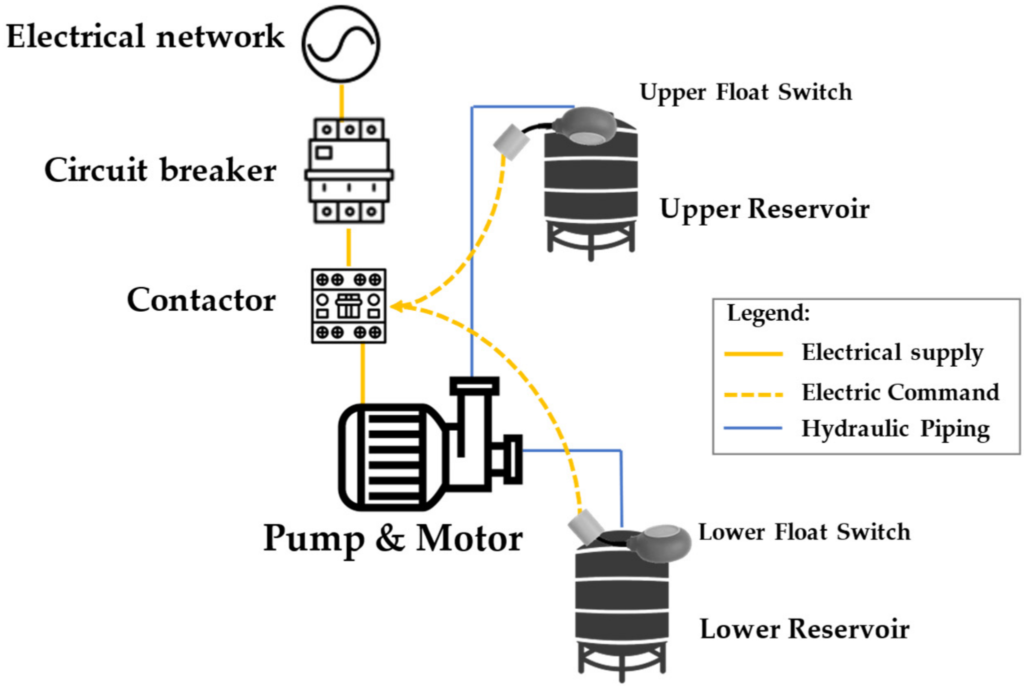

Figure 2. A traditional electrical schematic of the pumping system.

2.1. Identification of the Main Technologies of I4.0

Identifying the leading I4.0 technologies depended on a review of the literature and considered publications from 2018 to June 2021. The Scopus scientific base was used, applying the keyword, and review and industry 4.0 was restricted to English-language titles.

The concept of I4.0 comprises a variety of technologies that often cannot be distinguished clearly. There are several solidly defined methods to apply I4.0 technologies in manufacturing processes in small, medium, and large companies. Then, sixteen (16) papers were selected, as presented in Table 1.

Through the identification of the leading I4.0 technologies, six most common grouped terms were obtained, namely: Intelligent Sensors, Big Data & Data Mining, Cloud & Edge Computing, Machine Learning & Artificial Intelligence, Internet of Things (IoT), Human Machine Interface (HMI), Systems Integration & Network Operation, and Cyber Security, which were mapped in selected papers and their application possibilities discussed in relation to building pumping systems.

Table 1. I4.0 review papers published between 2018 and 2021.

#	Title	Journal	Year	Reference
1	From technological development to social advance: A review of Industry 4.0 through machine learning	Technological Forecasting and Social Change	2021	Lee and Lim [19]
2	Industry 4.0 as a data-driven paradigm: a systematic literature review on technologies	Journal of Manufacturing Technology Management	2021	Klingenberg et al. [20]
3	Industry 4.0: A technological-oriented definition based on bibliometric analysis and literature review	Journal of Open Innovation: Technology, Market, and Complexity	2021	Rupp et al. [21]
4	Evolutions and revolutions in manufacturers' implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework	Production Planning & Control	2021	Calabrese et al. [22]
5	Industry 4.0 triggered by Lean Thinking: insights from a systematic literature review	International Journal of Production Research	2020	Bittencourt et al. [23]
6	Maintenance transformation through Industry 4.0 technologies: A systematic literature review	Computers in Industry	2020	Silvestri et al. [24]
7	Industry 4.0 in the port and maritime industry: A literature review	Journal of Industrial Information Integration	2020	De la Peña Zarzuelo et al. [25]
8	Industry 4.0 and its impact in plastics industry: A literature review	Journal of Industrial Information Integration	2020	Echchakoui and Barka [26]
9	Information and digital technologies of Industry 4.0 and Lean supply chain management: a systematic literature review	International Journal of Production Research	2020	Núñez-Merino et al. [27]
10	The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review	Advances in Mechanical Engineering	2020	Sartal et al. [28]
11	The role of crowdsourcing in industry 4.0: a systematic literature review	International Journal of Computer Integrated Manufacturing	2020	Vianna et al. [29]
12	The smart factory as a key construct of industry 4.0: A systematic literature review	International Journal of Production Economics	2020	Osterrieder et al. [30]
13	Industry 4.0: A bibliometric review of its managerial intellectual structure and potential evolution in the service industries	Technological Forecasting and Social Change	2019	Mariani and Borghi [31]
14	Industry 4.0 in management studies: A systematic literature review	Sustainability	2018	Piccarozzi et al. [32]
15	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	Process Safety and Environmental Protection	2018	Kamble et al. [13]
16	Industry 4.0 framework for management and operations: a review	Journal of Ambient Intelligence e Humanized Computing	2018	Saucedo-Martínez et al. [33]

2.2. *Mapping of Application Possibilities of I4.0 Technologies in Building Pumping Systems*

The discussion of possibilities and the presentation of possible gains were developed by explaining the positive and negative points derived from applying appropriate I4.0 technologies to the case. Subsequently, the discussion of the implementation of the leading I4.0 technologies is presented in the research so that the pumping system can be considered Intelligent Pumping (4.0 Pumping) in a building system. The objective is to verify the possibilities of classifying the I4.0 technology, aiming at the gain in the useful life of the water pumping system, the connectivity with the user, and the increase in the energy efficiency of the building pumping system.

After surveying the leading I4.0 technologies (Table 1), 18 technologies are currently linked to I4.0 (Table 2), as the study identified and grouped according to the 22 terms found.

Table 2. Overview of I4.0 pillar concepts found in literature review papers.

Item	Technologies Linked to I4.0	Application in Building Water Pumping Systems	References Analyzed
1	Smart Sensors	•	[17,34–38]
2	Big Data & Data Mining	•	[17,39]
3	Cloud & Edge Computing	•	[39,40]
4	Machine Learning & Artificial Intelligence (AI)	•	[39–45]
5	Internet of Things (IoT)	•	[35,40]
6	Human Machine Interface (HMI)	◐	[46]
7	Systems Integration & Network Operation	◐	[47,48]
8	Cyber Security	◐	[49]
9	Autonomous Robotics	○	-
10	Automatic identification and digital product memory	○	-
11	3D printing	○	-
12	Augmented Reality or Virtual Reality	○	-
13	Simulations	◐	[6,50]
14	Additive and Intelligent Manufacturing	○	-
15	Machine-to-Machine (M2M) Communication	○	-
16	Knowledge-Based Systems (KBS) & Semantic Web	◐	[51]
17	Automated guided vehicles (AGV)	○	-
18	Cyberphysical Systems	○	-

• Directly applicable. ◐ Partially applicable. ○ Not yet identified application.

The technologies linked to I4.0 were classified into three possibilities based on the reading of the analyzed references: directly applicable, partially applicable, and still unidentified application. In Table 2, the 18 technologies linked to I4.0 are classified according to the current possibilities (2022) of application in building water pumping systems to implement Pumping 4.0 or Intelligent Pumping.

3. Industry 4.0: Applications in Systems and Intelligent Building Pumping

This section discusses I4.0 technologies that can be considered viable applications for building pumping systems, that is, technologies linked to I4.0 aimed at building the concept of Intelligent Pumping.

The identification of the possibilities of application of I4.0 technologies in pumping building systems took place through the analysis of compatibility, comparison, and feasibility of I4.0 technology versus pumping building systems. Also presented are successful applications of I4.0 technologies used in pumping systems in industry and sanitation.

3.1. Mapping and Identification of I4.0 Technologies Applicable in Building Pumping Systems

3.1.1. Smart Sensors

The use of sensors is essential for inserting a process in I4.0. The sensors can also monitor the system's energy efficiency and production of indicators that allow monitoring parameters and preventive maintenance programming to avoid downtime due to failure. The equipment (e.g., electric motor and centrifugal pump) can emit signs indicating acceleration of degradation. Therefore, evaluating the degradation throughout the life span of the equipment is essential. This way, machines and equipment's operating condition and integrity are monitored. Figure 3 is a typical degradation pattern of electrical and mechanical equipment.

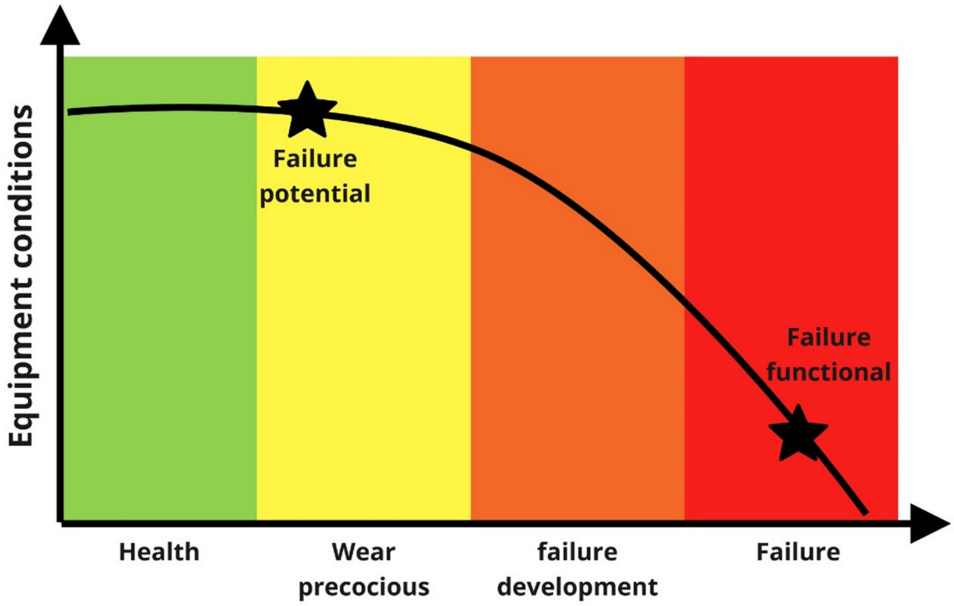

Figure 3. PF curve represents the condition of a component until functional failure. Source: Adapted from [52].

The point of functional failure is when the equipment fails to provide its intended function. Condition-based maintenance aims to detect the potential failure before the actual failure occurs. In this case, maintenance actions can be planned before the functional failure, with advantages such as reducing downtime, eliminating unexpected production stops, maintaining downtime, eliminating unexpected production stops, maintaining optimization, and reducing spare parts inventory.

Sensors for Hydraulic Measurements and Water Quality

A smart water network would integrate sensors, controls, and analytical components to ensure quality and efficient water supply. Smart meters and end-use detection devices can aid in leak detection. For example, continuous data from a smart residential meter can reveal a leak, showing a positive water flow when all accessories are off [17].

A theoretical smart water network starts at water harvesting, where smart meters, smart valves, pumps, and smart sensors are installed, with continuous monitoring along the water path, through the water treatment steps with more meters, valves, and smart pumps.

Within the city's water distribution system, water contaminant sensors are applied. End-use sensing devices, smart irrigation controllers, contaminant sensors, and smart meters can be used at end-user sites. Finally, the water goes through the sewage system to treat effluents, and the same technologies used at the beginning of the system are also used [34].

The quality of the water consumed by users can be affected by several factors, such as various contaminants, materials from corrosion of the pipe, distribution, accidents, and even terrorism. Contaminant sensors in a smart water network can alert consumers to potential problems before consumption [34].

The persistent storage of measured data allows for monitoring possible changes in water quality parameters (physical, chemical, and biological parameters). It can even prevent a series of diseases transmitted by water via analyzing data from measures of domestic water. (Potential of hydrogen; Turbidity; Temperature; Reduction of oxidation potential; Electrical conductivity), providing a preliminary laboratory analysis if necessary. The data collected can indicate deviations in standards and anomalies and predict future water quality trends using machine learning techniques. If the water is not within acceptable standards, the pumping system is not activated [35].

Sensors for Measuring Mechanical Quantities

Analyzing mechanical vibration data from electric motors is universally accepted as an excellent technique for detecting mechanical failures, especially among the most common failures, such as alignment defects, bearing failure, mechanical load breakdown, and ventilation [36].

Using smart sensors for vibration, acoustic, and flow measurements makes it possible to identify pump parameters variations. The set of sensors makes it possible to predict cavitation problems, one of the leading causes of pump downtime. Sensing can guarantee the optimal functioning of the centrifugal pump at different operating points [37].

Vibration sensors (accelerometers), in addition to being low cost, are reliable for early detection of failures of both the electric motor and the centrifugal pump, enabling optimization and maintenance planning and reducing the probability of failure [38].

Sensors for Measuring Electrical Quantities

Changes in the form of the electric current wave, also known as the electrical signatures of electric motor currents, are an essential way of applying methodologies to detect rotor problems, stator asymmetries, defects in the cooling system, and faults in the bearings or the coupling system. These failures reduce the efficiency of the electric motor before bringing the equipment to a complete stop [53].

Electronic current waveforms are collected by current sensors installed in the electrical panels or as part of the electric motor's Variable Speed Drives (VSDs). Figure 4 illustrates the topology with the primary sensors highlighted in the discussion in Section 3.1.1.

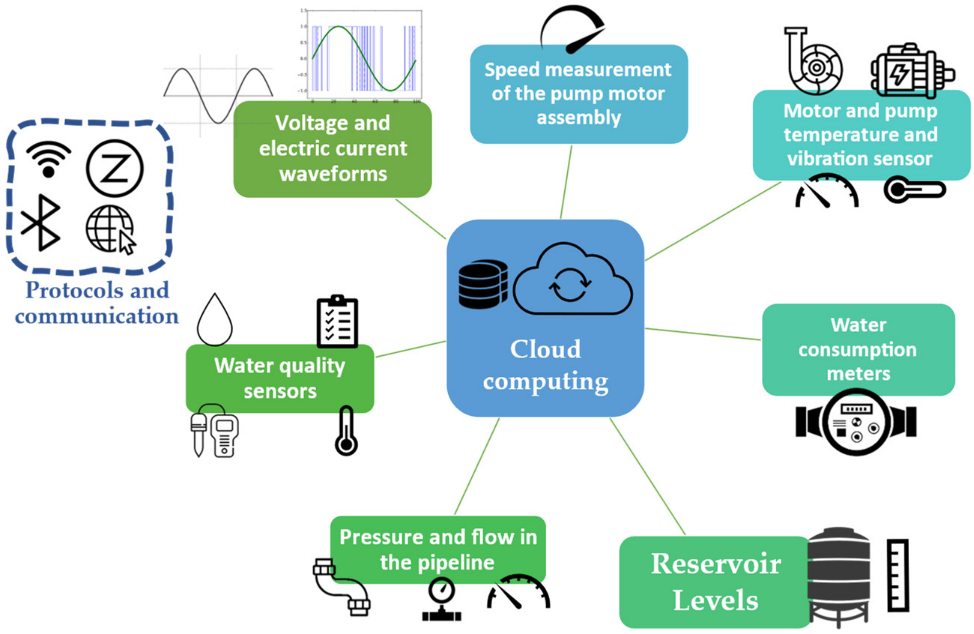

Figure 4. Key Smart Sensor Measurements for Smart Pumping.

The temperature sensors in the electric motor and the centrifugal pump are essential for evaluating the operating condition of this equipment. Upper and lower reservoir level sensors must assess pumping system turn-on moments. The speed transducer (tachometer) to measure the speed of the motor-pump assembly assists in determining the loading of the electric motor and the operating of the pump point. Figure 4 presents items related to cloud computing, big data, and Systems Integration that will be discussed in subsequent topics.

3.1.2. Big Data & Data Mining

The implementation of new sensor monitoring and control technologies, combined with the availability of high computational power, changed the traditional approach to designing and managing water systems and enabled the development of new data-based techniques powered by Big Data [17]. Big Data is already a reality for water supply companies in large cities, but it can also become a reality for water pumping building systems. When smart metering becomes more present in systems, a large amount of data will be collected, stored, and processed to make decisions aimed at improving supply [39].

With the use of smart meters in each consumer unit, it is possible to perform the automatic collection of consumption, self-diagnosis of the system, and monitor the status of the quantity and quality of water, enabling remote management and saving decisions by the user. With this technology applied on a large scale, it will be possible to provide meter readings instantly, generate domestic leak reports for each user, and even send smartphone alerts [39]. In addition to this term, others such as Cloud & Edge Computing, Machine Learning & Artificial Intelligence, Internet of Things IoT, Human Machine Interface (HMI), Systems Integration & Networking, and Cyber Security, are linked to the monitoring and previous solutions of possible system failures and problems.

3.1.3. Cloud & Edge Computing

In pumping systems, cloud computing allows data from sensors and meters installed in the electrical and hydraulic network to be readily available to various stakeholders responsible for asset maintenance or even users. The mass of measurement data is uploaded to the cloud computing facility for continuous analysis [39].

3.1.4. Machine Learning and Artificial Intelligence

The optimization of the water pumping system, aiming at the lowest consumption of electricity, and meeting the need for water supply, can be carried out using Variable Speed Drives (VSDs). Combining machine learning and Artificial Intelligence (AI) to make decisions based on data from pressure and flow sensors in pipes and electricity consumption enables the system to perform at the best efficiency point [41].

Artificial intelligence through machine learning makes it possible to generate algorithms to identify long-term trends that analyse historical data collected from sensors. Long-term trends can inform the maintenance period and enable action before failure occurs. For example, the vibrations of the motor-pump set are one of the leading failure indicators of both the electric motor and the pump [43].

The manufacturer's performance curve of a hydraulic pump shows the region with the best operational efficiency. Pump performance simulations can be carried out using machine learning techniques, thus making it possible to operate at the points or in the best efficiency region, reduce electrical energy consumption, avoid vibrations and excessive wear, improve maintenance, and timely maintenance downtime [44].

In a sanitary sewage pumping system, the flow decreases with the increase in the size of the contamination particle or sludge, for example. With the pressure and flow reading and using a machine learning algorithm, through the knowledge of the system's operating patterns, it is possible to identify the high effort of the system for significant impurity, and to act by turning off the pumping system [45].

3.1.5. Internet of Things (IoT)

In the more general framework of Industry 4.0, the recent development of IoT technologies applied to smart grids has opened up new opportunities in the management of water network systems [17]. Monitoring water quality is critical to consumer health. In this perspective, recently developed systems based on smart sensor technology combined with recent advances in the IoT can contribute to drinking water quality management. It will also inform building users, in real-time, of access to the leading quality indicators of water [35], according to the topology in Figure 4.

Figure 5 presents a simplified schematic of the IoT process for water quality monitoring.

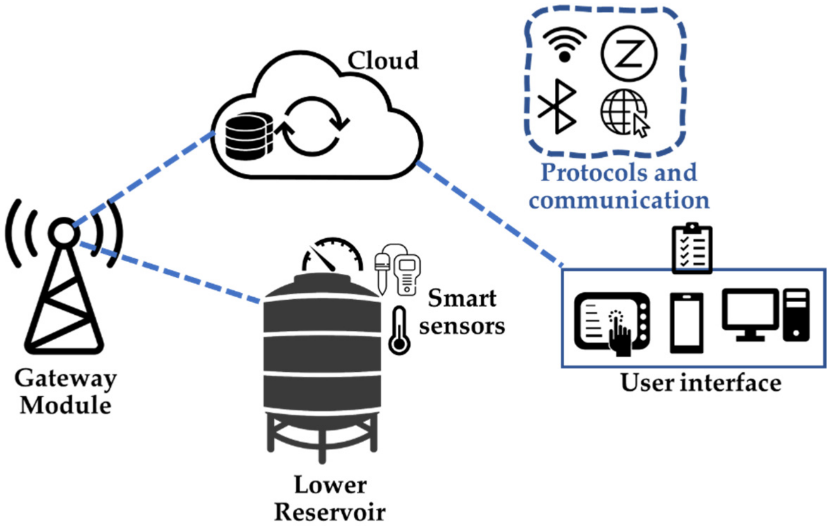

Figure 5. Simplified schematic of the IoT process for water quality monitoring.

The same topology presented in Figure 5 can be applied to several other sensors presented in Section 3.1.1. For example, the application of vibration sensors can be applied in centrifugal pumps for diagnostics of the pump's operating state and in avoiding failures. With data being stored in the cloud, patterns of behaviour are processed and analyzed by Machine Learning and expressed by IoT [40].

3.1.6. Human Machine Interface (HMI)

From the perspective of I4.0, the HMI is a device that mediates the interaction between an operator/user and a pumping system, where the user can give operating commands and visualize the process. Viewing on computers, smartphones, and even displays is entirely possible in this concept. The pumping system visualization process is commonly visualized through a SCADA system (Supervisory Control and Data Acquisition), providing users with an interactive layout of the system.

3.1.7. Systems Integration & Network Operation

The rapid growth of large urban residential areas necessitates the expansion and modernization of existing water pumping facilities. The process automation system based on the use of integration via network operation through industrial protocols, Programmable Logic Controllers (PLC), and Supervisory Control and Data Acquisition (SCADA), represents the best way to improve the technological process of distribution of water [47].

The automation of the pumping system using systems integrated with a network with the support of PLCs that may even be available in VSDs being visualized by SCADA can provide several gains. Such benefits include: general supervision and remote control of all equipment, reliability of measurement data by monitoring, continuity of water distribution and protection of water quality, reduction of water resource losses, detection of water leaks made by monitoring online consumption or pressure drop, real-time alarms triggered by any equipment failure in the pumping system, optimization of exploration and maintenance costs, and preparation of an automated database [48].

3.1.8. Cyber Security

From abstraction to end-use management, evolution in water supply systems through computing hosts, smart sensors, IoT layers, edge computing, wireless networks, and artificial intelligence has increased and will increase the possibilities of cyber-attacks because they operate in a network. Tuptuk et al. (2021) [49] highlighted the importance of protecting water infrastructure from malicious entities that may carry out industrial espionage and sabotage against these systems.

3.2. Implementation of I4.0 Technologies in Building Pumping Systems

Based on the characterization of the technologies linked to I4.0, its implementation is directly related to electronic and computational resources. Thus, one of the main elements of this application is using VSDs to drive and control the pump motor set, enabling the drive and control of the system electronically. VSDs are typically used in applications that need to control the flow of the pumping fluid, and this system has also become advantageous in applications that do not require speed control.

With the implementation of new electric motor technology, VSDs have become even more present in motor systems, as they are mandatory for the operation of motors, such as Permanent Magnet Synchronous Motors (PMSM) and Synchronous Motors. Reluctance Motors (SynRM) should assume a more significant role in the coming years, as they reach higher efficiency levels than the traditional Squirrel Cage Rotor Induction Electric Motors (SCIM) traditionally used in pumping systems [54].

According to Huse et al. 2020 [55], the significant productivity gains with the application of VSDs in electric motors that drive hydraulic pumps to pump water are mainly:

1. Pump speed control maintaining a pressure requested by the system.
2. Applying VSDs reduces motor wear due to reduced speed, vibration, and torque.
3. Soft start of the motor and gradual accelerations to reduce large electrical transients where high-starting currents can cause voltage drops in the electrical network.
4. Soft start of the motor and gradual accelerations, reducing the mechanical stress of the shaft, as well as the thermal stresses in the windings and mechanical stresses in the couplings and belts.
5. Reduction of sudden changes in water speed (transients), which may result in water hammer, cavitation, and vibration of the pump motor assembly [42].
6. A small reduction in speed or flow can significantly reduce energy usage.
7. Reduction in the maintenance fee of the motor-pump set.
8. A total of 20 to 40% energy consumption, a typical 38% water leakage reduction, 53% reduced breakdowns, and extended motor pump life.

A pumping system using VSD is shown in Figure 6.

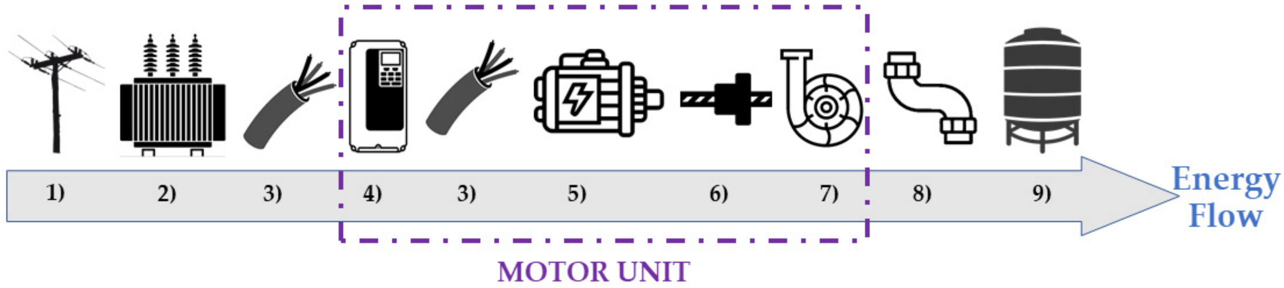

Figure 6. Pumping system using VSD. Source: Adapted from [18].

As one of the pillars of I4.0 is network operation, the role of VSDs in this context is not that of a simple electronic trigger. In addition to being power processors, VSDs have become elements of the information chain, increasingly used as sensors or intelligent controllers. For the application of technologies linked to I4.0, VSDs play a fundamental role, characterized by intelligent action through various resources aimed at continuous connectivity with the various devices, and performing electrical data acquisition and electric motor control [56].

The electrical energy savings achieved are remarkable when controlling the speed of the pumping system using the VSDs. Opportunities to improve the energy efficiency of the water pumping system fall into three distinct categories: (i) component selection, (ii) dimensioning of the pumping system, and (iii) variable speed control of the pumps.

In the context of I4.0, for the formation of Intelligent Pumping, the various elements of the system, such as motors, drives, sensors, and controls, are interconnected and connected to the cloud—where data is stored, processed, and analyzed, and decisions are made as discussed in Section 3.1. After the decision is made, the intelligent equipment that acts as the operation of the Intelligent Pumping System is the VSDs. For this reason, it is the central equipment for the conception of this new concept, as shown in Figure 7.

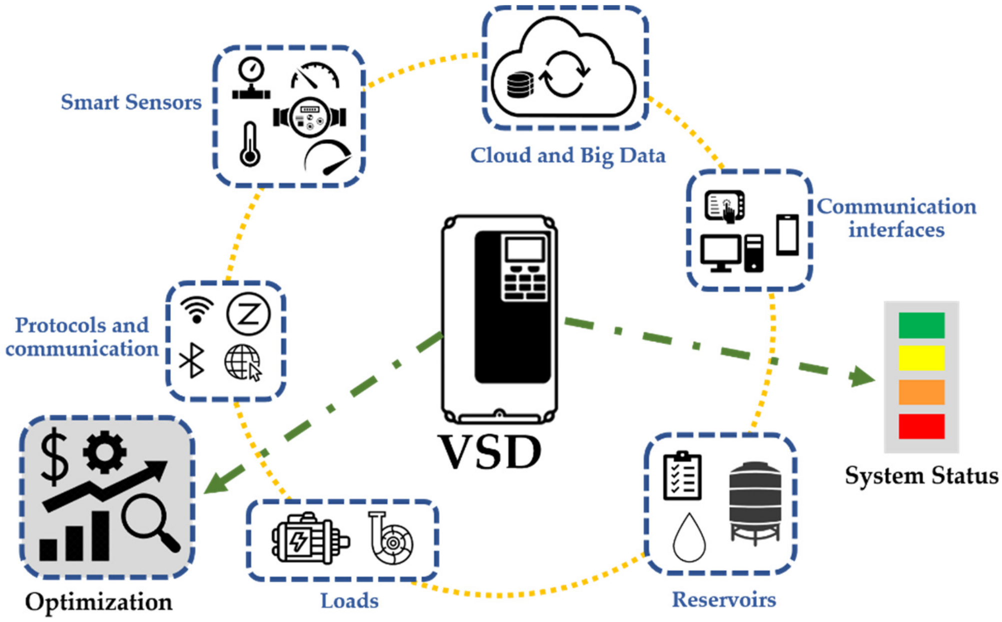

Figure 7. VSD is a core element of Smart Pumping.

3.2.1. Operation at the Point of the Best Performance

To achieve the maximum performance of the motor pump set during its operation (i.e., the different demands from pressure and flow throughout the day), VSDs are commonly used in industrial pumping systems and the sanitation sector. However, the application is still not widespread in pumping systems installed in residential or commercial buildings.

In a building water pumping system, the motor-pump set is designed to meet a specific value of rotations, with this value reaching pressure and flow, providing a specific performance. This is considered the operating point of the system.

The motor-pump set is desired to work with pressure and flow values to meet the variable demand typical of user requests. For this, the VSD controls the speed of the set, seeking operational optimization so that the system operates in the region known as the Best Efficiency Point (BEP). This is when the ratio between the system flow (m^3/h) and the electrical energy consumed (kWh) is the maximum possible.

The location of the operating point is mandatory to optimize the energy efficiency of the pumping system. A VSD-powered pumping application is achieved using an algorithm already available in most current VSDs. Modern VSDs are equipped with conventional flow vs. head (QH) and (QP) to determine pump flow [57].

3.2.2. Demand Side Management (DSM) Using VSD

The DSM is a set of forecasting techniques and demand services based on the balance between supply and demand. Its application has significant success records for industrial pumping stations and the sanitation sector. There are expectations of applicability and success also for the cases of water pumping building systems.

Figure 8 shows operating ranges when the VSD is present. The operating ranges are delimited by the pump curves with nominal speed (N1) and minimum viable speed (N3), and can be explored to reach the best performance point (BEP) of the motor-pump set.

In the building pumping system, the flow demanded by the piping system is modified according to the population's immediate needs (Figure 8; points A, B, and C).

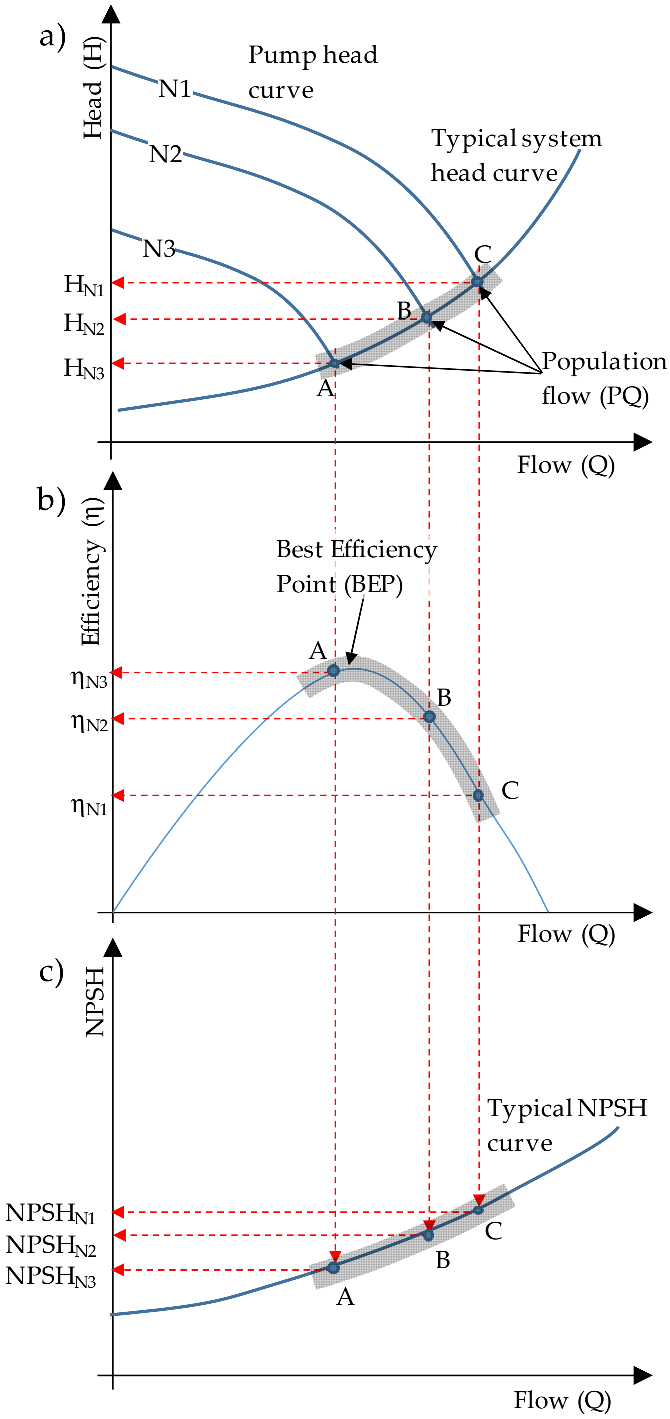

Figure 8. Operating range of centrifugal pump with VSD: (**a**) evolution of Head and Flow with the variable speed; (**b**) evolution of Efficiency and Flow with the variable speed; (**c**) evolution of NPSH and Flow with the variable speed.

The without of VSD means that the head (H), the flow (Q), the yield (η), and the cavitation indicator (NPSH) are kept constant (Figure 8a; point C), disregarding the immediate need of the population. For example, the population's immediate need is at point A, but the motor-pump assembly operates only at point C; or, the population's immediate need is at point B, but the motor-pump assembly operates at point C.

In these cases, the population's immediate needs are served by numerous starts/stops of the motor-pump set (Figure 8a; N1) with short operating times. This reduces the life of the equipment due to the excessive number of starts/stops and the operation with low efficiency, as can be seen in Figure 8b. On the other hand, the presence of the VSD associated with I4.0 and DSM techniques allows the effective use of the operating range (Figure 8a; points A, B, C with curves N1, N2, N3; yields h1, h2, h3, as per Figure 8b; NPSH1, NPSH2, NPSH3, as per Figure 8c). Therefore, increasing equipment life span and reducing operating/maintenance costs (better yields, fewer starts/stops, and operation without cavitation) is important. Essential gains in equipment life span and energy efficiency are obtainable with the right combination of VSD, I4.0, and DSM.

Already, several optimization methods are widely known in the industry and are in use in water pumping building systems, such as Multiobjective optimization [58], Genetic algorithm [20], Mixed-integer nonlinear programming [6], multi-criteria analysis [51], Multi-Objective Mixed Integer Linear Programming [58], and Mixed-Integer Nonlinear Programming [59]. Table 3 shows some optimization methods applied in building water pumping systems.

Table 3. Traditional optimization methods that can be applied in the building water pumping system.

Item	Method	Paper	Journal	Year	Reference
1	Multi-objective optimization	An Updated Survey of GA-Based Multiobjective Optimization Techniques	ACM Computing Surveys	2020	Coello [60]
2	Genetic Algorithm	Decision support for sustainable option selection in integrated urban water management	Environmental Modelling & Software	2008	Klingenberg et al. [20]
3	Mixed-integer nonlinear programming	Optimization and validation of pumping system design and operation for water supply in high-rise buildings	Optimization and Engineering	2021	Müller et al. [6]
4	Multi-criteria analysis	An Analysis on Optimization of Living and Fire Water Supply Systems of Small High-Rise Residential Blocks	Earth and Environmental Science	2017	Yuan [51]
5	Multi-objective mixed integer linear programming	Integrating energy and water optimization in buildings using multi-objective mixed-integer linear programming	Sustainable Cities and Society	2020	Emami Javanmard et al. [58]
6	Mixed-integer nonlinear programming	Optimization of Pumping Systems for Buildings: Experimental Validationof Different Degrees of Model Detail on a Modular Test Rig	Operations Research Proceedings 2019	2019	Müller et al. [59]

3.3. Research Limitations

- The research was limited to evaluating the possibilities of application of I4.0 technologies in a building water pumping system, but these technologies could be applied in other types of drives such as: compression, elevation, ventilation, etc.
- The research did not delve into the discussion of communication protocols between the various systems.
- We recommend continuing the research with the construction of an IoT architecture for application in a pumping system using I4.0 technologies, enabling the experimental validation of the proposal.

4. Conclusions

The building water pumping system is an integral and fundamental part of the services for the proper functioning of the buildings. With the new paradigms of I4.0, buildings also point to integrated and increasingly autonomous intelligence systems.

This research presented some of the technologies of I4.0 that can already be used in water pumping systems for buildings. With the application of the concepts, the improvements are structured into four pillars: (i) increase in the energy efficiency of the system, (ii) increase in the useful life of the system, reducing failures, (iii) improvement in the control and predictability of the system, and (iv) possibility of monitoring.

Most of the research activities on pumping systems focus on water supply systems, heat pumps and irrigation systems in agriculture. There are few concerns in the literature about building water pumping systems, which calls for the need to continue researching the subject.

The application of I4.0 technologies seeking to form intelligent pumping systems will reduce water loss, waste, quality of water consumed, user control, and improvements in energy efficiency and service continuity, moving towards an intelligent and flexible pumping system.

Intelligent sanitation is a fundamental component of the formation of Smart Cities. However, it is necessary to move toward intelligent building systems, promoting the incorporation of Intelligent Sensors, Big Data, IoT, etc. This wave of data brings new possibilities in building water design and management and economic prospects.

For advances in research, more coordination between academia, industry, and government is needed to guide the deployment of smart building systems in the real world. The publications date of the references used in this research demonstrates the current concept of I4.0 and the broad field of application of technologies for the construction of a connected society.

Author Contributions: Conceptualization, D.F.d.S. and E.L.A.d.G.; methodology, D.F.d.S. and E.L.A.d.G.; validation, D.F.d.S., E.L.A.d.G., H.T., I.L.S. and W.T.P.d.S.; investigation, D.F.d.S., E.L.A.d.G. and W.T.P.d.S.; resources, H.T. and I.L.S.; writing—original draft preparation, D.F.d.S., E.L.A.d.G., I.L.S., H.T. and W.T.P.d.S.; writing—review and editing, D.F.d.S., E.L.A.d.G., H.T., I.L.S. and W.T.P.d.S.; supervision, H.T. and I.L.S.; funding acquisition, I.L.S. and H.T. All authors have read and agreed to the published version of the manuscript.

Funding: National Electric Energy Agency (ANEEL): Project number 00390-1086/2018 (ENEL)—Integrated assessment of distributed generation, demand management, monitoring, quality, performance of the network, aimed at optimizing investments and tariff regulation in the underground network, and Project number 00061-0054/2016 (CESP)—Analysis of the efficiency of complementary energy storage with hydroelectric plants, using electrochemical and hydrogen storage technologies; National Council for Scientific and Technological Development (CNPq): Project 870814/1999-0, Process 142323/2020-9.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the National Council for Scientific and Technological Development (CNPq) for the scholarship made available to the first author through the project 870814/1999-0, process 142323/2020-9, so that he could dedicate himself to his PhD research in this and related fields. The authors thank Richardson M Abraham-A for improving the translated manuscript. The authors thank Rodolfo Quadros and João Lopes for reading and contributing to the research. The authors would like to thank the professors of PEA5733-1/4—Automation and Society, responsible for introducing the discussion of Industry 4.0 at the Polytechnic School of Engineering of the University of Sao Paulo. The authors are grateful for the reviewers' criticisms, which contributed to improving this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yannopoulos, S.I.; Lyberatos, G.; Theodossiou, N.; Li, W.; Valipour, M.; Tamburrino, A.; Angelakis, A.N. Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide. *Water* **2015**, *7*, 5031–5060. [CrossRef]
2. Rio Carrillo, A.M.; Frei, C. Water: A key resource in energy production. *Energy Policy* **2009**, *37*, 4303–4312. [CrossRef]
3. *World Urbanization Prospects The 2018 Revision*; UN Department of Economic and Social Affairs: New York, NY, USA, 2019.
4. Abergel, T.; Delmastro, C. *Tracking Buildings 2021*; International Energy Agency: Paris, France, 2021.
5. Plappally, A.K.; Lienhard, V.J.H. Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4818–4848. [CrossRef]
6. Müller, T.M.; Leise, P.; Lorenz, I.S.; Altherr, L.C.; Pelz, P.F. Optimization and validation of pumping system design and operation for water supply in high-rise buildings. *Optim. Eng.* **2020**, *22*, 643–686. [CrossRef]
7. Altherr, L.C.; Leise, P.; Pfetsch, M.E.; Schmitt, A. Resilient layout, design and operation of energy-efficient water distribution networks for high-rise buildings using MINLP. *Optim. Eng.* **2019**, *20*, 605–645. [CrossRef]
8. De Souza, D.F.; Salotti, F.A.M.; Sauer, I.L.; Tatizawa, H.; de Almeida, A.T.; Kanashiro, A.G. An assessment of the impact of brazilian energy efficiency policies for electric motors. *Energy Nexus* **2021**, *5*, 100033. [CrossRef]
9. Arun Shankar, V.K.; Umashankar, S.; Paramasivam, S.; Hanigovszki, N. A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system. *Appl. Energy* **2016**, *181*, 495–513. [CrossRef]
10. Bortoni, E.C.; Bernardes, J.V.; da Silva, P.V.V.; Faria, V.A.D.; Vieira, P.A.V. Evaluation of manufacturers strategies to obtain high-efficient induction motors. *Sustain. Energy Technol. Assess.* **2019**, *31*, 221–227. [CrossRef]
11. De Almeida, A.; Fong, J.; Brunner, C.U.; Werle, R.; Van Werkhoven, M. New technology trends and policy needs in energy efficient motor systems—A major opportunity for energy and carbon savings. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109384. [CrossRef]
12. Carravetta, A.; Giugni, M.; Malavasi, S. Application of innovative technologies for active control and energy efficiency in water supply systems. *Water* **2020**, *12*, 3278. [CrossRef]
13. Kamble, S.S.; Gunasekaran, A.; Gawankar, S.A. Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Saf. Environ. Prot.* **2018**, *117*, 408–425. [CrossRef]
14. Shaikh, P.H.; Nor, N.B.M.; Nallagownden, P.; Elamvazuthi, I.; Ibrahim, T. A review on optimized control systems for building energy and comfort management of smart sustainable buildings. *Renew. Sustain. Energy Rev.* **2014**, *34*, 409–429. [CrossRef]
15. Ding, Z.; Liu, R.; Li, Z.; Fan, C. A thematic network-based methodology for the research trend identification in building energy management. *Energies* **2020**, *13*, 4621. [CrossRef]
16. Lytras, M.D.; Visvizi, A. Who uses smart city services and what to make of it: Toward interdisciplinary smart cities research. *Sustainability* **2018**, *10*, 1998. [CrossRef]
17. Di Nardo, A.; Boccelli, D.L.; Herrera, M.; Creaco, E.; Cominola, A.; Sitzenfrei, R.; Taormina, R. Smart urban water networks: Solutions, trends and challenges. *Water* **2021**, *13*, 501. [CrossRef]
18. De Souza, D.F.; da Guarda, E.L.; Sauer, I.L.; Tatizawa, H. Energy Efficiency Indicators for Water Pumping Systems in Multifamily Buildings. *Energies* **2021**, *14*, 7152. [CrossRef]
19. Lee, C.; Lim, C. From technological development to social advance: A review of Industry 4.0 through machine learning. *Technol. Forecast. Soc. Chang.* **2021**, *167*, 120653. [CrossRef]
20. Klingenberg, C.O.; Borges, M.A.V.; Antunes, J.A.V. Industry 4.0 as a data-driven paradigm: A systematic literature review on technologies. *J. Manuf. Technol. Manag.* **2021**, *32*, 570–592. [CrossRef]
21. Rupp, M.; Schneckenburger, M.; Merkel, M.; Börret, R.; Harrison, D.K. Industry 4.0: A technological-oriented definition based on bibliometric analysis and literature review. *J. Open Innov. Technol. Mark. Complex.* **2021**, *7*, 68. [CrossRef]
22. Calabrese, A.; Levialdi Ghiron, N.; Tiburzi, L. 'Evolutions' and 'revolutions' in manufacturers' implementation of industry 4.0: A literature review, a multiple case study, and a conceptual framework. *Prod. Plan. Control.* **2021**, *32*, 213–227. [CrossRef]
23. Bittencourt, V.L.; Alves, A.C.; Leão, C.P. Industry 4.0 triggered by Lean Thinking: Insights from a systematic literature review. *Int. J. Prod. Res.* **2021**, *59*, 1496–1510. [CrossRef]
24. Silvestri, L.; Forcina, A.; Introna, V.; Santolamazza, A.; Cesarotti, V. Maintenance transformation through Industry 4.0 technologies: A systematic literature review. *Comput. Ind.* **2020**, *123*, 103335. [CrossRef]
25. De la Peña Zarzuelo, I.; Freire Soeane, M.J.; López Bermúdez, B. Industry 4.0 in the port and maritime industry: A literature review. *J. Ind. Inf. Integr.* **2020**, *20*, 100173. [CrossRef]
26. Echchakoui, S.; Barka, N. Industry 4.0 and its impact in plastics industry: A literature review. *J. Ind. Inf. Integr.* **2020**, *20*, 100172. [CrossRef]
27. Núñez-Merino, M.; Maqueira-Marín, J.M.; Moyano-Fuentes, J.; Martínez-Jurado, P.J. Information and digital technologies of Industry 4.0 and Lean supply chain management: A systematic literature review. *Int. J. Prod. Res.* **2020**, *58*, 5034–5061. [CrossRef]
28. Sartal, A.; Bellas, R.; Mejías, A.M.; García-Collado, A. The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. *Adv. Mech. Eng.* **2020**, *12*, 1687814020925232. [CrossRef]
29. Vianna, F.R.P.M.; Graeml, A.R.; Peinado, J. The role of crowdsourcing in industry 4.0: A systematic literature review. *Int. J. Comput. Integr. Manuf.* **2020**, *33*, 411–427. [CrossRef]
30. Osterrieder, P.; Budde, L.; Friedli, T. The smart factory as a key construct of industry 4.0: A systematic literature review. *Int. J. Prod. Econ.* **2020**, *221*, 107476. [CrossRef]

31. Mariani, M.; Borghi, M. Industry 4.0: A bibliometric review of its managerial intellectual structure and potential evolution in the service industries. *Technol. Forecast. Soc. Chang.* **2019**, *149*, 119752. [CrossRef]
32. Piccarozzi, M.; Aquilani, B.; Gatti, C. Industry 4.0 in management studies: A systematic literature review. *Sustainability* **2018**, *10*, 3821. [CrossRef]
33. Saucedo-Martínez, J.A.; Pérez-Lara, M.; Marmolejo-Saucedo, J.A.; Salais-Fierro, T.E.; Vasant, P. Industry 4.0 framework for management and operations: A review. *J. Ambient Intell. Humaniz. Comput.* **2018**, *9*, 789–801. [CrossRef]
34. Mutchek, M.; Williams, E. Moving Towards Sustainable and Resilient Smart Water Grids. *Challenges* **2014**, *5*, 123–137. [CrossRef]
35. Jan, F.; Min-Allah, N.; Düştegör, D. IoT Based Smart Water Quality Monitoring: Recent Techniques, Trends and Challenges for Domestic Applications. *Water* **2021**, *13*, 1729. [CrossRef]
36. Antonino-Daviu, J. Electrical Monitoring under Transient Conditions: A New Paradigm in Electric Motors Predictive Maintenance. *Appl. Sci.* **2020**, *10*, 6137. [CrossRef]
37. Mousmoulis, G.; Karlsen-Davies, N.; Aggidis, G.; Anagnostopoulos, I.; Papantonis, D. Experimental analysis of cavitation in a centrifugal pump using acoustic emission, vibration measurements and flow visualization. *Eur. J. Mech. B/Fluids* **2019**, *75*, 300–311. [CrossRef]
38. Myhre, B.; Petersen, S.; Ugarelli, R. Using Wireless Vibration Monitoring to Enable Condition-based Maintenance of Rotating Machinery in the Water and Wastewater Industries. *Procedia Eng.* **2014**, *89*, 1397–1403. [CrossRef]
39. Mounce, S.R.; Pedraza, C.; Jackson, T.; Linford, P.; Boxall, J.B. Cloud based machine learning approaches for leakage assessment and management in smart water networks. *Procedia Eng.* **2015**, *119*, 43–52. [CrossRef]
40. Hu, Q.; Ohata, E.F.; Silva, F.H.S.; Ramalho, G.L.B.; Han, T.; Rebouças Filho, P.P. A new online approach for classification of pumps vibration patterns based on intelligent IoT system. *Measurement* **2020**, *151*, 107138. [CrossRef]
41. Filipe, J.; Bessa, R.J.; Reis, M.; Alves, R.; Póvoa, P. Data-driven predictive energy optimization in a wastewater pumping station. *Appl. Energy* **2019**, *252*, 113423. [CrossRef]
42. Dutta, N.; Palanisamy, K.; Subramaniam, U.; Padmanaban, S.; Holm-Nielsen, J.B.; Blaabjerg, F.; Almakhles, D.J. Identification of water hammering for centrifugal pump drive systems. *Appl. Sci.* **2020**, *10*, 2683. [CrossRef]
43. Bhardwaj, A.S.; Saraf, R.; Nair, G.G.; Vallabhaneni, S. Real-time monitoring and predictive failure identification for electrical submersible pumps. In Proceedings of the Society of Petroleum Engineers—Abu Dhabi International Petroleum Exhibition and Conference 2019, ADIP 2019, Abu Dhabi, UAE, 11–14 November 2019.
44. Achieng, K.O. Evaluating pump performance using laboratory observations and machine learning. *ISH J. Hydraul. Eng.* **2019**, *27*, 174–181. [CrossRef]
45. Subramaniam, U.; Dutta, N.; Padmanaban, S.; Almakhles, D.; Kyslan, K.; Fedak, V. Identification of sludge in water pumping system using support vector machine. In Proceedings of the International Conference on Electical Drives and Power Electronics, Nový Smokovec, Slovakia, 24–26 September 2019; pp. 403–408.
46. Feng, H.; Wang, Y.; Qiao, L.; Ganwei, B.; Zhu, J. Internet of Thing System to Extract Hierarchical Healthy and Efficiency Information for Pump Station Optimization. In Proceedings of the 2018 2nd International Conference on Big Data and Internet of Things, Beijing, China, 24–26 October 2018. [CrossRef]
47. Stancel, E.; Stoian, I.; Kovacs, I.; Gyurka, B.Z.; Balogh, S. Urban water supply distributed control system. In Proceedings of the 2008 IEEE International Conference on Automation, Quality and Testing, Robotics, Cluj-Napoca, Romania, 22–25 May 2008; pp. 316–320. [CrossRef]
48. Bayindir, R.; Cetinceviz, Y. A water pumping control system with a programmable logic controller (PLC) and industrial wireless modules for industrial plants—An experimental setup. *ISA Trans.* **2011**, *50*, 321–328. [CrossRef] [PubMed]
49. Tuptuk, N.; Hazell, P.; Watson, J.; Hailes, S. A Systematic Review of the State of Cyber-Security in Water Systems. *Water* **2021**, *13*, 81. [CrossRef]
50. Makropoulos, C.K.; Natsis, K.; Liu, S.; Mittas, K.; Butler, D. Decision support for sustainable option selection in integrated urban water management. *Environ. Model. Softw.* **2008**, *23*, 1448–1460. [CrossRef]
51. Yuan, M. An Analysis on Optimization of Living and Fire Water Supply Systems of Small High-Rise Residential Blocks. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *94*, 012118. [CrossRef]
52. Ochella, S.; Shafiee, M.; Sansom, C. Adopting machine learning and condition monitoring P-F curves in determining and prioritizing high-value assets for life extension. *Expert Syst. Appl.* **2021**, *176*, 114897. [CrossRef]
53. Garcia, M.; Panagiotou, P.A.; Antonino-Daviu, J.A.; Gyftakis, K.N. Efficiency Assessment of Induction Motors Operating Under Different Faulty Conditions. *IEEE Trans. Ind. Electron.* **2019**, *66*, 8072–8081. [CrossRef]
54. Fong, J.; Ferreira, F.J.T.E.; Silva, A.M.; de Almeida, A.T. IEC61800-9 system standards as a tool to boost the efficiency of electric motor driven systems worldwide. *Inventions* **2020**, *5*, 20. [CrossRef]
55. Huse, S.N.; Kale, R.D.; Dhote, V.P. Development of Smart Water Supply System for University Water Supply Through Automation and Real-Time Operations. *J. Inst. Eng. Ser. B* **2020**, *101*, 497–510. [CrossRef]
56. Hanigovszki, N. Developments and Trends in the Adjustable Speed Drives Industry. Proceedings of 2019 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) & 2019 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) , Istanbul, Turkey, 27–29 August 2019; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2019; pp. 51–56.

57. Hammo, S.; Viholainen, J. Testing the accuracy of pump flow calculation without metering. *World Pumps* **2005**, *2005*, 36–39. [CrossRef]
58. Emami Javanmard, M.; Ghaderi, S.F.; Sangari, M.S. Integrating energy and water optimization in buildings using multi-objective mixed-integer linear programming. *Sustain. Cities Soc.* **2020**, *62*, 102409. [CrossRef]
59. Müller, T.M.; Altherr, L.C.; Leise, P.; Pelz, P.F. Optimization of Pumping Systems for Buildings: Experimental Validation of Different Degrees of Model Detail on a Modular Test Rig. In *Operations Research Proceedings*; Springer International Publishing: Cham, Switzerland, 2020; pp. 481–488. [CrossRef]
60. Coello, C.A.C. An updated survey of GA-based multiobjective optimization techniques. *ACM Comput. Surv.* **2000**, *32*, 109–143. [CrossRef]