IoT Based Automatic Diagnosis for Continuous Improvement

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Competitiveness determines a company's survival in the market, and companies that adhere to Lean Manufacturing (LM) practices have assumed competitive positions at a global level. The LM approach focuses on delivering value to the customer and reducing waste. Through Continuous Improvement (CI), one of the foundations of LM, the constant elimination of waste is achieved (activities that do not add value), and the constant search for process efficiency improvement is implemented. CI professionals are responsible for helping organizations identify the inefficiencies' root causes in the production process, and implementing solutions to eliminate waste. Starting from holistic analyses of the current situation of the production system (derived from Key Process Indicators (KPI) monitoring and/or overall performance mapping, using, e.g., Value Stream Mapping), a detailed diagnosis of the identified critical activity or KPI is usually required for a CI project. This detailed diagnosis involves the presence of the CI team in the Gemba (the place where the action occurs) for a couple of hours, to observe and acquire data about machine activity and operators' movements and actions, matching it with machine states, as well as collecting distance run by the operators, task times, etc. In this research, this diagnosis will be referred to as Detailed Diagnosis (DD) for the CI project. The DD is crucial in almost all problem-solving projects, as the way to obtain specific data, information, and knowledge for the root cause analysis phase. Traditionally, the DD for CI projects is done through stop-watch analysis and "pen&paper" logic, disregarding the level of digitalization of the production process .

Internet-of-Things | industrial Internet-of-Things | Lean Manufacturing | Lean & Green 4.0 | continuous improvement | Industry 4.0

1. Detailed Diagnosis of Manufacturing Workstations

Continuous Improvement (CI) professionals help organizations to overcome efficiency problems by finding the root causes of problems (performance and KPI's abnormal behavior) and implementing, most often, Lean-based solutions to increase productivity [1][2][3]. When a problem arises (a systematic deviation that implies significant variability and/or a tendency towards the target value established for a Key Process Indicators (KPI)) [4][5], a study of the situation is necessary to understand currently used procedures and to find the problem's root causes: a specific Detailed Diagnosis (DD) is required. A DD relies on observations, data collection, and measurements of processes, people, and the machine–operator relationship [6][7]. The traditional way to obtain a DD is based on methods and a time-consuming study, with filming or/and direct observation of the workstation (machine/operator), done by the CI professionals, consuming considerable time, or limiting the analyzed time via the lack of resources (or intentionally to minimize cost) [8][9][10]. Some authors emphasize the specificity of the DD for CI since it requires, besides the equipment status, the acquisition of information regarding the operator's interaction with equipment, movements of operators, and transports originated by them [11][12].

This need for specific observation and measurement defines the type of data necessary for a DD. In a non-exhaustive way, in a DD for CI it is necessary to collect information regarding the location of the operator in the various stages of the process, and the various states of the machines (operation, setup, micro-stops, waiting times, among others); is also necessary to know the duration of these phases and states, and, in some cases, the distance traveled by the operators and the time spent in each location [13][14][15]. These collected data allow for detailing the availability, the performance, and the quality of the performance. A detailed understanding of the parcels of the Overall Equipment Effectiveness (OEE) for the equipment under analysis will help in finding the root causes that lead to the solution [15]. These parcels include the setup activities, maintenance activities, micro-stops, and waiting times, among others. Additional information may include the total energy consumption in each step of the process, the consumption of raw material, the energy consumption per setup time (determining the energy that does not add value to the product), and the relationship between the consumption of raw material and the number of non-conformities (material/energy waste indicator). This will allow operational and environmental performance analyses in an L&G logic [16].

A typical DD report to support problem-solving in a CI project is summarized in **Figure 1**, even though this has to be built using data collected manually (including the machine and/or operator timeline). Lean-related tools are often used to help CI professionals to communicate the results of the DD, such as (i) the Yamazumi chart, showing the total cycle time for each operator when executing a process in the production flow [17][18]; (ii) the Spaghetti Diagram, showing the physical movement of a “work object” through the processes defining the start and end value in the value stream [19]; (iii) an operator–machine chart depicting the relation of the operator movements to the machine status [20]. A DD report created by a CI Team, such as the one shown in **Figure 1**, can require several days of stop-watch analysis, following the operator on the shop floor and identifying the ongoing tasks for several hours, and inputting data into the computer and elaborating graphs.

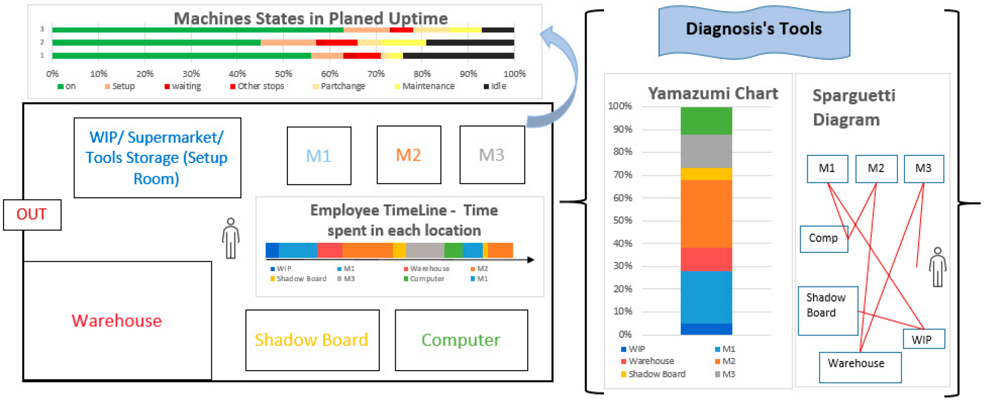

Figure 1. A common report of a DD created by a CI Team.

The specificity of DD for CI and the fact that is only required when a performance problem is detected are the logical reasons to keep this data acquisition off of the digitalization platform of a production system [7][21]. Nevertheless, the time consumed by the CI professionals might be several days for a unique problem-solving project; to avoid this time (and cost), the user may employ a DD with very limited information (causing a poorer root cause analysis) [22][23].

2. Lean Manufacturing, Lean&Green, and Industry 4.0

The designation Lean Manufacturing (LM) was first used by John Krafick, a researcher at the Massachusetts Institute of Technology, in a publication to refer to the Toyota Production System (TPS) [24]. The TPS was conceived with a focus on reducing waste to increase the competitiveness of the company based on the CI and a set of principles, methods, and tools, summarized in the House of TPS [21]. In this model, the base is the principles, the pillars are the means and tools to be used, and the roof is the result one wants to achieve. CI is positioned at the center of the pillars, meaning that TPS has the empowerment of people as its epicenter. Some authors put the people themselves at the center of the house [25][26], making it explicit how the culture of sustained improvement involves and depends on people [27].

In addition to the search for production output, operational CI, and waste reduction, several authors mention, mainly after 2000, that competitive industries need to pay attention to environmental and social concerns [28]. Other approaches, when combined with LM, can have a great positive impact, such as “Green Manufacturing” methodologies, with environmentally oriented actions, which help to reduce environmental impacts [29]. L&G represents LM evolution, acting in the direction of mapping and quantifying operations that consume unnecessary time and resources (materials, energy, consumables, etc.), and seeking the continuous improvement of these processes [16][30]. L&G’s dependence on a large amount of data, as referred to by several authors [29][31][32], makes the raising of I4.0 the proper time for L&G implementation [16][28]. When implemented, L&G becomes a pillar of sustainable development within a company, also contributing to and being a part of the transition to I4.0 [28][29], and I5.0 soon after. In this way, the Twin Transition, also called the Digital Circular Economy, is sought, in which integrated solutions with a technological and sustainable bias are pursued, favoring the optimization of resources that are essential for the planet [33][34].

I4.0 is a paradigm that introduces a new perspective on how manufacturing can be enhanced with new technologies to improve process and resources efficiency, and reduce waste [35], with some authors concluding that I4.0 technological solutions came to increase the level of competitiveness through the convergence between the physical and digital worlds [36]

[37]: the manufacturing process becomes intelligent, flexible, adapted and optimized, with data integration, including cloud/intranet, service-orientation and interoperability (the ability of two systems to exchange data and share information and knowledge) [38][39].

According to Kamble et al. [40], a smart manufacturing system benefits from the contribution of three major technologies: a cyber–physical system (CPS), cloud computing, and the Internet-of-Things (IoT). In an industrial context, several CPSs communicate and interact, forming a cyber–physical production system (CPPS)—the smart production system. The communication among CPS, and the integration with physical computational entities (machines, robots, sensors, etc.) associated with human decisions, is done by the IIoT system, which makes the smart production process autonomous and intelligent, being able to decide and trigger human actions [41]. Adding all these factors together with cloud computing, Big Data and Analytics, and conventional systems makes it possible to create Smart Factories [40][42].

Several authors discuss the interdependence of LM and I4.0 to implement both successfully [25][43]. Understanding how this can be accomplished has been the focus of several researchers, making it clear that LM, or even L&G, and I4.0 have common goals, and the I4.0-based smart factory needs L&G approaches, and vice versa, to increase social, operational and resources efficiency and effectiveness [36][44][45][46][47], with human factors having a huge relevance in this accomplishment [48]. The next section helps to understand the specific relevance of several I4.0 technologies to integration with LM and L&G, including CI.

3. The Relevance of IoT in the Detailed Diagnosis for Continuous Improvement

Aiming to deepen the analysis of the correlation between the pillars of LM and the technologies of I4.0, a comprehensive study was performed, and some articles with systematic reviews on the subject were found. In 2017, Wagner et al. [49] presented a study that points out the correlations between I4.0 technologies and Lean principles, by means of an impact matrix. The article presents a practical case study that shows that I4.0 applied in Just-in-Time (JIT) delivery helps to support and stabilize LM based on the integration of Big Data, Data Analytics, and Machine to Machine (M2M). Later, Rosin et al. [43] presented a study based on 115 papers published in the SCOPUS and Google Scholar search engines, dated until the end of 2019. This work correlates the I4.0 technologies with Lean principles and methods. Based on the publication list of Rosin et al. [43], a pictogram (**Figure 2**) was built by the authors of the current research to easily understand, based on the published documents, the level of relevance of the several I4.0 technologies to the Lean principles and methods.. From the numbers presented in the circles, there is a strong correlation between the I4.0 technologies in Lean pillars, with the most impactful being IoT technology, with 39 connections. This result expresses the versatility and utility of IoT in I4.0, which is presented in several papers, such as those by Okano et al. [50] and Peralta et al. [51].

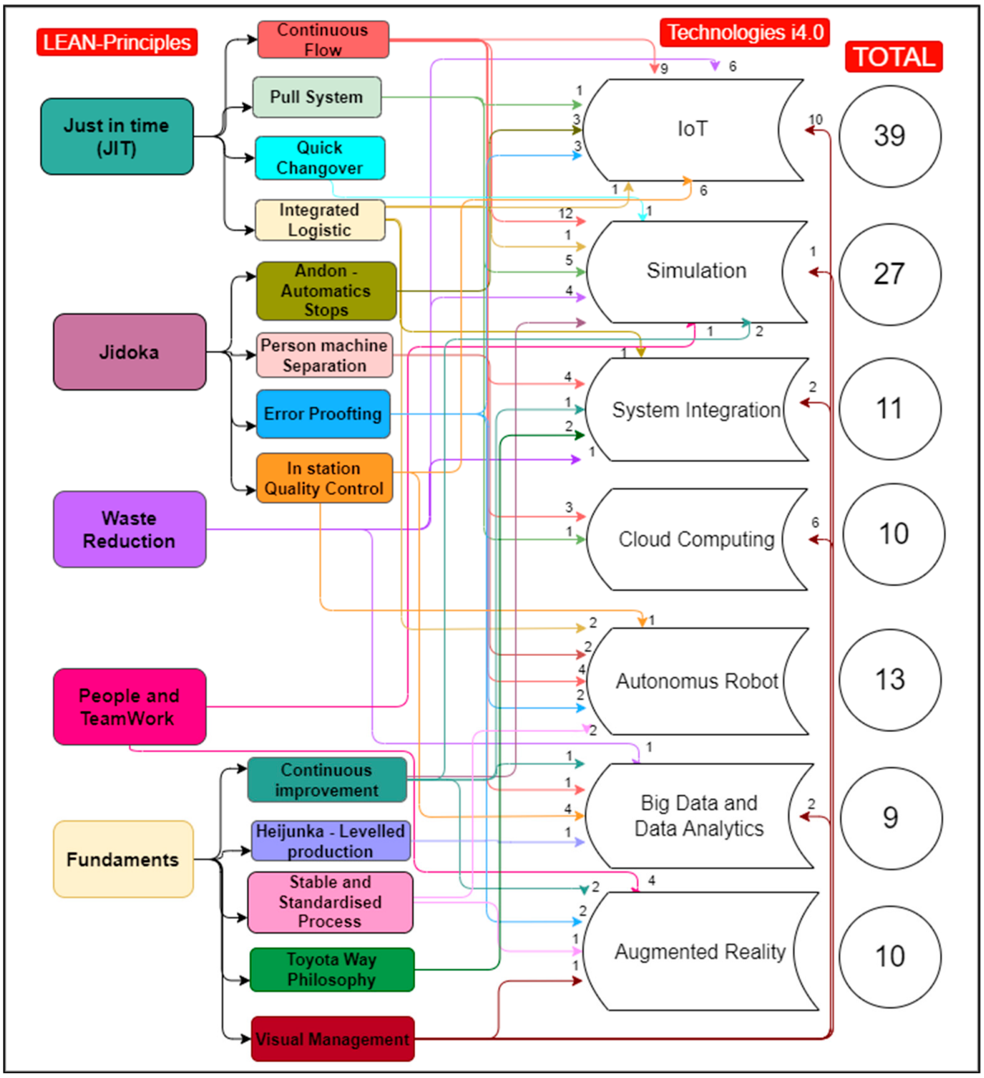

Figure 2. Correlation between Lean principles and technologies of I4.0, based on Rosin et al. [43], a literature review comprising papers from 2011 to 2019.

Remaining on the topic of the article by Rosin et al. [43], in the broader context of LM, IoT aims at the vertical integration of systems between suppliers and customers to facilitate the identification and sharing of the value delivered to the customer [52]. With regard specifically to the principles, the use of IoT in JIT makes it possible to track products in real-time and send production progress data [44][49]. The joint effort of IoT and visual management to democratize information and popularize knowledge leads to a presentation of the collected data in a way that is visually accessible to those involved [25][53]. Regarding the Pull System, IoT helps in the synchronization of workstations and contributes to the better use of Kanbans, enabling its digitization and de-materialization [25][44][54]. Jidoka, also known as the LM's autonomation pillar, employs the strong influence of IoT combined with technologies such as Big Data and Autonomous Robots to perform quality control in real-time, through error detection and correction, and defect trend identification [43]. In the reduction of waste, the IoT can be used for real-time product tracking, reducing unnecessary transport [25][54][55]. Despite these relevant impacts of IoT, Rosin et.al. [43] concluded that it does not have a significant expression in the pillars of Continuous Improvement and People and Work Teams. In these more human-centered pillars, the most active I4.0 technologies are Virtual Reality (VR) and Augmented Reality (AR) in the context of facilitating training with visual interfaces [56]. Since problem-solving projects are integrated into continuous improvement, there is a clear gap in the use of IoT technologies for traditional problem-solving, which reinforces the importance of this research.

In 2020, Gallo et al. [36] used a compilation of 25 papers created by searching for the keywords “Industry 4.0” and “Lean production” on the SCOPUS and Web of Science platforms. Only papers written in British English were selected, excluding papers from geographic origins such as North America and Oceania, and in this way the authors justified the low number of articles as a result of the research. It aimed at identifying which I4.0 tools can be implemented in LM, and which ones can contribute to the greater success of this methodology. Technologies such as IoT, Big Data, Robotic, CPS, and Cloud Computing were cited, and IoT and Big Data were classified as "basic tools", essential for promoting greater flexibility and competitiveness. The IoT tool is present in 61% of the papers, and Big Data appears in 50%. Narula et al. [57] showed data indicating that cloud manufacturing, simulation, IIoT, and horizontal and vertical integration impact 100% of Lean tools, while cybersecurity and big data analytics impact 93% of Lean tools. These data indicate that the IoT has reached a prominent position compared to other technologies, due to its vast field of application and versatility.

Another element strongly cited in Gallo et al. [36] is the attention to the human factor. Despite talking about tools and technologies, he argues that innovation is not supported without the human factor, and integration between the parties needs to happen to generate a favorable social environment for the implementation of technologies, which is very much in line with the proposal of Industry 5.0, and once again reiterates the importance of the present research.

To gain an updated view of the importance of IoT in LM, a specific search was carried out in this research on the SCOPUS platform with the words "IoT" OR "IIoT" OR "Internet of Things" OR "Industrial Internet of Things" AND "Lean Manufacturing" inserted in the title, key word and abstract fields, focusing on articles in the period between 2021 to 2022, because the period before 2020 has already been covered in the other articles. Twelve papers were found, and it was noted that they can be classified into two large groups: (i) six of them position IoT in a generic way as one of the technologies of I4.0, and (ii) six of them describe specific IoT applications in the Lean realm. The first group of papers confirms a solid future for Lean 4.0, where IoT is essential, [57][58], but they do not give special attention to this discussion since they mostly focus on a general analysis of IIoT's relevance to LM development [59][60][61][62]. Four of the latter six publications offer no specific insights about CI, presenting applications of IoT to facilitate the performance monitoring of a production system [63], the planning of manufacturing and maintenance tasks [37], the management of autonomous guided vehicles, the assembly assistance of virtual reality [3][64][65] and other types of production automation [66], and the better understanding and vision of the supply chain [67]. One of the publications even states that all LM methods, except CI, benefit from greater effectiveness when combining them with the IoT [48]. The closest reference to the IoT's impact on CI in this set of papers is made by Lu et al. [68], proposing the integration of IoT with the EVA simulation framework (Efficiency Validate Analysis) to build up a digital twin-enabled VSM approach, which can be considered to support the CI projects, but without relating it with problem-solving projects.

Therefore, based on previously published literature surveys on LM and L&G together with I4.0 technologies, and on the survey done in this research, no specific research was found exploring the application of those technologies in the DD to CI projects. This enhances the purpose of the current research, enabling it to cover the gap that was also identified by other authors [22][45][69].

4. IoT-Related Devices Availability

Conscious of the absence of publications regarding the application of IoT to DD for CI, the authors decided to include an analysis of the existing devices and components in the IoT realm that are already used to execute part of the data acquisition and information processing necessary to perform a DD .

The IIoT has many areas of application, focusing mainly on Asset Tracking, Predictive Maintenance, Security Monitoring, and Machine Monitoring/Performance, the latter being the area most related to the support of DD. The specific needs of an industrial environment demand several characteristics of IIoT devices: mechanical robustness, electromagnetic protection, electrical supply integrity (voltage drops), the guarantee of signal integrity, and cybersecurity soundness [70].

A comparative market analysis of available IIoT-related devices and products was carried out in **Table 1**, identifying its features and types of sensors. The most common built-in sensors aim at measuring temperature and humidity, power and energy, pressure, acceleration, magnetic field, and light. In some of the devices, interesting features can be found: quick and non-intrusive installation (Plug & Play solutions, for example, magnets, stickers); a simple web interface and cloud-based dashboard for data visualization; quick access to asset data via QR code; resistance and long battery life. Although the electronic devices and systems listed in **Table 1** are embedded with the most diverse types of sensors, allowing equipment monitoring, they do not cover some of the requirements necessary to reach a DD for CI. As referred to in **Section 1**, a key aspect analyzed by Lean professionals is the movements of workers throughout the plant and their correlation with the work of the machine—aspects that these devices do not cover. Other aspects not covered are the identification of the individual operator and the use of proximity sensors to measure the distance to a nearby person or object.

These findings enhance the need to propose an innovative concept to automatize the DD (the ADD). Despite the support that existing IIoT solutions provide, the most challenging factor in combining DD and IIoT is related to the degree to which devices can simultaneously monitor operators' actions and the states of machines [71]. Naturally, the operator's monitoring must respect individual data protection and promote wellbeing. The ADD concept covers the identified gap by contributing to the adoption of I5.0 by positioning human beings in this new context, in the search for a more sustainable, resilient industry with a more robust social environment [16][28][29][72].

Table 1. IIoT products analyzed in the market study and their features.

Name/Company/Objectives	Features	Sensors
Cisco—Cisco Industrial Asset Vision All- in-one solution that simplifies asset and facility monitoring in outdoor or indoor environments.	Choice of 11 sensors and Cisco LoRaWan gateway. Backed by Osco security. Cloud-based dashboard. Deploy the sensors and the gateway in min, using a QR code. Automated alerts.	Temperature and humidity. Door and window. Water leakage. Light level. Room occupancy. Machine or product temperature. Machine vibration.
Movus—Fit Machine Continuous condition monitoring solution that monitors temperature, vibration, and acoustics. Uses AI/ML to understand and monitor asset operation and health 24/7.	Multiple sensor types. Quick install using magnets. Cloud-based dashboard. Can use existing Wi-Fi infrastructure or the Movus gateway. QR code for quick access to machine data. ML-based failure prediction.	Temperature and humidity, (indoor) pressure. Machine temperature. Accelerometer. Microphone.
Bosch—Sense Connect Detect (**SCD**)**-** Attaches to most machines/components. Collects data, wirelessly via Bluetooth and visualized via mobile app, to reduce maintenance costs, maximize machine production, and drive better business decisions.	Equipped with a few sensors and Bluetooth technology. Easy data visualization via mobile app. Easy install (sticker), resistant and attaches to most assets. Battery included.	Light intensity. Temperature. Magnetometer. Accelerometer.
Bosch—Connected Industrial Sensor Solution (**CISS**) Small multi-sensor device for harsh industrial environments. Provides machine condition monitoring + early detection and localization of potential issues. Data gathered, via Bluetooth and presented on an app, enables further development of predictive and remote maintenance.	Equipped with several sensors and Bluetooth technology. Easy data visualization via mobile app. Easy to install, resistant (−20° to 80°) but no battery (needs wiring).	Temperature and humidity (indoor). Light intensity. Machine or product temperature. Pressure. Accelerometer. Gyroscope. Magnetometer. Microphone.
Bosch—Cross Domain Development Kit (**XDK**) Combines a wide array of MEMS sensors with a microcontroller. An ARM Cortex M3 processor analyzes, processes and transmits the sensor data. Monitors, controls and analyzes products remotely via Bluetooth or wireless network.	Equipped with sensors. BT and wireless network. Includes ready-to-use software package. Easy installation. Device needs to be programmed. Includes rechargeable battery.	Temperature and humidity (indoor). Light intensity. Machine or product temperature. Pressure. Accelerometer. Gyroscope. Magnetometer. Microphone.
Bosch—Intelligent Vibration Analysis System (**IVAS**)**—PROTOTYPE** Compact and robust equipment 2 MEMS acceleration sensors, for high -bandwidth and high-resolution vibration measurements. Integrates into existing communication infrastructure and offers possibilities to implement use case-specific algorithms on the sensor device.	Two accelerometers (high bandwidth + sensitivity). No wireless technology. No web interface or dashboard. Easy installation. Device needs to be programmed. No battery.	

Name/Company/Objectives	Features	Sensors
Bosch—TRACI Wireless and secure sensor solution equipped with LoRa and BLE connectivity for location and asset tracking.	Equipped with sensors, GNSS and BT/wireless network technology. Alerts for accident, maintenance, geophone and temperature. Very robust and battery life of up to 5 years.	Product and machine temperature. Accelerometer. Microphone.
Sensolus—SNIT 3 Ultra/Compact Low-power, plug and play solution to manage smaller assets. Universal solution for tracking and locating valuable non-powered assets in indoor and outdoor locations in an extremely simple way.	GPS and sensors. Compact format, does not include pressure sensor. Simple web interface and cloud-based dashboard with alerts. Quick install (plug and play solution) and 5-year battery life.	Product and machine temperature. Pressure. Accelerometer. Magnetometer. Microphone.
Eliko—UWB RTLS 2D pilot kit The 2D pilot is a great way to test a micro positioning use case.	Battery-powered tags; RTLS Server and software for four anchors; four-port PoE switch. RTLS manager for system configuration and visualization. Four anchors with ethernet and Wi-Fi connectivity options.	
Ifm-io—key + accessories Tank monitoring using a capacitive continuous level sensor. Measurement of compressed air consumption and leakage monitoring using a compressed air meters. Fan monitoring using vibration diagnosis sensors. Valve monitoring using valve sensors.	Equipped with sensors that need to be wired to the gateway. Web-based dashboard for data visualization and analysis. Non-intrusive but requires installation. Sends SMS/Mail Alerts.	Compressed air and leakage. Water level. Machine vibration. Valve.
Advantech—WISI 2410—LoRaWAN Wireless Condition Monitoring Sensor Replaces traditional human inspection, allowing manufacturers to achieve remote detection and 24 h monitoring. Diagnosing through ISO 10816 helps system integrators get started quickly, reducing the entry threshold for preventive maintenance.	Sensors Quick install and plug and play approach. Simple web interface and cloud-based dashboard. Coverage up to 5 km with 2 years of battery life.	Machine temperature. Accelerometer.
I-care Wi-care 100 Series System Plug and play wireless monitoring solution. Automated tracking of critical equipment, from continuous monitoring to once-a-week intervals, collecting reliably, deployed/configured quickly, permanently or used for spot checks during inspection.	Five sensors. Gateway (Wi-care 920). Signal transmission extender available. Quick install and plug and play approach. Simple cloud-based dashboard with real-time alerts/notifications.	Machine temperature. Machine vibration. Speed. Ultra sound.
Advantech Wzzard HVAC/Refrigeration/Energy/Condition-Based Monitoring Starter Kit Provides a non-intrusive, easily scalable and simple to install solution for monitoring. HVAC/refrigeration/energy/condition-based equipment without disrupting facility operations.	Starter kit with sensors. Simple cloud-based dashboard with alerts via SMS/Mail. SmartSwarm Gateway (connecting up to 100 sensors).	Temperature and humidity (indoor). Door and window. Current intensity. Machine temperature. Machine vibration. Energy consumption.

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