REVISTA INVESTIGACION OPERACIONAL
https://doi.org/10.5281/zenodo.23302380 **VOL. 48, NO.1, 64-80, 2027**

IOT-BASED MONITORING OF PHYSICAL RISK FACTORS AT A WORKSTATION: DOMINANCE-BASED SELECTION AND MINIMUM-COST SENSING ARCHITECTURE

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ABSTRACT

Occupational physical-risk assessment in small and medium industry is usually done with occasional campaigns using portable instruments, which are costly and give a snapshot rather than a record. This paper reports an IoT prototype that is designed for continuous monitoring of four physical factors at a single workstation — dry-bulb air temperature, relative humidity, sound level and illuminance — and demonstrated over a one-hour test with sixty-one-minute observations per variable, and, above all, formalises the two design decisions behind it. The mounting support is chosen by Pareto dominance over the eleven ordinal criteria declared by the study: the posture-correcting belt is no worse than the alternatives on all eleven criteria and strictly better on eleven against the overall and on five against the backpack, so the choice requires no weights and no compensatory ranking method. The sensing architecture is posed as a binary minimum-cost covering problem with requirement-specific eligibility and explicit electrical and interface constraints. Under the full requirement set declared by the study the model is infeasible, because no candidate measures wet-bulb or globe temperature and no noise sensor has a specified range or accuracy; within the modelled candidate set and constraints, the published USD 31 configuration is optimal under the reduced requirement set and when no supply rail above the 3.3 V logic level is considered available. Admitting the noise channel is a relaxed design assumption and does not certify that the sensor meets the 30–120 dBA requirement. The metrological scope supported by the available record is a single-point instrumental comparison per variable, not a validation, and the noise channel difference is reported in decibels rather than as a percentage. Heat-stress classification cannot be issued: WBGT requires wet-bulb and globe temperature, which the prototype does not measure.

KEYWORDS: occupational physical risk; Internet of Things; Pareto dominance; set covering; minimum-cost design; environmental monitoring.

MSC: 90C10, 90B50, 68M14.

RESUMEN

La evaluación de riesgos físicos laborales en la pequeña y mediana industria suele hacerse con campañas ocasionales de instrumentos portátiles, caras y que dan una fotografía en lugar de un registro. Este trabajo reporta un prototipo IoT que está diseñado para el monitoreo continuo de cuatro factores físicos en un puesto de trabajo —temperatura del aire de bulbo seco, humedad relativa, nivel sonoro e iluminancia—, demostrado en una prueba de una hora con sesenta observaciones de un minuto por variable, y, sobre todo, formaliza las dos decisiones de diseño que lo sostienen. El soporte de montaje se elige por dominancia de Pareto sobre los once criterios ordinales que el propio estudio declara: la faja correctora no es peor que las alternativas en ninguno de los once criterios y es estrictamente mejor en once frente al overol y en cinco frente a la maleta, de modo que la elección no necesita pesos ni método compensatorio alguno. La arquitectura de sensado se plantea como un problema binario de cobertura a coste mínimo con elegibilidad declarada requisito por requisito y restricciones eléctricas y de interfaz explícitas. Bajo el conjunto íntegro de requisitos que el estudio declara el modelo resulta infactible, porque ningún candidato mide temperatura de bulbo húmedo ni de globo y ningún sensor de ruido tiene rango ni exactitud especificados; dentro del conjunto de candidatos y de las restricciones modeladas, la configuración publicada de USD 31 es óptima bajo el conjunto reducido y cuando no se considera disponible una alimentación superior al rail lógico de 3,3 V. Admitir el canal de ruido es un supuesto de diseño relajado y no acredita que el sensor satisfaga el requisito de 30 a 120 dBA. El alcance metrológico que sostiene el registro disponible es una comparación instrumental puntual por variable, no una validación, y la diferencia del canal de ruido se reporta en decibelios y no en porcentaje. No se emite clasificación de estrés térmico: el índice TGBH exige temperatura de bulbo húmedo y de globo, que el prototipo no mide.

PALABRAS CLAVE: riesgo físico laboral; internet de las cosas; dominancia de Pareto; cobertura de conjuntos; diseño a coste mínimo; monitoreo ambiental.

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1. INTRODUCTION

Assessment of a workstation's physical risk factors —temperature, humidity, noise and lighting— is usually carried out through occasional campaigns using portable instruments. The procedure is correct but costly, requires specialized personnel, and produces a snapshot of the workstation at a given moment, not a record of how those factors vary over a working day. In small and medium industry this limitation is compounded, because the frequency of the campaigns is set by budget rather than by risk.

Ecuador's occupational-accident record gives the measure of the problem. Figures 1 and 2 show the work accidents reported in 2022 [9] and the occupational diseases recorded between 2015 and 2022 in five provinces [10]. The workstation's environmental conditions play a direct role in a good part of that case load, and they are also the ones an instrumentation system can monitor continuously without interfering with the task.

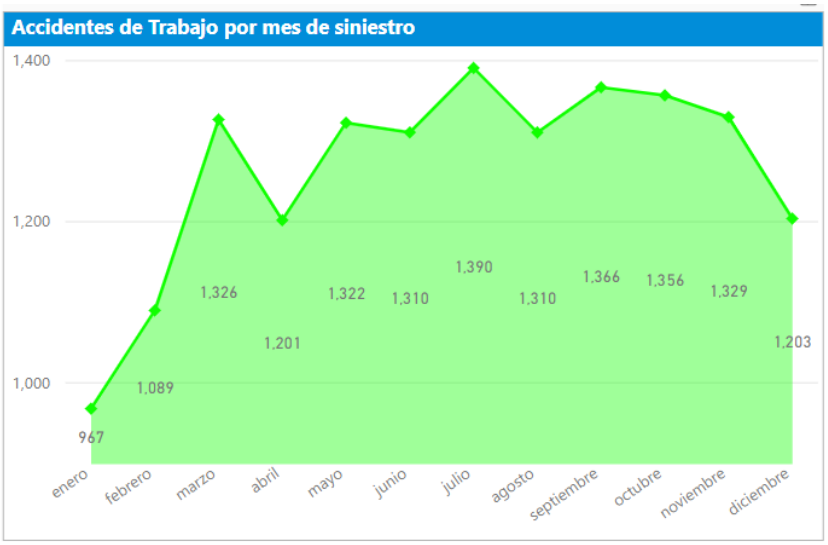


Figure 1. Work accidents reported in Ecuador in 2022 [9].

Enfermedades Profesionales Receptados						
Año/Provincia	**Pichincha**	**Guayas**	**Chimborazo**	**Cotopaxi**	**Azuay**	**Sumatoria**
2015	462	81	19	29	13	604
2016	367	51	8	15	11	452
2017	630	174	9	25	9	847
2018	578	165	15	22	31	811
2019	446	182	7	19	11	665
2020	262	82	8	10	20	382
2021	321	123	12	4	21	481
2022	115	65	5	3	9	197
					TOTAL	**4439**

Figure 2. Occupational diseases recorded between 2015 and 2022 in five provinces [10].

This paper reports an Internet-of-Things-based monitoring prototype, designed to continuously record four physical factors of a workstation and publish them on a cloud platform. The contribution, however, is not the prototype itself: equivalent devices exist in the literature. What is added here is the formalization of the two design decisions that determine it, and a precise statement of how far —and how far not— what the system can claim actually reaches.

The first decision is where to mount the sensor set on the worker. The study compares three supports on eleven criteria, and here it is resolved by Pareto dominance, which requires no weights. The second is which sensors and which gateway make up the system, which is posed as a binary minimum-cost covering problem with eligibility declared

requirement by requirement. Neither decision requires a compensatory multicriteria method, and the paper argues why.

The scope is stated from the outset so that there is no misreading. The system measures air temperature, relative humidity, sound level and illuminance. It does NOT measure posture, joint angles, force, repetitiveness or physical load, so it does not characterize ergonomic risks: the posture-correcting belt is here a mounting support, not a postural measurement instrument. Nor does it measure wet-bulb or globe temperature, without which the WBGT index cannot be computed and, therefore, no heat-stress classification can be issued. The ergonomic literature is cited as context, not as a measured result.

2. STATE OF THE ART

Environmental monitoring of workstations with connected devices is a well-established line of work. MQTT-based systems for safety surveillance in factories have been reported [13], as have remote monitoring of environmental variables with low-cost hardware [5], safety and health systems for construction workers [16], and monitoring of firefighting teams in emergency situations [14]. In the field of wearable technologies, there are recent reviews of the role of wearable devices in occupational safety [23] and work using sensors to estimate mental workload [19] or predict perceived fatigue through time-series methods [6].

It is worth distinguishing, however, two families that the literature sometimes conflates. A system that measures environmental variables of the worker's surroundings characterizes PHYSICAL risks. A system that estimates posture, effort or repetitiveness —such as the real-time ergonomic assessment system of [15]— characterizes ERGONOMIC risks, and for that it needs different instrumentation: accelerometry, goniometry or computer vision. The prototype reported here belongs to the first family. Environmental ergonomics, which deals with the thermal, acoustic and lighting environment [7], is the conceptual framework it falls under, but that does not turn its measurements into measurements of postural load.

3. METHODOLOGY

Development followed a sequential Waterfall-type cycle [1]: regulatory analysis, requirements definition, component selection, implementation, instrumental comparison and proof of concept in a real environment.

3.1 Regulatory framework

The framework currently in force in Ecuador is Executive Decree 255, “Occupational Safety and Health Regulation,” published on 2 May 2024 [2], which repealed Executive Decree 2393. Its operational development is established through Ministerial Agreement MDT-2024-196 [17], whose Annex 3, Technical Standard on Occupational Safety and Hygiene, sets the minimum technical criteria on premises conditions, lighting and ventilation, noise and contaminating agents.

Decree 255 does not merely retain Articles 53 to 56 of Decree 2393: the current framework reorganizes those matters and refers them to the technical standard in Annex 3, so references should be made to the latter and not to the repealed articles.

The criteria this paper uses, and their scope, are the following.

Noise.

Annex 3 sets occupational exposure to continuous noise so that no worker is exposed for eight hours or more to an equivalent continuous sound pressure level above 85 dB(A) [17]. The regulated quantity is, therefore, an equivalent level over a reference period, not an instantaneous reading or the arithmetic mean of several readings. The arithmetic mean of values in decibels has no physical meaning, because the scale is logarithmic; the equivalent continuous level is obtained through Eq. (1):

$$L_{\mathrm{Aeq}} = 10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} 10^{\frac{L_i}{10}} \right] \quad (1)$$

where L_i is the level measured in interval i and n is the number of intervals. This distinction determines what can and cannot be concluded from the field test in Section 4.3.

Thermal environment.

Assessing heat risk requires the wet-bulb globe temperature (WBGT) index, which combines wet-bulb temperature, globe temperature and, outdoors under solar load, dry-bulb temperature [12]. The prototype measures dry-bulb temperature only. It can therefore report the workstation's ambient temperature, but it CANNOT issue a heat-stress classification, and this paper does not issue one at any point.

Lighting.

Annex 3 sets lighting categories by task type [17]. The 100-lux threshold for textile workshops comes from the table of the repealed Decree 2393 and is not attributed to the current standard. The Annex 3 category applicable to the specific task observed at the company could not be determined from the sources consulted, so Section 4.3 reports the measured illuminance without issuing a compliance judgment. Fixing a threshold for convenience so that the measurement comes out insufficient would be exactly the error this analysis is meant to avoid.

Relative humidity.

The 30-to-70% comfort ranges the study uses come from the Technical Guide of Spain's National Institute for Occupational Safety and Health [11]. They are kept here as an EXTERNAL COMFORT REFERENCE and not as an Ecuadorian occupational-exposure limit, which is a different thing.

3.2 Monitoring system requirements

From the above follow the requirements the system must cover, stated here exactly as the study declares them, and gathered in table 1, because they are the input to the model in Section 3.5:

Requirement	Quantity	Declared requirement
TBS	Air or dry-bulb temperature	±0.5 °C, range 0 to 40 °C
TBH	Wet-bulb temperature	±0.5 °C, range 0 to 40 °C
TG	Radiant or globe temperature	±0.5 °C, range 0 to 40 °C
HR	Relative humidity	range 30 to 70 %
RUI	Sound pressure level	range 30 to 120 dBA
LUX	Illuminance level	range 0 to 1000 lux

Table 1. Measurement requirements declared by the study. TBH and TG are needed for the WBGT index and are kept here because their treatment in the decision model is informative.

3.3 Sensor selection

Tables 2 through 5 gather the characteristics of the commercial components considered —table 2 for temperature, table 3 for humidity, table 4 for lighting and table 5 for sound level— with the values published by the study. Each specification was checked against the available source; cells the study itself declares «not specified» or «TBD» are kept as such, because an absent specification cannot certify a metrological requirement.

Parameter	**DHT11**	**DHT22**	**LM35**	**DS18B20**
Variable	TBS	TBS	TBS	TBS
Range	0 a 50 °C	−40 a 80 °C	−55 a 150 °C	−55 a 125 °C
Accuracy	±2 °C	±0.5 °C	±0.5 °C a 25 °C	±0.5 °C
Interface	single-wire serial	single-wire serial	analog	1-Wire
Output	digital	digital	10.0 mV/°C	digital
Supply	3 a 5.5 V	3 a 5.5 V	4 a 30 V	3 a 5.5 V
Cost	USD 4.00	USD 7.00	USD 2.00	USD 8.00

Table 2. Temperature sensors considered. The LM35's supply voltage is corrected to 4-30 V according to the manufacturer's datasheet [24]; its output is absolute, 10.0 mV/°C, so over the required 0-40 °C range it swings between 0 and 400 mV.

One point in the previous table deserves comment because it decides Section 4.5. That the LM35 requires at least 4 V of supply does not make it incompatible with a 3.3 V-logic gateway: these are two different things. The SUPPLY is resolved with the board's 5 V rail; the SIGNAL LEVEL that reaches the analog-to-digital converter is 0 to 400 mV over the required range, comfortably within the 3.3 V input. Discarding the LM35 on that basis would conflate the two constraints.

Parameter	**DHT11**	**DHT22**
Variable	Relative humidity	Relative humidity
Range	20 a 90 %	0 a 100 %
Accuracy	±5 %	±2 a 5 %
Interface	single-wire serial	single-wire serial
Output	digital	digital
Supply	3 a 5.5 V	3 a 5.5 V
Cost	USD 4.00	USD 7.00

Table 3. Relative-humidity sensors considered. The FC-28 is not included: it is a soil-moisture sensor based on conductivity between electrodes and does not measure atmospheric relative humidity, so it is not a candidate for this requirement.

Parameter	**BH1750**	**GL5528**
Variable	Illuminance	Illuminance
Range	1 to 65535 lux	not specified
Accuracy	not specified	not specified
Interface	I²C	analog
Output	digital, directly in lux	0 to supply voltage
Supply	3.3 V	3 a 5 V
Cost	USD 4.00	USD 3.00

Table 4. Lighting sensors considered**.**

Parameter	**DFR0034**	**KY-037**
Variable	Sound intensity level	Sound intensity level
Range	not specified	not specified
Accuracy	not specified	not specified
Interface	analog	analog and digital
Output	0 to supply voltage	analog and logic threshold
Supply	3.3 a 5 V	3 a 5 V
Cost	USD 8.00	USD 3.00

Table 5. Sound-level sensors considered. Neither publishes range nor accuracy, a fact that proves decisive in Section 4.5.

Parameter	**ESP8266 NodeMCU**	**ESP-WROOM-32**	**Raspberry Pi 3B+**
Microcontroller	ESP-8266 32-bit	ESP32 32-bit	BCM2837B0 Cortex-A53 64-bit
Frequency	80 MHz	80 / 160 MHz	1.4 GHz
Logic	3.3 V	3.3 V	3.3 V
Analog inputs	1, 10-bit	15, 10-bit	none
I²C	yes	yes	yes
WiFi / Bluetooth	yes / no	yes / yes	yes / yes
Cost	USD 12.00	USD 12.00	USD 130.00

Table 6. Boards considered as the gateway device. The ESP32's characteristics were checked against the manufacturer's datasheet [3].

3.4 IoT architecture and communication

The gateway publishes readings via MQTT over a broker, from which Node-RED collects them and forwards them to the Ubidots STEM platform [18, 25]. Figure 3 shows the structure of the communication and of the topics, table 6 the boards considered as gateway, and table 7 the topics created.

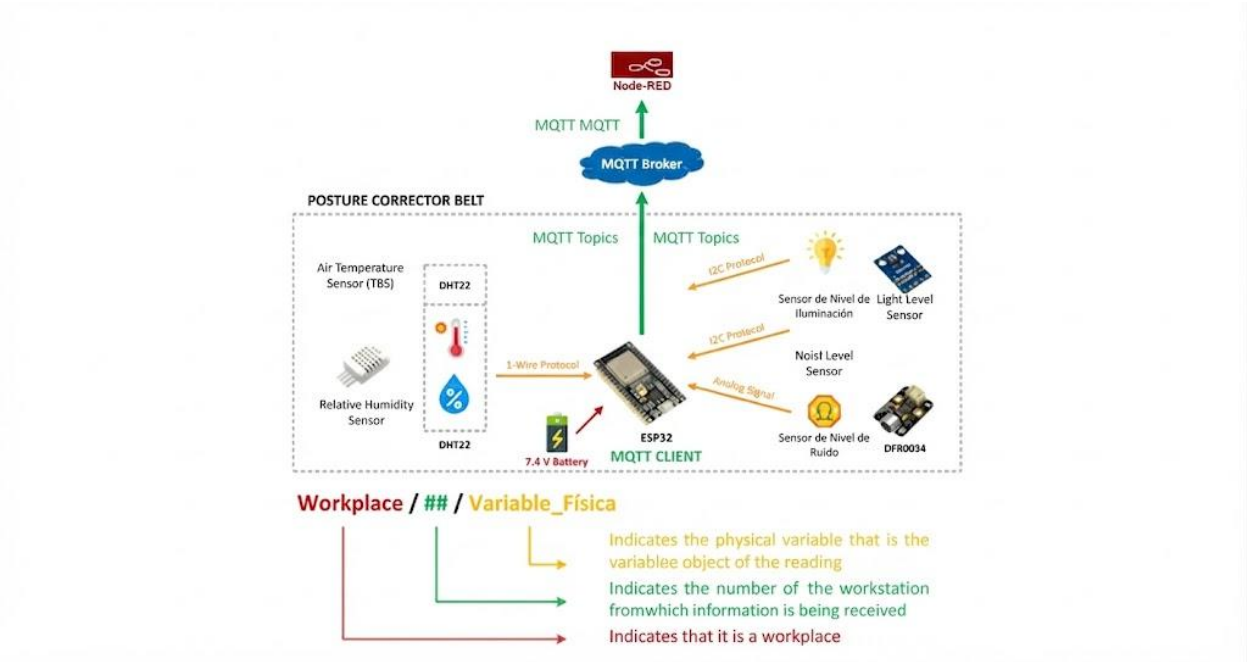


Figure 3. (a) Structure of the monitoring system's MQTT communication. (b) Structure of the MQTT topics.

Topic	Content
Workplace/01/Timestamp	publication date and time
Workplace/01/Temperature	air or dry-bulb temperature
Workplace/01/Humidity	ambient relative humidity
Workplace/01/Light	workstation illuminance level
Workplace/01/Noise	workstation sound level

Table 7. MQTT topics created for the monitoring system**.**

This configuration must be stated explicitly, because as it stands it is not fit for production. The broker used is HiveMQ's free public service [8], on port 1883 and without encryption, and the topics follow a predictable pattern that anyone can subscribe to. That is acceptable for a proof of concept and is not acceptable for an occupational-surveillance system in operation, where the readings are tied to a workstation and, therefore, to identifiable people.

A production architecture would require, at a minimum, TLS-encrypted transport, client authentication, authorization through access-control lists, unique device identifiers, protected credentials and dashboard access restricted to authorized occupational safety and health personnel. Accordingly, access to the information is not described here as available to any interested party, but to authorized occupational safety personnel.

3.5 Decision models

The two design decisions are formalized here, and it is worth stating why neither one needs a compensatory multicriteria method.

Choice of the mounting support.

The study compares three supports on eleven criteria using an ordinal scale. When one alternative is no worse than another on any criterion and is strictly better on at least one, it dominates it in the Pareto sense, and the problem is then solved without needing weights. The precise statement is this: any component-wise monotone utility that respects

the declared directions of the criteria cannot rank a dominated alternative above the one that dominates it; if it further assigns positive relevance to at least one of the strictly improved criteria, the dominant alternative is strictly preferred.

Note what that statement does NOT say. It does not claim that any compensatory method produces the same order under any formulation, because that depends on normalizations and weights that are not fixed here. It claims something weaker and safer: that no monotone utility can reverse a dominance relation. That suffices, and that is why no compensatory order is computed.

Sensing architecture.

The second decision is indeed a genuine optimization problem, because the alternatives do not dominate one another: a sensor can be cheaper and cover less, or cover two requirements at once. It is posed as a binary minimum-cost covering problem. Let R be the set of measurement requirements, J that of candidate sensors and G that of gateways; let $x_{\mathrm{j}} \in \{0,1\}$ be the selection of sensor j, $y_{\mathrm{g}} \in \{0,1\}$ that of gateway g, and a_{rj} the matrix equal to 1 if sensor j validly satisfies requirement r. The objective function is Eq. (2):

$$\min Z = \sum_{j \in J} c_{\mathrm{j}} x_{\mathrm{j}} + \sum_{g \in G} c_{\mathrm{g}} y_{\mathrm{g}} \tag{2}$$

subject to the covering and single-gateway constraints of Eq. (3):

$$\sum_{j \in J} a_{\mathrm{rj}} x_{\mathrm{j}} \geq 1 \quad \forall r \in R, \quad \sum_{g \in G} y_{\mathrm{g}} = 1 \tag{3}$$

and to explicit compatibility constraints: number of available analog channels, I²C availability, required digital channels, admissible supply rail for each sensor, and output signal level against the converter's input limit.

Two clarifications about the coverage matrix, because the result depends on them. The first: eligibility is declared REQUIREMENT BY REQUIREMENT and not globally. That the DHT11 does not meet the required temperature accuracy says nothing about whether it covers relative humidity, and in fact it does. A single eligible-or-not status per component would have eliminated valid candidates. The second: electrical compatibility is assessed by separating the SUPPLY voltage from the SIGNAL LEVEL, and the latter is assessed at the supply voltage actually used, not at the catalog maximum.

4. RESULTS

4.1 Implemented prototype

Figure 4 shows the three mounting supports evaluated and the sensor network mounted on the chosen support. Figure 5 shows the finished prototype and figure 6 its use by a worker, which confirmed that the attachment does not interfere with the task.



(a) (b) (c)

Figure 4. Prototype mounting alternatives: (a) coverall, (b) school backpack/ posture-correcting belt. The belt acts here as an attachment support, not as a postural measurement instrument. (c) Sensor network wiring on a protoboard. Fitting of the posture-correcting belt.



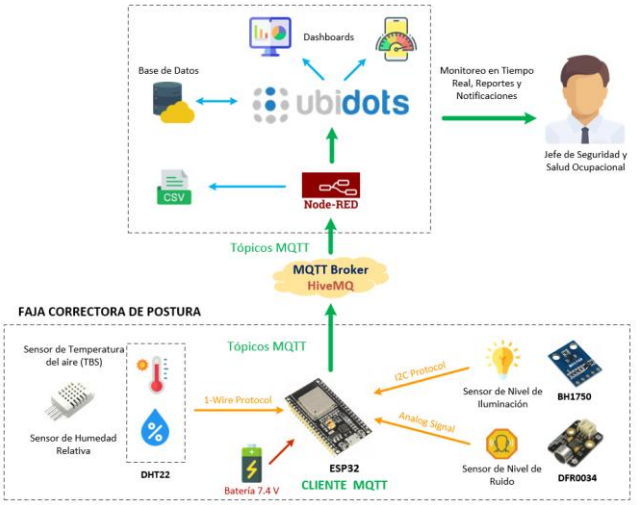
(a) (b)

Figure 5. Monitoring prototype: (a) open enclosure, (b) sensor placement**.**



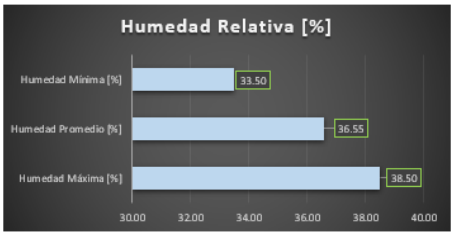
Figure 6. Use of the monitoring prototype by a worker.

Figure 7 shows the complete architecture of the developed application, with its perception, communication, processing and presentation layers, together with an example of the diagnostic report generated from the stored data.



Empresa:	Empresa de Textiles Insomet - Pastocalle			FECHA
Area de Trabajo:	Area 5 - Hilas	Factor Ambiental:	Humedad Relativa [%]	02/02/2023

Valores Condiciones Ambientales en puesto de trabajo			
Humedad Máxima [%]	38.50	Nº muestras superior al máximo	0
Humedad Promedio [%]	36.55		
Humedad Mínima [%]	33.50	Nº muestras inferior al mínimo	0
Humedad Máx Óptima [%]	75		
Humedad Min Óptima [%]	30		



Parámetros definidos por Normativas
1) La humedad estará comprendida entre el 30% y 70%.
2) En los locales o puestos de trabajo donde existan riesgos por electricidad estática el límite inferior de humedad será del 50%.
3) Las condiciones ambientales de los lugares de trabajo no debe suponer un riesgo para la SST.
4) En la medida de lo posible, deberán evitarse las humedades extremas.

PELIGROS	RIESGOS
Humedad baja	Piel seca agrietada
	Susceptibilidad a rinovirus
	Hemorragias nasales
	Problemas respiratorios
	Agravar alergias

Medidas Preventivas Necesarias
Implementar sistemas de humidificación que ayuden a elevar o mantener el porcentaje de humedad adecuados
Incorporar sistemas de ventilación para la correcta circulación del aire
Pausas de recuperación

Imprimir reporte de humedad

Firma Responsable

Figure 7. (a) Complete architecture of the developed IoT application. (b) Example diagnostic report for a variable over the measurement period.

4.2 Point comparison with commercial instruments

The prototype's readings were checked against three commercial instruments: a REED SD-2010 heat-stress meter [20], a REED R8080 sound level meter [21] and a REED R8150 light meter [22]. Figure 8 shows the layout of the instruments and the data received on the platform under the same scenario.

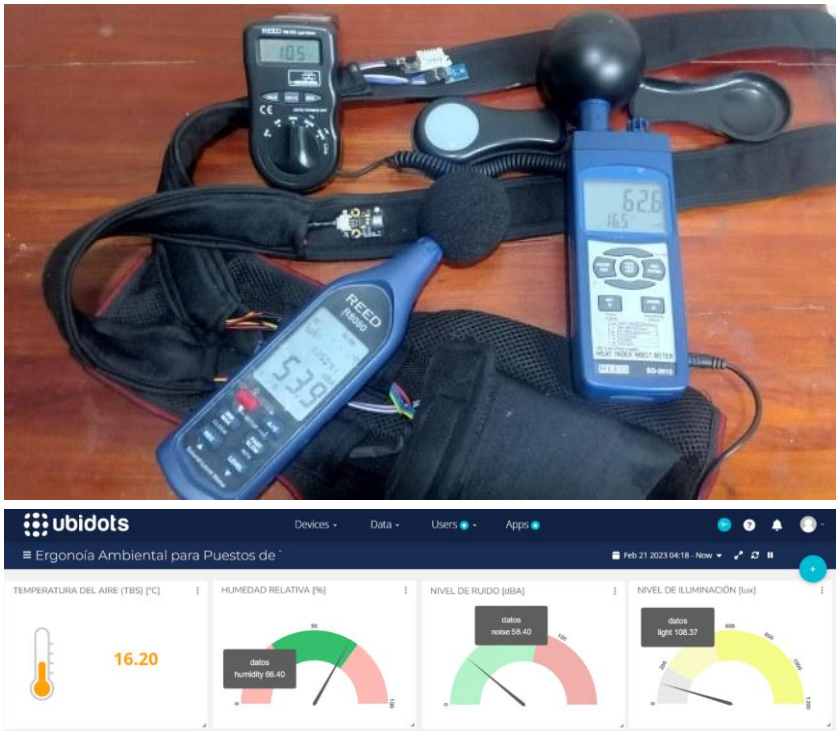


Figure 8. (a) Simultaneous measurement of the physical variables with commercial instruments. (b) Information received on the IoT platform.

The scope of this comparison must be stated precisely, because it determines what can be claimed in the rest of the paper. The available record contains a single paired observation per variable, the one from the scenario figure 9 illustrates. With only one pair of values it is not possible to compute mean bias, mean absolute error, root mean square error or an agreement interval, nor can the calibration set be separated from the validation set. Accordingly, what follows is reported as a SINGLE-POINT INSTRUMENTAL COMPARISON and under no circumstance as a metrological validation.

Variable	Unit	Reference instrument	Prototype	Difference
Dry-bulb temperature	°C	16.50	16.20	−0.30 °C
Relative humidity	%	62.60	66.40	+3.80 percentage points
Sound level	dBA	53.90	58.40	+4.5 dB
Illuminance	lux	105.00	108.37	+3.37 lux

Table 8. Single-point instrumental comparison: one paired observation per variable. The sound-channel difference is expressed in decibels rather than as a percentage, because the scale is logarithmic and a ratio between levels has no physical meaning.

Table 8 shows those four differences. No relative error is reported for the sound level: dividing two values in decibels does not produce an interpretable relative error. The correct difference is the level difference, +4.5 dB, calculated according to Eq. (4):

$$\Delta L = L_{\text{prototipo}} - L_{\text{referencia}} \tag{4}$$

There is a second caveat about the noise channel, and it is the most important one in this section. The study describes that the DFR0034 sensor was subjected to the same sound level as the sound-level meter to build a response curve and determine the scaling model. That is a CALIBRATION. The observation in table 9 comes from the same contrast procedure, so it does not constitute an independent validation: calibrating and validating on the same observations does not certify accuracy. The raw data of that response curve are not available, so the separation between the two sets could not be reconstructed.

4.3 Proof of concept in an industrial setting

A test was carried out at a branch of the Ecuadorian company INSOMET, which manufactures synthetic fabrics and yarns, located in the Pastocalle parish of Latacunga canton. After coordinating with the occupational safety officer and plant management, a workstation was instrumented. The test was configured to send one reading per minute over one hour, yielding sixty values for each variable.

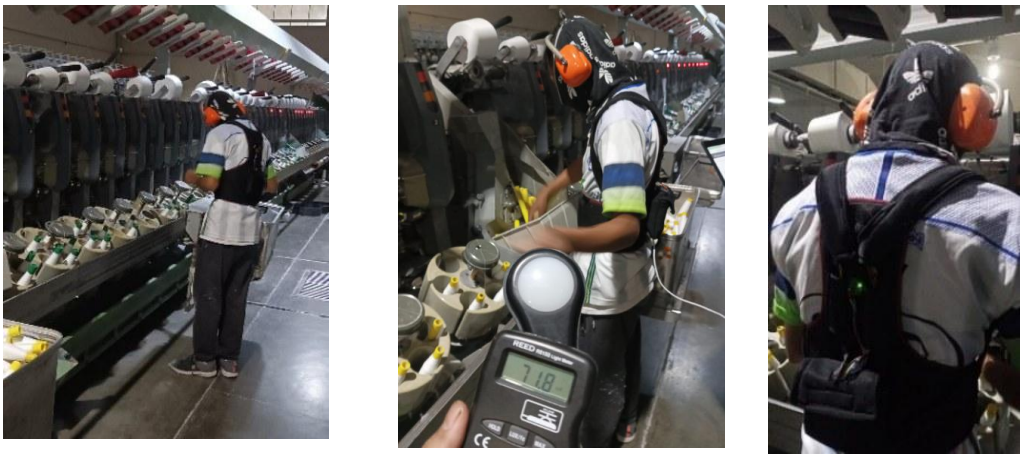


Figure 9. Conducting the proof of concept at the INSOMET company.

Figure 9 documents the installation of the prototype on the worker and the instrumented workstation during the test.

The sixty-value series are not available; only the qualitative conclusions of the proof of concept are retained. Accordingly, no descriptive summary of those series can be presented here — no mean, no dispersion, no range — and the equivalent continuous level of Eq. (1) cannot be computed either. Table 9 states what the proof of concept supports in light of the regulatory framework of Section 3.1.

Variable	What the study claimed	What the evidence supports
Temperature	«the air temperature is above the recommended value at all times», with recommended control actions	The system measures dry-bulb temperature. The WBGT index also requires wet-bulb and globe temperature, which are not measured, so NO heat-stress classification can be issued. Only the observed ambient temperature can be reported.
Relative humidity	«it is at all times within the parameters recommended by the regulations»	The 30-70 % range comes from a Spanish comfort guide [11], not from an Ecuadorian occupational exposure limit. It is kept as a comfort reference.
Sound level	«the average value is around the threshold value»	The regulated quantity is the equivalent continuous level over eight hours [17]. An arithmetic mean of decibels is not an equivalent level, and one hour of recording does not document a working day. Daily exposure CANNOT be inferred.
Illuminance	«it is not sufficient… the regulations set at least 100 lux for textile workshops»	That threshold comes from the table of the repealed Decree 2393. The category of the current Annex 3 applicable to the observed task could not be determined, so NO compliance judgment is issued.

Table 9. Interpretation of the INSOMET proof of concept under the current regulatory framework and the available data.

The result of the test, stated precisely, is that the system operated for one hour at a real industrial workstation, transmitted without interruption and did not interfere with the worker's activity. That establishes operational viability at one workstation, and nothing more: it is a proof of concept at a single workstation and does not authorize any generalization to Ecuadorian industry. For the cost comparison with the reference commercial set to keep holding in continuous operation, it would also have to hold that the sensors do not drift out of calibration beyond what is declared and that the wireless network keeps the same transmission rate without sustained packet loss; this paper verifies neither condition beyond the one-hour test.

4.4 Choice of support by dominance

Table 10 gathers the study's decision matrix, coded on the declared ordinal scale and with the direction of each criterion. The values have not been altered.

Criterion	Direction	Overall	School backpack	Posture-correcting belt
Donning time	min	3	1	1
Removal time	min	3	1	1
Influence on heat stress	min	3	2	1
Shared use among workers	max	0	1	1
Applicable to different workstations	max	0	1	1
Comfort of use	max	2	3	3
Weight	min	2	2	1
Sizes (adaptability)	max	1	2	3
Size	min	3	2	1
Potential handling damage	min	3	1	1
Cost	min	2	2	1

Table 10. The study's decision matrix on the declared ordinal scale. «min» denotes a cost criterion and «max» a benefit criterion.

On that matrix, the pairwise comparisons give the result in table 11.

Comparison	Criteria on which it is not worse	Criteria on which it is strictly better	Dominates?
Posture-correcting belt vs. Overall	11 of 11	11	yes
Posture-correcting belt vs. School backpack	11 of 11	5	yes
School backpack vs. Overall	11 of 11	9	yes

Table 11. Pairwise check of Pareto dominance over the eleven criteria.

The non-dominated set reduces to a single alternative, the posture-correcting belt. The belt is no worse than the coverall on any of the eleven criteria and is strictly better on all eleven; against the school backpack it is no worse on any and strictly better on five. The backpack, in turn, dominates the coverall with nine strictly better criteria. Given what was stated in Section 3.5, no component-wise monotone utility can rank the belt below the other two, so the choice is established without fixing weights and without computing any compensatory order.

The nature of the data should be made precise. This is dominance under the ORDINAL RATINGS DECLARED BY THE STUDY. Not all of those ratings come from measurement: donning time or weight could be measured, but ease of use or potential handling damage are judgments of the design team. The dominance result is sound given that set of ratings, and it inherits from it its status as expert judgment. In the vocabulary of typed indeterminacy: the measurable criteria (donning time, weight) are indeterminacy removable by further measurement, whereas the criteria based on the design team's judgment (comfort, handling damage) are constitutive of how the assessment was framed and are not resolved with more data of the same kind.

4.5 Minimum-cost sensing architecture

Table 12 presents the binary program's coverage matrix, declared requirement by requirement before solving. The FC-28 does not appear in the matrix: it measures soil moisture through conductivity between electrodes, not atmospheric relative humidity. This is not an unverified specification, but a different physical quantity altogether.

The model was solved by exact enumeration —the catalog is small— under five scenarios that differ in the set of requirements and in the eligibility criterion for the noise channel. Table 13 gathers the result of each one.

Component	TBS	TBH	TG	HR	RUI	LUX	Cost (USD)	Remark
DHT11	—	—	—	yes	—	—	4.00	±2 °C does not meet TBS; its 20-90 % range does cover RH 30-70 %
DHT22	yes	—	—	yes	—	—	7.00	±0.5 °C and 0-100 % RH: covers two requirements with one component
LM35	yes	—	—	—	—	—	2.00	±0.5 °C; supply ≥4 V, absolute output 0-400 mV over 0-40 °C
DS18B20	yes	—	—	—	—	—	8.00	±0.5 °C; TBS only and more expensive than the DHT22
BH1750	—	—	—	—	—	yes	4.00	1-65535 lux over I²C, direct output in lux
GL5528	—	—	—	—	—	—	3.00	range and accuracy «not specified»: does not certify LUX
DFR0034	—	—	—	—	relaxed	—	8.00	range and accuracy «not specified»; the article documents an empirical response curve against a sound-level meter
KY-037	—	—	—	—	relaxed	—	3.00	range and accuracy «not specified» and no empirical characterization

Table 12. Coverage matrix by requirement. No component certifies TBH or TG. On the noise channel none certifies it by specification; «relaxed» indicates that it can only be admitted by explicitly declaring its metrology as indeterminate.

Scenario	Requirements and criterion	Result
E1	Full requirements of the study, eligibility by published specification	INFEASIBLE. No candidate certifies TBH, TG or RUI.
E2	Without TBH or TG, eligibility by published specification	INFEASIBLE. No noise sensor publishes range or accuracy.
E3	As E2, admitting any noise sensor with indeterminate metrology	Optimum USD 25.00 — ESP-WROOM-32 with BH1750, DHT11, KY-037, LM35.
E4	As E3, requiring documented empirical characterization of the noise channel	Optimum USD 30.00 — ESP-WROOM-32 with BH1750, DFR0034, DHT11, LM35.
E4s	As E4, with no supply rail above the 3.3 V logic level	Optimum USD 31.00 — BH1750, DFR0034, DHT22, with ESP-WROOM-32 or ESP8266 NodeMCU interchangeably.

Table 13. Solution of the binary program under five scenarios. The first two are infeasible, and that infeasibility is the model's most informative result.

The infeasibility of E1 is not a flaw in the model: it is a finding about the system. The study itself declares wet-bulb and globe temperature among its requirements, needed for the WBGT index, and none of the components in its catalog measures them. The published architecture is therefore not the optimal solution of the declared problem, but that of a reduced problem in which those two variables were quietly dropped. That is exactly why Section 4.3 cannot issue a heat-stress diagnosis.

The infeasibility of E2 points to the same thing on another channel. Neither of the two noise sensors considered publishes range or accuracy, so under a specification-based eligibility rule the 30-to-120 dBA requirement cannot be certified with that catalog. The noise channel only enters the system if it is explicitly accepted that its metrology is indeterminate.

Among the feasible scenarios the most useful result is not the cost, but the active constraint. Under the criterion closest to what the study actually applied —E4, which requires empirical characterization on the noise channel and therefore selects the DFR0034— the optimum is USD 30.00, not USD 31.00: replacing the DHT22 with the LM35-plus-DHT11 pair covers temperature and humidity for USD 6.00 instead of USD 7.00, at the cost of using an extra analog channel that the ESP-WROOM-32 has to spare. The published configuration turns out optimal only under E4s, that is, when no supply above the 3.3 V logic rail is considered available and the LM35 is excluded for being unable to be powered.

The feasibility of E4 constitutes a relaxed scenario for the design analysis and does not certify that the DFR0034 metrologically satisfies the original 30-to-120 dBA requirement. What E4 expresses is only that the component is admitted under a relaxed design assumption, because an empirical characterization of its response exists; that characterization is a calibration, not an independent validation, and the sensor still does not publish range or accuracy.

Put directly: within the set of candidates and the modeled constraints, the USD 31.00 configuration is optimal under scenario E4s, in which no supply above 3.3 V is considered available for the sensors. The LM35 requires at least 4 V of supply, although its output signal is indeed compatible with the 3.3 V converter; the study describes power from a 7.4 V LiPo battery through the board's regulator, which makes it plausible that such a rail exists, but does not document its direct availability to the sensor. Settling that question —a five-minute hardware check— decides between USD 30.00 and USD 31.00 within the model, without the available record allowing a statement of which of the two scenarios physically describes the built system.

In E4s the optimum is reached indifferently with the ESP-WROOM-32 or the ESP8266 NodeMCU: both cost USD 12.00 and both satisfy the constraints of the minimal solution, which uses a single analog channel. The study's choice of the ESP-WROOM-32 is thus confirmed by the model, not imposed by it, and its justification is the channel margin for future expansion, not cost.

4.6 Comparison of acquisition costs

The study presented this section as a return-on-investment calculation. The figure it reports is arithmetically correct —(4730 − 1715)/1715 = 1.76— but it does not constitute an ROI, because a return on investment requires a time horizon, recurring costs, calibration, maintenance, replacement, platform or subscription cost, labor savings, assessment frequency, service life and monetized benefits. None of those elements is available, so the section is limited to a comparison of acquisition costs, gathered in table 14.

Item	Amount (USD)
Reported cost of the reference commercial instrumentation set	4 730
Reported acquisition and development cost of the prototype	1 715
Potential difference in acquisition cost	3 015

Table 14. Comparison of acquisition costs. This is not a return-on-investment analysis and does not authorize any conclusion about financial viability.

This comparison does not pit functionally or metrologically equivalent systems against each other; the commercial set incorporates capabilities the current prototype does not reproduce.

From this comparison it follows that the prototype's reported acquisition cost is lower than that of the reference set of commercial instruments. It does not follow that the system is financially viable, because that depends on recurring costs and monetized benefits that are not known here.

5. DISCUSSION

The prototype works: it measures four physical factors, publishes to the cloud, operates for one hour at a real industrial workstation without interfering with the task, and its reported acquisition cost is lower than that of the reference set of commercial instruments. That result is solid and supports the proposal as a proof of concept.

The analysis bounds that result rather than confirming it. The two design decisions are established with methods appropriate to their structure: dominance for the choice of support, which needs no weights, and a binary covering program for the architecture, which is indeed an optimization problem. Reporting a closeness coefficient equal to unity as justification for the first decision was applying a compensatory method to a problem dominance had already solved; the unit value was, in fact, the sign that it was unnecessary. The systematic check of which elementary operations or perturbations actually move the ranking in multicriteria models follows the single-operation contrast formulation of Vega Falcón [26]. Separately, the integration of environmental factors into the assessment of occupational health and thermal comfort connects with the uncertainty and neutrosophic models applied to wellbeing and the medical sciences documented by Estupiñán Ricardo et al. [4].

The three limits that bound the scope are of a different nature and should not be conflated. The first is metrological: the available record contains one paired observation per variable, which allows a point comparison but not a validation, and on the noise channel it does not even allow calibration to be separated from validation. The second is regulatory: without wet-bulb or globe temperature there is no WBGT index and, therefore, no heat-stress classification, however

much ambient temperature is available; and the lighting category applicable to the observed task could not be determined from the sources consulted. The third is security: a public broker without encryption or authentication is adequate for a demonstration and not for monitoring the conditions of an identifiable workstation.

Once again, the system's scope must be stated explicitly. The prototype characterizes PHYSICAL risks of the work environment. It does not characterize ergonomic risks: it does not measure posture, joint angles, force, repetitiveness or physical load, and the fact that the mounting support is a posture-correcting belt provides no measurement of the wearer's posture.

From this follows a continuation agenda with clear priorities. Adding wet-bulb and globe-temperature sensors would turn the system into an instrument capable of assessing heat stress, which is the most limiting gap. Recording a comparison campaign with a sufficient number of paired observations, separating calibration from validation, would allow the point comparison to be replaced by a metrological characterization with bias, mean absolute error and agreement analysis. Sampling the sound channel at the appropriate rate would allow the equivalent continuous level of Eq. (1) to be computed and, with it, compared against the regulatory criterion in the correct quantity. And migrating to a broker with TLS and authentication is a prerequisite for any deployment outside the laboratory.

6. CONCLUSIONS

An IoT-based monitoring prototype was developed and tested, designed for continuous monitoring of four physical risk factors of a workstation —dry-bulb temperature, relative humidity, sound level and illuminance— which it publishes to a cloud platform via MQTT. The demonstrated test lasted one hour at a textile-plant workstation, with sixty one-minute observations per variable and without interfering with the worker's activity, which establishes operational viability at that workstation during that period; long-duration continuous operation was not experimentally validated.

The contrast with commercial instruments reaches the level of a single-point instrumental comparison: one paired observation per variable, with differences of −0.30 °C in temperature, +3.80 percentage points in relative humidity, +4.5 dB in sound level and +3.37 lux in illuminance. With only one pair of values per variable it is not possible to estimate bias, mean absolute error or agreement, and on the sound channel the calibration and the contrast come from the same procedure, so there is no independent validation.

The choice of mounting support is settled by Pareto dominance over the declared ordinal ratings: the posture-correcting belt is no worse on any of the eleven criteria and is strictly better on eleven against the coverall and on five against the school backpack. No component-wise monotone utility can reverse that order, so the decision requires no weights or compensatory method whatsoever.

The sensing architecture, posed as a binary minimum-cost covering program, produces a result not previously reported for this prototype. Under the full set of requirements the study itself declares, the model is INFEASIBLE, because no component in its catalog measures wet-bulb or globe temperature and no noise sensor publishes range or accuracy. Admitting the noise channel with indeterminate metrology and requiring documented empirical characterization, the optimum is USD 30.00; the published configuration of USD 31.00 is optimal only when no supply above the 3.3 V logic rail is considered available, a condition the study does not document.

The regulatory limitations are decisive and are stated without softening. No heat-stress classification is issued, because the WBGT index requires wet-bulb and globe temperature that the system does not measure. No lighting-compliance judgment is issued, because the Annex 3 category applicable to the observed task could not be determined. No workday sound exposure is inferred, because the regulatory criterion is an equivalent continuous level over eight hours and the measurement covers one hour. And the humidity ranges used are an external comfort reference, not an Ecuadorian occupational-exposure limit.

The work is, therefore, a proof of concept at a single workstation, with no generalization to Ecuadorian industry, intended for triage and trend monitoring and not as a substitute for a Class 1 sound level meter in regulatory measurements, with a metrological scope limited to the point comparison, and with a communications configuration

that is not fit for production. Within those limits, it shows that low-cost instrumentation allows the move from the occasional campaign to the continuous record, and that the design decisions of such a system admit formalization with operations-research methods appropriate to their structure.

ACKNOWLEDGMENTS

The authors thank the company INSOMET for the facilities provided for carrying out the proof of concept, and the worker who used the prototype during it.

Data availability: the dominance and binary-covering-program calculations are fully reproduced from the tables published in this paper. The proof-of-concept series and the raw calibration data for the sound channel are not available.

RECEIVED: MAY, 2026;
REVISED: OCTOBER, 2026.

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