Measurement System Analysis of IoT Devices for Illuminance Monitoring

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Abstract

Thanks to the significant development of the Internet of Things (IoT), measuring instruments have become accessible to everyone, enabling their use for various measurements. However, when people use Internet of Things (IoT) measuring instruments, they often rely on the results of these measurements without justification ,which can lead to incorrect decisions. This article presents the Citizen Science study that analyzes the most commonly used Internet of Things (IoT) measurement instruments, focusing on phone-based systems for conducting indoor lighting measurements using various phone models and software tools. The purpose of the study was ambivalent, as it aimed to involve students in scientific activities through Citizen Science experiments, which use statistical data analysis to assess the ability of phones to perform workplace indoor lighting measurements. During experiments, a measurement study analysis (MSA), a controlled experiment where a sample of items are measured multiple times by different devices and apps allowed us to separate the variation into specific sources – Gage Repeatability and Reproducibility (R&R) and to show differences between Internet of Things (IoT) devices designated for indoor lighting measurements. The conducted study provides knowledge to Internet of Things (IoT) measurement device users on how to perform MSA in order to self-assess the measurements being made and prevent the analysis of poorly collected data.

Keywords

Internet of Things (IoT) metrology, Internet of Thing-based systems (IoT-based systems) Illuminance, Citizen Science, Measurement System Analysis (MSA)

1. Introduction

The performance of the Internet of Things (IoT)-based systems is directly dependent on the quality of hardware and software. Software Quality Assurance (SQA) is a crucial factor for maintaining the quality of service of Internet of Things (IoT) based applications. Metrology Evaluation of the Internet of Things (IoT) Measurement Solutions was done by authors [1], who evaluated 158 Internet of Things (IoT) measurement solutions and came to the conclusion that the metrological coverage of Internet of Things (IoT) measurement solutions did not show improvement over the 2010 to 2021 timeframe. Despite this fact the Internet of Things (IoT) measurement tools play a crucial role in Citizen Science activities worldwide.

Environmental monitoring can be done by any citizen without even leaving their home, so we have a unique opportunity to involve many people in Citizen Science activities. Citizen Science is the non-professional involvement of volunteers in the scientific process, whether in the data collection phase or in other phases of research. The variety of Citizen Science and new sensors and smart phones make scientific research or environmental monitoring fun and interesting for young people. For many years, the focus was only on ambient air monitoring, so we can summarize the impact on our daily life only of Citizen Science for environmental policy projects. The research group

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conducted a review of 503 Citizen Science projects [3] and suggested how to assess the conditions under which Citizen Science can best support environmental policy and make a bigger impact on policy makers and involve more young people inside the Citizen Science activities in order to create society which will be able to drive Green transition with necessary digital tools. It should be emphasized that air quality studies accounted for only 7% of all projects.

It is stated that will also continue to support and incentivize the practice of open science by the R&I communities, through:

- improved interoperability and sharing of data ('as open as possible and as closed as necessary') and enhanced reproducibility of research results, which will in particular be a focus of several clusters, partnerships and missions;
- the involvement of the general public and other end-users through different participatory formats e.g., co-creation and deliberative exercises, citizen science, and user-led innovation modes of R&I, which will be promoted across the programme;
- the development and consolidation of the European Open Science Cloud (EOSC), the development of appropriate skills, and the diffusion and adoption of open science practices, which will be supported further;
- the availability of Open Research Europe (ORE), the open access peer reviewed publishing venue for Horizon 2020 and Horizon Europe beneficiaries, which will develop further, as well as the support to not-for-profit, scholarly open access publishing models.

This research contributes Open Science in Europe by including the following key aspects:

- Bring Science closer to citizens. To help young people acquire core future skills by participating in scientific activities at the professional and/or Citizen Science level by monitoring indoor lightning condition by using Internet of Things (IoT) devices;
- Improving Data Quality Framework for indoor lightning by standardization of metadata. Advancing an open science system and aligning national and EU policies to improve the production of FAIR [4, 5] research output.
- Creation of open to public educational resources. The recommendations on how to perform Citizen Science activities inside indoor lightning monitoring.
- Open research data. Datasets with indoor lightning will be uploaded to open access repositories or will be given at any request without restrictions to use it.

Improved traceability of citizen science data uses, both in science and for policy, is important to appreciate its impact and optimize its uses. This can be achieved by including persistent identifiers to uniquely identify citizen science datasets or through the development of a tool to track policy development [3].

Adherence to FAIR principles is included in the Grand vision of the SI Digital Framework in metrology at 2021 [6], so a harmonization for the communication of data of indoor lighting measurement devices will be of great benefit for international metrology and a big push for Internet of Things (IoT) industry to become a part or legal metrology by providing reliable data.

The structure of this article is organized by providing an overview of the theoretical framework concerning Measurement System Analysis (MSA) and its application to Internet of Things (IoT) based on illuminance measurement systems. The experimental design specifies device selection, measurement procedures, and data collection protocol. Two experiments were performed, one involving uncalibrated devices and another incorporating calibrated references and various mobile applications by presenting and analyzing the results.

2. Measurement system analysis

The data is obtained through measurements, or in other words, the measurement system is designed to collect data about the objects or environmental parameters that interest us. In practice, however, the following question arises whether data is reliable and can be trusted. This article explores the process of collecting data when performing lighting measurements with mobile phones, one of the most common Internet of Things (IoT) measurement tools. Measurement System is the combination of people, equipment, materials, methods and environment involved in obtaining measurements [7]. Analysis of measurement systems is not new, but with the advent of more and more Internet of Things (IoT) devices, it must also be applied by integrating MSA algorithms into software code in these measurement devices. From history we can see [8], that business often bypasses standardization and proposes solutions earlier than they are adopted by ISO or other international organizations. To this day, there is no unified standard that can be used to evaluate Internet of Things (IoT) measurement tools, however, we propose the use of standard ISO/IEC 17025:2017 (General Requirements for the Competence of Testing and Calibration Laboratories) [9] as the main document and perform the same procedures like accredited measuring laboratories follows.

Measurement System Analysis (MSA) – series of studies that explains how measurement systems perform is described in standard ISO 13053-2:2011 Quantitative Methods in Process Improvement — Six Sigma Part 2: Tools and Techniques [10]. A mobile phone, with its built-in sensors, is a measurement system that can be examined with the help of MSA. Metrological properties of the measuring instrument, that is the part of the measuring system, are described in International Vocabulary of Metrology [11]. The concept diagram of measurement systems is presented below in Figure 1, regardless of whether it will use low-cost or professional measuring instruments.

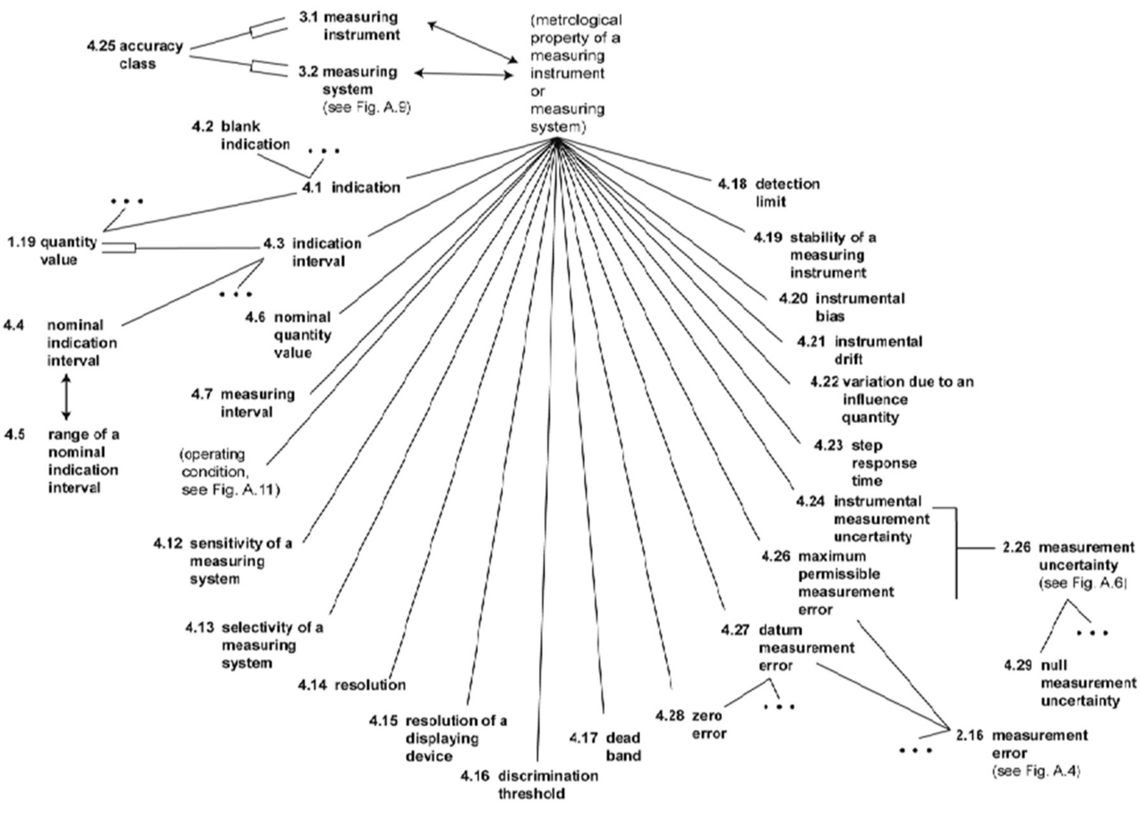


Figure 1: Metrological properties of measuring systems [11].

A measuring system may consist of one or more measuring instruments, the metrological characteristics of which may be as follows: range, bias, repeatability, stability, hysteresis, drift, effects of influencing quantities, resolution, discrimination, error and dead band. All these metrological characteristics contribute to measurement uncertainty.

MSA allows finding possible reasons for the uncertainty of the measurement system due to:

1. Resolution: the smallest increment of measurement variable that devices are capable of detecting.
2. Measurement accuracy (bias): the differences between what a measurement system 'reads' and what the true value is.
3. Linearity error: measurement bias across the usable range of the measuring system.
4. Stability: variability in the results given by a measurement system measuring the same characteristic and the same product over an extended period of time.
5. Repeatability: the difference between results of successive measurements on the same measurand (with all measurements carried out under identical measurement conditions: same measurement procedure; same observer, same measuring instrument, used under the same operating conditions, same location, the repetition over a short period of time.
6. Reproducibility: the difference between results of measurements on the same measure (with measurements carried out under different measurement conditions) [10].

In this study, the experiments will be limited to the MSA of different mobile phones and different software mobile applications.

The application of MSA in solving problems in different industry areas has been examined by the following authors [12, 13] and found that it helps to improve the processes.

During the experiment, the illumination inside the room was measured, i.e. the measurement system was collecting data which is measured on a continuous scale so we used an MSA method called Gauge Repeatability and Reproducibility (Gauge R&R). Regardless of the type of MSA being used, there are two key things we are usually interested in when we analyze a measurement system:

- If the same person or piece of equipment measures the same item over and over again, do we consistently get the same data? Repeatability assesses whether each person can measure the same item multiple times with the same measurement device and get the same value when measuring continuous data.
- If different people or pieces of equipment measure the same item, would they each get the same result? Reproducibility assesses whether different people can measure the same item multiple times with the same measurement device and get the same average value.

Measurement System Analysis works by setting up and running a controlled experiment to check the repeatability and reproducibility of the within appraiser and between appraiser agreement of the system [7].

After the Gauge R&R MSA is performed the usual decision criteria are:

- GRR< 10%: the measurement system is acceptable;
- 10%<GRR<30%: the measurement system needs improvement;
- GRR> 30 %: the measurement system is unsuitable.

The following section provides descriptions of the experiment and data that will then be analyzed using the MSA Gauge R&R method. The main document on which the research was based is the Reference Manual of Measurement System Analysis 4th edition [14].

3. Design of experiments

During the experiments, lighting measurements were carried out using mobile phones. The aim of the study was to find out:

- the extent to which measurements of non-calibrated Internet of Things (IoT) measuring devices can be relied upon;
- whether different software, illumination measurement programs influence the measurement results.

Lighting measurements were carried out in a room with covered windows, under artificial lighting, so that the measurement system would be exposed to as few environmental factors as possible. Mobile phones were randomly selected for measurements. Before taking measurements, it was made sure that the charge level of mobile phone batteries was between 80-90%, in addition, phone sensors and light-capturing cameras were wiped with a special cloth so that the optical measurements would not be distorted due to light damping by the detector's dirty surface. The data was fed into a specially prepared spreadsheet which allows the user to perform a complete Gauge R&R study (Figure 3). At the end of experiments Analysis of Variance (ANOVA) and Xbar/Range calculations are performed and conclusions formulated. ANOVA is a statistical test for Analysis of Variance for detecting differences in group means when there is one parametric dependent variable and one or more independent variables [15]. Xbar/Range is a graphical method that tracks variation between measurements, Xbar Chart for means and Range Chart for variability.

A common standard is to use a minimum of 10 parts for a Gauge R&R study, so we choose 10 different lighting levels which were adjusted by a dimmable lamp. The Lucas Nuelle Photovoltaic board CO4203-2A was used in the experiments. The experiment's setup is presented at Figure 2 and includes a dimmable 120W reflector lamp, integrated solar irradiance meter, Labsoft software with ability to measure irradiance.

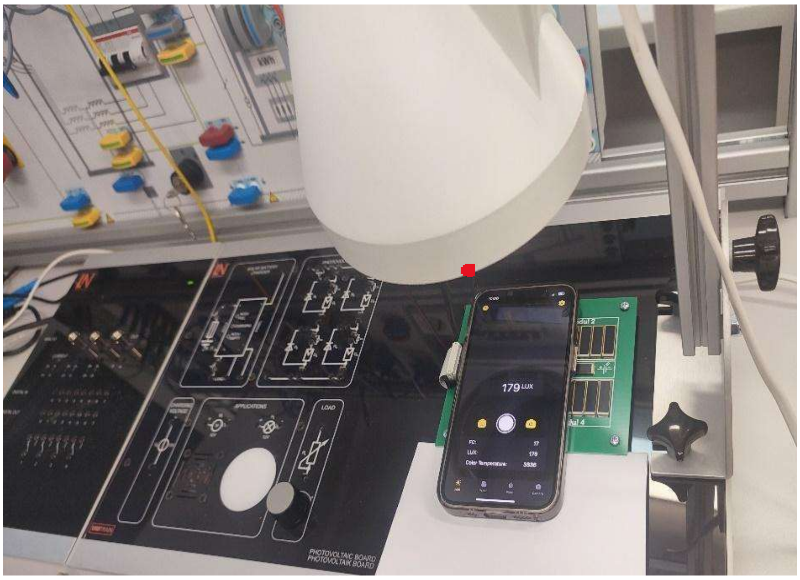


Figure 2: Experiment setup by Lucas Nülle - Photovoltaics (UniTrain)

Detailed specification of UniTrain Interface with virtual instruments are provided by the producer of equipment [1].

3.1 IoT Illuminance Measurement System Analysis by using random phones and applications

In this experiment 3 different phones were randomly selected from the class. The phone models and applications used during the experiment are next:

1. Iphone 15+ / Lux Light Meter & Exponometer for iPhone by Mindateq Sp.z o.o. ver 1.0.9
2. Iphone 13 / Lux Light Meter & Exponometer for iPhone by Mindateq Sp.z o.o. ver 1.0.9
3. Xiaomi 11T/ Phyphox Light for Android Version: 1.1.16

During the experiment the setup depicted in Figure 2 was used. The scale of dimmable lamp potentiometer was divided into 10 equal parts. At each position the irradiance of the photovoltaic board was recorded by built-in sensors and results are presented in the Table 1 below.

Table 1
Measurement of Experiment number 1

Position of lamp dimmer	1	2	3	4	5	6	7	8	9	10
Irradiance, W/m^2	30	30	30	285	400	520	645	800	925	920

At each measurement position the 3 phones were placed on the photovoltaic board at the same position under controlled light source by aligning the phones to the upper left position marked by red dot. The irradiance was kept the same for all 3 phones. The results were summarized in Gage Repeatability and Reproducibility Data Collection Sheet, which you can see in Figure 3.

Gage Repeatability and Reproducibility Data Collection Sheet

Part No. & Name:	Different levels of iluminance	Gage Name:	Mobile phone	Date:	11/3/25
Characteristics:	Illuminance	Gage Number:	Iphone 15+, Iphone 13, Xiomi 11T	Performed by:	KK HEI, UT
Specifications:		Gage Type:	Light meter		

Upper Spec	200	# of Trials =	3	K_1 =	0.5908	Xbar diff =	15852.1	D_4 =	2.58
Lower Spec	80000	# of appraisers =	3	K_2 =	0.5231	Rbarbar =	1405.1667	R_p =	60427
Total Tol	79800	# of parts =	10	K_3 =	0.3146				

Appraiser/Trial #		Part 1	2	3	4	5	6	7	8	9	10	Average
Iphone 15+	1	222	227	225	6654	16324	26824	42470	60708	69396	74529	29757.9
	2	221	222	224	7271	16699	27440	40807	57554	68922	79138	29849.8
	3	220	226	223	6263	15931	28697	38330	59598	71153	77319	29796
Average		221	225	224	6729.3333	16318	27653.667	40535.667	59286.667	69823.667	76995.333	$Xbar_a$ = 29801.233
Range		2	5	2	1008	768	1873	4140	3154	2231	4609	$Rbar_a$ = 1779.2
Iphone 13	1	185	187	177	6829	19787	24838	37727	51087	70023	65560	27640
	2	179	188	178	6593	16574	23314	38171	49110	67812	72701	27482
	3	180	188	180	7276	18473	25434	36952	50703	64759	74244	27838.9
Average		181.33333	187.66667	178.33333	6899.3333	18278	24528.667	37616.667	50300	67531.333	70835	$Xbar_b$ = 27653.633
Range		6	1	3	683	3213	2120	1219	1977	5264	8684	$Rbar_b$ = 2317
Xiomi 11T	1	295	297	293	3717	11291	12831	19823	27250	29875	34146	13981.8
	2	295	330	293	3717	11291	12831	19823	27250	29875	34146	13985.1
	3	295	330	293	3774	10188	12831	19823	27250	29875	34146	13880.5
Average		295	319	293	3736	10923.333	12831	19823	27250	29875	34146	$Xbar_c$ = 13949.133
Range		0	33	0	57	1103	0	0	0	0	0	$Rbar_c$ = 119.3
Part Average		232.44444	243.88889	231.77778	5788.2222	15173.111	21671.111	32658.444	45612.222	55743.333	60658.778	Xbarbar = 23801.333 R_p = 60427
[(Rbar a = 1779.2 + Rbar b = 2317 + Rbar c = 119.3) / # of appraisers = 3] = Rbarbar												Rbarbar = 1405.1667
(Max Xbar = 29801.2333333333) - Min Xbar = 13949.1333333333) = Xbar diff												Xbar diff = 15852.1
(Rbarbar = 1405.16666666667) x (D4 = 2.58) = UCL R												UCL R = 3625.33

Figure 3. MSA data collection spreadsheet with results

The spreadsheet allows the user to perform a complete Gauge R&R study. The ANOVA and Xbar/Range calculations were performed. During the experiment one operator was using three phones (Appraiser) and three trials (Trial#) accommodated at each measuring point (PART).
The percentage of equipment variation, appraiser variation, part variation, and the number of distinct categories that can be distinguished are shown in Figure 4.

Measurement Unit Analysis	% Total Variation
Repeatability - Equipment Variation (EV) EV = (Rbarbar) x (K_1) = (1405.16666666667) x (0.5908) = 830.17	Percent Equipment Variation %EV = 100 [EV / TV] = 100 [830.17 / 20756] = 4.000 %
Reproducibility - Appraiser Variation (AV) AV = SQRT{(Xbar diff x K 2)^2 - (EV/[(# parts) x (# trials)])} = SQRT(68761000 - 22973) = 8290.8	Percent Appraiser Variation %AV = 100 [AV / TV] = 100 [8290.8 / 20756] = 39.944 %
Repeatability & Reproducibility (GRR) GRR = SQRT[(EV^2) + (AV^2)] = SQRT [689180 + 68737000] = 8332.3	Percent Gage Repeatability & Reproducibility Variation %GRR = 100 [GRR / TV] = 100 [8332.3 / 20756] = 40.144 %
Part Variation (PV) PV = R_p x K_3 = 19010	Percent Part Variation %PV = 100 [PV / TV] = 100 [19010 / 20756] = 91.588 %
Total Variation (TV) TV = SQRT[(GRR^2) + (PV^2)] = SQRT [69427000 + 361380000] = 20756	Number of Distinct Categories that can be Distinguished ndc = 1.41(PV / GRR) = 1.41 (19010 / 8332.3) = 3.217 or approximately: 3

Trials	K_1
2	0.8862
3	0.5908

Appraisers	2	3
K2	0.7071	0.5231

Parts	K_3
2	0.7071
3	0.5231
4	0.4467
5	0.403
6	0.3742
7	0.3534
8	0.3375
9	0.3249
10	0.3146

Figure 4. Gage Repeatability and Reproducibility report

The numerical summary showed the results of all calculations used in the ANOVA and Xbar/Range method of analysis. The Variance, Standard Deviation and Percent of Variance for each variation component were calculated. At the end the Gauge R&R for Percent of Study Variation and Percent of Tolerance were calculated using 5.15 standard deviations (99% of the variation) and 6.0 standard deviations (99,7% of the variation) and ANOVA table is displayed in Figure 5.

Gage R&R Study - ANOVA Method

Variance and Standard Deviation Components

Source	St. Dev.	Variance	% of Variance
Total Gage R&R	12362.5	1.53E+08	22.48%
Repeatability	1281.277	1641671	0.24%
Reproducibility	12295.92	1.51E+08	22.24%
Operator	8081.442	65309702	9.61%
Operator*Part	9267.149	85880059	12.63%
Part to Part	22956.65	5.27E+08	77.52%
Total Variation	26073.73	6.8E+08	100.00%

Process Tolerance = 79800

Gage R&R Using 5.15 Standard Deviations (99%)

Source	Study Variation	% Study Variation	% of Tolerance
Total Gage R&R	63666.88	47.41%	79.78%
Repeatability	6598.577	4.91%	8.27%
Reproducibility	63324.01	47.16%	79.35%
Operator	41619.43	30.99%	52.15%
Operator*Part	47725.82	35.54%	59.81%
Part to Part	118226.7	88.05%	148.15%
Total Variation	134279.7	100.00%	168.27%

Gage R&R Using 6.0 Standard Deviations (99.7%)

Source	Study Variation	% Study Variation	% of Tolerance
Total Gage R&R	74175.01	47.41%	92.95%
Repeatability	7687.663	4.91%	9.63%
Reproducibility	73775.55	47.16%	92.45%
Operator	48488.65	30.99%	60.76%
Operator*Part	55602.9	35.54%	69.68%
Part to Part	137739.9	88.05%	172.61%
Total Variation	156442.4	100.00%	196.04%

Gage R&R Study - Xbar/Range Method

Variance and Standard Deviation Components

Source	St. Dev.	Variance	% of Variance
Total Gage R&R	8332.3	69427223	16.12%
Repeatability	830.17	689182.2	0.16%
Reproducibility	8290.8	68737365	15.96%
Part to Part	19010	3.61E+08	83.88%
Total Variation	20756	4.31E+08	100.00%

Process Tolerance = 79800

Gage R&R Using 5.15 Standard Deviations (99%)

Source	Study Variation	% Study Variation	% of Tolerance
Total Gage R&R	42911.35	40.14%	53.77%
Repeatability	4275.376	4.00%	5.36%
Reproducibility	42697.62	39.94%	53.51%
Part to Part	97901.5	91.59%	122.68%
Total Variation	106893.4	100.00%	133.95%

Gage R&R Using 6.0 Standard Deviations (99.7%)

Source	Study Variation	% Study Variation	% of Tolerance
Total Gage R&R	49993.8	40.14%	62.65%
Repeatability	4981.02	4.00%	6.24%
Reproducibility	49744.8	39.94%	62.34%
Part to Part	114060	91.59%	142.93%
Total Variation	124536	100.00%	156.06%

Number of Distinct Categories = 3

Figure 5. Gage Repeatability and Reproducibility ANOVA and Xbar/Range method results.

After the Gauge R&R MSA was performed, study variation by using ANOVA and Xbar/Range was more than 30%, so we can come to the conclusion that the measurement system is unsuitable and correction actions should be taken.

3.2 IoT Illuminance Measurement System Analysis by calibrated phone and three applications

After the first experiment we took corrective actions. We found that not all apps allow calibrating the phone illuminance sensors, so we selected the phones, which are close to a reference measuring device or true value. For this action the reference device Metrel Eurotest 61157 with type B lux meter sensor was used. The same phones which were used in the first experiment and software were used:

1. Android phone Redmi Note Pro 10. Application Phyphox Light for Android Version: 1.1.16
2. Iphone 15+ / Lux Light Meter & Exponometer for iPhone by Mindateq Sp.z o.o. ver 1.0.9
3. Iphone 13 / Lux Light Meter & Exponometer for iPhone by Mindateq Sp.z o.o. ver 1.0.9

As seen from the Figure 6, the relative error from Metrel Eurotest 61157 reference device (354 Lx) was next: Redmi Note Pro 10 – 1.66%, Iphone 15+ – -11.32% and Iphone 15+ – -97.76%. The closest measured value to the reference device showed the Android phone Redmi Note Pro 10, because of that, this device was used during the following experiment. The phone model M2101KG6 and the light sensor name : rohm_bu27030 ambient light.

During this experiment we wanted to test the influence on measurement results of the applications used for illuminance measurement by using the same phone.

The 3 different apps were used:

1. Lux Light ver. 1.0.7 by Phuongpn
2. Light meter ver 1.9 by Coolexp
3. Phyphox Light for Android Version: 1.1.16

Figure 6. Phone sensor value comparison with reference Metrel Eurotest 61157 device

Experiment was performed on the same setup depicted in Figure 2.

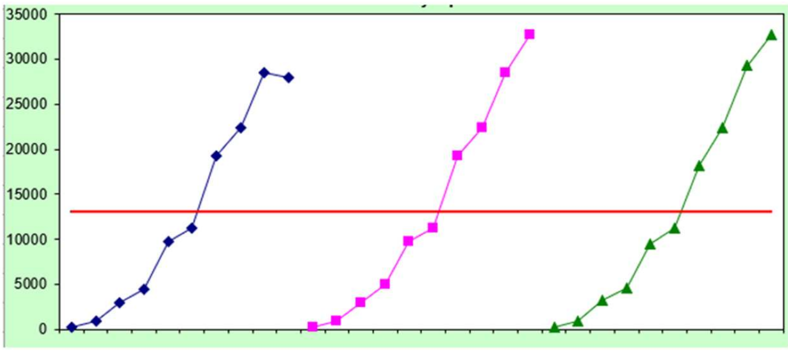
During the first experiment we noticed that the scale of the dimmable lamp potentiometer is nonlinear, so the next measurement points were selected in Table 2.

Table 2

Experiment 2 Investigation of different application for the illuminance measurement

Set point	1	2	3	4	5	6	7	8	9	10
Irradiance, W/m^2	30	100	200	300	405	500	600	705	800	900

All results were collected and written to the same spreadsheet depicted in Figure 3 and MSA was performed and ANOVA and Xbar/Range analysis was performed and graphically visualized (Figure 7).



a)

Gage R&R Using 5.15 Standard Deviations (99%)		
Source	Study Variation	% Study Variation
Total Gage R&R	1446.584	2.90%
Repeatability	211.768	0.42%
Reproducibility	1430.979	2.87%
Part to Part	49921.01	99.96%
Total Variation	49942.13	100.00%

b)

Gage R&R Using 5.15 Standard Deviations (99%)		
Source	Study Variation	% Study Variation
Total Gage R&R	4735.996	8.00%
Repeatability	962.3273	1.63%
Reproducibility	4637.195	7.83%
Operator	0	0.00%
Operator*Part	4637.655	7.83%
Part to Part	59024.97	99.68%
Total Variation	59214.67	100.00%

c)

Figure 7. a) Xbar Chart by using different Applications on the same phone b) ANOVA method c) Xbar/Range method

In the Xbar Chart we can see some variation at the 10th measuring point, but it is very small if we look to the MSA numerical values.

As we see from the results in Figure 7, the Total Gauge R&R study variation is below 10% by using ANOVA and Xbar/Range methods, respectively the measurement system is acceptable. In conclusion, we could claim that we did not find any big influence on measuring illuminance results by using different applications on the same mobile phone.

As we stated in the beginning of the experiment, we found a huge difference up to 97.76% while comparing to reference calibrated devices. This fact states the need to calibrate a mobile phone before starting experiments, despite these experiments belonging to Citizen Science activities.

4. Conclusions

This study demonstrated the value and limitations of using non-calibrated Internet of Things (IoT) devices, specifically mobile phones and various mobile applications for indoor illuminance measurement. Through a series of controlled experiments, the Gauge R&R method enabled us to evaluate the repeatability and reproducibility of measurements across different devices and software platforms. The findings confirm that while some mobile phones and apps provide fairly consistent readings, significant variability still exists between devices, however we did not find a big difference while using different software versions on the same phone. This variability underlines the importance of performing MSA prior to relying on IoT devices for scientific or policy-related decisions. Furthermore, our Citizen Science approach helped involve students and young researchers in real-world data collection and analysis, promoting open science principles and digital literacy. The results also highlight the necessity for harmonized metrology standards in Internet of Things (IoT)-based measurements. Future work should focus on creating unified calibration protocols, expanding the range of tested Internet of Things (IoT) sensors, and integrating automated MSA tools into commercial apps to improve data reliability and user trust.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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A. Online Resources

The Excel spreadsheet Gage Repeatability and Reproducibility (GR&R) study for calculation MSA can be downloaded at https://www.cpkinfo.com/files/GRandR_with_ANOVA_2.xls .