# INTERNATIONAL JOURNAL OF BUILT ENVIRONMENT & SUSTAINABILITY

eISSN 2289-8948

**Vol 8, No 3 (2021)**

https://ijbes.utm.my/

KERANA TUHAN UNTUK MANUSIA
UNIVERSITI TEKNOLOGI MALAYSIA
UTM
UNIVERSITI TEKNOLOGI MALAYSIA

# IJBES
## International Journal of Built Environment and Sustainability

Mail Address:
**International Journal of Built Environment and Sustainability**
Faculty of Built Environment and Surveying
Universiti Teknologi Malaysia
81310, Johor Bahru, Malaysia
Telephone: +60-7-5537382
Email: ijbes@utm.my


Cover Design and Type-set by: Shamsulhadi/Hairunnisa/Azman

**DISCLAIMERS:**

This publication is intended to enrich the knowledge in the field of built environment and sustainability. Therefore, you may use the materials contained herein for free as long as for the use of academic purpose. However, you must cite this scientific material properly.

The views expressed in this publication do not necessarily reflect the views of the Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia.



The IJBES is an international peer-reviewed Journal
Published in collaboration between Faculty of Built Environment and Surveying and Penerbit UTM

**E-ISSN: 2289-8948**
**ISSN: 1511-1369**

# IJBES

## Vol. 8, No. 3, 2021

## Table of Contents

### Articles

# IJBES
## Vol. 8, No. 3, 2021

## Table of Contents



## Communication

IJBES

**International Journal of Built Environment and Sustainability**
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 1-8

# The Accuracy of Satellite Derived Bathymetry in Coastal and Shallow Water Zone

**Kelvin Kang Wee Tang**
Department of Geoinformation, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.

**Mohd Razali Mahmud**
GeoCoastal Research Unit, Geospatial Imaging & Information Research Group (GI2RG), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.

**ABSTRACT**

Precise and accurate bathymetric measurements are conventionally acquired by means of ship-based acoustic equipment. Nevertheless, recent multispectral satellite imagery has been utilised as a substitute source to map the seabed topography which indicates new revolution in hydrographic surveying. This study assesses the satellite bathymetric depth's accuracy based on the vertical uncertainty as stated in the Standards for Hydrographic Surveys issued by the International Hydrographic Organization. Two empirical algorithms, namely, Dierssen's and Stumpf's approaches have been adopted to model the seafloor topography over the coastal and shallow water at Tanjung Kupang, Malaysia. The outcomes demonstrate a decent correlation between the derived water depths and the sounding values acquired from a ship-based acoustic survey. For instance, a total of 1,215 out of the 1,367 generated water depths by Stumpf's model have hit the minimum standard of survey in S-44. Similarly, out of the 1,367 samples from Diessen's model, 1,211 samples have met the minimum requirement listed in the survey standard. The results demonstrate both imageries derived bathymetry models convey promising results which can be ultilised for bathymetric mapping application. Therefore, this imagery derived bathymetry can be considered as an alternative bathymetric surveying technique to supply cost-effective solution and survey data to support the Blue Economy and Sustainable Development Goals 14.

**Article History**

Received: *17 August 2020*
Received in revised form: *23 March 2021*
Accepted: *17 May 2021*
Published Online: *31 August 2021*

**Keywords:**

Imagery derived bathymetry, Multispectral images, Bathymetric surveying

**Corresponding Author Contact:**

tkwkelvin2@live.utm.my

**DOI:** 10.11113/ijbes.v8.n3.681



## 1. Introduction

The Coastal zone is an area of the encounter between land and sea, where the interaction of the sea and land progressions often occurs. In fact, excess of more than half of the world's population today is currently accommodating in this versatile coastal zone. These densely populated coastal and shallow water areas are getting extremely versatile and dynamic (Syvitski et al. 2005). Changes in these regions can be related to natural morphological alteration as well as human activities which occur either gradually or happen out of the sudden. The importance of this prominent feature on the Earth is widely recognized by the international community, and it is reflected in the one of the United Nation Sustainable Development Goals (SDG). Ocean and sea issues are reflected in SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development. Thus, up-to-date survey data are essential for sustainable marine administration and development in the Blue Economy. More skilled staff and cost-effective solutions are required to offset and mitigate the threats to the aquatic environment.

Conventionally, bathymetric measurements are acquired via timely consuming ship-based acoustic systems like single beam echo sounding and multibeam system. Significant alterations over the seabed within a quick period may not be practically attempted via those acoustic methods. In short, some of the charts are outdated and may post potential hazards to the mariners. The prelude of remote detecting innovation has evolved new revolution in our hydrographic surveying industry since the previous decade. Today, the penetration capability of the electromagnetic spectrum into the water column has enabled human's capability to accomplish numerous missions including bathymetric derived from remotely sensed satellite images. Thus, the imagery derived bathymetry approach has wound up increasingly and been applied as a substitute approach to acquire new bathymetric data. The principle reason on the ground is that this inspiring method does not need extensive sum of money, time and energy when it comes to the nearshore and the coastal region.

Remote sensing using satellite technology has no doubt in delivering high resolution imagery for viewing purposes, likewise, it also allows us to reveal meaningful information out of the swift imagery collection. It has been applied as an effective supplemental approach to compromise the growing demands of up to date and comprehensive bathymetric depth data because of its tremendous spatial coverage and flexibility (Gao, 2009). Hence, this satellite bathymetry technique has substantiated itself as a beneficial reconnaissance instrument for nearshore imagery derived bathymetry mapping application (Mateo-Pérez *et al.*, 2020; Jégat *et al.*, 2016; Pe'eri *et al.*, 2013) as well as detecting the seafloor changes (Pacheco *et al.*, 2014; Darama *et al.*, 2019). In most of the earlier investigations, the majority of these depth retrieval algorithms are only practically work only across clear shallow ocean waters (Jawak *et al.*, 2015; Jégat *et al.*, 2016). Furthermore, some hydrographic offices from the European nations (e.g. UKHO, SHOM, etc.) have employed imagery derivation bathymetry extraction approach to update their nautical charts (Mavraeidopoulos *et al.*, 2017).

According to a synoptic review by Jawak *et al.* (2015), among the popular derivation models, Stumpf *et al.* (2003) and Lyzenga *et al.* (2006) are the widely used algorithms to deriving bathymetry information using remote sensing technologies. Nevertheless, most of the previous research works only focusing on statistical accuracy performance and examining the correlation ($r^2$) between derived depths and charted depths. In addition, this kind of research is less explored in the tropical environment setting and relatively new to a country like Malaysia (Najhan *et al.*, 2017). Consequently, this proposed paper attempts to evaluate the bathymetry derivation approach over the coastal and shallow water at Tanjung Kupang, Malaysia. This study is assessing the imagery derived bathymetry's accuracy derived by two empirical models. The allowable total vertical uncertainty (TVU) is referred to the Standards for Hydrographic Surveys that is published in the Special Publication No.44 (S-44) issued by IHO in 2020. Table 1 defines that the maximum allowable TVU for measuring water depths to be accomplished to achieve Special Order is limited to be within 0.25 metres, Order 1a and 1b are allowed to be 0.5 metres and roughly 1.0 metres for any bathymetric survey being conducted within a 10 metres water depth.

## 2.0 Area of Study

This study made an endeavour to estimate the bathymetric water depths at southwest of Johor Bahru, Malaysia, targeting the shallow and nearshore waters neighbouring to the Tanjung Kupang, Johor Bahru. Figure 1 illustrates the geographical location and coverage of the area of study which situated between 1° 18' N to 1° 21' N and 103° 34' E to 103° 38' E. Mostly, the aquatic circumscribing in this study area is highly turbid. It can represent and speak most of the seafloor conditions along the west coast districts in Peninsular Malaysia. By and large, the vast majority of the muddy shore face is bordered by level inclines with murky and turbid suspended dregs.

**Table 1** Minimum allowable total vertical uncertainty (modified from IHO, 2020)

| IHO Survey Order | $TVU = \sqrt{a^2 + (b \times d)^2}$ | | | |
|---|---|---|---|---|
| | **Standards Assessment (Value d = 10 m)** | | | |
| | **Special** | **1 a** | **1 b** | **2** |
| Maximum allowable TUV (95% Confidence level) | a = 0.25 m<br>b = 0.0075 m | a = 0.25 m<br>b = 0.0075 m | a = 0.25 m<br>b = 0.0075 m | a = 0.25 m<br>b = 0.0075 m |
| TVU | ±0.261 m | ±0.517 m | ±0.517 m | ±1.026 m |
| Feature Detection | Cubic features > 1 m | Cubic features >2 m, in depths up to 40 m; 10% of Depth beyond 40 m. | Not applicable | Not applicable |

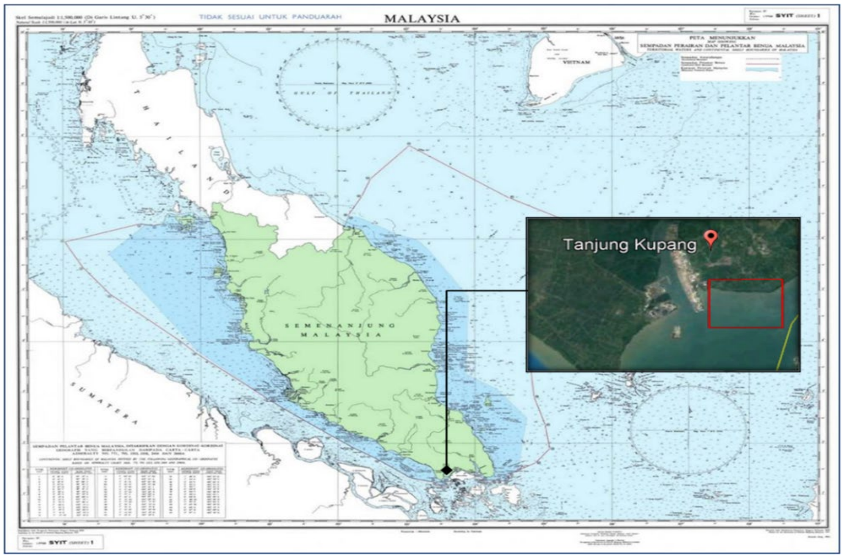



**Figure 1** The geographical location of the study area

## 3.0 Data and Methodology

This section briefly reviews the satellite imagery derived bathymetry methods embraced here is to extract the water depths from multispectral imagery. It outlines the two bathymetry derivation models, physical characteristics of the multispectral satellite imagery, supplementary data as well as the imagery processing software applied in this paper.

### *3.1 Methodology*

This dedicated paper fused both the remote sensing and geographical information system (RS & GIS) techniques to estimate the bathymetric depth values from the multispectral satellite imagery. The entire methodology, data processing workflow as well as the data assessment process is illustrated in Figure 2 below.

Selection of dedicated satellite imagery was determined based on the quality of the sensed imageries, area of the spectral coverage, ground pixel resolution as well as its spectrum range. Prior commencing the bathymetry derivation development, image pre-processing progression was conducted to abolish the unwanted path radiance, atmospheric effects and also filter out all the annoying sea surface reflectance. Subsequently, it was trailed with the geometric correction to get rid of the distortion errors. Next, a set of precise surveyed depths was discrete into two separate data sets. The first training dataset was adopted to construct the linear regression models, resolve the most fitting tuneable constant coefficient in bathymetry derivation algorithms. While, the second testing data was arranged for the data accuracy and assessment analysis.

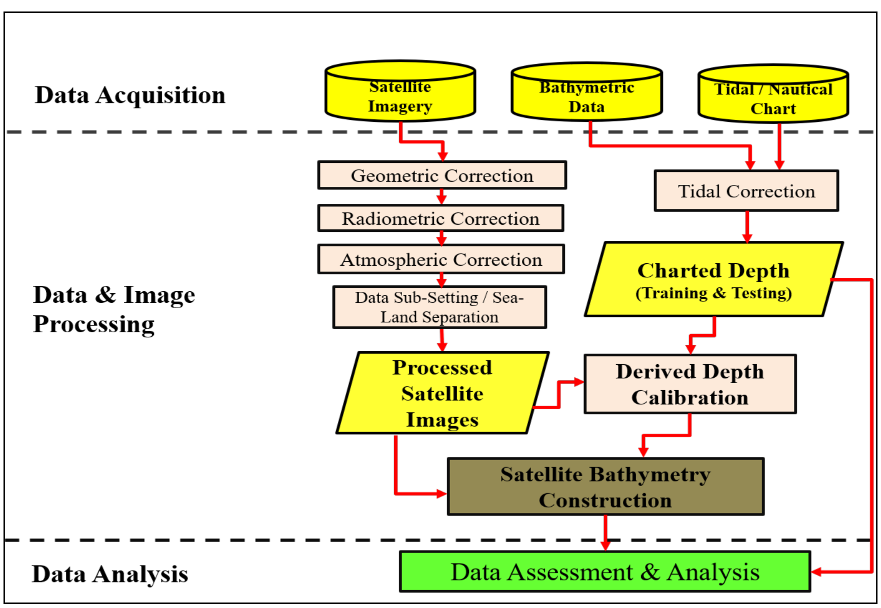



**Figure 2** The flowchart of the entire methodology and processing stages

### *3.2 Multispectral Spectral Images*

Landsat-8 multispectral satellite images acquired in June 27, 2013 were utilised in this feasibility study. Theoretically, short wavelength spectrum in the visible region is more desirable in imagery derived bathymetric mapping because these spectrums have a greater penetration into the aquatic environment. For instance, electromagnetic radiation of blue spectrum (0.45-0.52μm) and green spectrum (0.53-0.59μm) were chosen because of its low attenuation when passing through the water column if compared to other visible spectral.

Radiometric, atmospheric and geometric correction were conducted on to these images to remove unnecessary sea surface reflectance, unwanted path radiance and annoyed atmospheric effects as well as geometrically remove the distortion effect. Subsequently, those huge multispectral satellite images were cropped into smaller samples, comparatively small frame to optimise the satellite imagery processing.

### *3.3 In-situ Bathymetry Measurement*

A designated *in-situ* bathymetric survey had been conducted throughout the entire study area in August 2013. These precise bathymetric depths were acquired via single beam echo sounder fitted on a fully equipped survey boat, synchronized with precise positioning obtained from a differential global navigation satellite system. The bathymetric depths were collected across the planned 25 metres line spacing and 5 metres point interval apart survey lines in the study area. All the measured data were tidally correlated to become the reduced depths. Subsequently, the surveyed bathymetric depths were adopted in constructing the depth-retrieval algorithm and being utilised in data assessment processing later.

### *3.4 Derivation Algorithms*

This study attempts to determine the bathymetric depths over the shallow and coastal zone through two different empirical approaches. The derivation models by Stumpf *et al.* (2003) and Dierssen *et al.* (2003) adopted the fundamental principle of the Beer-Lambert Law, expressed the intensity of light decreases exponentially with the increasing of depth, primarily the observed reflectance from the optical sensor to the water depth. Henceforth, a linear inversion mathematical model could empirically express the relationship between the water-penetrating spectral.

#### 3.4.1 Stumpf's Model

Stumpf *et al.* (2003) invented a band-ratio algorithm to estimate the water depth (Z) through two tuneable constant coefficients ($m_0$ & $m_1$) and of two consecutive water-penetrating spectral bands ($R_i$ & $R_j$). It uses the division between detected reflectance log values to calculate depth of water and the ratio will estimate a simultaneous change when the depth change. Equation 1 shows the Stumpf's algorithm.

$$Z = m_0 * \frac{\ln(R_w(\lambda_i))}{\ln(R_w(\lambda_j))} - m_1 \quad (1)$$

Where,
Z = value from derived depth
$R_w$ = reflectance of $band_i$ & $band_j$
$m_0$ = tuneable constant
$m_1$ = offset of the depth
n = a constant value

#### 3.4.2 Dierssen's Model

Dierssen *et al.* (2003) addressed alike band-ratio idea to extract the water depth (Z). However, it is modelled slightly differently by presenting the log-difference between two detected reflectance values. Similarly, the water depth is estimated from two tuneable constant coefficients ($m_0$ & $m_1$) and the observed reflectance of two consecutive bands ($R_i$ & $R_j$) mathematically. Equation 2 below illuminates the Dierssen's algorithm:

$$Z = m_0 * \ln\left[\frac{nR_w(\lambda_i)}{nR_w(\lambda_j)}\right] + m_1 \quad (2)$$

Where,
Z = value from derived depth
$R_w$ = reflectance of $band_i$ & $band_j$
$m_0$ = tuneable constant
$m_1$ = offset of the depth
n = a constant value

#### 3.4.3 Least Square Regression

Least square regression is ordinarily being conducted to solve a solution where the equations happened to be more than the number of unknowns. This mathematical technique is decent for financing the most well-fitted line to a certain arrangement of focus by diminishing the total of the residuals' squares ended with the results of each single mathematical equation. Basically, it minimises the entirety of squared residuals or offsets between detected values against the close-fitting qualities conceded by a derivation model.

Henceforth, it was applied to estimate the best fitted value to mathematically unravel the two unknown tuneable constants in the two above mentioned designated equations. These diffuse attenuation coefficients were calculated using least square regression via Equation 3 and Equation 4 below. Consequently, the retrieved tuneable constants were then being applied back into the previous Equation 1 and Equation 2 to re-construct the bathymetric models for imagery derived bathymetric mapping.

$$\hat{x} = \left(A^T A\right)^{-1} A^T \hat{y} \quad (3)$$

$$\begin{bmatrix} m \\ c \end{bmatrix} = \left( \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_n & 1 \end{bmatrix}^T \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_n & 1 \end{bmatrix} \right)^{-1} \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_n & 1 \end{bmatrix}^T \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad (4)$$

### *3.5 Accuracy Assessment*

Assessment of data is a vital step in the defining the applicability of the derived bathymetric data which is usually referred as the data quality assurance too. Without a doubt, it includes an evaluation of a set of imagery derived bathymetric depths against the sounding depths measured by the ship-based acoustic system. Quantitative comparison was commenced to examine the accuracy between the derived depths and the actual surveyed soundings values. Assessment of data accuracy was featured based on several statistical approaches, correlation coefficient (r), correlation of determination ($r^2$), mean absolute error (MAE) as well as the root mean square error (RMSE) between both datasets.

## 4.0 Result and Discussion

This section discusses on the preliminary results and findings from this designated imagery derived bathymetry study. Serenely, Figure 3 illustrates various images representing the southwest of Johor, Malaysia, which include (a) Landsat-8 (RGB); (b) Nautical Chart; (c) Stumpf's model; and (d) Dierssen's model. Particularly, the seabed topography relief through their digital elevation models (DEM) is demonstrated in the following Figure 4 to Figure 5. Meanwhile, the descriptive statistical analysis and quantitative analysis of both models are shown in Table 2 and Table 3.

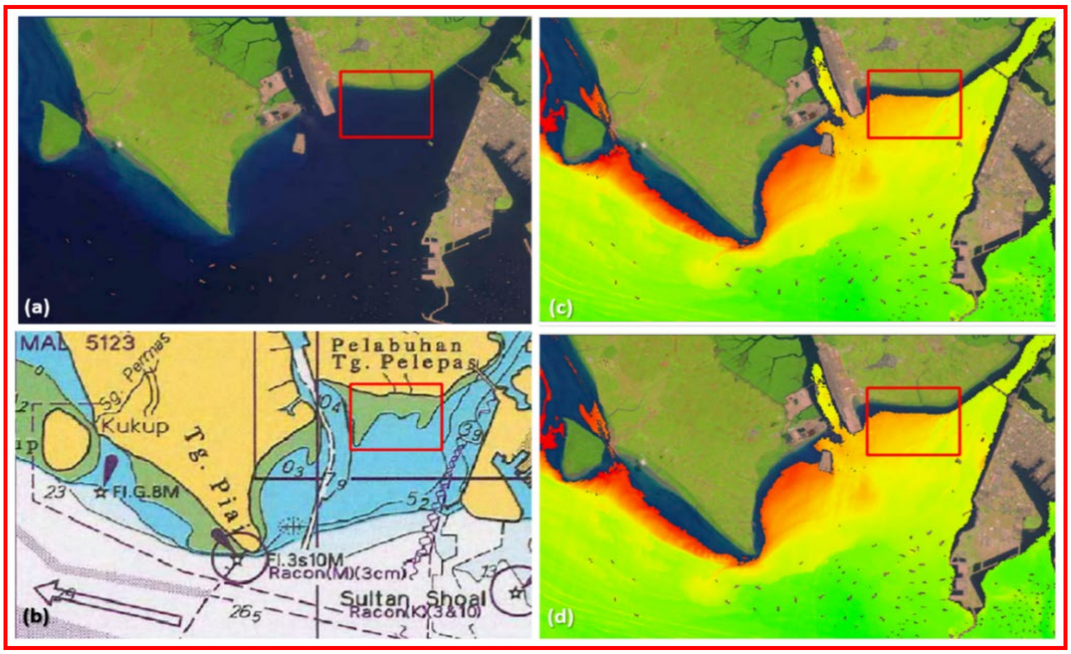



**Figure 3** Images showing the area of study. Image (a) Landsat-8 (RGB) (b) Nautical Chart (c) Stumpf's model & (d) Dierssen's model

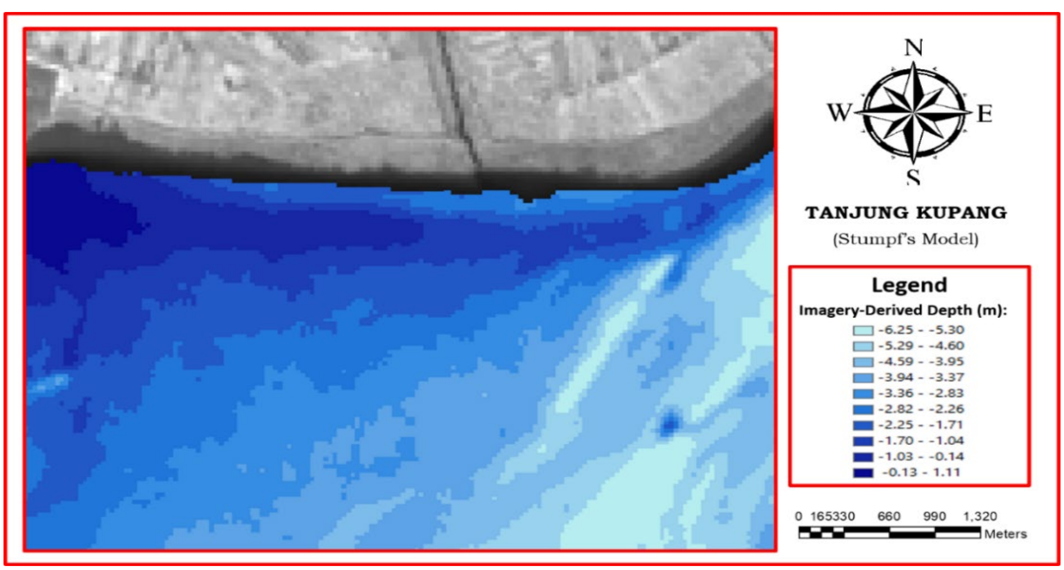



**Figure 4** Bathymetric model across the study area from Stumpf's model

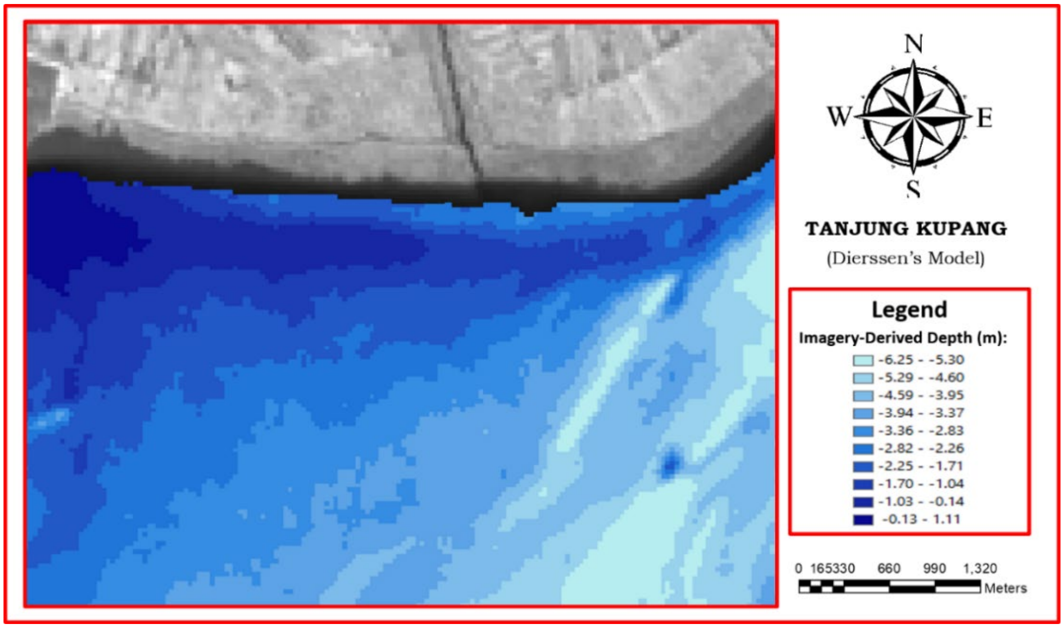



**Figure 5** Bathymetric model across the study area from Dierssen's model

So as to numerically access the accuracy of the imagery derived bathymetry depths, assessment of data was commenced using 1,367 check points, randomly extracted from the surveyed SBES dataset. In general, the statistical analysis indicates that Dierssen's model obtains 0.878 metres in term of its RMSE while Stumpf's model yields 0.885 metres for its RMSE. The MAE performs by Dierssen's model is equivalents to 0.629 metres, whereas Stumpf's model gets 0.631 metres for its MAE. Meanwhile, the $r^2$ value of Stumpf's approach is 0.5828 and Dierssen's approach is 0.5834. Overall, both models have shown a similar correlation coefficient, 0.76. The statistical analysis indicates that both derivation bathymetry models have delivered satisfying outcomes in this shallow and turbid aquatic environment.

**Table 2** Descriptive statistical analysis for Stumpf's and Dierssen's derivation models

| **Statistical Analysis** | **Imagery Derived Bathymetry model** | |
|---|---|---|
| | **Stumpf's Model** | **Dierssen's Model** |
| Root mean square error (RMSE) | 0.885 | 0.878 |
| Mean absolute error (MAE) | 0.631 | 0.628 |
| Correlation of determination ($r^2$) | 0.5828 | 0.5834 |
| Correlation coefficient (r) | 0.76 | 0.76 |

**Table 3** The quantitative analysis of Stumpf's and Dierssen's derivation models

| **Details** | **Stumpf's derivation model** | | **Dierssen's derivation model** | |
|---|---|---|---|---|
| | **Samples** | **Percentage (%)** | **Sample** | **Percentage (%)** |
| Total samples | 1367 | 100 | 1367 | 100 |
| IHO Passed | 1215 | 88.9 | 1211 | 88.6 |
| IHO Failed | 152 | 11.1 | 156 | 11.4 |
| Special order | 474 | 34.7 | 513 | 37.5 |
| Order 1a & 1b | 395 | 28.9 | 370 | 27.1 |
| Order 2 | 346 | 25.3 | 328 | 24.0 |

In general, both models have demonstrated adequate results. In terms of total vertical uncertainty (TVU) accomplishment rate, 88.9% and 88.6% out of the 1,367 samples generated from Stumpf's and Dierssen's derivation models are able accomplished the minimum IHO survey standards based on the IHO's guidelines; meanwhile, the result also shows that there are 152 samples (11.1%) generated from Stumpf's model and 156 samples (11.4%) by Dierssen's model yet to go along the base necessity set up established in IHO's survey standard, respectively.

Undeniably, 474 samples (34.7%) out of the total 1,367 samples from Stumpf's model and 513 samples (37.5%) out of the total 1,367 samples from Dierssen's model have fruitfully meet the class of Special Order; another 395 samples (28.9%) by Stumpf's model and 370 samples (27.1%) by Dierssen's model successfully fall under class Order 1a & 1b, while 346 points (25.3%) generated from Stumpf's model and 328 points (24.0%) generated from Dierssen's model successfully passed the minimum accuracy specification at least class Order 2 as per stipulated in IHO's S-44.

Dominant part of the previous investigations just focusing on benthic survey over the clear shallow water areas and the tropical coastal region is less examined. Also, most of the suggested bathymetric derivation studies neglected the accuracy perspective. To summarize, the above-mentioned derivation algorithms had successfully formed linear inversion mathematical models which could empirically express the relationship between the water-penetrating spectral through a relatively turbid water zone across the study area. Thus far, the correlation and minimum IHO survey standards performance analysis results obtained in this study indicated that band-ratio derivation algorithms may also work over the muddy and turbid water regions in the tropical environment setting. Based on the finding outcomes, this analysis showed that in the future, satellite remote sensing data can be utilised in determining the depth of water. This remote sensing and GIS technique could be recognized as a new survey technique to map the broad seabed topography along the coastlines.

## 5.0 Conclusion

In the culmination of examination, the objectives and goals are effectively achieved. It analyses the practicality of the imagery derived bathymetric mapping in relatively shallow and profoundly turbid aquatic environment in Tanjung Kupang, Malaysia. The comparative analysis between Stumpf's and Dierssen's empirical models against the precise single beam survey training dataset has been evaluated. In the course of an experiment, there is no overwhelming difference between the results from Stumpf's and Dierssen's derivation models. Additionally, it is capable to achieve the minimum TVU specification stipulated in the IHO's S-44 document.

However, when looking into a more comprehensive point of view, the RMSE and MAE are showing greater values than the allowed TVUs as per specified in Order Special and Order 1a & 1b. The water clarity and turbidity has always been the key factor that determines the level of penetration level for visible wavelengths in the water column for bathymetry derivation. The absorption and scattering of spectrum triggered by the dissolved organics and suspended particles as well as dregs in water column do influent the maximum depth of penetration in the turbid region. In short, it will lead to an incorrect shoaling in bathymetric depth retrieval. Like most other scientific researches, this preliminary findings and outcomes indicate that there are needs for further extensive study, probably in unravelling the testing site into few different depth zones and apply extra ground-truthing points to redefine the most appropriate linear regression analysis on each designated depth zone. Perhaps, such tactic can formulate multi-linear regression models to define the most suitable constant diffuse attenuation coefficients based on each designated water depth in a more ideal algorithm.

In short, this satellite bathymetry technique does not require any equipment mobilisation necessities, offers a quick and effective solution to unveil seafloor relief over a broader area of study. The encouraging preliminary results can be an alternative source of bathymetric data when mapping the coastal and shallow water in tropical region. Conversely, this imagery derived bathymetry can be considered as cost-effective bathymetric surveying solutions to supply more up-to-date survey data to governing the marine administration and development in the Blue Economy and to support the initiative of SDG 14.

## Acknowledgement

The authors would like to express their appreciation to GeoCoastal Research Unit (Gi2RG), Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia (UTM) and the Department of Survey and Mapping Malaysia (DSMM). All the financial resources and research facilities supported under Research University Grant (Vote Number: Q.J130000.2527.17H97) is also highly acknowledged.

## References

Bramante, J. F., Raju, D. K. & Sin, T. M. (2013). Multispectral Derivation of Bathymetry In Singapore's Shallow, Turbid Waters. *International Journal of Remote Sensing*, 34(6): 2070-2088.

Darama, Y., Selek, Z. & Selek, B. (2019). "Determination of sediment deposition of Hasanlar Dam using bathymetric and remote sensing studies." *Natural Hazards*, 97(1): 211-227.

Dierssen, H. M., Zimmerman, R. C., Leathers, R. A., Downes, T. V., & Davis, C. O. (2003). Ocean Color Remote Sensing of Seagrass and Bathymetry in The Bahamas Banks By High-Resolution Airborne Imagery. *Limnology and Oceanography*, 48(1part2): 444-455.

Gao, J. (2009). Bathymetric Mapping by Means of Remote Sensing: Methods, Accuracy and Limitations. *Physical Geography*, 33(1): 103-116.

Hamylton, S. M., Hedley, J. D., & Beaman, R. J. (2015). Derivation of High-Resolution Bathymetry from Multispectral Satellite Imagery: A Comparison of Empirical and Optimisation Methods Through Geographical Error Analysis. *Remote Sensing*, 7(12): 16257-16273.

International Hydrographc Organization (2020), *IHO Standards for Hydrographic Surveys* (6th Edition). Monaco: IHO Publication S-44.

Jawak, S. D., Vadlamani, S. S., & Luis, A. J. (2015). A Synoptic Review on Deriving Bathymetry Information Using Remote Sensing Technologies: Models, Methods and Comparisons. *Advances in Remote Sensing*, 4(02): 147.

Jégat, V., Pe'eri, S., Freire, R., Klemm, A., & Nyberg, J. (2016). Satellite-Derived Bathymetry: Performance and Production. In *Canadian Hydrographic Conference, May* 16-19.

Lyzenga, D. R., Malinas, N. R., & Tanis, F. J. (2006). Multispectral bathymetry using a simple physically based algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, 44(8): 2251-2259. doi:10.1109/Tgrs.2006.872909

Mateo-Pérez, V., Corral-Bobadilla, M., Ortega-Fernández, F. & Vergara-González, E. P. (2020). "Port Bathymetry Mapping Using Support Vector Machine Technique and Sentinel-2 Satellite Imagery." *Remote Sensing* 12(13): 2069.

Mavraeidopoulos, A. K., Pallikaris, A., & Oikonomou, E. (2017). Satellite Derived Bathymetry (SDB) and Safety of Navigation. *The International Hydrographic Review (17)*.

Pacheco, A., Horta, J., Loureiro, C., & Ferreira, Ó. (2015). Retrieval of Nearshore Bathymetry from Landsat 8 Images: A Tool for Coastal Monitoring In Shallow Waters. *Remote Sensing of Environment*, 159: 102-116.

Pe'eri, S., Parrish, C., Azuike, C., Alexander, L., & Armstrong, A. (2014). Satellite Remote Sensing as A Reconnaissance Tool for Assessing Nautical Chart Adequacy and Completeness. *Marine Geodesy*, 37(3): 293-314.

Said, N. M., Mahmud, M. R., & Hasan, R. C. (2017). Satellite-Derived Bathymetry: Accuracy Assessment on Depths Derivation Algorithm for Shallow Water Area. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, XLII-4/W5: 159-164.

Said, N. M., Mahmud, M. R., & Hasan, R. C. (2018). Evaluating Satellite-Derived Bathymetry Accuracy from Sentinel 2A High-Resolution Multispectral Imageries for Shallow Water Hydrographic Mapping. Paper presented in *9th IGRSM International Conference and Exhibition on Geospatial & Remote Sensing*, Kuala Lumpur, Malaysia.

Sánchez-Carnero, N., Ojeda-Zujar, J., Rodríguez-Pérez, D., & Marquez-Perez, J. (2014). Assessment of Different Models For Bathymetry Calculation Using SPOT Multispectral Images In A High-Turbidity Area: The Mouth Of The Guadiana Estuary. *International Journal of Remote Sensing*, 35(2): 493-514.

Stumpf, R. P., Holderied, K., & Sinclair, M. (2003). Determination of Water Depth with High-Resolution Satellite Imagery Over Variable Bottom Types. *Limnology and Oceanography*, 48(1): 547-556.

Su, H. B., Liu, H. X., & Heyman, W. D. (2008). Automated Derivation of Bathymetric Information from Multi-Spectral Satellite Imagery Using A Non-Linear Inversion Model. *Marine Geodesy*, 31(4): 281-298.

Syvitski, J. P., Vörösmarty, C. J., Kettner, A. J., & Green, P. (2005). Impact of Humans on The Flux of Terrestrial Sediment To The Global Coastal Ocean. *Science*, *308*(5720): 376-380.

Tsolakidis, I. and M. Vafiadis (2019). "Comparison of Hydrographic Survey and Satellite Bathymetry in Monitoring Kerkini Reservoir Storage." *Environmental Processes*, 6(4): 1031-1049.

Zheng, G., Chen, F., & Shen, Y. (2017). Detecting the Water Depth of The South China Sea Reef Area from Worldview-2 Satellite Imagery. *Earth Science Informatics*, 10(3): 331-337.

UTM UNIVERSITI TEKNOLOGI MALAYSIA

IJBES

International Journal of Built Environment and Sustainability
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 9-15

# Mapping and Estimation of Above-ground Grass Biomass using Sentinel 2A Satellite Data

**Isa Muhammad Zumo**
Department of Surveying and Geoinformatics, Federal Polytechnic, Damaturu, Nigeria.

**Mazlan Hashim, Noor Dyana Hassan**
Geoscience and Digital Earth Centre, (INSTeG), Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.

**ABSTRACT**

Above-Ground Grass Biomass (AGGB) mapping and estimation is one of the important parameters for environmental ecosystem and grazing-lands management, particularly for livestock farming. However, previous models for estimation of AGGB with satellite imagery has some difficulty in choosing a particular satellite and vegetation index that can build a good estimation model at a higher accuracy. This study explores the potentiality of Sentinel 2A data to derive a satellite-based model for AGGB mapping and estimation. The study area was Skudai, Johor in Malaysia Peninsular. Grass parameters of forty grass sample units were measured in the field and their corresponding AGGB was later measured in the laboratory. The samples were used for modelling and assessment. Four indices were tested for their fitness in modelling AGGB from the satellite data. The result from the grass allometric analysis indicates that grass height and volume demonstrate good relationship with the measured AGGB ($R^2$ = 0.852 and 0.837 respectively). Vegetation Index Number (VIN) has the best fit for modeling AGGB ($R^2$ = 0.840) compared to other vegetation indices. The derived satellite AGGB estimate was validated with the assessment field and allometry derived AGGB at RMSE = 15.89g and 44.45g, respectively. This study demonstrate that VIN derived from Sentinel 2A MSI satellite data can be used to model AGGB estimation at a good accuracy. Therefore, it will contribute to providing reliable information on AGGB of grazing lands for sustainable livestock farming.

**Article History**

Received: *18 August 2020*
Received in revised form: *19 March 2021*
Accepted: *17 May 2021*
Published Online: *31 August 2021*

**Keywords:**

Grass, Biomass Estimation, Mapping, Satellite Data

**Corresponding Author Contact:**

mazlanhashim@utm.my

**DOI:** 10.11113/ijbes.v8.n3.684



## 1. Introduction

Grasslands are among the most popular types of covered vegetation, covering over 31.5% of the world's land mass (Latham et al. 2014). It is one of the sustainable resources and provides a significant portion of livestock with the food source (Herrero et al,2013), however, previous models for estimation of AGGB with satellite imagery has some difficulty in choosing a particular satellite and vegetation index that can build a good estimation model at a higher accuracy. Many studies have used remote sensing data such as Landsat (Powell et al 2010, De et al, 2012, Hansen and Loveland 2012), world view, thematic mapper and MODIS data product to examine the mapping and estimation of AGGB. In addition to vegetation indices, spectral bands, image transformation algorithms are often used to identify AGGB modeling variables (Zang and Kovacs 2012, Mutanga et al 2012). Because different remote sensing data are available with different spectral and spatial resolutions, a large number of potential variables can be used (Myint et al, 2011). However, the correct identification of key variables is critical to the accurate mapping and estimation of above-ground biomass and the selected variables can vary considerably depending on the grass species, the time of investigation, the location of the study and the remotely sensed data themselves (Karlson et al, 2015; Dube et al 2014)**.** Another key problem for investigating grass studies is the use of a proper modelling algorithm (Yuyun et al 2019).

Understanding variations in AGGB at various scales is becoming extremely critical among interested parties, like farmers, ecologists and scholars (Sibanda et al 2017). Remote sensing researchers have accumulated experiences on the assessment of vegetation/physiognomic types and their ecological state (Mucina, 2019). Recently, the usefulness of earth observation (EO) data has become much more popular and viable with an increase in available sensors as well as innovations to obtain robust quantitative information on grass biomass. (Bastin et al, 2014). Knowing that different EO methodologies were evaluated in aboveground biomass quantification, no study showed a consistent, accurate and repeatability operational method for estimating biomass at smaller to larger scales (Sibanda et al 2017). This is due to the variations in vegetation's biophysical, environmental and topographical characteristics in space and time (Popescu et al 2009, Montesano et al 2013). Previous studies have reported even higher correlations between grass biomass and vegetation indexes (e.g., Mutanga, et al 2012). Most of them, however, investigated 'simpler' vegetation communities (often monospecific) on relatively flat ground and uniform soil.

In this study, Sentinel 2A MSI was used to estimate the AGGB in Skudai, Johor, Malaysia Peninsula. The satellite derived AGGB was later validated with the grass allometry derived and the assessment field AGGB. Therefore, the objective of this paper is to derive a satellite transformation model for AGGB estimation from ground sample points to Sentinel 2A MSI satellite data. Four grass species were identified (Figure 1) in the study area, although they belong to one of the largest and most economically and ecologically important families of plants, they exist as minor components next to forest of the plant community in the area. The grasses are *Pennisetum purpureum* (elephant grass), Ottochloragraccillima (creeping grass), Genus stipa (needle grass) and Poacea grass.

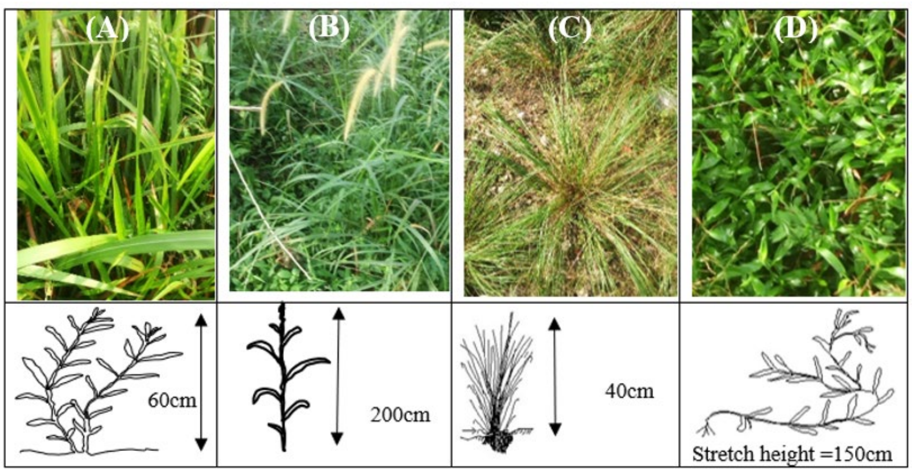



**Figure 1.** Dominant grass in the study area (A)Elephant grass (B) Poacea grass (C) Needle grass (D) Creeping grass

## 2. Material and Method

### *2.1 Description of Study Area*

The study area was Universiti Teknologi Malaysia (UTM) campus, Skudai in the State of Johor Bahru, Peninsular Malaysia. The total area was 1,222 hectares. It lies between 170000mN to 172500mN and 346000mE to 351000mE (Figure 2.). The average yearly rainfall is 250 mm, the wettest month is in November with an average of 320 mm. June and July are overall the driest months with an average of 130 mm. Temperatures rise above 30°C (86°F) throughout the day and drop rarely below 20°C (68°F) during the night. Temperature is 27°C at an average. (Country data and statistics (2019))

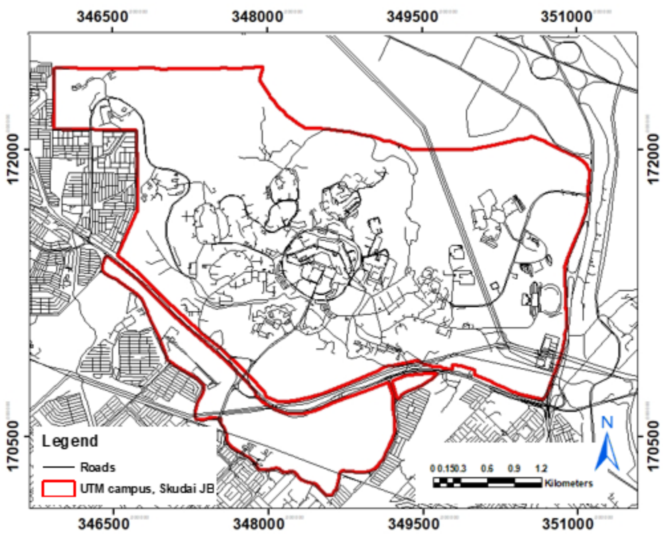



**Figure 2.** Study area
**Source:** INSTeG UTM

### 2.2 *Material*

The materials used for this study are the field data and Satellite data. The remotely sensed data were derived from the Sentinel 2A imagery. It has thirteen bands and a spatial resolution of 10m. Two bands were used in this study; the red band (central λ of 665nm) and a near-infrared band (central λ of 842nm) as was investigated by many scholars (Yuyung, 2019, Rongrong 2018, Li et al 2016, Zumo et al 2021, Ali et al 2017). The data was downloaded on 18th July 2018 at the period when grasses were fully saturated**.** In-situ data are the grass allometry and the measured GAB of some selected sample points. Ground control and validation sample points were measured using the quadrant method. Forty samples for each of the four different dominant grass species were harvested at $1m^2$ grids for both the controls and assessment. Five samples' points were measured in each plot. This was done in order to avoid degradation/destruction of the environment by minimising the sample size and meeting up with the required specification. The mean and the standard deviation of the measured biomass for samples in each plot was computed (see Table 1)

**Table 1** Statistics of collected samples

| | No. of samples/plots | Range of AGGB | Mean | Std. dev. |
|---|---|---|---|---|
| Total No. of samples | 40 | 38.21 - 197.32 | 118.63 | 9.87 |
| Samples collected modelling | 20 | 41.21 - 195.00 | 117.88 | 9.84 |
| Sample collected for assessment | 20 | 38.21 - 197.32 | 109.23 | 8.97 |

### 2.3 *Method*

The method used in this study were grass allometry modelling, satellite transformation modelling and validation of results. This demonstrated as flowchart in Figure 3

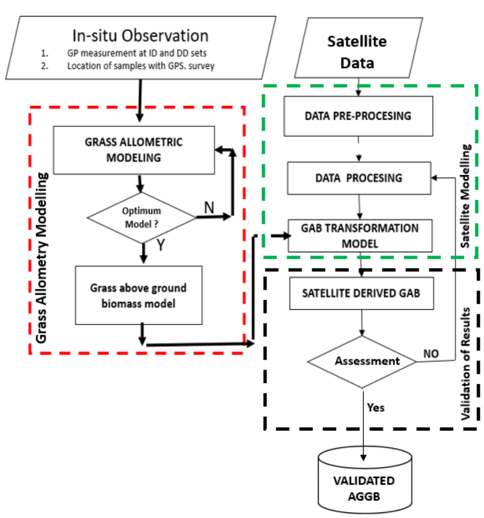



**Figure 3.** Flowchart of methodology

Maximum grass height, stem diameter, grass volume and leaf area were measured from the field as in-situ observation. (Figure 1). Grass volume was measured using displacement method, and density of each grass was calculated from its measured mass and volume. The clipped vegetation was dried at 40.6°C for 72 h in an air forced oven. The vegetation was then weighed when dried to get the mass per sample and eventually calculate the biomass production in tons per hectare. Location of the grass samples were acquired using the Global Positioning System (GPS) for easy location of the sample points in the image. This study considers the use of the most common Vegetation indices as Normalized Distribution of Vegetation Index (NDVI), Vegetation Index Number (VIN), Ratio Vegetation Index (RVI) and Normalized Difference Index (NDI) for the modelling of AGGB estimation.

#### 2.3.1 Grass Allometry Modelling

Linear regression between the five measured grass variables and the field AGGB was carried out. Grass height and volume was found to have a has a good level of fitness for AGGB estimation. The relationship between the stem diameter, leaf area and grass density were poor. Therefore, grass height and grass volume were used for modelling the AGGB estimation.

### 2.3.2 Satellite Transformation Modelling

Reflectance values of band 4 (Red) and band 8 (NIR) were extracted from the pixel of each respective band of the sample points. The pixel location was identified by the GPS acquired coordinates during the sample data acquisition. The four vegetation indices were calculated using their respective formular (Table 2.)

**Table 2.** VIs and equations

| VI | Equation |
|---|---|
| NDVI | (NIR-R)/(NIR+ R) |
| VIN | NIR/R |
| NDI | (NIR-R) |
| RVI | *R*/NIR |

A linear regression between the calculated indices and the in-situ AGGB was conducted in order to determine which of these indices that will be best for modelling AGGB of the entire study area. The relationship of each of the VIs was indicated by $R^2$.

## 3. Result

### *3.1. Allometry Result*

The result for grass allometry indicates that stem diameter, leaf area index and grass densities have a poor fitness for AGGB estimation. Their $R^2$ = 0.256, 0.182 and 0.312, respectively. This indicates that they are not suitable predictors for AGGB estimation. Grass height and grass volume has a good level of fitness at $R^2$ = 0.852 and 0.837, respectively. They were used for allometry AGGB modelling to derive 5 allometry models for this study. Level of performance for each derived allometry model was in Table 3.

**Table 3** Model Summary

| Model | Model Equation | a | b | c | $R^2$ | Std. Error. |
|---|---|---|---|---|---|---|
| 1 | AGGB = a + b(ht.) | 25.131 | 2.644 | | 0.798 | 38.638 |
| 2 | AGGB = a + b(vol.) | 76.973 | 0.480 | | 0.885 | 31.790 |
| 3 | AGGB = $ae^{b*ht.}$ | 93.922 | 0.011 | | 0.801 | 31.400 |
| 4 | AGGB = $ae^{b*vol.}$ | 116.150 | 0.002 | | 0.884 | 27.280 |
| 5 | AGGB = a + b(ht.) + c(vol.) | 28.266 | 1.301 | 0.315 | 0.987 | 13.760 |

Model 5 has the best result of $R^2$ and least standard error. Thus, it was considered as the most suitable model to use in the study for AGGB estimation, taking grass height and grass volume as the most suitable predictors. Average height and volume of grass samples were identified and measured. AGGB was later determined for each sample using the created allometric model 5.

### *3.2 Spectral Result*

The four indices namely NDVI, VIN, RVI and NDI has a good level of fitness ($R^2$ = 0.828, 0.840, 0.818, and 0.742 respectively (Figure 4A - 4D). Among the four, VIN has the best fitness and was selected for the AGGB modelling.

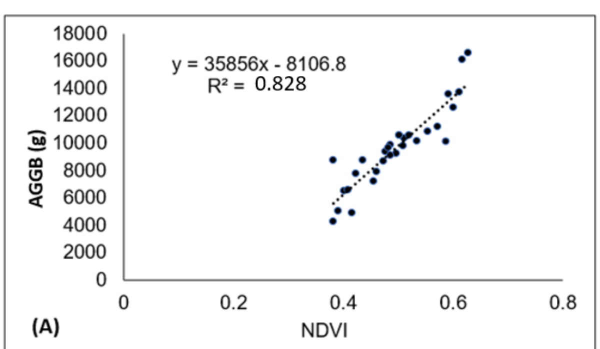



**Figure 4A** Biomass and NDVI relationship

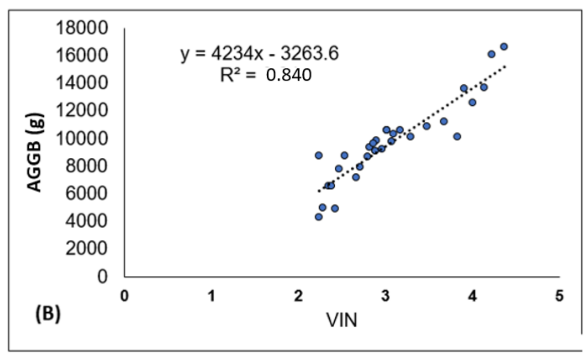



**Figure 4B** Biomass and VIN relationship

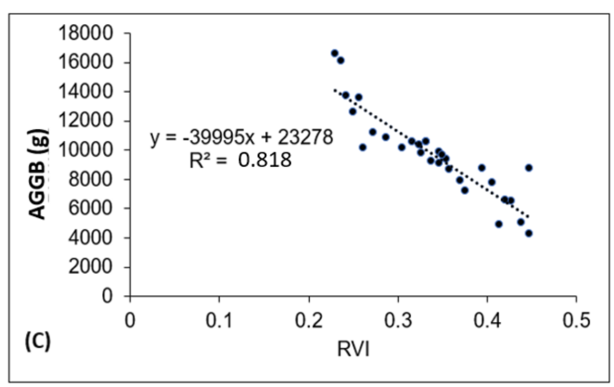



**Figure 4**C AGGB and RVI relationship

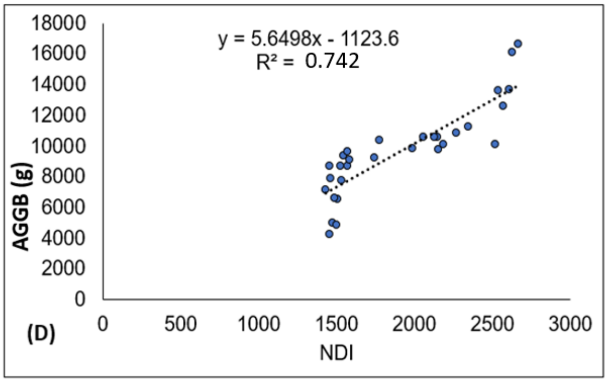



**Figure 4D** Biomass and NDI relationship

Using VIN model equation, Pixel-based sampling of AGGB was calculated for all grasses on the grid equivalent to the pixel size of the image.

$$AGGB = 4234x - 3263.6 \quad (1)$$

Where, AGGB is the grass biomass in grammes of a pixel of interest and x is the VIN image.

The VIN map calculated for the entire study area has a range of 0 to 10, but VIN of the grass sample points calculated from the image is within the range of 2 to 4. Areas covered by grasses were extracted from the satellite imagery using Boolean operation (Figure 5A). 1 represents areas all values from 2 – 4 (grass areas) while 0 represent any other values (non-grass areas). The Boolean map was multiplied by the VIN map to get the VIN grass map (Figure 5B). the VIN grass map was substituted in eqn 1 to get 1 to get the total AGGB of the study area. The AGGB map was presented in Figure 5C.

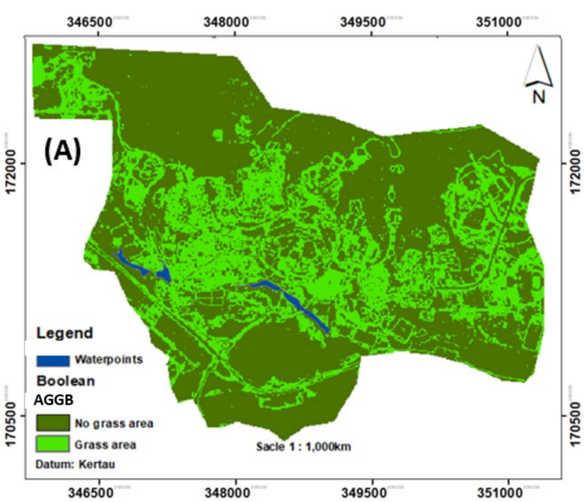



**Figure 5**A Boolean grass map

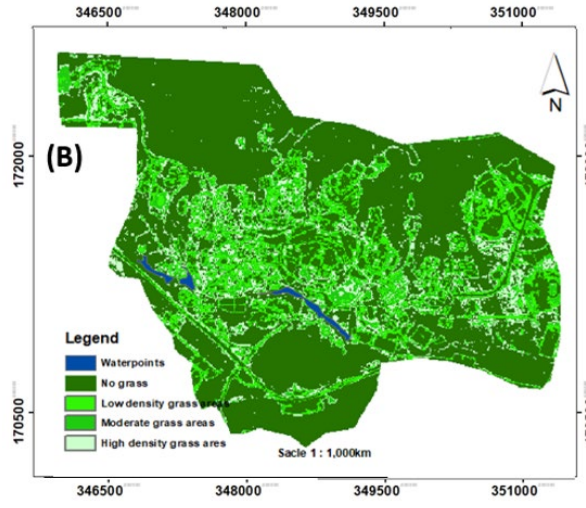



**Figure 5**B Grass VIN map

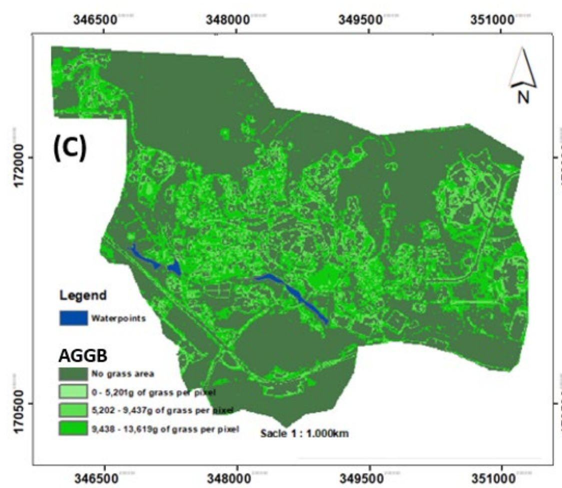



**Figure 5**C AGGB map

### *3.3 Assessment of Result*

Independent evaluations of the spectral derived AGGB were verified by validation field samples and allometric calculated AGGB. From the assessment, the model developed meets the assumption of a linear models (Figure 6A and Figure 6B).

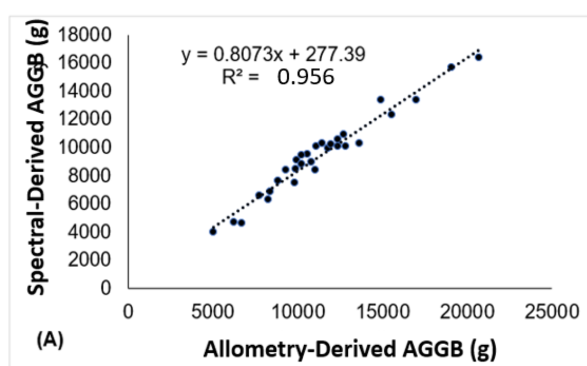



**Figure 6 A**. Model validation with Allometry Derived AGGB

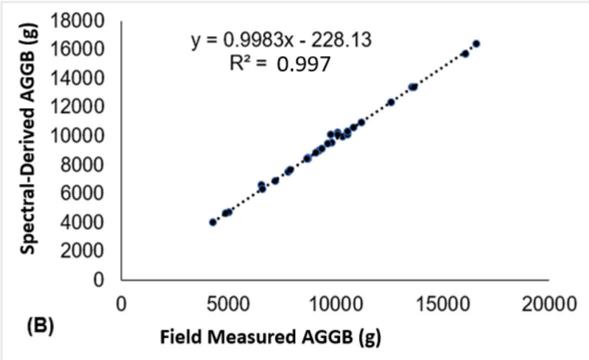



**Figure 6B** Model validations with field AGGB

The satellite derived AGGB has a level of fitness with the allometry and the field measured AGGB ($R^2$ = 0.956, $R^2$ = 0.997) and a good accuracy at RMSE = 15.90. and RMSE = 44.45 respectively

## 4. Discussion

Grass allometry model used in this study found out that grass height and grass volume are the most suitable predictors for estimating AGGB. This agrees with Oliveras (2014) where he finds out that plant height was the best predictor of biomass estimation. In this paper, stem diameter, density and leaf area show no relationship with AGGB. This contradicts the AGB estimation of woody plants where DBH is one of the best predictors of AGGB as was documented by many scholars (Ubay et al (2018).

NDVI and RVI have been popularly used in recent decades to estimate biomass at a regional level (Jiang et al., 2015). They were criticized, however, for problems with saturation at high density vegetation levels (Li et al., 2014). Our study tested four of the most frequently used VIs for modelling AGGB estimation in a densely vegetated region. These are NDVI, RVI, VIN and NDI. VIN was found to be the most suitable VI for the modelling the estimation of AGGB using Sentinel 2A data. However, this may be verified by further studies using different satellite data with different vegetation species. VIN shows a significant relationship with grass biomass where $R^2$=0.84.

The grass distribution in the study area covers 221.8 hectares out 1,222. The study area is a forested region with few grass species. Most grasses were found by the roadside, behind buildings and in playing fields. Very little grasses that was meant for grazing of livestock. The maximum AGGB within 10m$^2$ was 13,672.08g and the minimum was 3,014.12g. The total estimated AGGB was 323,183,164.70g equivalent to 1.46 tons per hectare. This result was similar to Cisneros et al., (2020) with 1.8 tons per hectare in a similar tropical region likes Skudai; when he used Sentinel 2 MSI data. Result from other studies that use MODIS was 0.5 tons per hectare (He et al., 2014), HJ satellite was 1.22 tons per hectare (Zhou et al., 2016).

## 5. Conclusion

AGGB mapping and estimation is crucial for evaluating the health and of grassland eco system including grazing areas. Despite some sources of error, satellite data constituted a sufficiently accurate indicator of grass biomass and allowed biomass estimation and production of maps at a local and regional levels. This study confirmed that Sentinel 2A MSI as the best satellite data for AGGB estimation. Among the vegetation indices analyzed, Vegetation Index Number (VIN) derived from satellite data estimates AGGB at a good accuracy compared to other indices. The result obtained in this study will be beneficent in the decision-making processes regarding the expanding of grazing livestock in the study area, hence, contributing in the sustainable agriculture and food security.

## Acknowledgements

The authors sincerely acknowledge Tertiary Education Trust Fund (TETFund), Nigeria for sponsoring this study. We also acknowledged all staff of Physics and Chemistry Laboratory, UTM, particularly Mrs. Aninsah Salikin, Mr. Saiful Rshid and Mr Muhammad Salehuddin Baharuddin by providing the laboratory facilities needed for the analysis in this study.

## Funding

This work was partially funded by the Ministry of Education Malaysia using FRGS grant (Ref: Vote no. 5F211 – Remote Sensing-Based Seagrass Ecosystem Services), as offset test of grass allometry models.

## References

Ali, I., Cawkwell, F., Dwyer, E., & Green, S. (2017). Modeling Managed Grassland Biomass Estimation By Using Multitemporal Remote Sensing Data—A Machine Learning Approach. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 10(7): 3254-3264.

Bastin, J. F., Barbier, N., Couteron, P., Adams, B., Shapiro, A., Bogaert, J., & De Cannière, C. (2014). Aboveground Biomass Mapping Of African Forest Mosaics Using Canopy Texture Analysis: Toward A Regional Approach. *Ecological Applications*, 24(8): 1984-2001.

Country Data and Statistics (2019). www.worlddata.info › Asia › Malaysia. Accessed on 28th June 2019.

Cisneros, A., Fiorio, P., Menezes, P., Pasqualotto, N., Van Wittenberghe, S., Bayma, G., & Furlan Nogueira, S. (2020). Mapping Productivity and Essential Biophysical Parameters of Cultivated Tropical Grasslands from Sentinel-2 Imagery. *Agronomy*, *10*(5): 711.

Dube, T., Mutanga, O., Elhadi, A., & Ismail, R. (2014). Intra-And-Inter Species Biomass Prediction In A Plantation Forest: Testing The Utility Of High Spatial Resolution Spaceborne Multispectral RapidEye Sensor And Advanced Machine Learning Algorithms. *Sensors*, *14*(8): 15348-15370.

De Sy, V., Herold, M., Achard, F., Asner, G. P., Held, A., Kellndorfer, J., & Verbesselt, J. (2012). Synergies Of Multiple Remote Sensing Data Sources For REDD+ Monitoring. *Current Opinion in Environmental Sustainability*, 4(6): 696-706.

Hansen, M. C., & Loveland, T. R. (2012). A Review Of Large Area Monitoring Of Land Cover Change Using Landsat Data. *Remote sensing of Environment*, *122*: 66-74.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., & Obersteiner, M. (2013). Biomass Use, Production, Feed Efficiencies, And Greenhouse Gas Emissions From Global Livestock Systems. *Proceedings of the National Academy of Sciences*, 110(52): 20888-20893.

He, B., Li, X., Quan, X., & Qiu, S. (2014). Estimating the aboveground dry biomass of grass by assimilation of retrieved LAI into a crop growth model. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *8*(2): 550-561.

Jiang, Y., Tao, J., Huang, Y., Zhu, J., Tian, L., & Zhang, Y. (2014). The Spatial Pattern Of Grassland Aboveground Biomass On Xizang Plateau And Its Climatic Controls. *Journal of Plant Ecology*, *8*(1): 30-40.

Karlson, M., Ostwald, M., Reese, H., Sanou, J., Tankoano, B., & Mattsson, E. (2015). Mapping Tree Canopy Cover And Aboveground Biomass In Sudano-Sahelian Woodlands Using Landsat 8 And Random Forest. *Remote Sensing*, 7(8): 10017-10041.

Li, F., Chen, W., Zeng, Y., Zhao, Q., & Wu, B., (2014). Improving Estimates Of Grassland Fractional Vegetation Cover Based On A Pixel Dichotomy Model: A Case Study In Inner Mongolia, China. *Remote Sensng*. 6: 4705–4722.

Lathen, C., Zhang, Y., Chow, J., Singh, M., Lin, G., Nigam, V., & Thistlethwaite, P. A. (2014). ERG-APLNR Axis Controls Pulmonary Venule Endothelial Proliferation In Pulmonary Veno-Occlusive Disease. *Circulation*, *130*(14): 1179-1191.

Mutanga, O., Adam, E., & Cho, M. A. (2012). High Density Biomass Estimation For Wetland Vegetation Using Worldview-2 Imagery And Random Forest Regression Algorithm. *International Journal of Applied Earth Observation and Geoinformation*, *18*: 399-406.

Myint, S. W., Gober, P., Brazel, A., Grossman-Clarke, S., & Weng, Q. (2011). Per-Pixel vs. Object-Based Classification of Urban Land Cover Extraction Using High Spatial Resolution Imagery. *Remote sensing of environment*, *115*(5): 1145-1161.

Mucina, L. (2019). Biome: Evolution Of A Crucial Ecological And Biogeographical Concept. *New Phytologist*, *222*(1): 97-114.

Montesano, P. M., Cook, B. D., Sun, G., Simard, M., Nelson, R. F., Ranson, K. J., & Luthcke, S. (2013). Achieving Accuracy Requirements For Forest Biomass Mapping: A Spaceborne Data Fusion Method For Estimating Forest Biomass And Lidar Sampling Error. *Remote Sensing of Environment*, *130*: 153-170.

Oliveras I., Maarten V. D., Yadvinder M., Nelson C., Carlos M., Flor Z. & Torbjørn H. (2014). Grass Allometry and Estimation of Above-Ground Biomass In Tropical Alpine Tussock Grasslands: Austral Ecology 39: 408–415

Popescu, S. C., Zhao, K., & Gatziolis, D. (2009) Comparing the Accuracy of Aboveground Biomass Estimates and Forest Structure Metrics at Large Footprint Level: Satellite Waveform Lidar vs. Discrete-Return Airborne Lidar. *AGU* Fall Meeting.

Powell, S. L., Cohen, W. B., Healey, S. P., Kennedy, R. E., Moisen, G. G., Pierce, K. B., & Ohmann, J. L. (2010). Quantification Of Live Aboveground Forest Biomass Dynamics With Landsat Time-Series And Field Inventory Data: A Comparison Of Empirical Modeling Approaches. *Remote Sensing of Environment*, *114*(5): 1053-1068.

Rongrong W., Peng W., Xiaolong W., Xin Y., & Xue D. (2018). Modeling Wetland Aboveground Biomass In The Poyang Lake National Nature Reserve Using Machine Learning Algorithms And Landsat-8 Imagery. *Journal of Applied Remote Sensing*, 12(4): 46029_1 – 046029_12

Sibanda, M., Mutanga, O., Rouget, M., & Kumar, L. (2017). Estimating Biomass Of Native Grass Grown Under Complex Management Treatments Using Worldview-3 Spectral Derivatives. *Remote Sensing*, *9*(1), 55.

Ubay, M. H., Tron E., Ole M. B., & Emiru B. (2018). Aboveground Biomass Models for Trees and Shrubs of Exclosures In The Drylands Of Tigray, Northern Ethiopia. Journal of Arid Environments 156: 9–18

Yuyun C., Longwei L., Dengsheng L., & Dengqiu L. (2019). Exploring Bamboo Forest Aboveground Biomass Estimation Using Sentinel-2 Data. *Remote Sensing*. 11: 7.

Zhang, C., & Kovacs, J. M. (2012). The Application of Small Unmanned Aerial Systems for Precision Agriculture: A Review. *Precision agriculture*, *13*(6): 693-712.

Zhou, X., Zhu, X., Dong, Z., & Guo, W. (2016). Estimation of biomass in wheat using random forest regression algorithm and remote sensing data. *The Crop Journal*, *4*(3): 212-219.

Zumo, I. M., Hashim, M., & Hassan, N. (2021). Mapping Grass Above-Ground Biomass of Grazing-lands using Satellite Remote Sensing. *Geocarto International*, 1-13.

IJBES

International Journal of Built Environment and Sustainability
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 17-25

# The Riyadh Urban Growth Boundary: An Analysis of the Factors Affecting its Efficiency on Restraining Sprawl

**Mohamed Saleh Amer**
Department of Urban and Regional Planning, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.

**Mohammad Rafee Majid**
Department of Urban and Regional Planning, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.

**Tahar A. Ledraa**
Department of Urban Planning, College of Architecture and Planning, King Saud University, Riyadh, Saudi Arabia

## ABSTRACT

Recently, research on sprawl was increasing due to its impacts on the economy, society, and environment. Several studies have focused on the application of containment strategies to curb urban sprawl. Urban growth boundaries (UGBs) were among the containment policies adopted to tackle the issue of sprawling cities. This paper set out to undertake an analysis of the factors influencing the performance of the UGB of Riyadh City. A qualitative data analysis using NVivo12 software was adopted. To collect the required data of UGB, semi-structured interviews were conducted with nine experts involved in urban management, Riyadh city development, and other planning agencies. If the application of UGB policy in the western countries has managed to restrain more or less city sprawl, its replication to the case of Riyadh seems to have had some adverse impacts. That is, instead of controlling urban sprawl, it has stimulated it. The reasons may lie in the deficiency of monitoring and evaluation of urban studies, free provision of infrastructure, and lack of coordination between different city planning agencies. Understanding the factors affecting the UGB efficiency will assist policymakers and urban planners in reducing the spread of scattered and leapfrog residential development, lowering the cost of service supply and promoting infill development.

**Article History**

Received: *13 September 2020*
Received in revised form: *17 May 2021*
Accepted: *19 May 2021*
Published Online: *31 August 2021*

**Keywords:**

Urban growth boundary; Growth Management; Urban Sprawl; Urban Containment strategies; Saudi Arabia

**Corresponding Author Contact:**

Saleh1983@graduate.utm.my

**DOI:** 10.11113/ijbes. v8. n3.704



## 1. Introduction

During the past thirty years or so, growth management strategies have come to the forefront of the urban planning agenda to respond to inefficient land-use practices and to curb the sprawl of cities. The literature is abundant on the policy measures to halt the scattering urban development in western countries. However, little studies have been undertaken on sprawl containment policies in Middle East cities. The growth management strategies adopted were mainly compact city strategies, decentralized concentration strategies, and rural and open space preservation strategies. The policy measures adopted range from restrictive measures like urban growth boundaries, green belts, car park restrictions, and development fees to densification measures such as making denser cities more attractive, revitalization policies and the provision of public transport. Different zoning techniques such as maximum/minimum densities and mixed-uses, etc. were often used to implement such policies (Miceli & Sirmans, 2007; Heim, 2001; Pendall & Puentes, 2008; Zhang, 2011; Horn, 2014).Urban growth boundary (UGB) has been used as a measure to curtail the negative consequences of sprawl. It consists of delineating a boundary beyond which urban development would not be allowed. It designates the line between urban and rural areas and hence, the use of different land-use policies and regulations to direct urban development within the UGB to control the scale, time sequence, and shape of the urban area (Calthorpe & Fulton, 2001; Pendall et al., 2002). Its implementation, however, has been subject to a heated political debate in countries where it is implemented, and at times, it has even been legally challenged and sporadically amended (Loughman, Mourning, & Toros, 2011).

City planning authorities have widely used UGBs as a growth-management measure to control future urban planning development (Han et al., 2009; Ball et al., 2014; Wang et al., 2014; Hall, 2014; Yue et al., 2016; Mubarak, 2004; Rudolf, 2017; Millward, 2006; Cho, 2005). It has been argued to be an effective way to curb urban sprawl and tackle similar problems (Alshuwaikhat & Adenle, 2016; Sullivan, 2015; Strauss & Neamtu, 2006; Al-Hathloul, 2017).

The state of Oregon in the US has always been an outstanding example of successfully using UGBs to control urban growth. In their article, Nechyba & Walsh (2004) claimed that urban growth boundaries have so far become a popular strategy to limit sprawl. They argued that UGBs could be an effective instrument to control the expansion of urban areas. In their study on urban growth boundary and sprawl in Xinyi District in Taipei, Taiwan, Lai & Wang (2019) reached similar conclusions as they could not find enough evidence to suggest that urban sprawl took place outside the UGB there.

However, when assessing the impact of such boundary on urban growth in Knox County, Tennessee, Cho et al. ( 2007) got to a different conclusion in which the UGB employed in 2001 failed to curtail urban sprawl in the region. Similarly, in recent research Ladraa & Saleh (2018) found significant discrepancies between what was actually built and what was intended to be built according to planners' projections. They concluded that the UGB strategy was unable to reach the set up goals due to the absence of a planning evaluation process. Likewise, in investigating the effectiveness of UGB in Hangzhou, China, Li (2014) concluded a deficient performance of the UGB compared to what had been planned. This was due to the defective planning techniques used in formulating the UGB, he argued. This has led Kim (2019) to conclude that while UGBs are capable of controlling the scattered and leapfrogging expansions as well as encouraging compact and contiguous development, the strategy does not always function as planned or guarantee the desired results.

## 1.1 Urban Growth Management and Sprawl in Riyadh

Riyadh, the capital city of Saudi Arabia, is located in the middle of the kingdom (see fig 1). It is considered one of the fastest-growing cities in the world. Within the span of half a century, Riyadh has increased from a small old town surrounded by walls to a modern city, more than a hundred times larger with an area of 2435 square kilometers (Alqahtany, 2014).

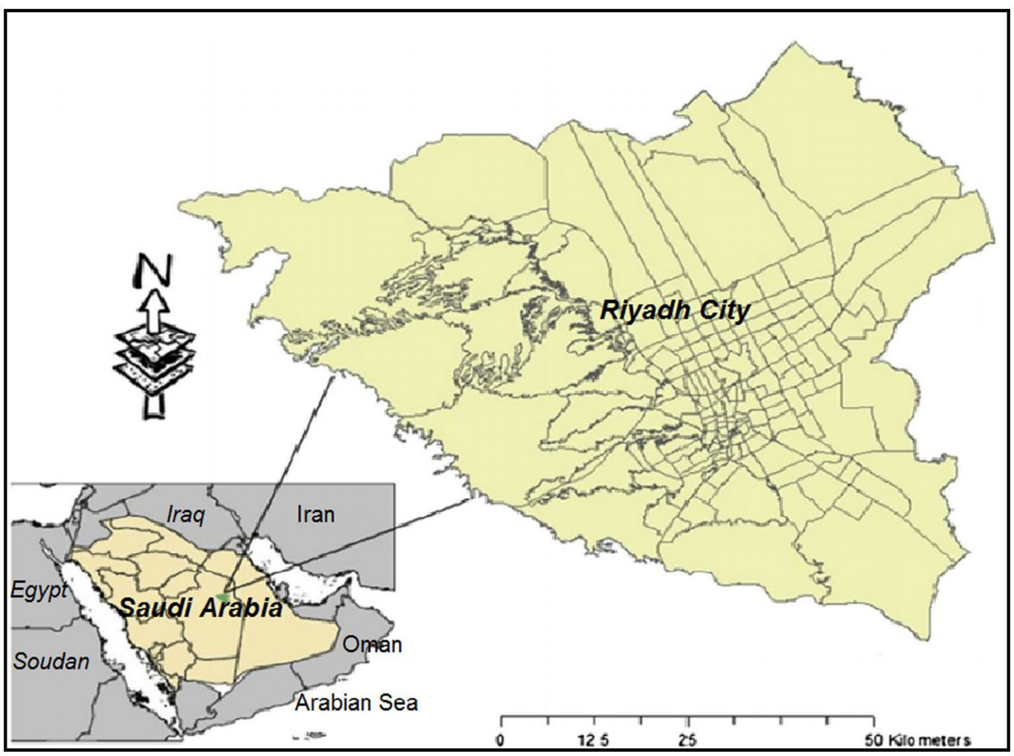



**Figure. 1** Location of Riyadh and Al Riyadh UGB (Alotaibi & Potoglou, 2018)

The urban transformation of Riyadh is divided into five stages, coinciding with the urban development of the city (see Fig. 2). The first stage began with King Abdulaziz constructing of Al-Murabba' administrative complex outside the old town. The next phase to the mid-1960s, influenced by modern designs that were introduced to the city. Then, in the late 1960s, the third period began with the introduction of the Dioxides urban master plan. Afterward, stage four commenced with the oil boom of the mid-1970s and updating of the Riyadh master plan. The fifth phase, managing urban growth, came at the end of 1989 when The Ministry of Municipal and Rural Affairs (MOMRA) undertook the UGB projects. The primary purposes of the UGB project were to control sprawl by encouraging infill development, reduce the cost of the provision of infrastructure and amenities for new development through better coordination, and ensure the sustainability of the natural environment around the city through proper preservation measures (Al-Hathloul, 2017).

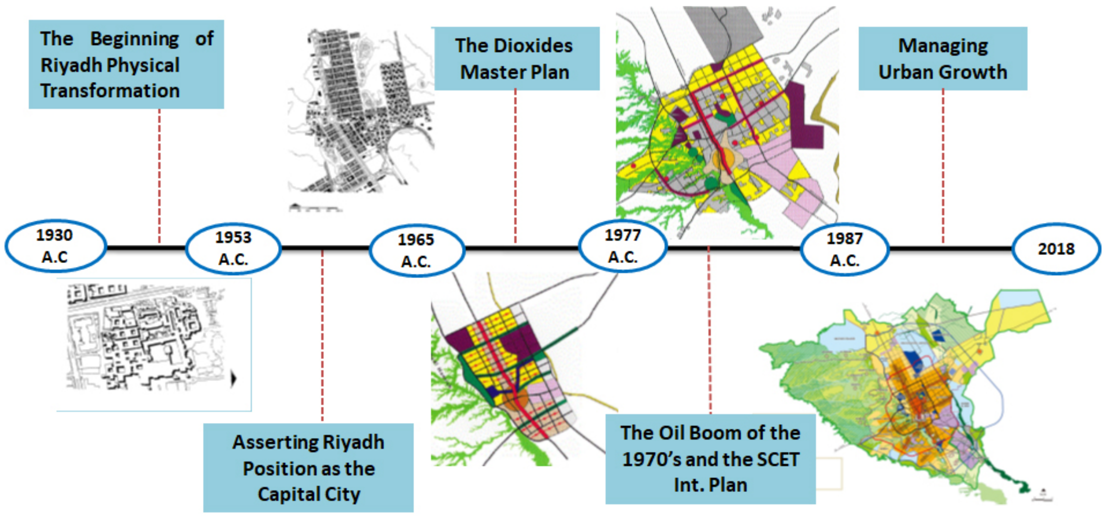



**Figure. 2** Timeline of Riyadh Urban Growth Phases

In 1986, the Council of Ministers suspended the approval of new land subdivision projects in all Saudi cities due to the unplanned and unmanageable rapid urban expansion of these cities. Subsequently, MOMRA launched the Urban Growth Boundary Policy (UGBP) between 1986-1989 for 100 Saudi cities, Riyadh city was on top of them (Mubarak, 2004). Therefore, the research finding will reveal its significance in rectifying the process of UGB as a tool in managing the growth not only in Riyadh but also in the 100 cities where the first stage of UGB was implemented.

In a recent study, Altuwaijri (2018) used remote sensing and GIS Techniques to measure Riyadh urban extension between 1987 and 2017. He concluded that the city experienced sprawl, especially to the northern part. Rahman (2016) used Shannon's Entropy to analyze urban land use and sprawl in Riyadh. He found that the city was sprawling towards the North, South, and South-East. Many studies have shown that Riyadh UGB has seen limited success ((Mubarak, 2004; Rahman, 2016; Al-Hathloul, 2017; Altuwaijri, 2018).

This research is undertaken under the contention that UGBs that fail to inhibit sprawl may cause some counterproductive effects that cause sprawl to be stimulated rather than restricted. This paper seeks to answer the fundamental question: was UGB's plan-making stage and implementation and monitoring stage properly done to promote sprawl-restraining procedures? In other words, what went wrong during plan-making and in the implementation and monitoring phases?

## 2. Methodology

In-depth face-to-face semi-structured interviews were undertaken with nine experts in the urban management sector between April 10th and May 20, 2019 (see Table .1). Prior to the in-depth interviews, a pilot study was conducted with three experts on the first draft of the open-ended questions to check their wording, reliability and validity. Based on their feedback, some questions were reformulated accordingly. The expert interviewees were selected to represent the three institutions involved in managing Riyadh UGB, i.e. the Ministry of Municipalities and Rural Affairs (MOMRA), Riyadh Municipality, and Al-Riyadh Development Authority (ADA), which has just been renamed the Royal Commission for Riyadh. Their job titles range from deputy minister, deputy mayor, head of a department, to advisors. They all have well over 20 years of experience respectively. Thus, their positions and years of experience matter much in their designation as experts of Riyadh UGB.

**Table. 1** Experts profile

| Expert code | Position | Date of interview | Years of Experiences |
|---|---|---|---|
| **Expert 1** | Former Deputy Minister | May 18, 2019 | 30+ |
| **Expert 2** | Former Deputy Mayor | April 21, 2019 | 30+ |
| **Expert 3** | Former Deputy Minister | April 25, 2019 | 30+ |
| **Expert 4** | Urban Planning Advisor | April 21, 2019 | 30+ |
| **Expert 5** | Urban Planning Advisor | April 15, 2019 | 30+ |
| **Expert 6** | Urban Planning Professor | May 10, 2019 | 30+ |
| **Expert 7** | Head of Department | April 16, 2019 | 20+ |
| **Expert 8** | Head of Department | April 24, 2019 | 20+ |
| **Expert 9** | Urban Planning Advisor | April 12, 2019 | 20+ |

The interview questions were structured to provide the researchers with in-depth knowledge on many aspects such as: the UGB delineation process, how regulations were developed, the role of Riyadh urban agencies on plan-making and implementation, sprawl drivers, urban decision making, infrastructure provision, subdivision procedures, and the coordination between different urban departments. Appointments with interviewees were made either by phone calls or visits to their offices in the workplaces. They were made fully aware of the purpose of the research and why they were selected for the interview. Well before the interview meetings, copies of the questions together with an A1-sized, hardcopy color map for Riyadh built-up area and UGB limits were shared with all participants (see Figure 3).

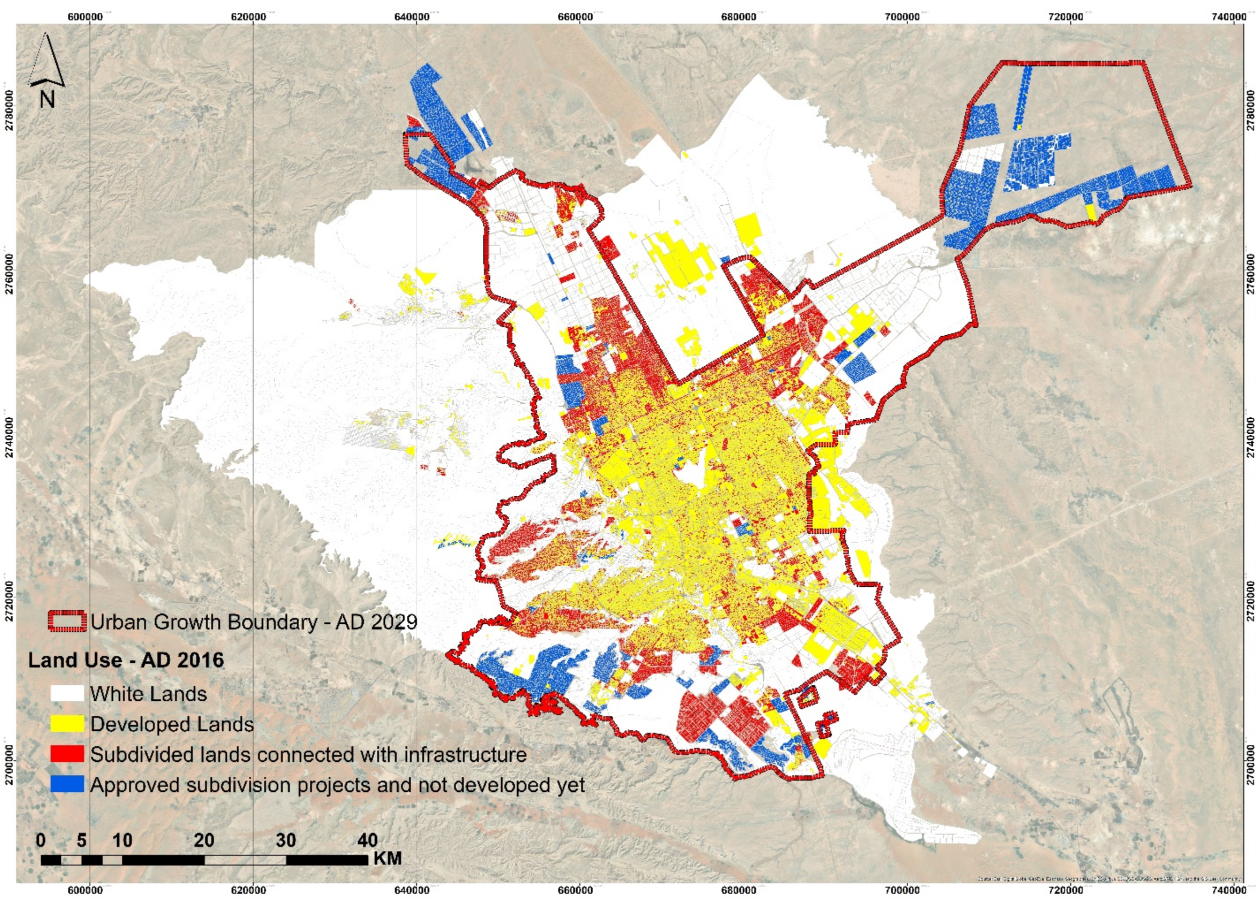



**Figure. 3** Riyadh Urban Growth Boundary AD 2029 and Land Use - AD 2016, (Developed by the researchers)

The recorded data were transcribed and translated into English. Soft copies were sent back to the participants to ensure that the translations accurately reflected their views. NVivo 12 plus qualitative data analysis software was used to generate themes and the coding process to categorize the research variables. Tools like Matrix coding and word frequency were used to analyse and interpret the coded data to ensure that the findings of the interviews echoed the viewpoints of the respondents correctly.

## 3. Results and Discussion:

This section discusses the finding with regard to the crucial factors underlying the inefficiency of Riyadh UGB as a measure to curtail sprawl. The data collected through interviews with experts were processed to answer the primary question of the study. The purpose was to identify the factors that influence the success of the UGB by analyzing the planning stage and the implementation and monitoring stage. Figure 4 illustrates the experts' perceptions of the factors that influence UGB's success in controlling growth and curbing sprawl in Riyadh. Also, it presents how many times each expert coded the factor.

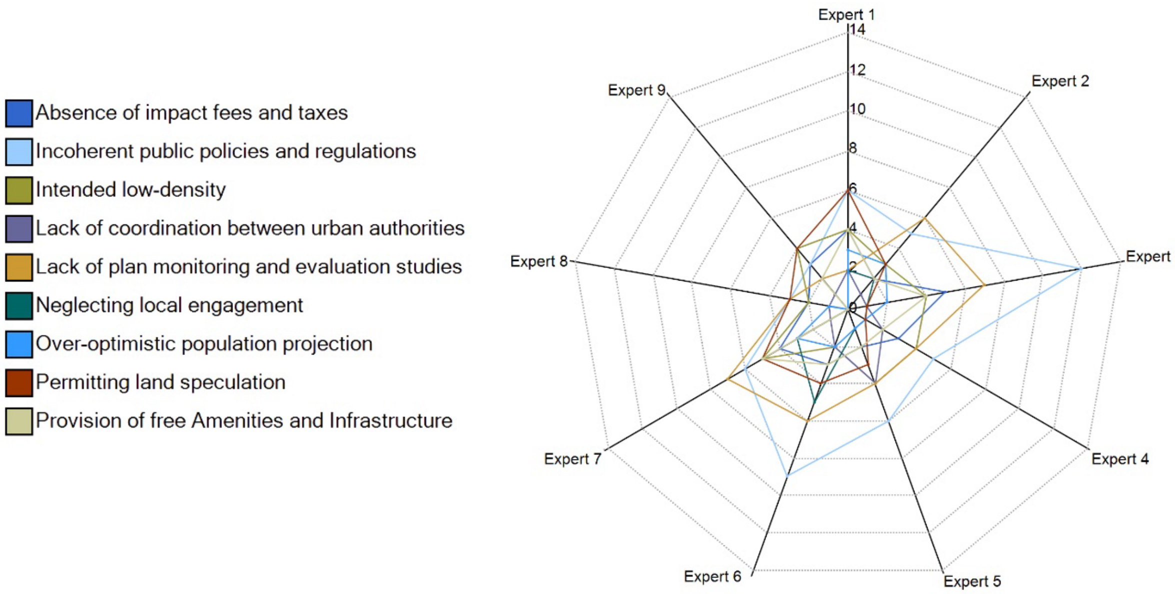



**Figure. 4** Experts' perceptions of the factors influence UGB effectiveness in curtailing the sprawl in Riyadh (created by NVivo 12).

### *3.1 Plan Making Stage*

The expert interviewees concurred that the main weakness of Riyadh UGB lies in the study elaboration stage. Three significant drawbacks in the study preparation made the UGB less capable of halting sprawl from taking place in Riyadh.

#### 3.1.1 Over-Optimistic Population Projection

The Riyadh UGB was supposed to house some 12 million inhabitants by the year 2020. The actual number of Riyadh residents to date does not exceed 6.5 million. This overestimation has led to larger areas of vacant lands within the UGB, which represent something around 45% of the total Riyadh area. As Expert 3 put it:

*"Riyadh policymakers have overestimated the city population growth. They have thus included more land into the UGB to meet the future expected demand. However, what Riyadh got out of this erroneous population growth estimate, has been scattered and leapfrog development".*

Expert 3 said that *"the vacant land required was calculated on the basis of population projections to the year 2020. Then a safety net of twenty percent was added. It is believed that a big mistake was made by adding twenty percent. This safety margin should not have been added in the first place. This safety margin was largely to blame for the sprinkled low-density city sprawl".* This argument has been endorsed by Expert 5

(personal interview, April 15, 2019) and Expert 9 (personal interview, April 12, 2019).

#### 3.1.2 Intended Low-Density

The average residential density within the UGB was about 60 People/Ha, whereas, the United Nation average density standards is 150 People/Ha. Many respondents have emphasized that such density has not only led to consuming many acres of lands but also to increase the cost of infrastructure.

*"Riyadh residential density is among the lowest in the world. Most of the residential dwellings consist of villas with an average area between 400 to 600 square meters. With a density of ten to twelve dwellings per hectare, Riyadh cannot sustain its urban challenges,"* argued Expert 4 (personal interview, April 21, 2019).

#### 3.1.3 Neglecting Local Engagement

The participation of residents and other stakeholders in discussions about the development scenarios, and which lands can be developed first is necessary for the efficiency of UGB. As one respondent put it:

*"If the UGB policy is to succeed, it has to win the support of all concerned parties, residents and stakeholders."* By Expert 6 (personal interview, May 10, 2019).
*"three planning institutions, Al-Riyadh Development Authority (ADA), the Ministry of Municipalities and Rural Affairs (MOMRA) and Riyadh Municipality, collaborated together to set up the city UGB. Unfortunately, this work was done in the absence of community participation."* Said by Expert 1 (personal interview, May 18, 2019).

Expert 5 argued against community participation in Riyadh UGB. He said: we in the MOMRA have deliberately ignored it because we believe that city residents are not well aware of what the UGB is all about. For local stakeholders, they seek only their own profit over the public interest. Another expert replied if there is a lack of awareness among the public, it is therefore incumbent upon the planning authorities in the MOMRA, ADA, and NGOs to explain the role of the UGB to the general public and increase their awareness of the general interest over the private one.

### *3.2 Implementation And Monitoring Stage*

#### 3.2.1 Lack Of Plan Monitoring And Evaluation Studies

Plan monitoring and evaluation studies are essential to check the performance of the urban growth boundary. Effective monitoring and evaluation studies can not only assist city planners in determining the factors of success or failure of a plan but also to supports policymakers to make any adjustments to the UGB if necessary. With regard to the lack of plan monitoring and evaluation studies, respondents said:

*"Riyadh Municipality was forced to ignore its role in conducting monitoring and evaluation studies because it was overwhelmed with the implementation process."* by Expert 3 (personal interview, April 25, 2019).

*"Urban sprawl is a major issue in Riyadh. It is unsustainable and leads to many other problems like inciting car movement, causing strip development, declining the city centre, hampering walkability, etc. The problem is, there has not been any study to evaluate the UGB so far. Such evaluation is more than necessary."* by Expert 6 (personal interview, May 10, 2019).

The absence of plan monitoring and evaluation in Riyadh has promoted new residential developments to spillover within the UGB and beyond. Pieces of evidence can be seen in the scattered development to the North and North East of Riyadh.

#### 3.2.2 Incoherent Public Policies And Regulations

For the Riyadh UGB to work efficiently, it has to be coupled with a set of planning policies and regulations to control and manage urban growth. Rules related to building codes, land subdivision approvals, and infrastructure provision regulations need to accompany UGB implementation phases. Interviewees tend to agree that the current building codes favoring lower densities challenge the concept of compact development. Riyadh urban regulations prohibited multi-families housing and commercial uses inside the districts; Only two-story single-family housing is permitted. Multi-story apartments are only allowed on roads 30 meters wide and over. The commercial ribbon development encouraged expansion along the arterial roads, even outside the current built-up areas.

*Current policies encouraged people to build their houses and live everywhere within UGB regardless of the distance between the current built-up areas and the new developments."* Said, Expert 5 (personal interview, April 15, 2019).

*"I would say that policies contributed to sprawl in different ways. Any developer can subdivide his land at any time, regardless of the location of the project within or beyond the UGB. Furthermore, the planning regulations do not link the approval of subdivision projects with the actual supply and demand for housing in Riyadh. Lack of actions to penalize investors who develop areas not connected to the main built-up area of the city."* by Expert 4 (personal interview, April 21, 2019).

Expert 6 agreed with the idea that urban regulations tend to support development to occur anywhere within the UGB. He said:
*"Planning policies in Riyadh seem to be geared to favor speculation. Any developer can subdivide his land to sell the parcels without any requirement to develop and build the lots."*
*"Municipal regulations have promoted single land use, low-density development, providing free infrastructure, and zero land fees. All these have encouraged land speculation that led to the scattered, leapfrog, and ribbon development patterns".* said by Expert 9 (personal interview, April 12, 2019).

Many expert respondents mentioned the outdated regulations have contributed to increasing vacant lands within the UGB. It is essential to formulate land-use regulations that support continuity and concentration of new development while inhibiting scattered growth from taking place in any location on the urban periphery neglecting the cost of the infrastructure and negative impacts on the environment.

*"Urban regulations allow commercial use development alongside all streets with 30 meters wide and over. Developers usually insist on land subdivision planners to provide more 30 meters wide streets so that they can sell more larger lots for commercial use, which is financially rewarding to speculators."* by Expert 6 (personal interview, May 10, 2019).

*"By law, we cannot exclude any land inside the approved UGB from the development or change the advantages that have been given to that*

*land. The existing regulations do not support shrink's decisions. Therefore, the rules of UGB should be promoted to do its function effectively. I would say, the city officers should develop the current regulations to managing the growth, reducing land speculations, and transforming the city into compacted growth."* by Expert 7 (personal interview, April 16, 2019).

The idea of shrinking UGB was raised since the current boundary is too loose, but there was a dilemma as the supportive legislation was lacking. Planning authorities also realized that the existing regulations were much in favor of the private developers. As Expert 2 put it:

*"Regulation has to be developed to consider the actual need for land, economy, and society. Furthermore, we did our plans for 25 years, which has been proven that it is not efficient. We should do a framework for the development for five years to aedchieve our 25-year plan."*

Expert 4 said that:

*"To be frank, right now, the legislation we use is only to manage the existing urban development. Therefore, there is a need for new legislation to control growth and reduce sprawl to a minimum".*

*"The issue can be corrected at the next stage of the UGB. By developing regulations to support the municipality on the decision of UGB shrinking to curtail leapfrog development and impose new land fees structure for infill development. To control the scattered patterns of developments, then it is necessary to establish the UGB only for the next five years instead of twenty-five years currently adopted. All the above can encourage the developer to invest in ample sites within the pre-existing urban growth boundary that can be found to meet the housing needs of the projected population of Riyadh."* by Expert 8 (personal interview, April 24, 2019).

Since the Cabinet has approved the urban growth boundary and its regulations, the local authority cannot withdraw the right of developing lands from the people after giving them that privilege. The municipality should accept and approve all subdivision plans as long as these projects are within UGB, and they follow the building codes. Policymakers should formulate resilient land-use regulations to deal with the changes in UGB, facilitate the high-density developments, and define the needed lands precisely for the next five years to avoid the problems associated with the overestimated areas for 20 years.

*There is a famous saying "planning must have teeth," but the municipality's planning department teeth seem to be extracted to the point that many affluent developers do no longer fear them.* Said by Expert 6 (personal interview, May 10, 2019).

UGB was primarily generated to promote the creation of a well-managed urban growth by restricting leap-frog expansion over surrounding rural areas. Policies are designated to create well-ordered urban areas by promoting new developments. Municipal regulations should, therefore, introduce the 'carrots' and 'sticks' approaches, to avoid scattered and low-density urban expansion and push towards high-density in areas suitable for infill development.

### 3.2.3 Provision of free Amenities and Infrastructure

Generally, urban amenities and infrastructures such as schools, hospitals, water and wastewater, roads, and transportation services are necessary components in containing and managing the growth when used correctly. Many respondents emphasized the role of amenities and infrastructure in causing sprawl in Riyadh. By law, the municipality must provide infrastructure to any project within the UGB in the current phase regardless of how far they can be from the existing built-up area.

Expert 2 said, *"The sprawl is a result of the failure of the market in the distribution of resources such as public services and infrastructure."*

The development in the west part of Riyadh is a glaring example of the role of infrastructure in encouraging sprawl. West of Riyadh was restricted from residential growth due to the geographical obstacles like the valley known as "Wadi Hanifah." When the Municipality constructed bridges, paved roads, and supported the necessary services, the low-density residential development expanded over the prepared lands. Two interviewees reported that the defective design of the boundary of urban growth led to the failure of the growth management as the west part of Riyadh was linked to the current phase of UGB. Because of these linkages, the valley does no longer plays its role as a natural limit to development.

### 3.2.4 Lack Of Coordination Between Urban Authorities; Municipality, MOMRA, And ADA

Another factor that has been taken to account for exacerbating urban sprawl was attributed to the lack of coordination between different planning agencies. The responsibilities of the three leading planning institutions in Riyadh, namely the Municipality, MOMRA, and ADA, were overlapping and even sometimes conflicting. This conflict has led to inconsistencies in the decision-making process between different planning authorities, which has, in the end, negatively impacted city growth management. As an example, the establishment of the UGB was made by MOMRA, whereas its implementation and monitoring were held by Riyadh municipality. The ADA, however, took in charge the role of making Riyadh Strategic Plan and regulating the land uses within the limits of the UGB. Three different missions for three different planning institutions on the same UGB.

It must be stressed that the UGB is a much more potent instrument than the strategic plan. The UGB gets its power from the Cabinet of Ministers, which is the highest institution in the country, whereas the strategic plan gets its authority from the minister of MOMRA, which is a lower institution than the former. As a result, the strategic plan was taken loosely so much so that the Municipality has taken many actions not always in accordance with the strategic plan stipulates. The ADA itself has allowed many development projects in total breach of its own strategic plan orientations. One expert respondent cited many examples where the Municipality has breached the not only approved some residential subdivisions but provided them with the necessary services and infrastructures in complete disregard of its own UGB guidelines.

Two MOMRA delegates for urban management pointed out that:
*"The lack of integration between the respective urban authorities in Riyadh resulted in overlapping powers and negatively impacted the management of the city's growth significantly."* by Expert 5 (personal interview, April 15, 2019).

*"Riyadh has the privilege of having the Riyadh Development Authority, that can use the power of providing services to control the development, but it has not used this power yet."* by Expert 7 (personal interview, April 16, 2019).
*"There is not only a lack of coordination among different authorities such as the ministry of transportation, housing, and MOMRA but also between the various departments in the same ministry."* Argued by Expert 8 (personal interview, April 24, 2019).

#### 3.2.5 Absence Of Impact Fees And Taxes

Impact fees and taxes have not ever been used in Riyadh before 2016; in other words, taxes have been used after 28 years of implementing the UGB in Riyadh. The current tax computation system has increased the price of housing instead of encouraging infill development. A former deputy minister and several other experts said taxes play a vital role in increasing vacant lands within UGB. However, the current fees system is rising the price of land because of the low percentage of taxes, which makes developers add this amount to buyers. Policymakers used a "one size fits all" approach to design the tax system as they took the whole city as one unit. They should have categorized vacant lands according to their locations instead.

Many experts discussed the absence of impact fees and taxes encouraged developers to consume more lands providing residential projects with very low density and single land use to get much revenue using the advantage of the free infrastructure. Although not necessarily the purpose, the absence of taxes has encouraged residents to live in big houses for a single-family.

#### 3.2.6 Permitting Land Speculation

Six out of nine interviewees mention to consequences of the speculation on the efficiency of UGB on restricting sprawl in Riyadh, where people tend to invest in vacant lots "white lands," considering land as the safest place to hold cash. The formidable issue with speculation is that it decreases the supply available for the current development and reduces the willingness to in-fill development. Another problem with land speculation within the UGB is that the inflation of land appreciation near the urban-edge caused some speculators to keep their lands out of the real estate market.

Due to the allocation of substantial land for housing projects within the UGB in numbers far beyond the projected future need, insufficient regulations of land development, absence of taxes on surplus property, and the leniency in the approval of land subdivisions have led speculators to make easy money by taking advantage of buying and selling vacant lands without building real projects. Such activities promoted premature growth as a consequence of a lack of adequate planning foresight that does not lead to actual residential developments. The result was leapfrog and fragmented development patterns.

## 4. Conclusion

In this paper, the researchers employed semi-structured interviews with experts who played a significant role in managing the growth of Riyadh for many years to determine and interpret the reasons behind the weaknesses of Riyadh UGB that have ultimately promoted urban sprawl. The findings provided a deep understanding of the vulnerabilities that adversely impacted the efficiency of the UGB. Recognizing the weaknesses in the preparation and implementation of the urban growth boundary is the first step for city planners and policymakers to potentially produce worthwhile insights into managing the growth as well as curtailing sprawl.

Findings show that the deficiencies of UGB in Riyadh were driven by some flaws that occurred in the preparation at the legislation stage (e.g., overestimated required lands for future growth, disregard of public involvement, absence of impact fees, and tax regulations, and low-density development). Many other mistakes that happened during the implementation and monitoring phase (e.g., providing free amenities and infrastructure, overwhelmed municipality by implementation tasks and overlooking monitoring and evaluation studies, applying outdated regulations, and approving more land subdivisions regardless of land speculation activities). And above all, lack of coordination between various planning agencies and miscommunication among them.

Riyadh's urban authorities, such as MOMRA, ADA, and Riyadh municipality, should develop more stringent regulations to combat scatter development and promote compacted growth. Impact fees, permitting density in the built-up residential area, and infill development Incentives, all these strategies, and others work effectively against urban sprawl and support the compacted development. The study's implications would boost urban management to reduce sprawl, not only in Riyadh but also in the other 99 Saudi cities that used the same approach as Riyadh.

These results spark several new research opportunities. It would be beneficial to investigate these influential causes quantitatively, including assessing the sprawl and the effect of each factor on it. Furthermore, the position of urban governance and urban finance will directly affect UGB performance, which should be explored in future research.

## Acknowledgements

The researchers would like to thank experts who enthusiastically offered their time and for their collaboration in conducting interviews to produce this paper. We would also like to extend our appreciation to the School of Graduate Studies (SPS) - UTM for their ongoing encouragement and financial support.

## References


Al-Hathloul, S. (2017). Riyadh Development Plans in the Past Fifty Years (1967-2016). *Current Urban Studies*, 05(01): 97–120. https://doi.org/10.4236/cus.2017.51007

Alotaibi, O., & Potoglou, D. (2018). Introducing Public Transport and Relevant Strategies in Riyadh City, Saudi Arabia: A Stakeholders' Perspective. *Urban, Planning and Transport Research*, 6(1): 35–53. https://doi.org/10.1080/21650020.2018.1463867

Alqahtany, A. M. (2014). The Development of A Consensus-Based Framework For A Sustainable Urban Planning of The City of Riyadh. Cardiff University.

Altuwaijri, H. (2018). Urban Extension of the City of Riyadh (1987-2017) Using Remote sensing and GIS Technique. *Journal of Architecture and Planning*, 30(2): 195–213.

Ball, M., Cigdem, M., Taylor, E., & Wood, G. (2014). Urban growth boundaries and their impact on land prices. *Environment and Planning A*, 46(12): 3010–3026. https://doi.org/10.1068/a130110p

Calthorpe, P., & Fulton, W. (2001). The Regional City. Island Press.

Cho, S.-H., Omitaomu, O. A., Poudyal, N. C., & Eastwood, D. B. (2007). The impact of an urban growth boundary on land development in Knox County, Tennessee: a comparison of two-stage probit least squares and multilayer neural network models. *Journal of Agricultural and Applied Economics,* 39(3): 701–717.

Han, H., Lai, S., Dang, A., Tan, Z., & Wu, C. (2009). Effectiveness of Urban Construction Boundaries in Beijing: an Assessment. J*ournal of Zhejiang University Science A*, 10(9): 1285–1295. https://doi.org/10.1631/jzus.A0920317

Heim, C. E. (2001). Leapfrogging, Urban Sprawl , and Growth Management. *American Journal of Economics and Sociology*, 6(1): 245–283.

Horn, A. (2014). Urban Growth Management Best Practices: Towards Implications for the Developing World. I*nternational Planning Studies*, 20(December 2014): 131–145. https://doi.org/10.1080/13563475.2014.942513

Kim, J. H. (2019). Exploring the Determinants of Variations in Land Use Policy Outcomes: What Makes Urban Containment Work? *Journal of Planning Education and Research,* (June), 39: 1-14. 0739456X1986530. https://doi.org/10.1177/0739456X19865300

Ladraa, T., & Saleh, M. (2018). Urban Growth Boundary Plans Evaluation for Small and Medium-Sized Cities in Saudi Arabia. Majmaa and Hurimla UGB plans as a Case study. *Emirates Journal for Engineering Research (EJER)*, 23(1): 1–15.

Lai, S., & Wang, L. (2019). Do Urban Growth Boundaries Contain Urban Sprawl? Explanations and Empirical Examination. *Urban Planning International,* 34(1): 64–70. https://doi.org/10.22217/upi.2017.570

Loughman, C., Mourning, R., & Toros, T. (2011). Management of Urban Growth and Sprawl: An Evaluation of Urban Growth Boundary in Portland, Oregon. Retrieved from https://www.academia.edu/11692106/Management_of_Urban_Growth_and_Sprawl_An_Evaluation_of_Urban_Growth_Boundary_in_Portland_OR_2011_?auto=download Retrieved date: 23 June 2020

Miceli, T. J., & Sirmans, C. F. (2007). The holdout problem, urban sprawl , and eminent domain. *Journal of Housing Economics,* 16: 309–319. https://doi.org/10.1016/j.jhe.2007.06.004

Mohammed, I., Alshuwaikhat, H. M., & Adenle, Y. A. (2016). An approach to assess the effectiveness of smart growth in achieving sustainable development. *Sustainability (Switzerland)*, 8(4): 397 https://doi.org/10.3390/su8040397

Mubarak, F. A. (2004). Urban Growth Boundary Policy and Residential Suburbanization: Riyadh, Saudi Arabia. *Habitat International*, 28(4): 567–591. https://doi.org/10.1016/j.habitatint.2003.10.010

Nechyba, T. J., & Walsh, R. P. (2004). Urban sprawl. *Journal of Economic Perspectives,* 18(4): 177–200.

Pendall, R., Martin, J., & Fulton, W. (2002). Holding the Line: Urban Containment in the United States. The Brookings Institution Center on Urban and Metropolitan Policy. California. https://doi.org/Yes

Pendall, R., & Puentes, R. (2008). Land-use regulations as territorial governance in U.S. metropolitan areas. Boletin de La Asociacion de Geografos Espanoles, 181–206.

Rahman, M. T. (2016). Land Use and Land Cover Changes and Urban Sprawl in Riyadh, Saudi Arabia: An Analysis Using Multi-Temporal Landsat Data and Shannon's Entropy Index. In XXIII ISPRS CONGRESS, COMMISSION VIII 41: 1017–1021. https://doi.org/10.5194/isprsarchives-XLI-B8-1017-2016

Strauss, E. J., & Neamţu, B. (2006). Policy Tools for Addressing Urban Sprawl: Urban Growth Boundaries. Transylvanian Review of Administrative Sciences, 2(16), 136–153. Retrieved from http://rtsa.ro/tras/index.php/tras/article/view/237 Retrieved date: 15 July 2020

Sullivan, E. J. (2015). Urban Growth Management in Portland, Oregon. In Oregon Law Review, 455–498.

Wang, L. G., Han, H., & Lai, S. K. (2014). Do plans contain urban sprawlα A comparison of Beijing and Taipei. *Habitat International,* 42: 121–130. https://doi.org/10.1016/j.habitatint.2013.11.001

Zhang, Z. (2011). Urban growth management: Approaches, experiences and implications to China's urban planning. *Advanced Materials Research*, 243–249: 6725–6728. https://doi.org/10.4028/www.scientific.net/AMR.243-249.6725

Zheng Li. (2014). Evaluating the Effectiveness of Urban Growth Control Boundary in Comprehensive Land Use Plan through a Conformance-Based Approach. Radboud University.

IJBES

**International Journal of Built Environment and Sustainability**
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 27-45

# Feasibility of Vertical Rainwater Harvesting via In-situ Measurement of Wind-driven Rain Loads on Building Facades in a Tropical Climate

**Mozhgan Samzadeh**
Faculty of Built Environment, University of Malaya, Jln Profesor Diraja Ungku Aziz, 50603 Kuala Lumpur

**Nazli Che Din, Zunaibi Abdullah, Muhammad Azzam Ismail**
Department of Architecture, Faculty of Built Environment, University of Malaya, Jln Profesor Diraja Ungku Aziz, 50603 Kuala Lumpur

**Norhayati Mahyuddin**
Department of Building Surveying, Faculty of Built Environment, University of Malaya, Jln Profesor Diraja Ungku Aziz, 50603 Kuala Lumpur

## ABSTRACT

Rainwater is an alternative water resource to fulfill sustainable management of freshwater particularly in the regions receive abundant annual amounts of precipitation such as tropical Malaysia. To collect and store rainwater, rainwater harvesting system has been practiced since ancient from horizontal surfaces mostly rooftop of buildings in urban areas. Nowadays, this method in modern urban areas with tall buildings is considered inadequate and uneconomical because the ratio of facade surface areas is much higher than the ratio of roof surface areas. On the other hand, all rain has a horizontal velocity due to wind acting upon rain droplets which is called wind-driven rain (WDR). Growing tall buildings and the presence of WDR phenomenon make building façade surfaces the available promising surfaces to harvest substantial rainwater vertically and more efficiently. This article presents a one-year field measurement results that aims at quantifying the WDR loads impinged on the vertical facade areas of a pilot building located at the main campus of the University Malaya in Kuala Lumpur, Malaysia. Detailed descriptions of the gauge design, building, the measurements of on-site WDR, rainfall duration time, and weather data are presented. Records show that monsoon winds characteristics have significant influence on the WDR loads on the building facades compare to horizontal rainfall intensity. Finally, the collected in-situ data are exploited to validate data and determine WDR coefficient (γ) to estimate the amount of WDR on a building façade via an empirical WDR relationship. Results show the feasibility of each square meter of vertical façade area to supply 12% of non-potable or 4.9% of potable water-usage per capita per day.

**Article History**

Received: *05 January 2021*
Received in revised form: *26 March 2021*
Accepted: *17 May 2021*
Published Online: *31 August 2021*

**Keywords:**

Wind-driven rain; Vertical Rainwater harvesting; Building facade; Measurement data; Monsoon wind

**Corresponding Author Contact:**

nazlichedin@um.edu.my

**DOI:** 10.11113/ijbes. v8. n3.736



## 1. Introduction

By 2030, the world is projected to face a 40% global water deficit under the business-as-usual (BaU) season (Connor, 2015), and the demand is expected to continue increasing at 1% per year until 2050, accounting for an increase of 20 to 30% above the current level of water use; mainly due to rising demand in the industrial and domestic sectors (WWAP, 2019). Over 2 billion people live in countries experiencing high water stress, and about 4 billion people experience severe water scarcity during at least one month of the year (WWAP, 2019).

The distribution and availability of freshwater resources, through precipitation and runoff, can be erratic, with different areas of the globe receiving different quantities of water over any given year (Connor, 2015).

In respect of the physical alternatives to fulfill sustainable management of freshwater, two main categories of solutions can be identified: (i) reduction of water consumption; and (ii) identification of new water resources (Silva et al., 2015). To date, much attention has been given to the former option and only limited attention has been given to the latter (Wu et al., 2017).

For buildings in general and residential buildings in particular, one of the most promising alternative water resources is the rainwater (Lade et al., 2015).Traditionally, the majority of researches have concentrated their studies on roof rainwater harvesting (RWH) system (Canavan, 2008; Cho et al., 2020; Dobravalskis et al., 2018). However, in urban areas with new tall buildings, the ratio of facade surface areas is much higher than the ratio of roof surface areas. Thus, rain more and mainly falls onto the buildings' facades and usually, rooftop rainwater collection can be considered inadequate (Adriano et al., 2011) or impossible when the roof has been used as a roof garden (SDI, 2003). On the other hand, as Dobravalskis et al. (2018) declared, all rain has a horizontal velocity due to wind acting upon rain droplets which is called wind-driven rain (WDR). Due to this characteristic, WDR hits all buildings' facades even those with a completely vertical angle, and it makes buildings' facades as the available potential surfaces for vertical RWH. This new approach to water resource management brings along more benefits in comparison with the horizontal RWH such as; harvesting potential cleaner water because it collects rainwater before ground/roof contamination occurs and utilizes without significant treatment for non-potable purposes; facade areas have not only larger surfaces but also are more unused spaces compared to rooftops in modern urban areas (Dobravalskis et al., 2018). Accordingly, new buildings can benefit from integrated vertical RWH from facade areas in order to optimize their water consumption and minimize their impact on the environment (Beorkrem et al., 2018). Wind-driven rain has been studied in building science as a moisture source with potential negative effects on the building envelope. But in a recent lab and miniature building (L × W × H = 1 × 1 × 2 m3) experiment study by Cho et al. (2020), it has been declared that the amount of rainwater collected from the wall could be very significant compared to the roof area however, the amount of rainwater possibly obtained by a building facade has not been investigated yet. Their study recorded a total set of 40 WDR data collection with 1hr measurement duration for each in one year.

In this study, WDR as a potential water resource to be collected and utilized from vertical façade of buildings for rainwater harvesting system has been investigated. This real-time one-year wind-driven rain measurement method has been implemented for the first time to quantify the amount of accumulated rainwater impinged on a one-story building (L × W × H = 18.60 × 6.40 × 3.50 m3) facades in a tropical climate as an alternative water resource for the rainwater harvesting system. According to the annual rainfall trends in Kuala Lumpur by UNFCCC (2015), rain mostly occurs in the afternoons and evenings, therefore only nocturnal precipitation (12 a.m. to 6 a.m.) was excluded in this study and a total set of 94 WDR data collection (~119 hrs.) events during one year were continuously recorded.

In terms of gauges neither standard design principles, nor industrial manufacturing exists to collect rainwater, and to the knowledge of the authors, so far no yearly measurement of WDR in building science has been applied in a tropical climate. This paper is divided into two parts (i) a brief review on the WDR gauge design principles, and (ii) results of a one-year experimental method to collect WDR from the vertical building facades at the campus of the University of Malaya in Malaysia. First part overviews design instructions and characteristics of seven different types of wall-mounted WDR gauges produced for the measurement purposes by researchers around the world in order to produce an accurate and reliable gauge for their measurement purposes. Second part presents the building, the gauge design instruction, and one-year experimental data collection and results.

### *1.1 Wind Driven Rain Definition*

According to Foroushani (2013), WDR or driving rain is rain that is carried (driven) by wind and driven onto building envelopes with vector intensity causing oblique rain with the influence of gravity (Figure 1). Wind-driven rain or driving rain is the result of complex interactions among wind, rain, and building envelopes.

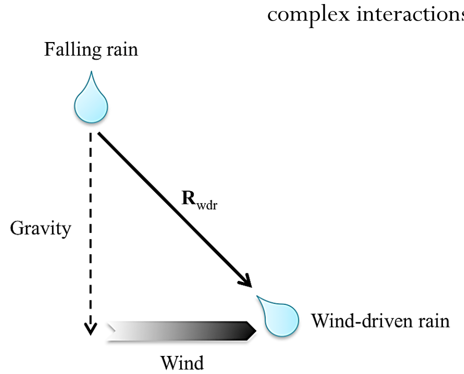



**Figure 1** Wind-driven rain vector

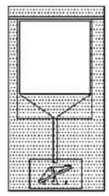
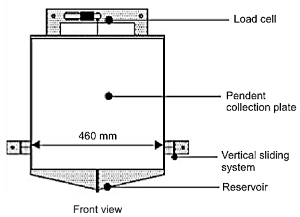
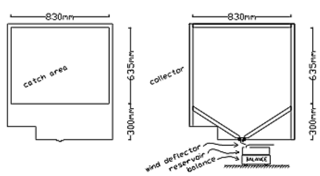
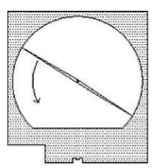
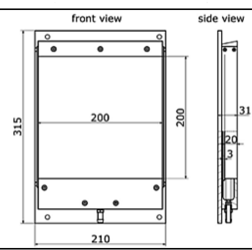
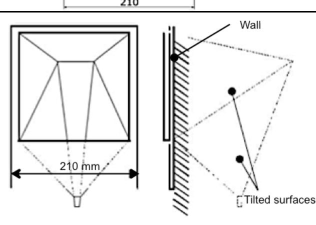
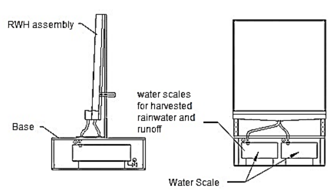
### *1.2 Wind Driven Rain Gauges*

WDR gauges were initially made up of plate, composed of a collection area and a reservoir that are linked via a drainage channel Hogberg (1999); (Masters et al., 2013):

1. A catchment area (a shallow tray) mounted on the building facade; raindrops hit the tray, drip downwards and are collected via:
2. A drainage channel; which leads the collected rainwater to:
3. A reservoir or a water flux gauge; which enables the measurement of instantaneous driving rain intensities.

Seven different types of WDR gauges are presented in the following section. Table 1 illustrates the types of gauges, materials, sizes, and their function to wind-driven rain intensity.

**Table 1** Details of the applied WDR gauges

| Name | Type | Principle | Material / Min. intensity | Catchment area |
|---|---|---|---|---|
| **CTH** |  | Traditional collector with tipping bucket (Vtip=1g) | Perspex (solid transparent plastic made of polymethyl methacrylate) $\frac{1\text{tip}}{20\text{min}} = 0.09\text{mm/h}$ | 0.18 x 0.18 = 0.032 $m^2$ |
| **TUD** |   | Collector weighted by a strain gauge ($\Delta$m=~3g) | Stainless steel $\frac{1.3\text{g}}{10\text{min}} \approx 0.04$ mm/h | 0.46 x 0.46 = 0.21 $m^2$ |
| **TUE-I** |   | Rectangular catchment area with reservoir (2 liters) and balance ($\Delta$m=1g) | Teflon coating (Polytetrafluoro ethylene) $\frac{0.1\text{g}}{20\text{min}} = 0.001\text{mm/h}$ | 0.527 $m^2$ |
| **TUE-II** |  | Round catchment area with a rotating wiper with reservoir (3 liters) and balance ($\Delta$m=1g) | Teflon coating (Polytetrafluoro ethylene) $\frac{0.1\text{g}}{20\text{min}} = 0.001\text{mm/h}$ | 0.492 $m^2$ |
| **EMPA** |   | Rectangular catchment area with reservoir (1 ml) | Aluminum & Glass 0.025 mm/h (10min period) | 0.2 x 0.2 = 0.04 $m^2$ |
| **TILTED-CTH-II** |   | Collection area is tilted surfaces and deeply recessed | - | - |
| **KUT** |   | Square catchment area with two water-measuring scales for WDR and Rainwater Runoff | Stainless steel expanded metal mesh facade panel 0.14 mm/s ≈ 0.005 mm/h | 1 $m^2$ |

### 1.2.1 CTH Gauge

The traditional WDR gauge (CTH) with a small catchment area was developed at the Chalmers University of Technology, Sweden. Its material is Perspex and the reservoir is measured by a tipping bucket with a tipping volume equal to 1g of water (Figure 2). "One tipping in 20 min represents a driving rain intensity of 0.09 mm/h" (Hogberg, 1998; Hogberg et al., 1999).

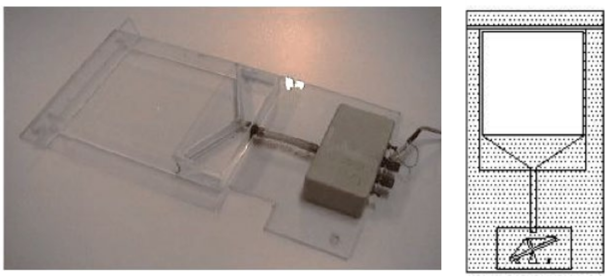


**Figure 2** Wind-driven rain gauge CTH (from Hogberg et al. (1999))

### 1.2.2 TUD Gauge

Kragh et al. (1998) designed an improved WDR gauge at the Technical University of Denmark (TUD to reduce the measurement errors of remaining droplets on the catchment area (Figure 3). This gauge came with a 'load cell' on top of the device to record rainwater both in the reservoir and on the catchment area (Blocken et al., 2004). The collector is made out of a "stainless steel tray with a net mounted on the tray to reduce raindrop bouncing" (Hogberg et al., 1999). The Readings were recorded every 10 min to reduce the measurement error due to the sensitivity of the gauge to wind fluctuations (FJR van Mook, 2002).

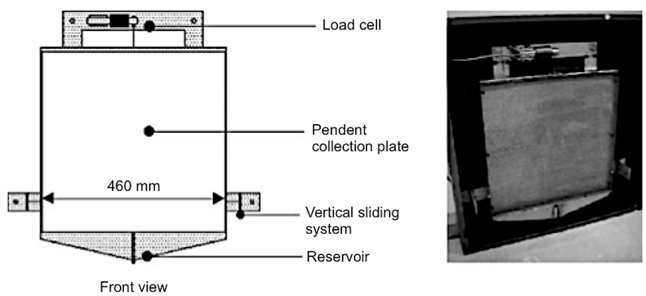



**Figure 3**. Wind-driven rain gauge TUD (FJR van Mook, 2002) from Blocken et al. (2006a) reused with permission)

### 1.2.3 TUE-I Gauge

The gauge TUE-I has been manufactured at the Eindhoven University of Technology, Netherlands. This gauge (Figure 4) has a larger catchment area (0.527 m2) compared to CTH (0.032 m2). Teflon surface finish intends to enhance the process of dripping down the rainwater droplets to the reservoir (Hogberg et al., 1999). The drops collect by a large funnel to the reservoir (Van Mook, 1998). A balance measures the reservoir with an accuracy of 0.1g.

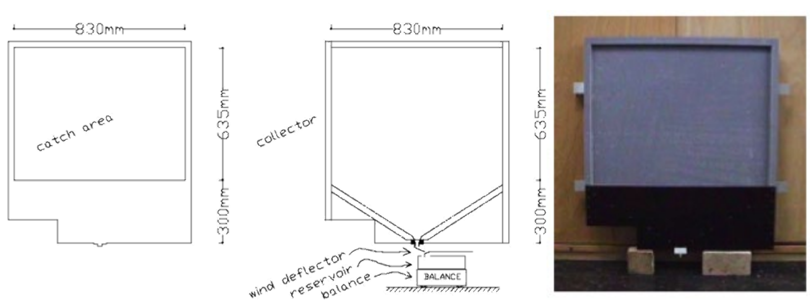



**Figure 4** Wind-driven rain gauge TUE-I (from Van Mook (1998)

### 1.2.4 TUE-II Gauge

Gauge TUE-II is similar to gauge TUE-I, but it is equipped with a rotating wiper (Figure 5). The wiper collects all droplets on the catchment surface and doesn't let any remain on the surface. A rain indicator automatically switches on the wiper. "The speed is approx. 1 rotation per 3 seconds; after every 5 seconds, the wiper rests during 5 s to reduce wear and tear" (Van Mook, 1998).

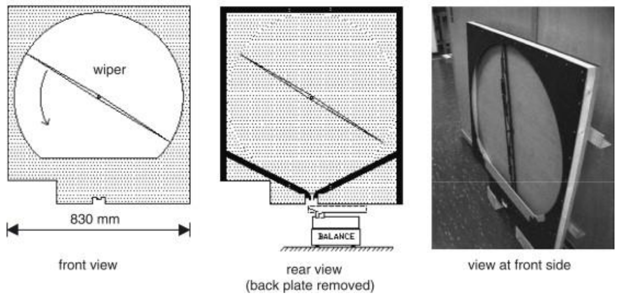



**Figure 5** Wind-driven rain gauge TUE-II from Blocken et al. (2006a) reused with permission)

### 1.2.5 EMPA Gauge

The EMPA WDR gauge was produced at the campus of the Swiss Federal Laboratories for Materials Science and Technology based on the guidelines of Blocken et al. (2006a) and Kubilay et al. (2014). The gauge frame is made of aluminum and the catch surface is ordinary glass sheets to promote runoff (Figure 6). A connecting pipe conveys rainwater from catchment to the reservoir. The reservoir is placed inside the building to prevent frost and evaporation issues from the reservoir (Kubilay et al., 2014).

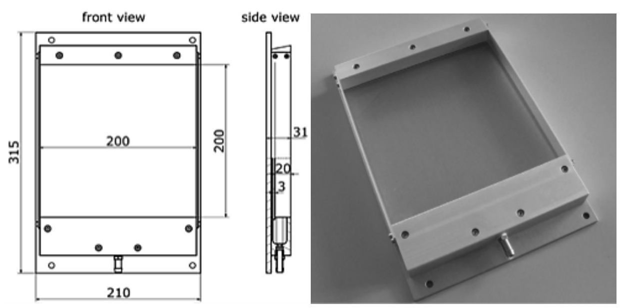



**Figure 6** Wind-driven rain gauge EMPA (from (Kubilay et al., 2014) reused with permission)

### 1.2.6 TILTED/CTH-II Gauge

Hogberg (2002) at the Chalmers University of Technology, Sweden developed a WDR gauge with a deeply recessed catchment area composed of tilted surfaces to prevent raindrops splashing (Figure 7). In the Blocken et al. (2006a) was stated that the performance of this gauge in terms of the amount of accumulated rainwater was better than that of non-recessed gauges for high wind speed and heavy rainfall intensities.

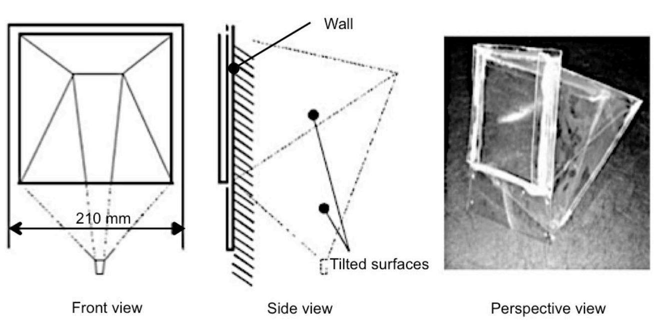



**Figure 7** Wind-driven rain gauge Tilted; CTH-II (© Hogberg (2002) from Blocken et al. (2006a) reused with permission)

#### 1.2.7 KUT Gauge

The KUT gauge (Figure 8) was constructed in the Kaunas University of Technology, Lithuania to measure the rainwater collection rate (Dobravalskis et al., 2018). It is composed of two main parts; the RWH stand and the main control unit. The stand is a hermetic box with a depth of 58 mm: the front layer is an architectural facade panel of stainless steel expanded metal mesh. WDR permeates through the panel into the box and flows into the scale 1 via an outlet hose, and the Rainwater Runoff that flows down on the outer of the mesh surface leads into another gutter and is measured by scale 2. The base consists of the main control unit; includes water-measuring scales, and a bulky volume (1000 mm x 970 mm x 300 mm) made out of cement particleboard covered in aluminum sheeting to ensure the stability of the base in windy outdoor conditions.

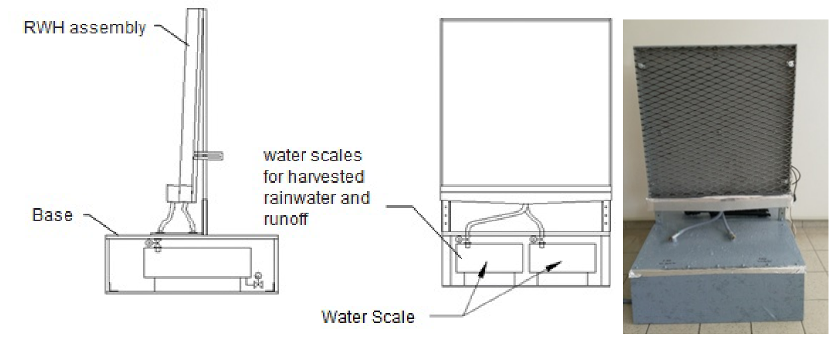



**Figure 8** Wind-driven rain gauge KUT (© Dobravalskis et al. (2018))

## 2. Material and Methods

### *2.1 Measurement Setup*

The measurement setup is located at the main campus of the University of Malaya in the city of Kuala Lumpur, Malaysia, latitude 3°0715 and longitude 101°3923. A pilot building was instrumented with 8 wind-driven rain gauges with high WDR acquisition resolution. The principal aim of this field measurement is to measure and compare the spatial distribution of WDR amount on the facades of the test building over a year from April 2017 to March 2018.

### *2.2 Climate*

Malaysia is a tropical country that is relatively rich in water resources with an average annual rainfall of 2562.35 mm over the study area from 2007 to 2016 (Tan, 2018). Although Malaysia has never experienced any serious water crisis in the past few decades, uneven distribution of rainfall over space and time has led to some areas suffering from dry spells, while others have been affected by major flooding (Hafizi Md Lani et al., 2018). These facts reveal that RWH in Malaysia as a promising alternative water resource and flash flood reduction is crucial and has a high potential. Malaysia's climate is characterized by three main components namely temperature, wind pattern, and rainfall (Bahari et al., 2017). In this section, wind and rainfall patterns are described as the main parameters affecting the WDR phenomenon.

#### 2.2.1 Wind

The winds over the country are generally light and variable. There are, however, some uniform periodic changes in the wind flow patterns. Northeasterly winds prevail during the boreal winter monsoon (locally known as the northeast monsoon) from November to March. Southwesterly winds prevail during the boreal summer monsoon (locally known as the southwest monsoon) from May to September (MESTECC, 2018). These monsoons are separated by two shorter inter-monsoon periods.

#### 2.2.2 Rainfall

Rainfall is characterized by two rainy seasons associated with the southwest monsoon (SWM) from May to September and the northeast monsoon (NEM) from November to March (Suhaila et al., 2009; Tangang, 2001). The monsoon winds and topography are likely the main factors controlling the magnitude of the spatial rainfall variation in the country (Wong et al., 2016). The Titiwangsa Range is a mountain range that forms the backbone of the Peninsula. During the northeast monsoon (NEM), stronger winds blow to the exposed areas, e.g., the east coast of Peninsular Malaysia (Camerlengo et al., 1997; Juneng et al., 2007; Lim et al., 2013), thus these areas receive a substantial high amount of rainfall. Higher wind speeds promote more evaporation, which destabilizes the boundary layer and triggers deep convection, and hence, increases rainfall (Back et al., 2005). These features have enabled Malaysia to be blessed with abundant annual rainfall, with an average ranging from about 2,000 mm to 4,000 mm (MESTECC, 2018). During the southwest monsoon and the inter-monsoon periods, heavy rain from convective showers and thunderstorms occur in the late afternoons and evenings. Figure 9 shows the annual rainfall for Peninsular Malaysia from 1951 to 2015 (MESTECC, 2018). For this period, there is a very slight decreasing trend in the rainfall for Peninsular Malaysia. For a shorter time frame from 1990 onwards, increasing trends in rainfall are observed for Peninsular Malaysia.

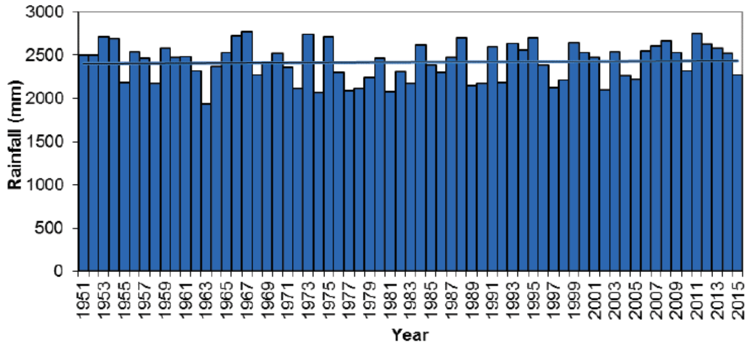



**Figure 9** Annual rainfall trends for Peninsular Malaysia, source: (MESTECC, 2018)

### 2.2.3 Weather in 2017

In 2017, the climate in Malaysia was greatly influenced by the natural climate variability due to normal weather conditions and neutral ENSO (Bahari et al., 2017).

ENSO index was neutral starting from January 2017 till the end of November 2017. A weak La Niña condition started in December 2017. Throughout 2017, Malaysia did not experience long-lasting hot and dry weather (Bahari et al., 2017). The haze phenomenon, drought, and heatwave also did not happen. Table 2 illustrates the period of seasons experienced in Malaysia in 2017.

**Table 2** Periods of seasons in Malaysia in 2017. Data derived from (Bahari et al., 2017)

| Seasons | Duration |
|---|---|
| Monsoon Transitional Period | April 2017 to 16th May 2017 |
| Southwest Monsoon | 17th May 2017 to 5th October 2017 |
| Monsoon Transitional Period | 6th October to 12th November 2017 |
| Northeast Monsoon | 13th November to 27th March 2018 |

In 2017, most of the stations recorded a consistent average wind speed compared to the long-term average (Bahari et al., 2017). Generally, throughout the year 2017, Malaysia has experienced normal weather and climate conditions.

## *2.3 UM WDR Gauge: Design and Installation*

As previously stated, to date WDR gauges have not been industrially produced; there are various types of gauges that researchers applying for their measurement purposes. Table 1 presented 7 types of WDR gauges with differences in shape, dimensions, material, function, and the accuracy of measurements.

The WDR gauge for this experimental study was manufactured at the University of Malaya (UM), Kuala Lumpur, Malaysia based on the gauge comparison results derived from the literature review and the goal of this research. In the study carried out by Blocken et al. (2005a) to design a WDR gauge, five possible error sources were presented. Table 3 shows the modifications and arrangements have been made to reduce errors and minimize the biases in the measurement process for the present experimental research:

**Table 3**. Possible error sources while designing WDR gauge and modifications to minimize

| No. | Possible error sources (Blocken et al., 2005a) | Modifications / Arrangements (by author) |
|---|---|---|
| **1** | adhesion-water evaporation | All parts of the gauge have been made of Acrylic sheets as an integrated device to promote water runoff. |
| **2** | evaporation from the reservoir | The bucket was covered with plastic between the upper cover and the bucket. |
| **3** | splashing of drops from the collection area | The catchment area is 20 x 20 $cm^2$, and the rime around it has a height of 3 cm to minimize splashing from in and out of the gauge. |
| **4** | condensation on the collection area | Measurement has been done right after the rain stopped. |
| **5** | wind errors | The rime height around the gauge has been increased by 1 cm compared to the EMPA gauge to decrease wind error. |

1. All parts of the WDR gauge collector at UM were made of a 10 mm Acrylic sheet and assembled heat pressing to avoid any drop leaking from the possible gaps. The material allows the rainwater drips down into the tube with the least possibility of water adhesion on the surface compared to the materials have been applied in the literature (Aluminium, Plate, Polytetrafluoroethylene, Stainless steel) and the size of collector area according to the recommendation by (Blocken et al., 2005a, 2005b, 2006a) was considered 20 x 20 cm2 to reduce the evaporation.
2. To minimize evaporation from the reservoir, it was covered by two layers: (1) a plastic layer from inside to avoid water absorption and ventilation (2) a square shape plywood surface from outside to avoid solar radiation losses.
3. The collection area is 20 x 20 cm2 to reduce the rate of water splashing because the bigger collector area the more rate of splashing error occurs. The height of rim around the collector area was increased 1 cm compared to the EMPA model to reach 3 cm height in order to minimize water splashing either from inside or outside the catchment area and also the possibility of entering water run-off from the surrounding area of the gauge.
4. The connector part to the tube has the same material as the collector and integrated to the collector via two internal slop surfaces. These surfaces allow the effective shedding of runoff rainwater from the catchment area into the tube and the reservoir respectively. The tube is a rubber-hose sealed from both external sides to the connector and the reservoir cover, and the reservoir is an ordinary bucket with a volume of 15 Litres. The length of the tube is at the shortest possible length located outside the building on the facade, buckets are also located outside the building along with the WDR gauges; in a tropical climate, normally there is no water freezing possibility even in the rainy days.
5. To reduce the wind error, (1) the area of the collector was designed at the practical minimum size based upon the previous studies, and (2) the height of rime around the gauge has been considered 3 cm (Figure 10).

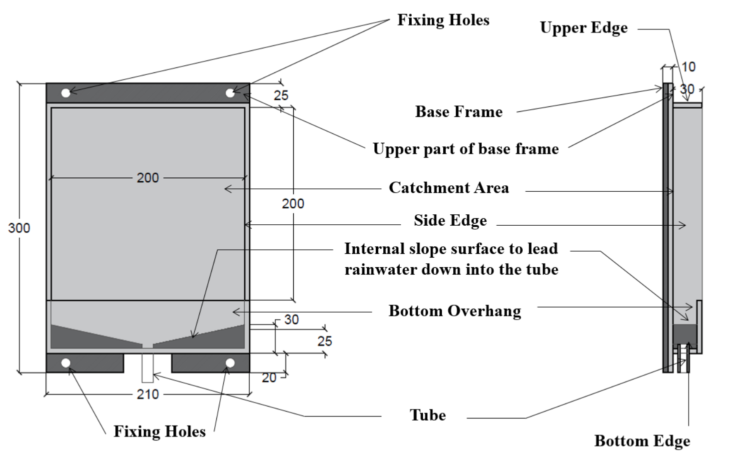



**Figure 10** Elevation and section of the WDR gauge collector. Dimensions (in mm).

## *2.4 Pilot Building and Building Site*

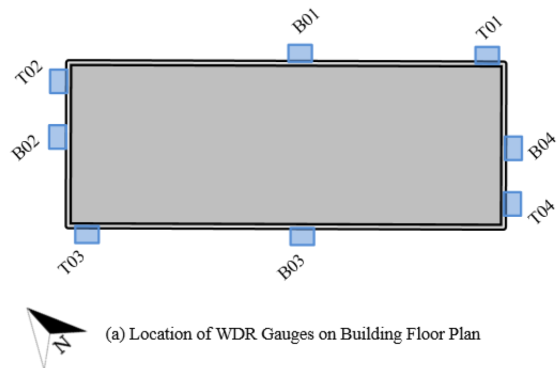
Figure 11 illustrates an aerial view of the measurement site. The building has dimensions L × W × H = 18.60 × 6.40 × 3.50 m3. The long side is facing the northeast and exposed to a downhill open space. The southwest side is facing a pilot parking lot at 13 m distance, on its southeast and northwest sides are open parking area and the closest adjacent buildings are at 19.50 m and 25.70 m distance respectively. Different types of adjacencies around the building have made it a favorable building for wind-driven rain measurement study at the campus in an urban area.


**Figure 11** Aerial view of the building site

## *2.5 Experimental Method*

### 2.5.1 WDR Measurement

Eight WDR gauges were installed on the facades of the pilot building at the campus of UM. The building is a flat-roof with no overhang. Kubilay et al. (2014) stated that the WDR distribution on the building facades shows the highest catch ratio values belonged to the top corners and the least values to the middle-lower two-third of the facade. Accordingly, the present study installed WDR gauges on 4 facades of the building; 2 on each facade; one on top corner edge (2.75 m height) and one on middle two-third of the facade height (1 m height) to receive and measure the maximum and minimum accumulated WDR impinged into the gauges (Figure 12). The amount of WDR was collected by the reservoirs were measured manually immediately after the rain stopped every day.



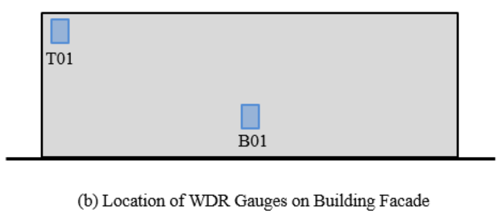




**Figure 12** The orientation of the pilot building and locations of the WDR gauges on the building: (a) Floor plan and (b) the facade (not to scale).

### 2.5.2 Meteorological Data Measurement

A meteorological mast was installed at 3.50 m height to measure the on-site wind direction, wind speed, and wind gust (Figure 13). Its location is at the nearest point to the building model and also out of the constant flux layers around the buildings in an open area to obtain the actual data recorded.

**Figure 13** The pilot building and position of the WDR gauges on the facades (a) South view (b) Meteorological mast on the roof of the building at the parking area.

## 3. Measurement Results

A year measurement was conducted and categorized during four periods of tropical seasons experienced in Malaysia based on Table 2 in 2017. The first period was from April to 16th May 2017 as the First Monsoon Transitional Period. The second period of measurement was from 17th May to 5th October 2017; Southwest Monsoon season, and the third period was from 6th October to 12th November 2017: the Second Monsoon Transitional Period. The fourth and last season of measurement was 13th November to 27th March 2018 as the Northeast Monsoon season.

Figure 14 illustrates an overview of 94 WDR events measured by 8 wall-mounted gauges (top corner and lower middle of the facades) over the 4 tropical seasons of Malaysia. As the annual report of UNFCCC (2015) on the rainfall trends in Kuala Lumpur declared that rain occurs mostly in the afternoons and evenings, in this study, nocturnal precipitation (12 a.m. to 6 a.m.) and also those diurnal accumulated precipitations with the amount of fewer than 1 ml were excluded from the record. The total duration of the monitored rain events over the 4 periods in this experimental research was 7115 minutes (~119 hrs.).

The following subsections consist of the meteorological data and cumulative WDR of each season period, categorized in 4 seasons. Each season is presented with (i) table of wind speed, wind direction, wind gust, rainfall duration time, horizontal rainfall, and rainfall intensity measured by the meteorological mast installed at the site, and (ii) graph of cumulative WDR manually measured by the 8 wall-mounted gauges installed on the building facades.

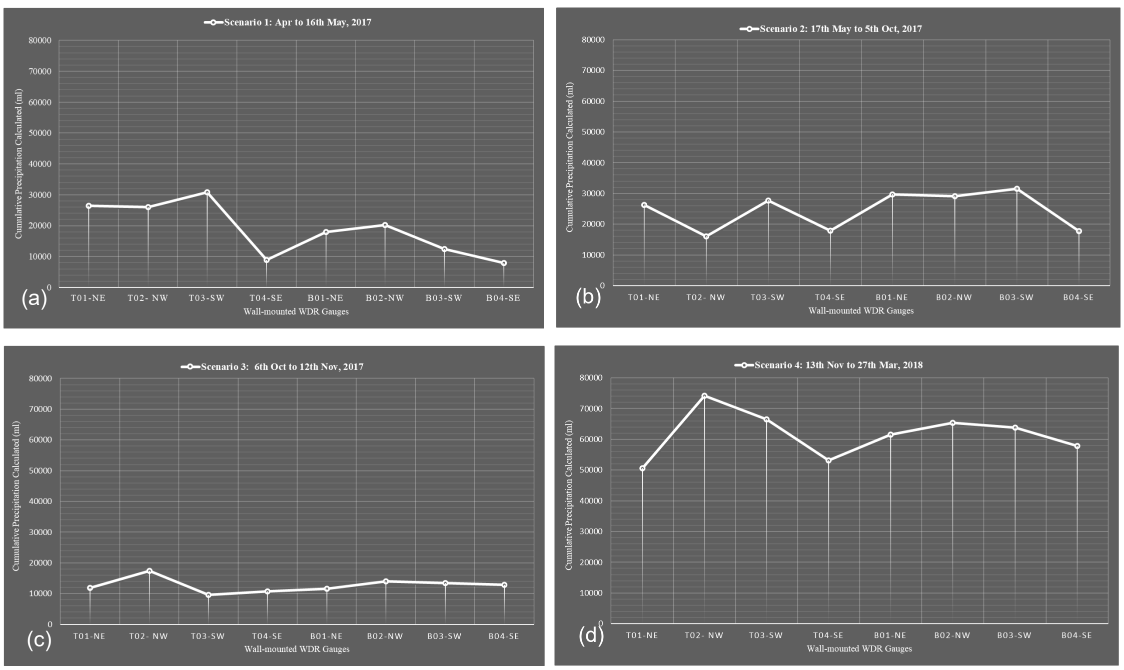



**Figure 14** Cumulative precipitation calculated on the basis of Season 1: April to 16th May 2017 (a), Season 2: 17th May to 5th October 2017 (b), Season 3: 6th October to 12th November 2017 (c), and Season 4: 13th November to 27th March 2018 (d).

### *3.1 Season 1: Monsoon Transitional Period; April to 16th May, 2017*

The meteorological data record of reference wind speed, reference wind direction, wind gust, horizontal rainfall intensity, and rainfall duration from April to 16th May 2017 during the daily rain events is shown in Table 4. The number of rainy days in this period is 14 days with a precipitation duration of 1210 minutes. The total horizontal rainfall amount is 35.72 mm, mostly less than 2 mm/hr, and only one occasion is reached 11.6 mm/hr. The wind speed fluctuating between 1-6 km/hr, the wind gust between 2-8 km/hr, and the wind direction is mostly west-southwest, almost normal to the building surface

**Table 4** The meteorological data record of Monsoon Transitional Period; April to 16th May 2017

| Date | Rainfall Duration Time (min) | Wind Speed (km/h) | Wind Direction | Wind Gust (km/h) | Horizontal Rainfall intensity (mm/hr) |
|---|---|---|---|---|---|
| 21-Apr-16 | 150 | 5 | WNW | 8 | 1.25 |
| 23-Apr-16 | 135 | 4 | W | 6 | 3.34 |
| 24-Apr-16 | 60 | 4 | SW | 5 | 4.7 |
| 25-Apr-16 | 20 | 5 | SE | 6 | 0.59 |
| 26-Apr-16 | 65 | 4 | SW | 5 | 2.1 |
| 28-Apr-16 | 30 | 6 | SW | 8 | 0.99 |
| 29-Apr-16 | 175 | 3 | ENE | 5 | 3.27 |
| 30-Apr-16 | 45 | 6 | NW | 8 | 1.33 |
| 2-May-16 | 60 | 5 | SW | 7 | 2.78 |
| 5-May-16 | 110 | 4 | NNE | 8 | 1.59 |
| 7-May-16 | 165 | 3 | WNW | 6 | 5.9 |
| 10-May-16 | 60 | 1 | WSW | 2 | 1.28 |
| 12-May-16 | 105 | 4 | NNW | 8 | 0.8 |
| 13-May-16 | 30 | 4 | WSW | 6 | 5.8 |

Figure 14(a) shows the cumulative precipitation calculated from 8 WDR gauges over 1st monsoon transitional period of the year. As the figure illustrates the gauges T03-SW among top gauges and the B02-NW among the bottom ones have received the highest amount of WDR; (i) the wind direction is mainly from west to southwest (ii) the longest duration of daily rainfall belongs to the events with north directions (T01-NE, T02-NW, B01-NE, B02-NW). The average wind speed for both SW and N directions is almost equal (Table 4).

### *3.2 Season 2: Southwest Monsoon; 17th May to 5th October, 2017*

The meteorological data record for the rain event on 17th May to 5th October 2017 is shown in Table 5. The number of rainy days in this period is 22 days with a precipitation duration of 1495 minutes. The total horizontal rainfall amount is 45.03 mm, mostly less than 2 mm/hr and a few occasions between 3 to 6 mm/hr intensity. This rain event has wind speed and a wind gust of more than 1.5 times the ones in the previous season; the wind speed fluctuating between 3-10 km/hr, the wind gust between 4-12 km/hr. The main wind direction in this season, as its name implies and the weather station was recorded, is west-southwest (Table 5).

Figure 14(b) illustrates the cumulative precipitation calculated from 8 WDR gauges over Southwest Monsson. As the figure illustrates the gauges T03-SW among top gauges and the B03-SW among the bottom ones have received the highest amount of WDR; (i) both from the southwest facade facing the prevailing wind direction of west to the southwest over this season.

**Table 5** The meteorological data record of Southwest Monsoon; 17th May to 5th October 2017

| Date | Rainfall Duration Time (min) | Wind Speed (km/h) | Wind Direction | Wind Gust (km/h) | Horizontal Rainfall Intensity (mm/hr) |
|---|---|---|---|---|---|
| 20-May-16 | 40 | 6 | SW | 7 | 1.37 |
| 23-May-16 | 25 | 7 | NNW | 8 | 0.66 |
| 25-May-16 | 25 | 5 | NNW | 8 | 2.39 |
| 3-Jun-16 | 80 | 6 | E | 4 | 2.72 |
| 9-Jun-16 | 90 | 7 | NW | 10 | 4.6 |
| 11-Jun-16 | 60 | 3 | WNW | 6 | 2.78 |
| 12-Jun-16 | 60 | 4 | NNE | 8 | 3.22 |
| 14-Jun-16 | 25 | 6 | WNW | 8 | 2.75 |
| 17-Jun-16 | 40 | 10 | ESE | 12 | 1.24 |
| 19-Jun-16 | 90 | 4 | NNE | 7 | 3.15 |
| 11-Jul-16 | 45 | 7 | WSW | 8 | 0.35 |
| 12-Jul-16 | 20 | 5 | SSW | 8 | 1.98 |
| 13-Jul-16 | 110 | 6 | WSW | 7 | 1.15 |
| 14-Jul-16 | 80 | 8 | SW | 10 | 0.16 |
| 20-Jul-16 | 75 | 7 | SSW | 8 | 0.39 |
| 21-Jul-16 | 90 | 7 | S | 8 | 0.85 |
| 22-Jul-16 | 90 | 7 | SW | 8 | 0.95 |
| 11-Aug-16 | 60 | 8 | WNW | 10 | 0.73 |
| 23-Aug-16 | 105 | 4 | WNW | 7 | 0.25 |
| 30-Aug-16 | 105 | 4 | ESE | 7 | 4.72 |
| 31-Aug-16 | 60 | 8 | SSW | 10 | 5.45 |
| 1-Sep-16 | 120 | 5 | SSW | 8 | 7.59 |

Note that, the average daily rainfall duration of this season (67 min) is lower than the season 1 (86 min), while its average horizontal rain (49.45 mm) is higher than season 1 (35.72 mm), and also its accumulated WDR amount (195,978 ml) is much higher than the season 1(150,489 ml). Consequently, even though the average rainfall duration is lower than the previous season but the wind speed has been stronger with more consistent wind direction and thus accumulated more horizontal and wind-driven rain over this season.

### *3.3 Season 3: Monsoon Transitional Period; 6th October to 12th November, 2017*

The meteorological data record for the rain event from 6th October to 12th November 2017 is shown in Table 6. The number of rainy days in this period is 13 days and the precipitation duration is 1090 minutes which are shorter than both previous seasons.

The total horizontal rainfall amount is 20.43 mm, mostly less than 1.5 mm/hr and only one occasion with 5 mm/hr intensity. This rain event has wind speed and a wind gust of even more than season 2; the wind speed fluctuating between 2-14 km/hr, the wind gust between 3-17 km/hr, but the horizontal rainfall amount is less than half of the season 2. This season is a shorter one, and more homogeneous in terms of wind speed values and wind directions; wind direction fluctuations display a more isotropic distribution (Table 6). During the first half (October), the wind speed is high and daily rainfall duration is low. In the second half (November), wind speed decreases, daily rainfall duration increases, and rainfall intensity is relatively higher and homogeneous. The wind direction is mostly from west fluctuating from Northwest in October to Southwest in November.

Figure 14(c) shows the cumulative precipitation calculated from 8 WDR gauges over the 2nd monsoon transitional period of the year. As the figure indicates the gauges T02-NW among the top gauges and the gauge B02-NW among the bottom gauges on the facade have collected the highest amount of WDR during this season. The figure also indicates there are not noticeable sharp differences between the rest of gauges in terms of accumulated WDR amount and the graph has a homogeneous trend in general

**Table 6** The meteorological data record of Monsoon Transitional Period; 6th October to 12th November 2017

| Date | Rainfall Duration Time (min) | Wind Speed (km/h) | Wind Direction | Wind Gust (km/h) | Horizontal Rainfall Intensity (mm/hr) |
|---|---|---|---|---|---|
| 12-Oct-16 | 40 | 14 | WNW | 17 | 0.58 |
| 16-Oct-16 | 75 | 12 | NW | 14 | 0 |
| 24-Oct-16 | 60 | 5 | NW | 10 | 0.11 |
| 25-Oct-16 | 30 | 11 | NW | 13 | 0.67 |
| 27-Oct-16 | 35 | 4 | W | 6 | 2.95 |
| 29-Oct-16 | 195 | 6 | WNW | 9 | 1.16 |
| 3-Nov-16 | 60 | 6 | W | 8 | 1.09 |
| 6-Nov-16 | 40 | 4 | W | 4 | 0.15 |
| 7-Nov-16 | 45 | 6 | WSW | 9 | 1.23 |
| 9-Nov-16 | 180 | 7 | SW | 8 | 4.41 |
| 10-Nov-16 | 120 | 4 | WSW | 7 | 3.76 |
| 11-Nov-16 | 150 | 2 | SW | 3 | 2.19 |
| 12-Nov-16 | 60 | 4 | WNW | 7 | 2.13 |

### *3.4 Season 4: Northeast Monsoon; 13th November to 27th March, 2018*

The meteorological data record for the rain event on 13th November to 27th March 2017 is shown in Table 7. The number of rainy days in this period is 44 days and the precipitation duration is 3845 minutes which are the highest compared to the previous 3 seasons of the year.

The total horizontal rainfall amount is 60.76 mm, mostly less than 1 mm/hr and a few occasions between 2 to 5 mm/hr intensity. Hence this season consists of average daily rainfall duration (87 min) almost the same as season 3 (83 min) but in the longest period (44 days and 3845 min) which resulted in a sharp increase in the amount of horizontal rainfall. This rain event has wind speed and a wind gust of about the same as season 3; the wind speed fluctuating between 1-13 km/hr, and the wind gust between 2-15 km/hr. The wind direction in this season, as its name implies and the weather station was recorded, is mostly northeast and northwest respectively and short periods switches to the southwest.

Figure 14(d) shows the cumulative precipitation calculated from 8 WDR gauges over the northeast monsoon period. The maximum annual precipitation duration along with the effective wind speed during this season leads to the highest cumulative WDR amount with the maximum difference compared to the previous seasons. However, the main wind direction is northeast but the gauges facing northwest and southwest (T02-NW, T03-NW, B02-SW) have accumulated more WDR amount during this season. Two factors have influenced this result; (i) the precipitation duration, and (ii) wind speed which have been more variable in terms of their values (Table 7) in contrary to the season 3 as the most homogeneous season.

**Table 7** The meteorological data record of Northeast Monsoon; 13th November to 27th March 2018

| Date | Rainfall Duration Time (min) | Wind Speed (km/h) | Wind Direction | Wind Gust (km/h) | Horizontal Rainfall Intensity (mm/hr) |
|---|---|---|---|---|---|
| 13-Nov-16 | 60 | 3 | N | 6 | 1.8 |
| 15-Nov-16 | 70 | 3 | S | 4 | 1.32 |
| 18-Nov-16 | 180 | 5 | NW | 8 | 6.24 |
| 24-Nov-16 | 45 | 1 | WSW | 2 | 3.43 |
| 25-Nov-16 | 135 | 4 | SSW | 4 | 1.1 |
| 27-Nov-16 | 150 | 2 | W | 3 | 3.4 |
| 28-Nov-16 | 120 | 3 | SW | 3 | 0.11 |
| 29-Nov-16 | 165 | 7 | NE | 12 | 1.42 |
| 1-Dec-16 | 50 | 3 | WNW | 5 | 0.56 |
| 2-Dec-16 | 105 | 5 | NW | 6 | 0.9 |

| | | | | | |
|---|---|---|---|---|---|
| 3-Dec-16 | 70 | 5 | NW | 7 | 1.23 |
| 9-Dec-16 | 35 | 2 | NW | 2 | 1.38 |
| 10-Dec-16 | 50 | 6 | NW | 8 | 1.23 |
| 13-Dec-16 | 60 | 13 | WNW | 15 | 0 |
| 17-Dec-16 | 90 | 3 | ENE | 5 | 4.44 |
| 19-Dec-16 | 55 | 7 | W | 9 | 2.53 |
| 25-Dec-16 | 100 | 5 | NE | 8 | 4.35 |
| 26-Dec-16 | 105 | 4 | NNE | 7 | 1.08 |
| 27-Dec-16 | 50 | 5 | ENE | 8 | 0.4 |
| 31-Dec-16 | 75 | 4 | NE | 6 | 0.03 |
| 3-Jan-17 | 80 | 5 | ENE | 11 | 1.02 |
| 17-Jan-17 | 90 | 4 | SW | 6 | 2.22 |
| 19-Jan-17 | 165 | 3 | SSW | 6 | 1.56 |
| 20-Jan-17 | 105 | 4 | WSW | 5 | 5.44 |
| 23-Jan-17 | 45 | 4 | NE | 7 | 0.05 |
| 24-Jan-17 | 30 | 4 | WNW | 6 | 2.84 |
| 25-Jan-17 | 40 | 4 | SSW | 5 | 2.16 |
| 26-Jan-17 | 50 | 1 | NE | 2 | 0.15 |
| 28-Jan-17 | 80 | 2 | WNW | 3 | 0.7 |
| 30-Jan-17 | 45 | 3 | SE | 3 | 0.38 |
| 4-Feb-16 | 175 | 3 | NW | 6 | 0 |
| 5-Feb-16 | 100 | 6 | SSW | 10 | 0.77 |
| 15-Feb-16 | 150 | 5 | ENE | 10 | 1.3 |
| 18-Feb-16 | 25 | 5 | E | 10 | 0 |
| 19-Feb-16 | 170 | 1 | ENE | 3 | 0.24 |
| 22-Feb-16 | 130 | 2 | ENE | 5 | 0 |
| 23-Feb-16 | 140 | 5 | NNE | 6 | 0.02 |
| 28-Feb-16 | 40 | 4 | NNE | 7 | 0.65 |
| 4-Mar-16 | 85 | 5 | NW | 10 | 0 |
| 8-Mar-16 | 55 | 3 | WNW | 5 | 0.44 |
| 10-Mar-16 | 20 | 5 | W | 6 | 0.33 |
| 13-Mar-16 | 150 | 2 | WSW | 3 | 2.66 |
| 15-Mar-16 | 45 | 5 | NNW | 6 | 0.88 |
| 16-Mar-16 | 60 | 5 | NNE | 7 | 0 |

## 4. Discussion

The building site enables this research to experiment 3 different adjacency to the pilot building, the windward facades has/have: (i) no adjacent building, facing a downhill; wind flows freely with no obstruction (NE facade), (ii) a one-story adjacent building (same height as the pilot building) at 19.50 m (SE facade) and 25.70 m distance (NW facade) in an open parking area; windflow obstructs slightly by other buildings and trees, (iii) a pilot parking of a 10-story adjacent building at 13 m distance; wind flows with more obstruction in presence of the tall building (SW facade). Since the aim of this study is quantifying WDR loads on vertical facades of the urban buildings as an alternative water resource in the RWH system, this variety of the surrounding areas provides a real scenario similar to an urban building location and orientation with different levels of adjacency of surrounding buildings and landscapes. The WDR database derived from this measurement provides a direct indication of WDR quantification loads on building facades as the scope of this paper, and also as a crucial requirement for the development and validation of models that will be addressed in future research topics.

Comparison between WDR distribution on the building facades and calculated cumulative precipitation in all 4 seasons (Table 8 & Figure 15) show:

i. The NE facade has almost always received a noticeable amount of WDR even when wind direction has not been aligned with the facade orientation such as during seasons 1 and 2. The reason is the location of this facade which is facing a downhill open space with no obstacle in the surrounding area to distract or decrease the wind direction or speed value.

ii. Comparison between WDR catch ratio values of the top and bottom gauges shows despite the expectations from previous studies that top corner gauges would collect higher amounts than the bottom middle ones (section 2.5.1), 3 out of 4 seasons the bottom middle ones have received a higher amount of WDR. Only over season 1, the top gauges received 33,615 ml more than bottom gauges (61%). However, over seasons 2, 3, and 4 the bottom gauges received respectively 20,318 ml (55%), 2,368 ml (51%), and 4,109 ml (50%) more than the top gauges.

iii. NW and SW are among the directions with the highest catch ratio values in almost all the seasons. According to the results, these two directions are considered as the prevailing wind directions with the largest wind speed values over a year.

iv. The 2nd transitional monsoon, season 3, with the minimum number of rainy days (13 days), and total horizontal rainfall (20.43 mm) has cumulated the lowest amount of WDR (101,428 ml). This season is the shortest event (1090 min) with the most homogeneous flow of the wind in direction, velocity, and rainfall intensity (Table 8).

v. Northeast monsoon, season 4, with the maximum number of rainy days (44 days), highest average daily rainfall duration time (87.38 min) and total horizontal rainfall (60.76 mm) has remarkably cumulated the highest amount of WDR (493,065 ml), more than twice-fifth times each of the other three seasons (Table 8).

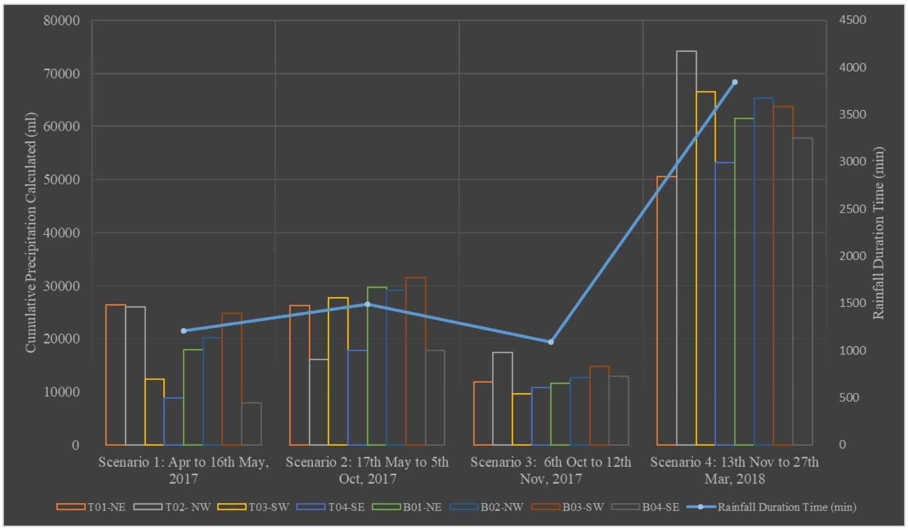



**Figure 15** 12 months measurements of WDR (ml) of 93 events divided into 4 tropical seasons by 8 wall-mounted gauges; installed on the top corner and lower middle of the facades (April 2017 - March 2018)

**Table 8** Seasonal variation of meteorological data derived from the mast and WDR gauges of 83* events (April 2017 - March 2018)

| Seasons Over A Year | Horizontal Rainfall Intensity $R_h$ (mm/hr) | $R_h^{0.88}$ | Wind Speed U (m/s) | $B \times H \times U \times R_h^{0.88}$ | In-situ Cumulated WDR (mm/hr) | Constant $\gamma$ |
|---|---|---|---|---|---|---|
| Season 1: Apr to 16th May, 2017 | 29.74 | 19.80 | 1.23 | 7.79 | 7.27 | 0.93 |
| Season 2: 17th May to 5th Oct, 2017 | 48.21 | 30.28 | 1.64 | 15.89 | 7.70 | 0.48 |
| Season 3: 6th Oct to 12th Nov, 2017 | 16.23 | 11.61 | 1.36 | 5.05 | 3.68 | 0.73 |
| Season 4: 13th Nov to 27th Mar, 2018 | 54.49 | 33.72 | 1.10 | 11.87 | 7.58 | 0.64 |

*All variables were subjected to the normality test (through IBM SPSS Statistic 26 software)

### *4.1 Application Of Empirical Equation To Validate The Measured Data*

As Blocken et al. (2005b) stated that experimental data are used for model development and validation, in this section the in-situ measurement data collected in 4 tropical seasons are exploited to determine WDR coefficient ($\gamma$) to estimate the amount of WDR on a building façade via an empirical WDR relationship. WDR relationships are frequently used as a tool to calculate WDR amount on building facades (Blocken et al., 2004, 2005b). In this study, the equation that has been developed by Cho et al. (2020) will be referred to:

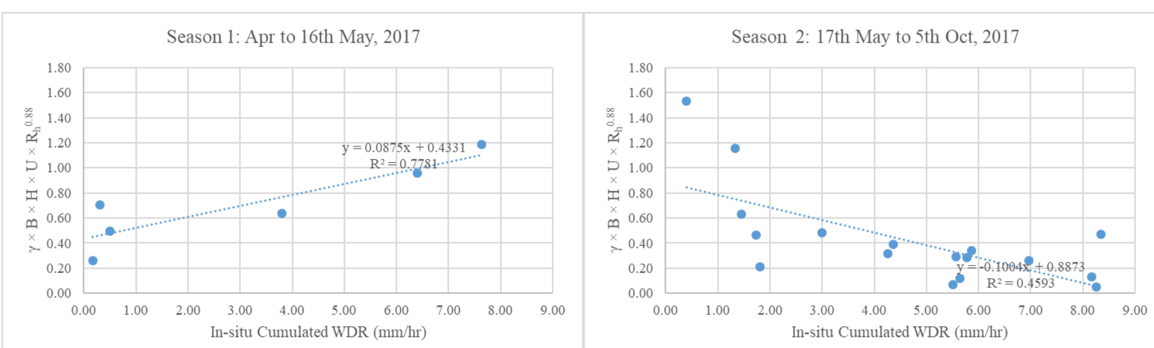
$$Q = \gamma \times B \times H \times U \times R_h^{0.88} \quad \text{Equation 1}$$

where Q is the sum of rainfall over the building façade (WDR), constant γ is the WDR coefficient, B and H represent the building width (m) and height (m) respectively, U is the horizontal wind speed (m/s), $R_h$ is the rainfall intensity (mm/hr). WDR rain equation globally is used not only to calculate WDR amount but also a wide range of Heat-Air-Moisture (HAM) transfer simulation programs (Blocken et al., 2005b) and also the European Standard Draft (CEN, 1997) have employed it in their calculation and assessment processes.

The constant γ is determined from hourly measurements of wind speed, horizontal rainfall intensity, area of WDR gauges, and WDR collected from in-situ measurement. Table 7 shows the total amount of WDR collected by 8 gauges in 4 different tropical seasons. The constant γ was calculated by comparing $B \times H \times U \times R_h^{0.88}$ value with cumulated in-situ WDR amount. Due to unique rainfall and wind patterns in the tropical climate, the calculation process has been conducted individually for each season and as indicated in the table the values differ from 0.48 to 0.98. In the literature, the minimum value for constant γ has been calculated as 0.02 by Lacy (1965) and Hens et al. (1994), and maximum as 0.26 by (Flori, 1992). According to the literature, the calculated values of γ in this study can be considered significantly high. The correlation between observed and calculated WDR amounts in all seasons also illustrate low R-squared values (Figure 2) ranging from 0.17 to 0.77. But the reasons for these high γ and low $R^2$ values could be explained by potential sources/possibilities affecting the values in this particular climate:

- Constant γ in equation 1 which has been developed under lab-observations (Cho et al., 2020), is a function of time, due to its dependency on wind speed, wind direction, and also rainfall intensity (Blocken et al., 2006b), and in a real measurement it is difficult to define particular values for the aforementioned parameters.
- Errors in observation are variable in time, particularly in heavy or prolonged precipitation which are main characteristics of tropical rainfall pattern; it has been illustrated in the data record of season 4 (Table 6) comprising the highest numbers of daily long-term precipitations (mostly more than one hour) and lowest $R^2$ value of 0.17 accordingly (Figure 2). However, this equation has been developed to estimate WDR amounts based on the hourly experimental data for U and $R_h^{0.88}$.
- Another parameter affecting the amount of WDR impinged on the wall in reality, is the wind guest speed which has not been considered in the equation, while makes a significant impact on the discrepancies between observed and calculated values.
- Equation 1 has considered all 4 walls of the typical building equally to estimate the amount of impinged WDR, however in reality WDR impinged on one or two façade(s) at a particular time based on the fluctuation of wind direction and also the orientation of the exposed walls.
- Therefore, the constant γ, in this study can be referred to as approximate estimation.

As a result and as Figure 16 clarifies the real-time variation of the constant γ and the in-situ measurement errors have resulted in the low $R^2$ values which indicates a low correlation between observed and calculated amounts of WDR. Seasons with larger rainfall durations such as seasons 2 and 4 have been encountered with more discrepancies. And on the other hand, seasons 1 and 3 claim that the equation and constant γ can be considered a valid tool to estimate the amount of WDR.



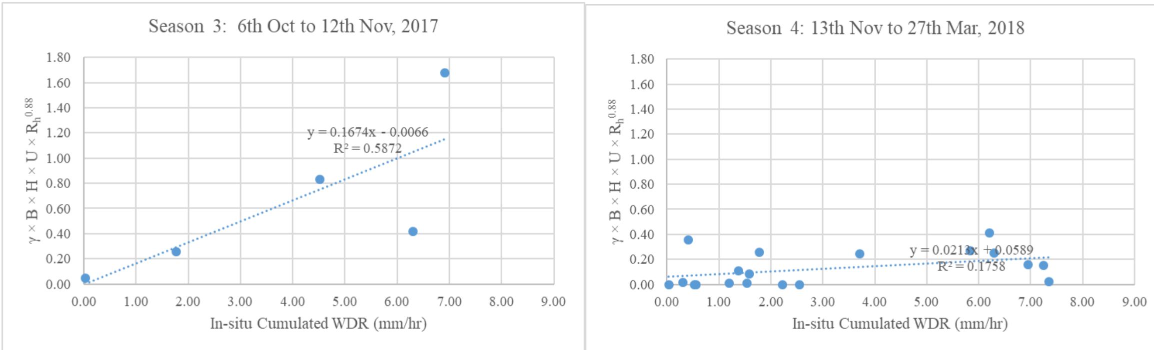



**Figure 16** Determination of R-squared value ($R^2$) of in-situ cumulated WDR and calculated WDR correlation based on equation 1 for each of 4 tropical seasons

In lab-observation, lower discrepancies are recorded, but as Blocken et al. (2005b) stated in reality [such as this study], larger discrepancies are unavoidable. Further research will specifically focus on the performance of this equation on each building façade in shorter periods of precipitation.

## 5. Conclusion

This research followed principles of the WDR field measurement method in building science. The WDR measurement was conducted on a single story pilot building in the tropical climate of Kuala Lumpur. The building was instrumented with 8 WDR gauges; 2 on each facade. This paper presented the principle guidelines to design and manufacture the gauge, description of the building, surrounding area, results of the one-year measurement of meteorological data and WDR, and also an empirical equation to validate the data. Topography and monsoon winds as the main factors impact the flow of the wind direction and velocity and consequently the WDR loads on building facade. However, the effectiveness of the wind depends on the monsoon characteristics which are not constant and vary in different seasons, but some seasons are individually nearly homogeneous. This character of the wind plays an important role in applicability of the equation because it directly affects the constant $\gamma$ value. Although 93 rain events data during one-year have been measured, but after data processing and normalization test (through IBM SPSS Statistic 26 software) prior to determine the constant $\gamma$, 10 events were excluded. And to calculate $R^2$ also only 43 events were considered as normal values for calculations based on normality test results.

It must be noted that wind guest speed which is mostly higher than wind speed in this climate as can be seen in tables 4-7, has a major contribution to the amount of cumulated WDR but has not been considered in the equation. It is necessary to assess and analyze its influence as another independent value in the calculation of WDR in future studies.

Referring to the lab-experiment by Cho et al. (2020), building walls can collect 50% more rainwater than roof area if the wall/roof ratio is only one, and when the ratio is 10 the amount of cumulated rainwater is higher even if the wind speed would be 1 m/s. On the other hand, as mentioned previously roof areas are no longer available in modern urban areas for the RWH system.

In this regard, the current real-time measurement from the vertical building façades proved the high potential and feasibility of WDR collection as an alternative water resource for the RWH system. 8 WDR gauges (8 × 0.04 $m^2$) were installed on 4 different facades and collected 26.23 mm/hr rainwater; which is equivalent to about 2,600 liters/$m^2$/year from building facade. According to the Malaysian Water Association (MWA, 2018), Malaysia needs to reduce its high water-usage (201 liters/capita/day) by 18% to reach the recommended water-usage by World Health Organization (WHO), i.e. 165 liters/capita/day. On the other hand, Bari et al. (2015) survey results revealed that 29% of household water consumption accounts for non-potable activities (toilet flushing and gardening). In conclusion, each square meter of vertical façade area has the capability to supply 12% of non-potable or 4.9% of potable water-usage per capita per day in the tropical climate of Malaysia.

The authors hope the present paper will stimulate further attempts in academia to promote industry's interest in vertical RWH from facades of growing high-rise buildings in urban areas as a new and more effective approach to harvest rainwater in comparison with the traditional horizontal RWH from rooftop or ground surfaces.

## Acknowledgement

This work was supported by the Institute of Research Management & Services (IPPP), Research Management & Innovation Complex, University of Malaya, Kuala Lumpur, Malaysia [grant number: RG317-14AFR].

## References

Adriano, T. E., Antonio, E. M., Rodolfo, G. N., & Mme. (2011). Rainwater Harvesting, Quality Assessment And Utilization In Region I E-International Scientific Research Journal 3(2), 145-155. http://www.eisrjc.com/documents/Rainwater_Harvesting_1325914607.pdf

Back, L. E., & Bretherton, C. S. (2005). The relationship between wind speed and precipitation in the Pacific ITCZ. *Journal of climate, 18*(20): 4317-4328. doi:https://doi.org/10.1175/JCLI3519.1

Bahari, Y. A. b., Pengarah, K., & Malaysia, J. M. (2017). Jabatan Meteorologi Malaysia, Annual Report 2017. Malaysia: Jabatan Meteorologi Malaysia Retrieved from https://www.met.gov.my/content/pdf/penerbitan/laporantahunan/laporantahunan2017.pdf. Retrieved on 17/02/2020

Bari, M., Begum, R. A., Nesadurai, N., & Pereira, J. J. (2015). Water consumption patterns in greater Kuala Lumpur: potential for reduction. *Asian Journal of Water, Environment and Pollution, 12*(3): 1-7.

Beorkrem, C., & Damiano, A. (2018). [Kak-Tos]: A Tool for Optimizing Conceptual Mass Design and Orientation for Rainwater Harvesting Facades *Humanizing Digital Reality* 603-612. Springer.

Blocken, B., & Carmeliet, J. (2004). A review of wind-driven rain research in building science. *Journal of Wind Engineering and Industrial Aerodynamics 92*: 1079–1130. doi: https://doi.org/10.1016/j.jweia.2004.06.003

Blocken, B., & Carmeliet, J. (2005a). *Guidelines for wind, rain and wind-driven rain measurements at test-building sites*. Paper presented at the Proceedings of the 7th Symposium on Building Physics in the Nordic Countries:Reykjavik.https://research.tue.nl/en/publications/guidelines-for-wind-rain-and-wind-driven-rain-measurements-at-tes

Blocken, B., & Carmeliet, J. (2005b). High-resolution wind-driven rain measurements on a low-rise building—experimental data for model development and model validation. *Journal of Wind Engineering and Industrial Aerodynamics, 93*(12): 905-928. doi: https://doi.org/10.1016/j.jweia.2005.09.004

Blocken, B., & Carmeliet, J. (2006a). On the accuracy of wind-driven rain measurements on buildings. *Building and Environment, 41*(12): 1798-1810. doi:https://doi.org/10.1016/j.buildenv.2005.07.022

Blocken, B., & Carmeliet, J. (2006b). On the validity of the cosine projection in wind-driven rain calculations on buildings. *Building and Environment, 41*(9): 1182-1189.

Camerlengo, A., & Demmler, M. I. (1997). Wind-driven circulation of peninsular Malaysia's eastern continental shelf. *Scientia Marina, 61*: 203-211. doi: http://scimar.icm.csic.es/scimar/pdf/61/sm61n2203.pdf

Canavan, D. H. (2008). Facade rainwater harvesting system: Google Patents.

CEN. (2009). Hygrothermal performance of buildings Climatic data Part 3: calculation of a driving rain index for vertical surfaces from hourly wind and rain data. Retrieved from https://www.sis.se/api/document/preview/910850/.Retrieved on 15/01/2020

Cho, E., Yoo, C., Kang, M., Song, S.-u., & Kim, S. (2020). Experiment of wind-driven-rain measurement on building walls and its in-situ validation. *Building and Environment, 185*: 107269. doi:https://doi.org/10.1016/j.buildenv.2020.107269

Connor, R. (2015). *The United Nations world water development report 2015: water for a sustainable world* (9231000713). Retrieved from https://sustainabledevelopment.un.org/content/documents/1711Water%20for%20a%20Sustainable%20World.pdf

Dobravalskis, M., Spūdys, P., Vaičiūnas, J., & Fokaides, P. (2018). Potential of harvesting rainwater from vertical surfaces. *Journal of Sustainable Architecture and Civil Engineering, 23*(2): 49-58. doi:https://doi.org/10.5755/j01.sace.23.2.21606

FJR van Mook. (2002). *Driving rain on building envelopes* (906814569X). Retrieved from Eindhoven University Press, Eindhoven, The Netherlands: http://fabien.galerio.org/drivingrain/fjrvanmook2002/

Flori, J. (1992). *Influence des conditions climatiques sur le mouillage et le sechage d'une facade verticale*: CSTB.

Foroushani, S. S. M. (2013). A Numerical Study Of The Effects Of Overhangs On The Wind-Driven Rain Wetting Of Building Facades. (Master), Ryerson University, Toronto, Ontario, Canada. https://doi.org/10.1016/j.jweia.2013.10.007

Hafizi Md Lani, N., Yusop, Z., & Syafiuddin, A. (2018). A review of rainwater harvesting in Malaysia: Prospects and challenges. *Water, 10*(4): 506. doi:https://doi.org/10.3390/w10040506

Hens, H., & Ali Mohamed, F. (1994). Preliminary results on driving rain estimation, Contribution to the IEA annex 24, Task 2 Environmental conditions T2-B-94/02. Retrieved from https://lib.ugent.be/en/catalog/rug01:000697882. Retrieved on 20/03/2021

Hogberg, A. (1998). *Microclimate description: to facilitate estimating durability and service life of building components exposed to natural outdoor climate*: Chalmers University of Technology.

Hogberg, A. (1999). *Microclimate measurement focused on wind-driven rain striking building surfaces.* Paper presented at the Proc. of the 5th Symp. on building physics in the Nordic Countries, Gothenburg.

Hogberg, A. (2002). *Microclimate Load: Transformed Weather Observations for Use in Durable Building Design*: Department of Building Physics, Chalmers University of Technology.

Hogberg, A., Kragh, M., & van Mook, F. (1999). *A comparison of driving rain measurements with different gauges*. Paper presented at the P*roceedings of the 5th Symposium of building physics in the Nordic Countries, Gothenburg.* http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.606.3604&rep=rep1&type=pdf

Juneng, L., Tangang, F., & Reason, C. (2007). Numerical case study of an extreme rainfall event during 9–11 December 2004 over the east coast of Peninsular Malaysia. *Meteorology and Atmospheric Physics, 98*(1-2): 81-98. doi:https://doi.org/10.1007/s00703-006-0236-1

Kragh, M. K., & Svendsen, S. (1998). Microclimatic conditions at the external surface of building envelopes. (Ph. D), Technical University of Denmark. Retrieved from https://core.ac.uk/download/pdf/13738237.pdf. Retrieved on 22/02/2017

Kubilay, A., Derome, D., Blocken, B., & Carmeliet, J. (2014). High-resolution field measurements of wind-driven rain on an array of low-rise cubic buildings. Building and Environment, 78: 1-13. doi:https://doi.org/10.1016/j.buildenv.2014.04.004

Lacy, R. (1965). Driving-rain maps and the onslaught of rain on buildings. Paper presented at the 2nd International CIB/RILEM Symposium on moisture problems in Buildings, August 16-19, 1965, Helsinki, Finland.

Lade, O., & Oloke, D. (2015). Modelling Rainwater System Harvesting in Ibadan, Nigeria: Application to a Residential Apartment. *American Journal of Civil Engineering and Architecture, 3*(3): 86-100. doi:10.12691/ajcea-3-3-5 http://pubs.sciepub.com/ajcea/3/3/5

Lim, E., Das, U., Pan, C., Abdullah, K., & Wong, C. (2013). Investigating variability of outgoing longwave radiation over peninsular Malaysia using wavelet transform. *Journal of Climate, 26*(10): 3415-3428. doi:https://doi.org/10.1175/JCLI-D-12-00345.1

Masters, F. J., Gurley, K. R., Prevatt, D. O., Rivers, B., & Kiesling, A. (2013). Wind-Driven Rain Effects on Buildings, Task Committee on Wind-Driven Rain Effects, Environmental Wind Engineering Committee, Technical Council on Wind Engineering, ASCE (12-00005-00). Retrieved from http://www.floridabuilding.org/fbc/commission/FBC_0613/HRAC/2012_2013_Task_3_Final_Report.pdf. Retrieved on 15/01/2017

MESTECC. (2018). Malaysia's Third National Communication and Second Biennial Update Report submitted to the United Nations Framework Convention on Climate Change in September 2018. Putrajaya, Malaysia: Ministry of Energy, Science, Technology, Environment and Climate Change Retrieved from https://unfccc.int/sites/default/files/resource/Malaysia%20NC3%20BUR2_final%20high%20res.pdf. Retrieved on 16/03/2020

MWA. (2018). Malaysia Water Industry Guide. Retrieved from The Malaysian Water Association, Kuala Lumpur, Malaysia: Retrieved on 22/03/2021

SDI. (2003). *A Study on Preventing Flood Damage and Water Saving through Rainwater Utilization*. Seoul Development Institute, Seoul, Korea.

Silva, C. M., Sousa, V., & Carvalho, N. V. (2015). Evaluation of rainwater harvesting in Portugal: Application to single-family residences. *Resources, Conservation and Recycling, 94*: 21-34. doi:https://doi.org/10.1016/j.resconrec.2014.11.004

Suhaila, J., & Jemain, A. A. (2009). Investigating the impacts of adjoining wet days on the distribution of daily rainfall amounts in Peninsular Malaysia. *Journal of Hydrology, 368*(1-4): 17-25. doi:https://doi.org/10.1016/j.jhydrol.2009.01.022

Tan, K. C. (2018). Trends of rainfall regime in Peninsular Malaysia during northeast and southwest monsoons. *Journal of Physics: Conference Series, 995*(1): 012122. doi:https://doi.org/10.1088/1742-6596/995/1/012122

Tangang, F. T. (2001). Low frequency and quasi-biennial oscillations in the Malaysian precipitation anomaly. *International Journal of Climatology: A Journal of the Royal Meteorological Society, 21*(10): 1199-1210. doi:https://doi.org/10.1002/joc.676

UNFCCC. (2015). Malaysia National Communication to The UNFCCC. Putrajaya, Malaysia: Ministry Of Natural Resources And Environment Malaysia Retrieved from https://unfccc.int/resource/docs/natc/malnc2.pdf.Retrieved on 22/03/2021

Van Mook, F. (1998). Description of the measurement set-up for wind and driving rain at the TUE. Report FAGO, 98, 44. https://www.persistent-identifier.nl/urn:nbn:nl:ui:25-f00fc883-07f8-4d9d-873e-e898d80750f1

Wong, C., Liew, J., Yusop, Z., Ismail, T., Venneker, R., & Uhlenbrook, S. (2016). Rainfall characteristics and regionalization in Peninsular Malaysia based on a high resolution gridded data set. *Water, 8*(11): 500. doi:https://doi.org/10.3390/w8110500

Wu, W., Dandy, G. C., Maier, H. R., Maheepala, S., Marchi, A., & Mirza, F. (2017). Identification of optimal water supply portfolios for a major city. *Journal of water resources planning and management, 143*(9): 05017007.

WWAP. (2019). The United Nations World Water Development Report 2019: Leaving No One Behind. Retrieved from https://reliefweb.int/sites/reliefweb.int/files/resources/367306eng.pdf12/04/2020

IJBES

International Journal of Built Environment and Sustainability
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 47-61

# The Impact of the COVID-19 on the Construction Industry in Vietnam

**Van Tam Nguyen**
Faculty of Construction Economics and Management, National University of Civil Engineering, Hanoi, Vietnam

**Bao Ngoc Nguyen, Toan Quoc Nguyen, Anh Tung Chu**
Faculty of Construction Economics and Management, National University of Civil Engineering, Hanoi, Vietnam

**Hai Tuan Dinh**
Faculty of Urban Management, Hanoi Architectural University, Hanoi, Vietnam

**ABSTRACT**

The COVID-19 pandemic has generated a wide range of socio-economic disruption, which causes devastating in numerous aspects. Our knowledge of the true health of the construction industry under the ravage of COVID-19 outbreak is largely based on very limited data. This study aims to assess the impact of pandemic on the construction industry through an investigation in Vietnam. Data were collected through 129 respondents whose online questionnaire survey completed according to their recent direct or indirect participation in delivering construction projects during the spread. The implications of COVID-19 on the construction industry were examined based on simple percentage analysis and Relative Importance Index approaches. Three principal facets of the construction industry were considered: firms' business activities, project performance, and workforce demand. The findings highlighted the multilevel, multidimensional nature of the epidemic consequences on the construction sector. Notably, the revenue and profitability, in a general sense, have decreased during the COVID-19 period, while most of the production and business costs had remained unchanged. Further, the pandemic was argued to impair construction practitioners' incomes and mental health and sabotage projects' schedule and cost.

**Article History**

Received: 12 January 2021
Received in revised form: 31 March 2021
Accepted: 17 May 2021
Published Online: 31 August 2021

**Keywords:**

Covid-19, construction industry, performance, impact, developing countries, Vietnam

**Corresponding Author Contact:**

ngocnb@nuce.edu.vn

**DOI:** 10.11113/ijbes. v8. n3.745



## 1 Introduction

It is the beginning of 2021, but the world is more uncertain than ever. At the beginning of the year 2020, many people expected a plump 2020 number to bring more confidence and optimism than 2019, a year full of changes. However, the reality has proved fierce. The Covid-19 pandemic, as of this writing, has caused nearly 40 million infections, more than 1 million 113,000 deaths in 235 countries, areas, or territories (The World Health Organization, 2020). The World Bank asserted that the Covid-19 pandemic had caused the most profound global crisis in decades, and the final consequences are still ambiguous (The World Bank Group, 2020). Accordingly, a minimum of 5.2% of the global economy will be in decline. The vast majority of emerging markets and developing economies will decline because of the pandemic, and it will also cause lasting damage to labour productivity and potential output. The latest data shows that the global economic recovery has slowed down, although there have been signs of improvement since the middle of this year (The World Bank Group, 2020). As noted by PricewaterhouseCoopers (2020), the Covid-19 outbreak has brought unprecedented challenges, which are expected to have a significant impact on Vietnam's economic development this year. The building sector, as opposed to other sectors, saw 4.5% growth in the first six months of the year, slightly higher than the

4.37% in the first quarter and yet lower than the 7.85% growth during the same period last year, showing that the industry is sluggish and reluctant in its recovery (Can, 2020).

Covid-19 has become a hot topic and has attracted much attention from the academia. In addition to the medical studies of Covid-19, researchers worldwide have proved responsive to academic publications upon the impact of Covid-19 on multiple areas. For example, education (Daniel, 2020), gender equality (T. M. Alon, M. Doepke, J. Olmstead-Rumsey, & M. Tertilt, 2020), small business outcomes (Bartik et al., 2020), strategies for mitigation and suppression (Walker et al., 2020), and refugee camps (Truelove et al., 2020). Multiple studies have been undertaken and published on built environment domain, but not as many as those in other areas. On the other hand, many authors, e.g. (Loayza & Pennings, 2020), (Ataguba & Ataguba, 2020), (Gerard, Imbert, & Orkin, 2020), claimed that the crisis could even be worse in low-income countries. Despite being a developing country with a high poverty rate, Vietnam is coping very well with the pandemic (P. L. Dinh & Ho, 2020; Le et al., 2020). Scholars and systematic assessments are essential as they will help stakeholders grasp the situation and impacts of the Covid-19 outbreak on socio-economic development (H. H. Dinh, 2020). This paper will draw an overall picture of Covid-19 and Vietnamese construction industry's performance, revealing the patterns of the professionals' thinking in the pandemic context. Considering the global spread of the coronavirus and the economic contractions, the empirical evidence in Vietnam is expected to yield valuable insights for other countries and regions to gain a solid recovery.

The goal of this study assessed the impact of the Covid-19 pandemic on construction activities through data collected in an investigation in Vietnam.
Accordingly, research objectives were specified as follow:

- To determine the aspects of the construction industry that have been impacted by the Covid-19 pandemic.
- To evaluate the impact of the Covid-19 pandemic on business activities of construction enterprises.
- To evaluate the impact of the Covid-19 pandemic on the construction workforce.
- To evaluate the impact of the Covid-19 pandemic on the performance of construction projects.
- To recommend measures against the negative effect of the Covid-19 pandemic on the construction industry.

## 2 Background of the study

COVID-19 and its variants will trigger waves of crisis over the coming months or worse, possibly for several years. The world, having said that, must adjust in order to accept this, as it would necessitate the transformation to the new normal (Välikangas & Lewin, 2020). We need to increase our ability to update and adapt to a continually changing situation in a way that has never been seen before. The Vietnamese government is in excellent control of the epidemic. However, its intervention has been widely criticised for the lack of systematicity and intensity (H. H. Dinh, 2020; Le et al., 2020). The number of deaths of COVID-19 is worrying, and this positively affects the mental health of the citizens such as anxiety over the unstable job, job loss, income reduction or even death (Gruber et al., 2020; Otu, Charles, & Yaya, 2020). Until the world fights Covid-19, the topic of the epidemic/pandemic's impact on economic sectors has not been particularly appealing to scholars. The world in the past few decades, on account of the development of medical science, has been free from fear and concern for pandemics (Burkle, 2020; Lum & Tambyah, 2020). There have been also many opinions that people, including scholars, show disregard for the impact of diseases on industries (Dixon, McDonald, & Roberts, 2002; Karlsson, Nilsson, & Pichler, 2014). Nevertheless, some epidemics/pandemics were significantly examined in association with industries' performance (see Table 1).

**Table 1** Scholarly interests in epidemic/pandemic impact on industries before Covid-19

| Epidemic/pandemic | Industry that was impacted | References |
|---|---|---|
| Influenza | Mining | (Phimister, 1973), |
| | Poultry | (Obayelu, 2007) |
| | Health Insurance | (Jim Toole & CERA, 2010) |
| | Tourism | (Page, Yeoman, Munro, Connell, & Walker, 2006), (Rassy & Smith, 2013), (Page & Yeoman, 2007) |
| | Finance | (Maldin et al., 2005) |
| HIV/AIDS | Construction | (Meintjes, Bowen, & Root, 2007), (Bowen, Dorrington, Distiller, Lake, & Besesar, 2008), (Harinarain & Haupt, 2014) |
| | Mining | (Matangi, 2006) |
| | Tourism | (Zengeni & Zengeni, 2012) |
| Generic | Oil and gas | (Flynn, Kaitano, & Bery, 2012) |

Using institutional audit methodology, Meintjes et al. (2007) drew our attention to the burden of HIV/AIDS pandemic on the South African construction industry. The most significant and most visible impact is the cost increase, i.e. increased financial outlays and decreased productivity. The measures, especially from the CIDB side, had been available, but were not practical and even caused many concerns. In the same vein, Bowen et al. (2008) adopted a quantitative approach pointed out the high prevalence of the virus in the workforce and its correlation with the South African construction industry structure. The findings from this study suggest that the high HIV/AIDS prevalence rate can have a deleterious effect on not only the construction industry but the South African economy as well. The meagre number of published studies in this theme, to a certain extent, reflects the ambiguous and loose link between the construction industry and the epidemiology.

As McGrail, Rickard, and Jones (2006) argue: 'There is often a long period from manuscript commencement to submission, revision, acceptance and, finally, publication.' Not to mention, in construction management research, the methods used in data collection such as interviews, focus groups and questionnaires are considered very time-consuming (Alshenqeeti, 2014; Gill, Stewart, Treasure, & Chadwick, 2008; MacLean, Meyer, & Estable, 2004). It seems that publishing in the construction sector has not been as fast and responsive as some other fields. Drawing on a case study of the ultra-rapid delivery of speciality field hospital, Luo, Liu, Li, Chen, and Zhang (2020) provide an in-depth analysis of the synthesis of product, organisation, and process (POP) approach and building information modelling (BIM). Megahed and Ghoneim (2020), at the same time, highlight the need to envision in what shape post-disaster architecture and antivirus cities might be. From a legal perspective, Hansen (2020) explores the potential of the Covid-19 outbreak as a force majeure in popular suites of a construction contract, i.e. NEC, JCT and FIDIC. Both Megahed and Ghoneim (2020) and Hansen (2020) adopted document review, former one exposing lessons in architecture and urban development, whereas the latter offers legal advice upon pandemic-related force majeure.

Meanwhile, Araya (2020) using agent-based modelling approach looks into the impact of the outbreak on construction project, stimulating the spread of COVID-19 among workers. In a similar vein, Afkhamiaghda and Elwakil (2020) propose a preliminary model and set of indexes of coronavirus spread into the construction site and workforce, implicating the urgency to diffuse cutting-edge technologies (e.g. Internet of Things, robotics). These studies, while both using the context of construction industry in a pandemic situation, delved into very different themes using distinct methods. Several studies have attempted to investigate the impact of COVID-19 on the local and regional construction industry. The reviews are not yet adequate due to the uncertainty of the current situation (Gamil & Alhagar, 2020). Bsisu (2020) investigates the impact of COVID-19 pandemic on Jordanian civil engineers and construction industry. Taken together, these findings would seem to suggest that engineering designers could work from home with reasonable performance. In contrast, site engineers do not believe that after the lockdown is lifted, construction workers will adhere to social distancing and wear essential personal protective equipment. Gamil and Alhagar (2020) claim that the most prominent impacts of Covid 19 are the suspension of projects, labor impact, job loss, time overrun, cost overrun, and financial implications. The findings shed light on the consequences of the sudden pandemics and raise awareness of the most critical impacts that cannot be overlooked. However, Ogunnusi, Hamma-Adama, Salman, and Kouider (2020) explain that some construction sectors of Sub-Saharan Africa (SSA) are exploring the opportunity that emanated with COVID-19 compared with many other nations of the world. Indigenous manufacturing is one of the promising sectors in the SSA with the interference to supply chain globally, emphasising the significance of fostering the local capacity to encourage industrial construction. Since COVID-19 causes the worldwide recession (T. Alon, M. Doepke, J. Olmstead-Rumsey, & M. Tertilt, 2020; Gallant, Kroft, Lange, & Notowidigdo, 2020; Guerrieri, Lorenzoni, Straub, & Werning, 2020), it is predictable if there will be many studies on the relationship between the construction industry and the economic recession. In the past, however, an inconsiderable amount of literature was published on that umbrella of topics, notably: employment (Hadi, 2011), crisis management (Sfakianaki, Iliadis, & Zafeiris, 2015), profitability (Yoo & Kim, 2015), and government influence (Tansey & Spillane, 2014). A growing body of literature has examined construction performance in developing countries such as Cambodia (Durdyev, Mohamed, Lay, & Ismail, 2017), Ghana (Kissi, Agyekum, Adjei-Kumi, Caleb, & Micheal, 2020), Ethiopia (Ofori, 2018). However, very little is known about the true health of the construction industry under the ravage of Covid outbreak. To the best of our knowledge, the literature has not discussed the multilevel and multidimensionality of epidemic implications. This study hopes to create a foundation for the pandemic's publications and policies' impact on the economy in general and construction industry aspects in particular. This is of utmost importance to prepare stakeholders for similar massive disasters of the future, preventing Covid19-like shocks and rethinking developing industries' resilience to global catastrophic uncertainties.

## 3 Research Methodology

The present study was conducted based on a questionnaire survey aimed at effectively collecting all the necessary data. The questionnaire was composed of two main parts. The first part contained demographic information of the participants (i.e., qualifications, positions, professional experience, and role in the construction project) whose primary purpose was to describe the participants to ensure reliability and strengthen research findings effectively. The second part included the list of identified aspects among the construction sector that has been impacted by the COVID-19 pandemic (i.e., business activities of construction firms, construction workforce, and construction project performance). Participants were selected to answer an online survey based on their previous direct or indirect participation in the implementation of construction projects in Vietnam during the COVID-19 pandemic.

### *3.1 Pilot Test*

Before distributing the questionnaire, a pilot study was carried out to verify the questionnaire and ensure that the information returned by the construction workforce would be appropriate to the goals of the present study. This stage was carried out by sending the questionnaire project to five experts with many years of experience and comprehensive knowledge on this subject. They assessed the validity of the questionnaire content, evaluated on the readability of the linguistics, and recommended additional factors in the questionnaire. After receiving their comments, the questionnaire was slightly changed.

### *3.2 Measurement Method*

For analysing data, this study used the simple percentage analysis combined with the Relative Importance Index (RII) method to measure the impact of the COVID-19 pandemic on construction activities. The RII method was used by numerous studies (i.e., (Alaghbari, Al-Sakkaf, & Sultan, 2019; Gunduz & Abdi, 2020; Hiyassat, Hiyari, & Sweis, 2016; Jarkas, 2015; Jarkas, Kadri, & Younes, 2012). The RII index was calculated based on Equation (1):

$$RII = \frac{\sum_{i=1}^{5} W_i x X_i}{\sum_{i=1}^{5} X_i} \quad (1)$$

Where: Wi is the rating given to each factor by the participant ranging from 1 to 5; Xi represented the percentage of respondents scoring and reflected the order number for the respondents; i is the order score ranging from 1 to 5.

For RII approach, the sample size was determined according to the following formula with a reliability of 95% (Hogg, Tanis, & Zimmerman, 2010):

$$m = \frac{z^2 \, x \, Px\,(1-P)}{\mathcal{E}^2} \quad (2)$$

$$n = \frac{m}{1+\frac{m-1}{N}} \quad (3)$$

Where: n is a sample size of limited population; m is a sample size of unlimited population; P is the degree of variance between the elements of the population (usually P = 0.5); $\mathcal{E}$ is tolerance (±3%, ±4%, ±5%,); z is the distribution value corresponding to the reliability of choice (95% confidence, z value is 1.96); N is the total number of responses collected.

**Table 2** Demographic of the respondents

| Items | Categories | Frequency | Percentage |
|---|---|---|---|
| Education levels | Under bachelor's degree | 2 | 70.7% |
| | Bachelor's degree | 87 | 1.6% |
| | Post bachelor's degree | 34 | 27.6% |
| Work experience (years) | 1-5 | 80 | 65.0% |
| | 6-10 | 14 | 11.4% |
| | 10-15 | 21 | 17.1% |
| | 16-20 | 7 | 5.7% |
| | > 20 | 1 | 0.8% |
| Organization involvement | Client | 28 | 22.8% |
| | Authority | 7 | 5.7% |
| | Contractor | 51 | 41.5% |
| | Supervision | 7 | 5.7% |
| | Consultant | 30 | 24.4% |
| Role in construction project | Project manager | 26 | 21.1% |
| | Site manager | 15 | 12.2% |
| | Site supervisor | 13 | 10.6% |
| | Designer | 7 | 5.7% |
| | Architect | 1 | 0.8% |
| | Company manager | 8 | 6.5% |
| | Cost estimator | 46 | 37.4% |
| | Authority | 7 | 5.7% |
| Organizational size | Micro (< 10 persons employed) | 10 | 8.1% |
| | Small (< 100 persons employed) | 68 | 55.3% |
| | Medium (< 200 persons employed) | 23 | 18.7% |
| | Big (> 200 persons employed) | 22 | 17.9% |
| Sector | State-owned | 35 | 28.5% |
| | Private-owned | 88 | 71.5% |
| Type of project | Building | 85 | 69.1% |
| | Transportation | 6 | 4.9% |
| | Infrastructure | 20 | 16.3% |
| | Industrial | 12 | 9.8% |
| Type of project fund | Public fund | 54 | 43.9% |
| | Private fund | 57 | 46.3% |
| | Offshore fund | 4 | 3.3% |
| | Mixed fund | 8 | 6.5% |
| Project capacity | Small scale (≤15 VND bil.) | 33 | 26.8% |
| | Medium to big scale (≥ 15 VND bil.) | 89 | 72.4% |
| | National important project | 1 | 0.8% |

### *3.3 Sampling and Data collection*

To determine the sample size needed through following formula in which z = 1.96; P = 0.5; pick $\varepsilon$ = 0.04 (4%). By using formulas (2) and (3) with value m = 600 and N = 129 the number of samples needed for this study is 107 samples.

Survey data was collected from a sample of respondents who had lately engaged with construction project(s) in Vietnam. The distribution of respondents appears to provide a rather diversified perspective from different positions in projects (i.e., project managers, site supervisors, design engineers, consulting engineers, architects, and authorities). An online questionnaire distributed a total of 150 samples through email. Only 129 answers were received, and 123 qualified responses (average age is 29.33, SD=5.911) for research that is more than the required sample size (107 samples), representing an effective rate of 82.0%.
The first part was to collect respondents' demographic information, including their categories of gender, education levels, work experience, organisation involvement in the construction projects, the role of the participant in the construction project, and project characteristics (i.e., type of project, type of project fund, and project capacity). Table 2 presents the demographic of the respondents under the investigation.

## 4 Results and Discussions

In this study, two software applications were applied to examine the findings, which are MS Excel 365 and SPSS 20. The analysis results have been calculated and assessed based on their simple percentage, and RII. This section consists of three main items which include the impact of the Covid-19 pandemic on business activities of construction enterprises, construction workforce, and performance of construction projects.

### *4.1 The impact of the Covid-19 pandemic on business activities of construction firms*

In the context of the global and domestic economies facing numerous challenges as a result of the complicated and protracted development of the Covid-19 pandemic, which has had a significant impact on the production and business activities of construction enterprises in various ways. As provided in Figure 1, 78.86% of construction companies have gone worse on their business and operation activities during the Covid-19 existing, while the figures for private-owned and public-owned enterprises at 81.82% and 71.43% respectively. 22.86% of public sector indicated that their activities have remained unchanged compared to private sector, at 18.18%. Only 5.71% of public enterprises have gone better on their business activities, whereas, there is no private enterprise has gone better during the Covid-19 pandemic period.

Figure 2 and Figure 3 show the impact of Covid-19 on revenue and profitability of construction enterprises. Accordingly, the revenue and profitability of most companies have decreased due to the Covid-19 pandemic, while a few companies recorded an increase in revenue and profitability.

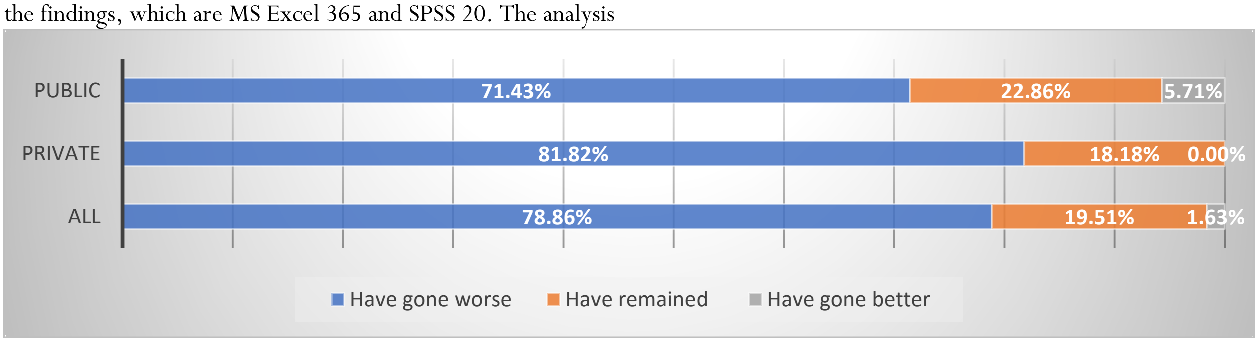



**Figure 1.** Impact of Covid-19 on business and operation of construction enterprises

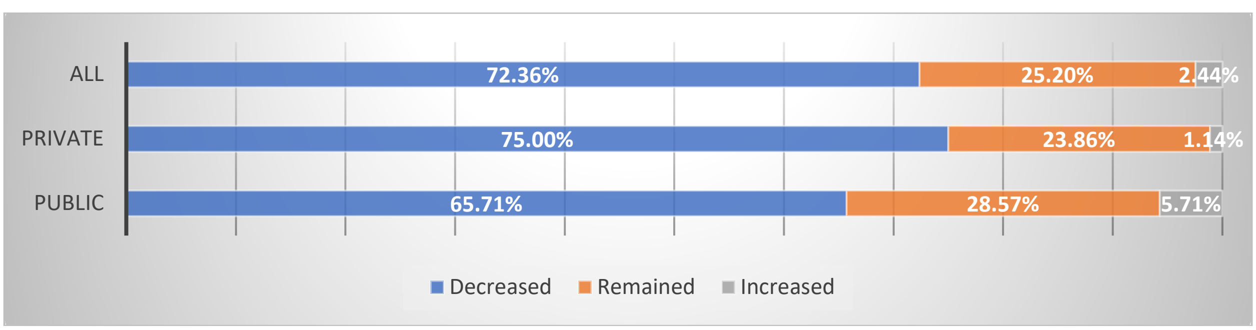



**Figure 2.** Impact of Covid-19 on revenue of construction enterprises

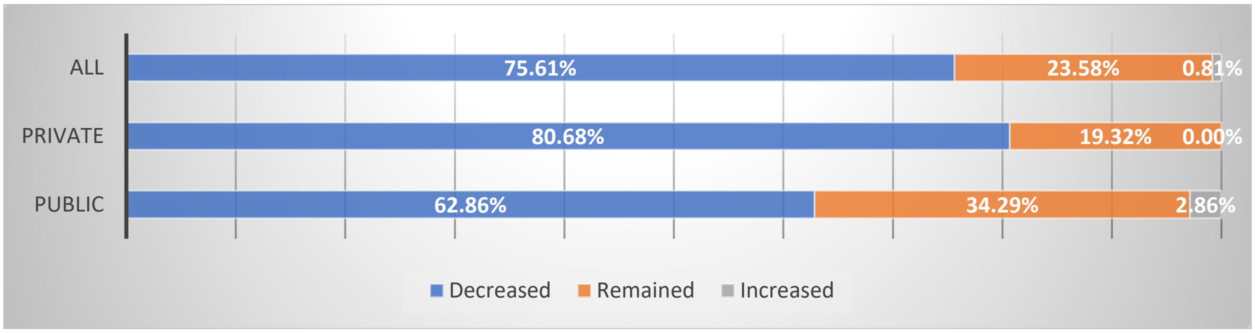



**Figure 3.** Impact of Covid-19 on profitability of construction enterprises

In terms of enterprises' revenue, 75.00% of private-owned firms have decreased their revenue, while the figure for public-owned firms is lower, at 65.71%. Only 2.44% of construction companies showed that their revenue has grown, whereas, these numbers of private and public sectors are 1.14% and 5.71%, in turn. For profitability of construction enterprises, 80.68% of private enterprises revealed that their profitability has gone down in comparison with 62.86% of public enterprises. Particularly, there is no private company that has increased its profitability during Covid-19, whereas, this figure for public companies is only 0.81%. The rest of construction firms indicated that their revenue and profitability remained unchanged although their activities are impacted by Covid-19.

For the construction sector, the cost of construction work consists of 60-70% of material costs, labor costs account for 10-20%, and the remaining 10-20% refers to machinery costs (El-Gohary & Aziz, 2014; McTague & Jergeas, 2002). Figure.4 to Figure 7 demonstrate the impact of Covid-19 on production and business costs of construction enterprises, which involve direct materials costs, direct labor costs, machinery ownership and operating costs, and indirect costs (i.e., company management cost, construction site management cost, delivery cost, and bank interest payments). Accordingly, most construction companies explained that although have affected Covid-19 pandemic, their production and business costs have remained unchanged, while the numbers of enterprises showed that their production and business costs have decreased.

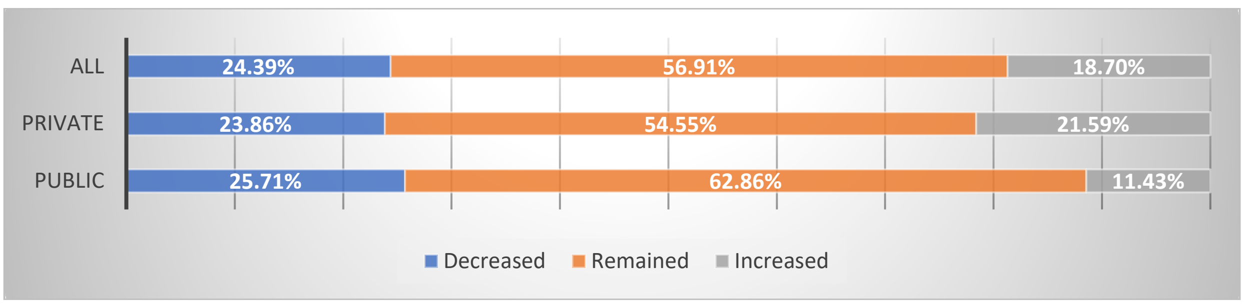



**Figure 4.** Impact of Covid-19 on direct materials costs

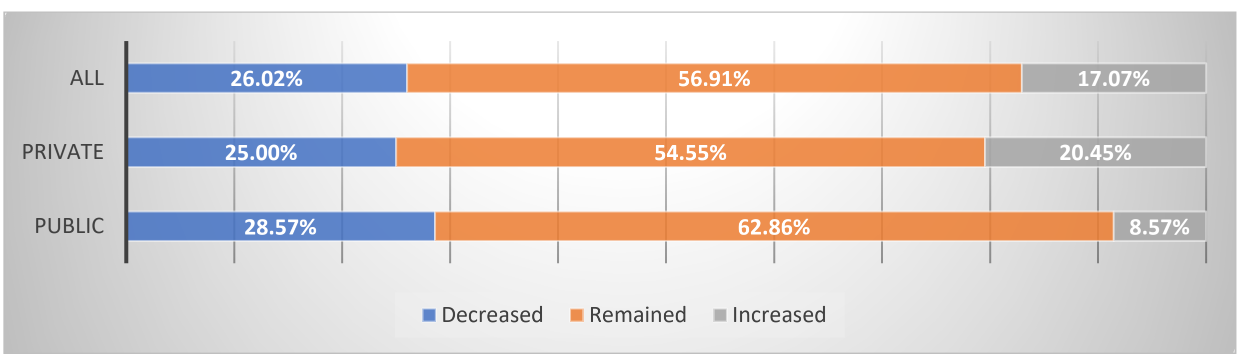



**Figure 5** Impact of Covid-19 on direct labor costs

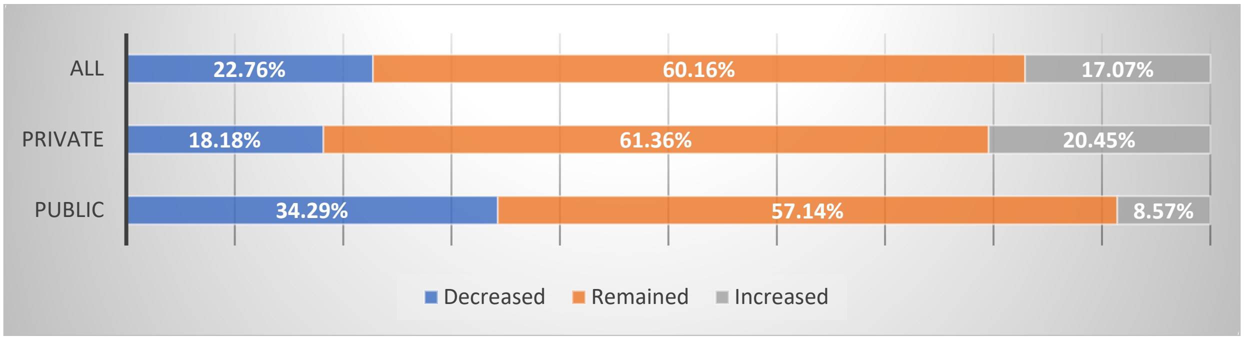



**Figure 6.** Impact of Covid-19 on machinery ownership and operating costs

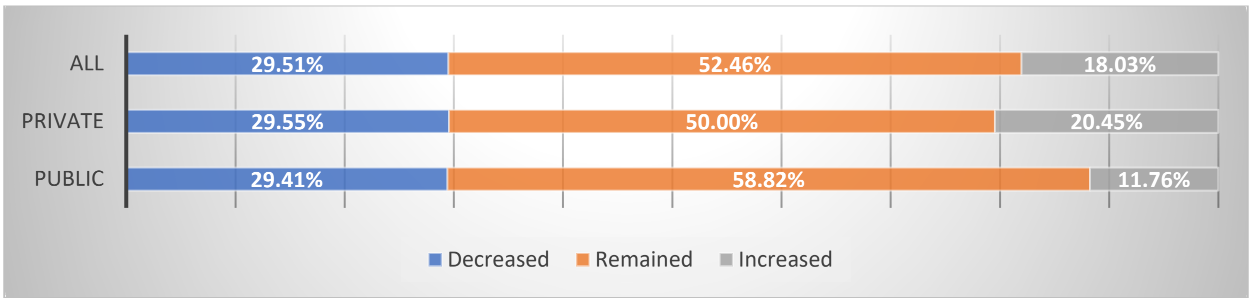



**Figure 7** Impact of Covid-19 on indirect costs

In terms of materials costs, 56.91% of construction companies indicated that direct materials costs have remained, whereas, these figures for private and public companies account for 54.55% and 62.86% respectively. 23.86% of private sector revealed that materials costs have decreased compared to 21.59% of this sector showed that materials costs have increased. However, only 11.43% of public sector explained that materials costs have increased, while this number of this sector showed that materials costs have decreased is higher, at 25.71%. In fact, disruptions on the supply chain of construction resources due to difficulties in mobilising especially importing materials like cement, steel, aluminum, and their products which cause materials costs increased (Afkhamiaghda & Elwakil, 2020; Al Amri & Marey-PÃ, 2020; Bsisu, 2020). For labor costs, the majority of enterprises demonstrated that direct labor costs have been unchanged, at 62.86% of public firms and 54.44% of private firms. In contrast, the percentages of companies suggested that labor costs that have increased are 8.57% for public sector and 20.45% for private sector.

For machinery costs, 61.26% of the private enterprises proved that machinery ownership and operating costs have remained unchanged, while this figure for public enterprises is lower, at 57.14%. Only 8.57% of public-owned companies showed that machinery costs have increased compared to 34.29% of the remaining public sector indicated that machinery costs have decreased due to Covid-19 pandemic. The rate of private enterprises demonstrated that machinery costs have increased or decreased are the same, at 20.45% and 18.18% respectively. The Covid-19 makes the idleness of resources like equipment, machinery, and tools, which causes machinery ownership and operating costs increased (Al Amri & Marey-PÃ, 2020; Gamil & Alhagar, 2020). In terms of indirect costs, half of private sector showed that indirect costs have remained, while this number of the public sector is higher, at 58.82%. The proportions of private and public enterprises indicated that indirect costs that have decreased are similar, at 29.55% and 29.51% respectively. These findings reveal that although construction enterprises are impacted by the Covid-19 pandemic, the majority of their production and business costs have remained unchanged.

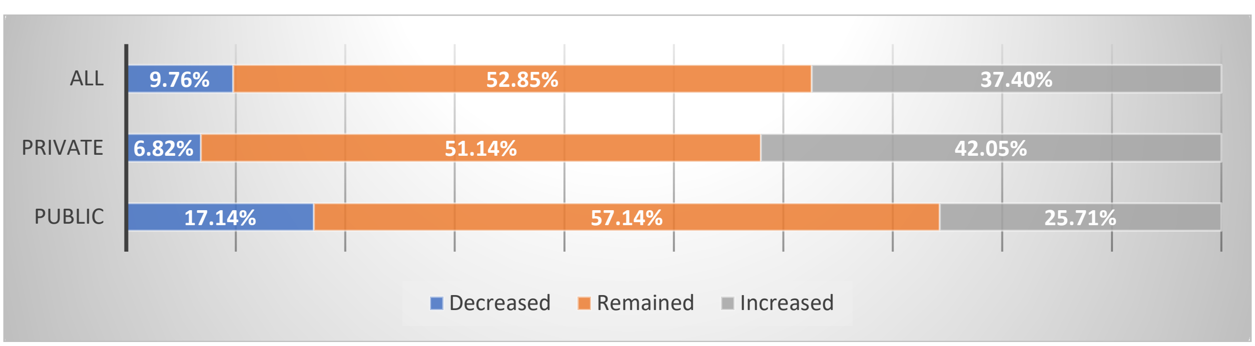



**Figure 8** Impact of Covid-19 on permanent labor demand of construction enterprises

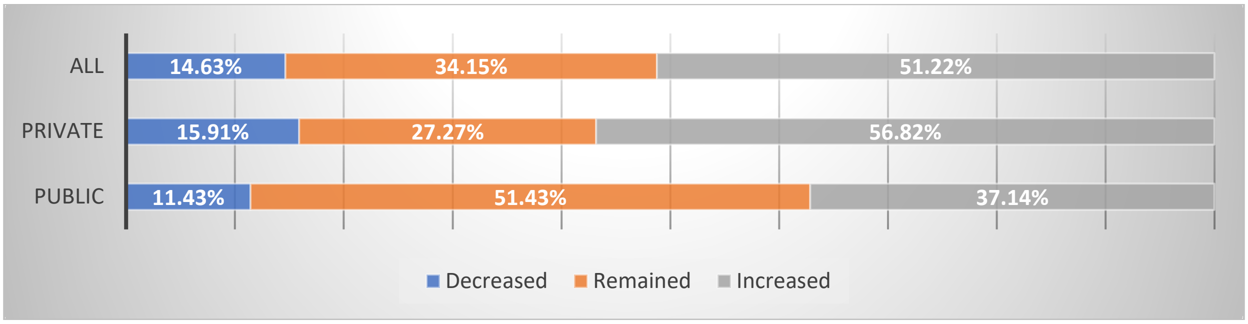



**Figure 9** Impact of Covid-19 on contractual labor demand of construction enterprises

The construction industry employs a large number of laborers compared to other industries, hence, labor demand for construction companies is significantly affected by the Covid-19 spread. The findings from the study of (Araya, 2020) indicated that the construction workforce of a construction project may be reduced by between 30% and 90% due to the COVID-19 pandemic. As provided in Figure 8 and Figure 9, the labor demand of enterprises has fluctuated during the Covid-19 existence. The majority of construction firms revealed that their permanent labor demand has remained unchanged, at 57.14% and 51.14% of public and private sectors respectively. However, only 6.82% of private-owned companies showed that their permanent work demand has decreased, whereas, this figure for public-owned companies is higher, at 17.14%. In contrast, the percentage of contractual labor demand of private enterprises has increased, accounting for 56.82%, while this number of public enterprises is only 37.14%. This finding indicates that private construction companies tend to use more of temporary labor during the Covid-19 pandemic than public construction companies.

As demonstrated in Table 3, the Covid-19 has a significant impact on numerous aspects of organisation and management of construction enterprises. The findings indicate that 'planning change' is ranked the 1st position, which proves that the Covid-19 has a high impact on planning change of both public and private enterprises (RII=3.00 and 3.27 respectively). This finding is supported by (Gamil & Alhagar, 2020) who demonstrated that construction planning is likely to be significantly affected during the Covid-19. With RII=2.89, 'policy-making change' is ranked 2nd by the respondents working in the public sector, while this aspect is ranked 3rd by those working in the private sector (RII=3.20). In contrast, participants working public sector ranked 'reward and well-being program' was 3rd position (RII=2.60), whereas, participants working public sector ranked this aspect was 2nd position (RII=3.26). The findings reveal that these two aspects of organisation and management of construction enterprises are noticeably affected by the Covid-19 pandemic. Communication in an enterprise is ranked 4th in both public and private sectors with RII=2.54 and 2.70, in turn, this indicates that this aspect is moderately affected by the Covid-19. Several different aspects such as work culture, competencies, reputation, of construction enterprises are ranked at the end positions (RII=2.53, 2.50, and 2.23 respectively), which proves that the Covid-19 pandemic have a low impact on these aspects of construction enterprises.

**Table 3** Impact of Covid-19 on organisation and management of construction enterprises

| Aspects | All (N=123) | | Public sector (N=35) | | Private sector (N=88) | |
|---|---|---|---|---|---|---|
| | RII | Rank | RII | Rank | RII | Rank |
| Planning change | 3.20 | 1 | 3.00 | 1 | 3.27 | 1 |
| Policy-making change | 3.11 | 2 | 2.89 | 2 | 3.20 | 3 |
| Reward and well-being program | 3.08 | 3 | 2.60 | 3 | 3.26 | 2 |
| Competencies | 2.50 | 6 | 2.11 | 6 | 2.65 | 5 |
| Reputation | 2.23 | 7 | 1.97 | 7 | 2.33 | 7 |
| Work culture | 2.53 | 5 | 2.31 | 5 | 2.61 | 6 |
| Interaction | 2.66 | 4 | 2.54 | 4 | 2.70 | 4 |

### 4.2 *The impact of the Covid-19 pandemic on construction workforce*

The labor market is being significantly affected by the Covid-19 pandemic, in which, its impact indicates the effect on the income of millions of construction laborers worldwide. Figure 10 illustrates the impact of Covid-19 on income of construction workforce. Accordingly, most respondents showed that their incomes have remained unchanged even though affected by the Covid-19, at 52.85%. 44.32% of respondents working in private sector explained that their incomes have decreased, while this figure for public sector is higher, at 48.57%. Only 2.27% of laborers working in private enterprises demonstrated that their incomes have increased during the Covid-19 spread, whereas, no laborer is working in public enterprises showed that their incomes have increased. This finding is supported by the RII result, which ranks income as the most affected in the first position with RII=3.33 (Table 4). The result proves that Covid-19 has a very high impact on construction workforce's incomes. Although their incomes are affected by the Covid-19, very few respondents have received support from their companies. As provided in Figure 11, only 7.95% of private-owned enterprises introduce on reward and well-being programs to support their employees, while this number of public-owned enterprises is higher, at 17.14%. In contrast, 51.14% of respondents working in private sector showed that their companies more difficult carried out to support programs in their workforce, whereas, this figure for public sector is 42.86%.

As provided in Table 4, with RII = 3.49, factor of 'mental health' is ranked the first position by the respondents working in the public sector, while respondents working in public sector assessed this factor is the second position (RII=3.25). This finding indicates that the Covid-19 pandemic has a significant impact on psychology of construction workforce. In fact, during the Covid-19 spread worldwide, many countries have experienced lockdown and quarantine time in a long time, which is the main cause negatively affected by human mental health (Torales, O'Higgins, Castaldelli-Maia, & Ventriglio, 2020; Xiong et al., 2020). The surveyed respondents ranked 'motivation' as the third position in both private and public sectors (RII=3.11 and 3.31 respectively), which proves that the Covid-19 has a moderately affected work motivation of construction workforce. Factors of 'productivity' and 'physical' of labors are ranked at the end with RII=3.02 and 2.90 respectively, which reveals that the Covid-19 has a low effect on productivity and physical of construction workforce. Recently, although Vietnamese construction labor productivity has been enhanced (Hai & Van Tam, 2019; Nguyen, Van Tam, Dinh, & Quy, 2020; Van Tam, Huong, & Ngoc, 2018; Van Tam, Quoc Toan, Tuan Hai, & Le Dinh Quy, 2021), the existence of Covid-19 can make a negative impact on construction productivity improvement. The finding is supported by (Alenezi, 2020) who demonstrated that the Covid-19 is a cause make low productivity of construction workers. In Oman, construction companies are also reducing their staff, and the workforce is mostly unemployed (Al Amri & Marey-PÃ, 2020).

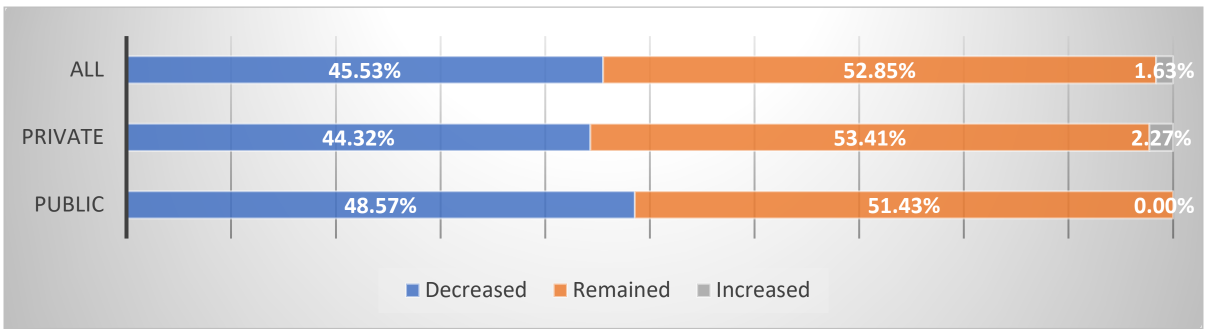



**Figure 10** Impact of Covid-19 on income of construction workforce

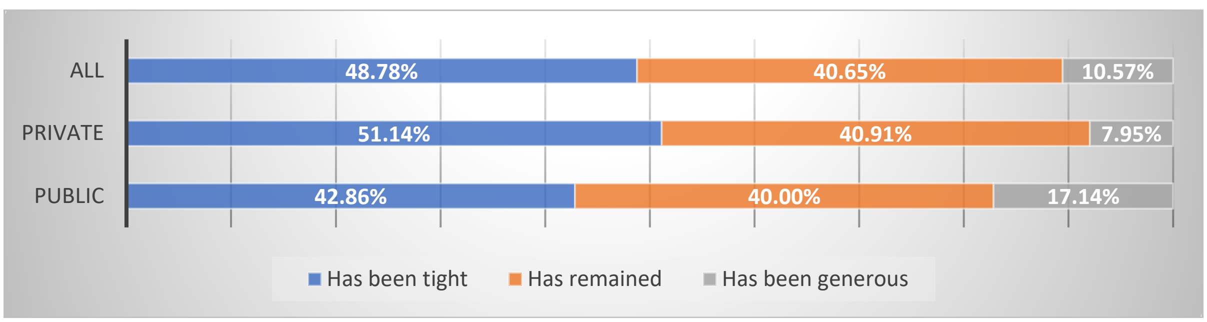



**Figure 11** Support of enterprises for their employees

**Table 4** Impact of Covid-19 on construction workforce

| Factors | All (N=123) | | Public sector (N=35) | | Private sector (N=88) | |
|---|---|---|---|---|---|---|
| | RII | Rank | RII | Rank | RII | Rank |
| Income | 3.33 | 1 | 3.34 | 2 | 3.32 | 1 |
| Mental health | 3.32 | 2 | 3.49 | 1 | 3.25 | 2 |
| Motivation | 3.17 | 3 | 3.31 | 3 | 3.11 | 3 |
| Productivity | 3.02 | 4 | 3.14 | 5 | 2.98 | 4 |
| Physical | 2.90 | 5 | 3.17 | 4 | 2.80 | 5 |

### *4.3 The impact of the Covid-19 pandemic on construction project performance*

Numerous construction projects globally are being impacted by the Covid-19 in various aspects. Figure12 to Figure 15 show the impact of Covid-19 on performance of construction project in terms of schedule, quality, cost, and safety. The surveyed respondents indicated that most construction projects have fallen behind schedule due to the effect of the Covid-19 pandemic, accounting for 61.79% of the total, while only 3.25% of respondents explained that construction projects have run ahead of schedule. This finding is supported by the results of the RII method (Table 5), with RII=3.33, 'schedule' is ranked the 1st position, which indicates that the Covid-19 has a very high impact on construction project schedule. This result is in the line with the study of (Afkhamiaghda & Elwakil, 2020; Al Amri & Marey-PÃ, 2020; Alenezi, 2020) which revealed the Covid-19 is a major cause of delays in construction projects in Kuwait, Oman, and South Africa. Similarly, 'project cost' is evaluated the 2nd by respondents working in both public and private sectors (RII=2.74 and 3.19, in turn), which reveals that the Covid-19 have a significant influence on construction project cost. Besides, 51.22% of respondents indicated that project cost has been increased, whereas, only 8.13% of respondents showed that project cost has decreased during the Covid-19 existing.

In contrast, the majority of respondents indicated that project quality has been remained and safety has been ensured within construction process. In particular, 82.93% of respondents explained that the quality of construction project is remained unchanged, while only 13.82% of respondents showed that project quality has been decreased. Besides, 73.17% of respondents demonstrated that safety of construction process has been ensured compared to only 14.63% of respondents suggested that safety of construction process has been decreased. These findings are supported by RII' results which ranked safety and quality of construction project at the end positions with RII=2.24 and 2.09 respectively, which proves that the Covid-19 have a low impact on safety and quality of construction project during the Covid-19 spread. The surveyed respondents ranked 'stakeholders communication' and 'environmental issue' are 3rd and 4th position (RII=2.80 and 2.27, in turn), which reveals that the Covid-19 pandemic has a moderate impact on stakeholder communication and environmental issue within construction process. These findings are further supported by (Alenezi, 2020) who explained that the Covdi-19 is a primary cause that makes poor safety conditions, poor scheduling and planning of project, and poor communication with other parties.

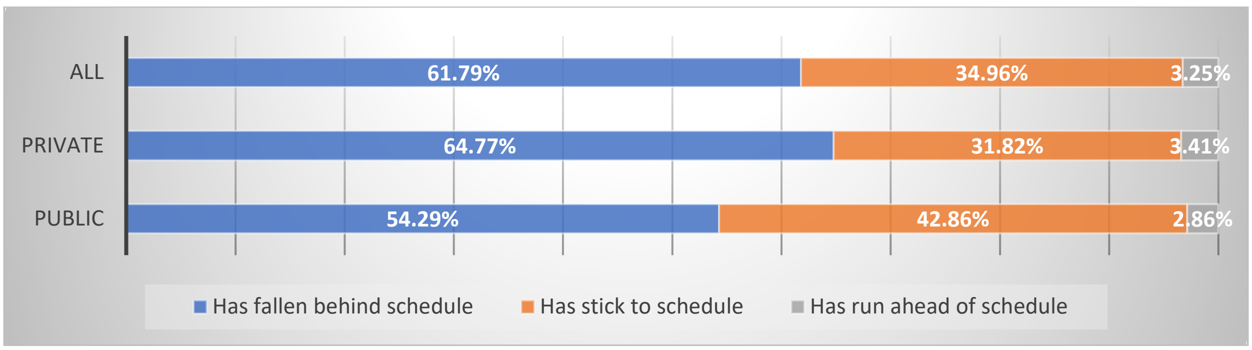



**Figure 12** Impact of Covid-19 on schedule of construction project

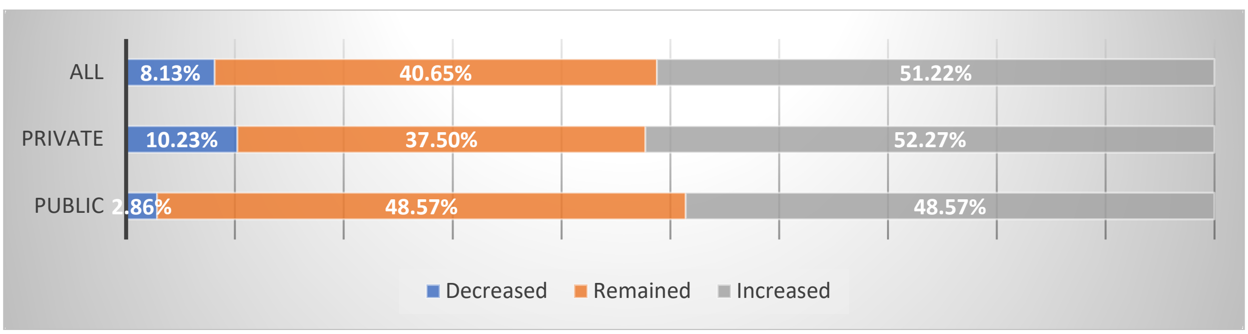



**Figure 13.** Impact of Covid-19 on cost of construction project

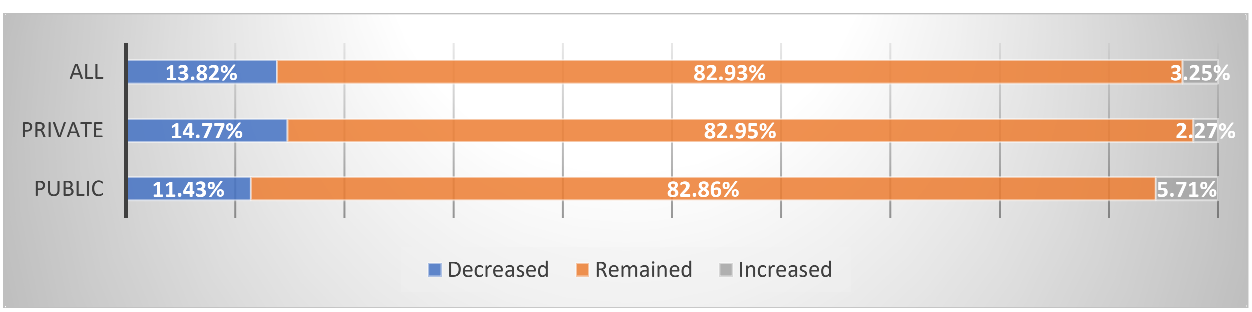



**Figure 14** Impact of Covid-19 on quality of construction project

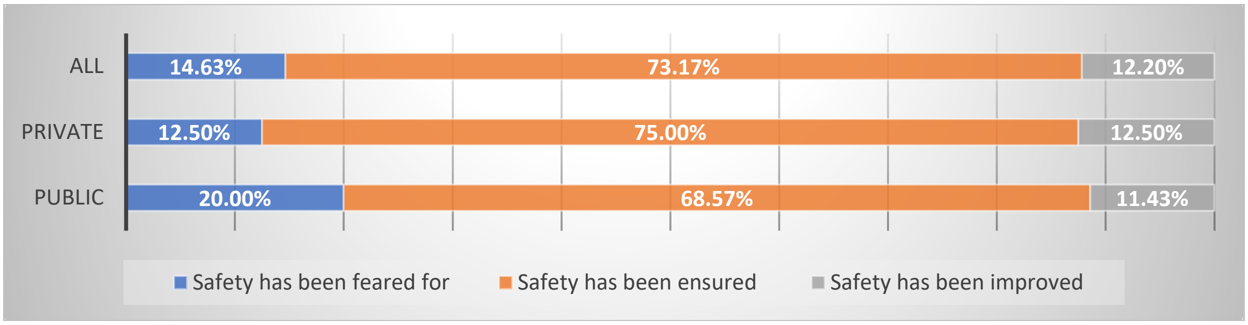



**Figure 15** Impact of Covid-19 on safety of construction process

**Table 5.** Impact of Covid-19 on performance of construction project

| Aspects | All (N=123) | | Public sector (N=35) | | Private sector (N=88) | |
|---|---|---|---|---|---|---|
| | RII | Rank | RII | Rank | RII | Rank |
| Schedule | 3.33 | 1 | 3.26 | 1 | 3.36 | 1 |
| Cost | 3.07 | 2 | 2.74 | 2 | 3.19 | 2 |
| Stakeholder communication | 2.80 | 3 | 2.54 | 3 | 2.90 | 3 |
| Environmental issue | 2.27 | 4 | 2.20 | 4 | 2.30 | 4 |
| Safety | 2.24 | 5 | 2.17 | 5 | 2.27 | 5 |
| Quality | 2.09 | 6 | 2.00 | 6 | 2.13 | 6 |

## 5 Conclusions and Recommendations

Construction activities, without exception, have also been affected by the pandemic. In general, the effects are negative and multilevel (Figure 16). In terms of organisational level operations, there has been a clear decline in overall revenue. Although some types of costs have been remain or reduced, they are caused by freezing in operation or shortage of contracts. Demand for labor has shown signs of increasing during the epidemic. This is quite surprising because it is the opposite of some other areas such as: gastronomy, tourism, service, or non-food retail (Spurk & Straub, 2020), leisure & hospitality and retail trade (Kurmann, Lale, & Ta, 2020). Having said that, construction businesses suffer in many ways. There is not much difference between the public and private sectors when the three most affected dimensions are composed of Planning change; Policy-making change and Reward and well-being program. Meanwhile, the reputation was considered almost not very affected. This is quite surprising compared to other studies where the authors believe that reputation could suffer a lot during times of crisis (Abimbola et al., 2010; Patterson, 1993; Šontaitė-Petkevičienė, 2014). According to the majority of the respondents, employee income and welfare were said to have decreased. This is understandable because the company's revenue has been hit hard in the context of the bleak market and the local shutdown in many places. This situation is likely to last, and even worsen, when the economic shock is on, not much different from the Spanish flu pandemic of 1918 (Brainerd & Siegler, 2003). In addition to income, both public and private practitioners believe that their psychology and motivation are seriously affected by the outbreak. This finding suggests a real need for models and policies related to mental health care at workplace. At project level, schedule, cost and communication were considered to be under the most pressure. We need to pay attention to this finding because the trio has long been seen as influential greatly to the success of the project (Andersen, Birchall, Jessen, & Money, 2006; Belout & Gauvreau, 2004).

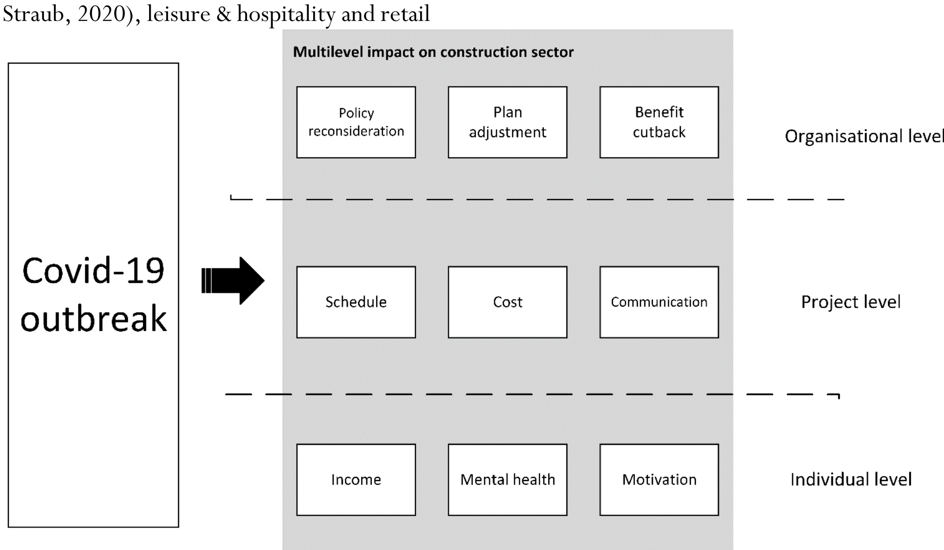



**Figure 16** Overview of Covid-19's major impacts on Vietnamese construction sector

Taken together, these results provide a rather panoramic picture of the construction industry in the Covid-19 era. A pandemic like an atomic bomb has already exploded, but has left many serious and persistent consequences. Research such as this paper, although still sketchy, will serve as the foundation for policy-makers and management to envision those consequences, towards building countermeasures to help revive the economy and the construction industry in particular.

Although the Vietnamese government introduced several supportive policies, construction businesses have also actively implemented solutions to maintain their business and operation activities and constrain the COVID-19 pandemic's negative impacts. Accordingly, many solutions have been implemented by construction enterprises such as cutting staffs; reducing workers' wages; reducing bonus and welfare regimes; reducing other costs (e.g. advertising, training); delaying in payment of wages and allowances to employees; negotiating on late payment of bank interest negotiating for advance payment; applying for a specific mechanism for businesses from the state. However, these solutions are still temporary, challenging to bring into play long-term effectiveness in the face of complicated developments of the COVID-19 epidemic. Therefore, in order to help construction businesses to ensure construction activities and towards long-term sustainable values in the case of the COVID-19 pandemic existing, the authors proposed several recommendations as follows:

(1) Restructuring the management system; rearranging human resources; providing a flexible working framework; developing a job management program in case employees work at home, helping keep tasks being interrupted, ensuring quality and productivity, and preventing risks caused by COVID-19.

(2) Developing immediate and long-term scenarios and measures to ensure regular, continuous, and less interrupted construction work during the COVID-19 outbreak. Both ensure labour safety, safety against epidemics, and ensure project implementation efficiency.

(3) Promoting the application of information technology to production and business activities to accelerate digital transformation in enterprises. From the work of planning, finance, management, human resources, salary, and site management. Stakeholders should integrate all work systems to build a system throughout the business. It is advised that the management integrate most business processes in business operations from the enterprise level to the management and implementation of construction site level.

(4) Ensuring a sustainable supply chain: enterprises should control and assess the degree of cooperation of suppliers, essential partners of the business, assess the availability of resources, the ability to cooperate, and the readiness of these partners to respond to diseases. Identifying vendors, backup, or alternative partners in an existing partner cannot support the business. Evaluating contract terms and insurance policies to ensure coverage within the contract's scope related to the delayed transfer of resources.

(5) Ensuring financial safety: Enterprises should control the actual cash flow that is regularly circulating to minimise the possibility of a shortage of cash flow due to the decline in revenue; ensuring the financial supply for activities at enterprises and construction sites to be carried out continuously. The impact on working capital in the supply chain should be appraised. Carefully review debt obligations to identify a possible breach of contract (penalty due to late progress, late payment of interest) and evaluating potential consequences. Actively connect with lenders and other stakeholders in the project to ensure payments are received on time and proactively rearrange debts and alternative financing sources. Assessing the consequences that occur when work is interrupted, delaying, and reviewing insurance policies to assess the likelihood of compensation for production disruptions and clarify coverage of coverage in an outbreak continue to have complicated developments.

This study has some limitations which have to be pointed out. This study was a local, not global, study conducted using web-based questionnaire survey data. The article does not include quantitative parameters to help the readers understand the extent of the damage. The depth of the study is also limited when there are no statistical analyses of correlation, causality or regression. In conclusion, the results of this study highlight the multilevel, multidimensional nature of epidemic impact on the construction sector. It would be beneficial to determine the key impacted areas in order to develop industry-wide policies on dealing with catastrophic events and developing in a new normal. Our study, being of an exploratory and interpretive nature, raises a number of opportunities for future research, for instance: status of construction workers' suffering and their solicitation; safe working solution in the context of an epidemic; or even rethinking construction industry reform strategies.

## Acknowledgments

We would like to thank the Editor and anonymous reviewers for their constructive comments and suggestions on improving the manuscript. All remaining errors are the sole responsibility of the authors.

## References

Afkhamiaghda, M., & Elwakil, E. (2020). Preliminary modeling of Coronavirus (COVID-19) spread in construction industry. *Journal of Emergency Management, 18*(7): 9-17.

Al Amri, T., & Marey-PÃ, M. (2020). Impact of Covid-19 on Oman's Construction Industry. *Technium Social Sciences Journal, 9*(1): 661-670.

Alaghbari, W., Al-Sakkaf, A. A., & Sultan, B. (2019). Factors affecting construction labour productivity in Yemen. *International Journal of Construction Management, 19*(1): 79-91.

Alenezi, T. A. N. (2020). Covid-19 Causes Of Delays On Construction Projects In Kuwait. In: IJERGS.

Alon, T., Doepke, M., Olmstead-Rumsey, J., & Tertilt, M. (2020). *This Time It's Different: The Role of Women's Employment in a Pandemic Recession*. Retrieved 23/03/2021 from https://www.nber.org/papers/w27660

Alon, T. M., Doepke, M., Olmstead-Rumsey, J., & Tertilt, M. (2020). *The impact of COVID-19 on gender equality*. Retrieved 23/03/2021 from https://www.nber.org/papers/w26947

Alshenqeeti, H. (2014). Interviewing as a data collection method: A critical review. *English linguistics research, 3*(1): 39-45.

Andersen, E. S., Birchall, D., Jessen, S. A., & Money, A. H. (2006). Exploring project success. *Baltic journal of management, 1*(2): 127-147.

Araya, F. (2020). Modeling the spread of COVID-19 on construction workers: An agent-based approach. *Safety science, 133*: 105022.

Ataguba, O. A., & Ataguba, J. E. (2020). Social determinants of health: the role of effective communication in the COVID-19 pandemic in developing countries. *Global Health Action, 13*(1): 1788263.

Bartik, A. W., Bertrand, M., Cullen, Z., Glaeser, E. L., Luca, M., & Stanton, C. (2020). The impact of COVID-19 on small business outcomes and expectations. *Proceedings of the National Academy of Sciences, 117*(30): 17656-17666.

Belout, A., & Gauvreau, C. (2004). Factors influencing project success: the impact of human resource management. *International journal of project management, 22*(1): 1-11.

Bowen, P., Dorrington, R., Distiller, G., Lake, H., & Besesar, S. (2008). HIV/AIDS in the South African construction industry: an empirical study. *Construction Management and Economics, 26*(8): 827-839.

Brainerd, E., & Siegler, M. V. (2002). *The economic effects of the 1918 influenza epidemic*. Retrieved 23/03/2021 from https://users.nber.org/~confer/2002/si2002/brainerd.pdf

Bsisu, K. A.-D. (2020). The impact of COVID-19 pandemic on Jordanian civil engineers and construction industry. *International Journal of Engineering Research and Technology, 13*(5): 828-830.

Burkle, F. M. (2020). Declining public health protections within autocratic regimes: impact on global public health security, infectious disease outbreaks, epidemics, and pandemics. *Prehospital and disaster medicine, 35*(3): 237-246.

Can, L. V. (2020). Update the impact of the COVID-19 epidemic on Vietnam's economic sectors. *Vietnam Financial and monetary magazine*. Retrieved 22/03/2021 from https://thitruongtaichinhtiente.vn/cap-nhat-tac-dong-cua-dai-dich-covid-19-doi-voi-cac-nganh-kinh-te-viet-nam-28398.html

Daniel, S. J. (2020). Education and the COVID-19 pandemic. *Prospects*, 1-6.

Dinh, H. H. (2020). Risks and issues: reactions of Vietnam and the experience to the world in the first wave of coronavirus pandemic. *Asian Education and Development Studies, 10*(2): 239-249. doi:10.1108/AEDS-07-2020-0165

Dinh, P. L., & Ho, T. T. (2020). How a collectivistic society won the first battle against COVID-19: Vietnam and their "weapons". *Inter-Asia Cultural Studies, 21*(4): 506-520.

Dixon, S., McDonald, S., & Roberts, J. (2002). The impact of HIV and AIDS on Africa's economic development. *Bmj, 324*(7331): 232-234.

Durdyev, S., Mohamed, S., Lay, M. L., & Ismail, S. (2017). Key factors affecting construction safety performance in developing countries: Evidence from Cambodia. *Construction Economics and Building, 17*(4): 48.

El-Gohary, K. M., & Aziz, R. F. (2014). Factors influencing construction labor productivity in Egypt. *Journal of Management in Engineering, 30*(1): 1-9.

Flynn, L., Kaitano, A.-E., & Bery, R. (2012). *Emerging pandemic threats and the oil and gas industry.* Paper presented at the International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production.

Gallant, J., Kroft, K., Lange, F., & Notowidigdo, M. J. (2020). *Temporary Unemployment and Labor Market Dynamics During the COVID-19 Recession*. Retrieved 22/03/2021 from https://www.nber.org/papers/w27924

Gamil, Y., & Alhagar, A. (2020). The Impact of Pandemic Crisis on the Survival of Construction Industry: A Case of COVID-19. *Mediterranean Journal of Social Sciences, 11*(4): 122-122.

Gerard, F., Imbert, C., & Orkin, K. (2020). Social protection response to the COVID-19 crisis: options for developing countries. *Oxford Review of Economic Policy, 36*(Supplement_1): S281-S296.

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *British dental journal, 204*(6): 291-295.

Gruber, J., Prinstein, M. J., Clark, L. A., Rottenberg, J., Abramowitz, J. S., Albano, A. M., Davila, J. (2020). Mental health and clinical psychological science in the time of COVID-19: Challenges, opportunities, and a call to action. *American Psychologist, 76*(3): 409–426. doi:10.1037/amp0000707

Guerrieri, V., Lorenzoni, G., Straub, L., & Werning, I. (2020). *Macroeconomic Implications of COVID-19: Can Negative Supply Shocks Cause Demand Shortages?* Retrieved 22/03/2021 from https://www.nber.org/papers/w26918

Gunduz, M., & Abdi, E. A. (2020). Motivational Factors and Challenges of Cooperative Partnerships between Contractors in the Construction Industry. *Journal of Management in Engineering, 36*(4): 04020018.

Hadi, A. (2011). Construction employment peaks before the recession and falls sharply throughout it. *Monthly Labor Review, 134*(4): 24-27.

Hai, D. T., & Van Tam, N. (2019). Application of the Regression Model for Evaluating Factors Affecting Construction Workers' Labor Productivity in Vietnam. *The Open Construction & Building Technology Journal, 13*(1): 353-362.

Hansen, S. (2020). Does the COVID-19 Outbreak Constitute a Force Majeure Event? A Pandemic Impact on Construction Contracts. *Journal of the Civil Engineering Forum, 6*(1): 201-214.

Harinarain, N., & Haupt, T. C. (2014). Drivers for the effective management of HIV and AIDS in the South African construction industry—a Delphi study. *African Journal of AIDS Research, 13*(3): 291-303.

Hiyassat, M. A., Hiyari, M. A., & Sweis, G. J. (2016). Factors affecting construction labour productivity: a case study of Jordan. *International Journal of Construction Management, 16*(2): 138-149.

Hogg, R. V., Tanis, E. A., & Zimmerman, D. L. (2010). *Probability and statistical inference*: Pearson/Prentice Hall Upper Saddle River, NJ, USA:.

Jarkas, A. M. (2015). Factors influencing labour productivity in Bahrain's construction industry. *International Journal of Construction Management, 15*(1): 94-108.

Jarkas, A. M., Kadri, C. Y., & Younes, J. H. (2012). A survey of factors influencing the productivity of construction operatives in the state of Qatar. *International Journal of Construction Management, 12*(3): 1-23.

Jim Toole, F., & CERA, M. (2010). Potential Impact of Pandemic Influenza On the US Health Insurance Industry.

Karlsson, M., Nilsson, T., & Pichler, S. (2014). The impact of the 1918 Spanish flu epidemic on economic performance in Sweden: An investigation into the consequences of an extraordinary mortality shock. *Journal of health economics, 36*: 1-19.

Kissi, E., Agyekum, K., Adjei-Kumi, T., Caleb, D., & Micheal, E. D. (2020). Exploring the influence of religious elements on performance factors in developing countries: a case of the Ghanaian construction industry. *International Journal of Productivity and Performance Management, ahead-of-print*(ahead-of-print). doi:10.1108/IJPPM-11-2019-0546

Kurmann, A., Lale, E., & Ta, L. (2020). *The impact of covid-19 on us employment and hours: Real-time estimates with homebase data*. Retrieved 11/03/2021 from https://www.lebow.drexel.edu/sites/default/files/1588687497-hbdraft0504.pdf

Le, H. T., Mai, H. T., Pham, H. Q., Nguyen, C. T., Vu, G. T., Phung, D. T., Ho, C. S. (2020). Feasibility of intersectoral collaboration in epidemic preparedness and response at grassroots levels in the threat of COVID-19 pandemic in Vietnam. *Frontiers in Public Health, 8*: 648.

Loayza, N. V., & Pennings, S. (2020). *Macroeconomic policy in the time of COVID-19: A primer for developing countries*. Retrieved 11/03/2021 from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3586636

Lum, L. H. W., & Tambyah, P. A. (2020). Outbreak of COVID-19–an urgent need for good science to silence our fears? *Singapore medical journal, 61*(2): 55.

Luo, H., Liu, J., Li, C., Chen, K., & Zhang, M. (2020). Ultra-rapid delivery of specialty field hospitals to combat COVID-19: Lessons learned from the Leishenshan Hospital project in Wuhan. *Automation in Construction, 119*: 103345.

MacLean, L. M., Meyer, M., & Estable, A. (2004). Improving accuracy of transcripts in qualitative research. *Qualitative health research, 14*(1): 113-123.

Maldin, B., Inglesby, T. V., Nuzzo, J. B., Lien, O., Gronvall, G. K., Toner, E., & O'Toole, T. (2005). Bulls, bears, and birds: preparing the financial industry for an avian influenza pandemic. *Biosecurity and bioterrorism: biodefense strategy, practice, and science, 3*(4): 363-367.

Matangi, C. N. (2006). Skills under threat: the case of HIV/AIDS in the mining industry in Zimbabwe. *Journal of International Development, 18*(5): 599-628.

McGrail, M. R., Rickard, C. M., & Jones, R. (2006). Publish or perish: a systematic review of interventions to increase academic publication rates. *Higher Education Research & Development, 25*(1): 19-35.

McTague, B., & Jergeas, G. (2002). *Productivity improvements on Alberta major construction projects: Phase I-Back to basics*. Alberta, Canada: Alberta Economic Development.

Megahed, N. A., & Ghoneim, E. M. (2020). Antivirus-built environment: Lessons learned from Covid-19 pandemic. *Sustainable Cities and Society, 61*: 102350.

Meintjes, I., Bowen, P., & Root, D. (2007). HIV/AIDS in the South African construction industry: understanding the HIV/AIDS discourse for a sector-specific response. *Construction Management and Economics, 25*(3): 255-266.

Nguyen, Q. T., Van Tam, N., Dinh, T. H., & Quy, N. L. D. (2020). Critical factors affecting labor productivity within construction project implementation: a project manager's perspective. *Entrepreneurship and Sustainability Issues, 8*(2): 751.

Obayelu, A. (2007). Socio-economic analysis of the impacts of avian influenza epidemic on households poultry consumption and poultry industry in Nigeria: empirical investigation of Kwara State. *Livestock Research for Rural Development, 19*(1): 4.

Ofori, G. (2018). *Developing the construction industries in developing countries to enhance performance: the case of Ethiopia*. Paper presented at the Seventh Ethiopian Construction Technology and Management Professionals Association (ECoTMPA) International Workshop on Recent Trends in Construction Industry.

Ogunnusi, M., Hamma-Adama, M., Salman, H., & Kouider, T. (2020). COVID-19 pandemic: the effects and prospects in the construction industry. *International journal of real estate studies, 14*(Special Issue 2): 120-128.

Otu, A., Charles, C. H., & Yaya, S. (2020). Mental health and psychosocial well-being during the COVID-19 pandemic: The invisible elephant in the room. *International journal of mental health systems, 14*: 1-5.

Page, S., & Yeoman, I. (2007). How VisitScotland prepared for a flu pandemic. *Journal of Business Continuity & Emergency Planning, 1*(2): 167-182.

Page, S., Yeoman, I., Munro, C., Connell, J., & Walker, L. (2006). A case study of best practice—Visit Scotland's prepared response to an influenza pandemic. *Tourism Management, 27*(3): 361-393.

Patterson, B. (1993). Crises impact on reputation management. *The Public Relations Journal, 49*(11): 48.

Phimister, I. R. (1973). The" Spanish" Influenza Pandemic Of 1918 And Its Impact On The Southern Rhodesian Mining Industry. *Central African Journal of Medicine, 19*(7): 8.

PricewaterhouseCoopers. (2020). *COVID-19 Impact Assessment*. Retrieved 10/03/2021 from https://www.pwc.com/vn/en/publications/vietnam-publications/economy-covid19.html

Raithel, S., Wilczynski, P., Schloderer, M. P., & Schwaiger, M. (2010). The value-relevance of corporate reputation during the financial crisis. *Journal of Product & Brand Management, 19*(6): 389-400.

Rassy, D., & Smith, R. D. (2013). The economic impact of H1N1 on Mexico's tourist and pork sectors. *Health economics, 22*(7): 824-834.

Sfakianaki, E., Iliadis, T., & Zafeiris, E. (2015). Crisis management under an economic recession in construction: the Greek case. *International Journal of Management and Decision Making, 14*(4): 373-389.

Šontaitė-Petkevičienė, M. (2014). Crisis management to avoid damage for corporate reputation: the case of retail chain crisis in the Baltic countries. *Procedia-Social and Behavioral Sciences, 156*: 452-457.

Tansey, P., & Spillane, J. P. (2014). Government influence on the construction industry during the economic recession 2007–2013.

The World Bank Group. (2020). *Global Economic Prospects*. Retrieved 11/11/2020 from https://openknowledge.worldbank.org/handle/10986/33748

The World Health Organization, W. (2020). *Coronavirus disease (COVID-19) pandemic*. Retrieved 19/12/2020 from https://www.who.int/emergencies/diseases/novel-coronavirus-2019

Torales, J., O'Higgins, M., Castaldelli-Maia, J. M., & Ventriglio, A. (2020). The outbreak of COVID-19 coronavirus and its impact on global mental health. *International Journal of Social Psychiatry*, 0020764020915212.

Truelove, S., Abrahim, O., Altare, C., Lauer, S. A., Grantz, K. H., Azman, A. S., & Spiegel, P. (2020). The potential impact of COVID-19 in refugee camps in Bangladesh and beyond: A modeling study. *PLoS medicine, 17*(6): e1003144.

Välikangas, L., & Lewin, A. Y. (2020). The lingering new normal. *Management and Organization Review, 16*(3): 467-472.

Van Tam, N., Huong, N. L., & Ngoc, N. B. (2018). Factors affecting labour productivity of construction worker on construction site: A case of Hanoi. *Journal of Science and Technology in Civil Engineering (STCE)-NUCE, 12*(5): 127-138. doi:https://doi.org/10.31814/stce.nuce2018-12(5)-13

Walker, P., Whittaker, C., Watson, O., Baguelin, M., Ainslie, K., Bhatia, S., Cattarino, L. (2020). The impact of COVID-19 and strategies for mitigation and suppression in low- and middle-income countries. *Science, 369*(6502): 413-422. doi:10.1126/science.abc0035

Xiong, J., Lipsitz, O., Nasri, F., Lui, L. M., Gill, H., Phan, L. Majeed, A. (2020). Impact of COVID-19 pandemic on mental health in the general population: A systematic review. *Journal of affective disorders*.

Yoo, S., & Kim, J. (2015). The dynamic relationship between growth and profitability under long-term recession: The case of Korean construction companies. *Sustainability, 7*(12): 15982-15998.

Zengeni, D. M., & Zengeni, N. (2012). Impact of HIV/AIDS to the tourism sector human resources: Case of selected hotels in Harare. *International Journal of Development and sustainability, 1*(3).

UTM UNIVERSITI TEKNOLOGI MALAYSIA

IJBES

**International Journal of Built Environment and Sustainability**
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 63-75

# Application of the INDI Model of the HQE²R Approach to Assess the Sustainability of a Neighbourhood: Case of Jijel City in Algeria

**Fouad Roula**
Research Laboratory LAUTr, Department of Architecture, Institute of Architecture and Town-Planning, University of Batna 1 Hadj Lakhdar, 05000, Batna, Algeria

**Ammar Bouchair**
Research Laboratory 'CBE', Department of Architecture, Faculty of Sciences and Technology, University Mohamed Seddik Benyahia, 18000, Jijel, Algeria

## ABSTRACT

Increased interest in developing sustainable urban areas has become an important feature in recent urban development studies. In fact, the question of neighbourhood sustainability assessment is a major part of this interest. Accordingly, a number of methods and tools for evaluating sustainable development projects in the urban areas have emerged particularly at district level. However, the urban development in Algeria is far from having achieved a clearly defined frame. This work therefore aims to demonstrate the contribution of sustainability assessment to any development project as well as the importance of the district level as a lever for local sustainable development. For this study, the district of the "Beach" formerly known as "Casino" located Jijel city centre, in Algeria, is chosen as a case study. We will focus on the assessment of its current state in relation to the principles and objectives of sustainable development, through a shared diagnosis of the Heritage, environmental Quality, Diversity, Integration, social Link (HQDIL) method and the INDicators Impact (INDI) model of the High Environmental Quality (HQE2R) approach. Along the same lines, a comparison between its initial state and the proposed development project by the land use plan study was made. The results obtained enabled us to draw up a detailed representation of each indicator on a sustainability scale. This led to deduce the degree of sustainability of the "Beach" district, thus to define the weak points, the strong points and to lead to a reflection on the issues and the action plan to be taken into account during a sustainable intervention on the latter. This work provides an aid to decision-making for researchers and urban actors, in order to orient urban development or renewal projects towards sustainability.

**Article History**

Received: 04 February 2021
Received in revised form: 02 May 2021
Accepted: 18 May 2021
Published Online: 31 August 2021

**Keywords:**

Sustainable, development, urban, district, assessment, INDI

**Corresponding Author Contact:**

fouad.roula@univ-batna.dz

**DOI:** 10.11113/ijbes. v8. n3.763



## 1. Introduction

In recent years, sustainable urban development strategies have become an interesting research field that has attracted the attention of a large number of researchers. This was motivated by a number of challenges that face the urban areas and cities in the future such as shortage of resources, atmospheric pollution, exploding technologies, climate change and global warming. However, the topic is far from having achieved its main goals especially when case studies meet the real context situations.

By its intermediate status between the building scale and that of the city, the district scale presents a unity and an entity on which the intentions of urban development should be focused to be sustainable. As stated by several authors the neighbourhood is defined as the relevant scale for any urban intervention (Catherine & OUTREQUIN, 2009a, 2009b; C Charlot-Valdieu & Outrequin, 2007; Dind, Thomann, & Bonard, 2007; Gagnon, 2012; Marconot, 2003). The neighbourhood is the place where the inhabitants live and is the social interaction environment (Dind et al., 2007). Certainly, the local and the often decisive scale. Da Cunha (2005) and C Charlot-Valdieu and Outrequin (2007) are based on the social component in their definition of the neighbourhood. They believe that the identity of a neighbourhood refers to the sociological context rather than the geographical one. Indeed, the neighbourhood remains the place where social ties are rebuilt, since it is at this level that the maximum social interactions are concentrated in a minimum amount of space and the place where the most profound manifestations of behaviour and lifestyles take place. In the same logic Bourdin(2003) emphasize on the district-city duality, stating that it is possible to believe that the city's production depends largely on that of its districts. On the other hand, Godard (1996) strongly criticizes this assumption according to which "for global development to be sustainable, it is sufficient that the development of each local space or urban ensemble is itself viable". This is not a question of transposing "generic" models (Da Cunha, 2011), but of providing specific responses for each territory.

In the light of the growing success of the concept of sustainable development and its variations, numerous reflections and research works are focusing on urban sustainability at the city, neighbourhood and even building levels (Ben Cheikh & Bouchair, 2004; Cherqui, 2005; Emelianoff, 2007; D Kaoula & Bouchair, 2018; Dalel Kaoula & Bouchair, 2019, 2020; Yepez-Salmon, 2011). Thus, confirming that it has become inevitable to reshape traditional urban policies and strategies. Today, the challenge is to ponder about the tools, mechanisms and devices to identify global problems at the at the local level, in particular that of the district. It has become clear that the district, the appropriate level of urban intervention, must take into account new global concerns, demands and issues, as well as the diversity of actors and lifestyles. In this context, assessment by indicators has become more generalised. Dahl (2008) listed more than 1200 reference systems in the field of the environment and sustainable development throughout the world. Indicator-based assessment is one of the means for implementing urban sustainability policies at the district level. Moreover, a system of indicators is a switch for moving towards sustainable development (C Charlot-Valdieu & Outrequin, 2004). Diagnosing the sustainable development of a district, therefore, leads to a certain number of relevant questions; the evaluation of which makes it possible to improve the decision-making process and provide "graphic representations" of the quality of life in the neighbourhood (Augiseau, 2009).

From the point of view of sustainable development, urban policies in Algeria have long been the subject of much criticism. Nowadays, it seems essential to wonder about the future of districts in Algerian cities in terms of urban sustainability, which has become a necessity than a choice. In the current alternative sustainable urban development trend, the sustainability assessment at the scales of the territory, city or district is intended to be a real urban management tool, a decision-making aid tool, or even a crucial means of moving towards sustainable urban development. In this sense, several questions arise, among others: What does an urban sustainability assessment system bring to the management and urban development of districts in Algerian cities? How SD elements can be integrated in urban planning?

Thus, this study focuses on assessing the sustainability of a neighbourhood using the HQDIL method and the INDI model of the HQE²R approach, based on a shared diagnosis of sustainable development in order to define the strengths, weaknesses, issues and envisioned actions.

This integrated HQE²R sustainable development approach was written by Philippe Outrequin and Catherine Charlot-Valdieu and developed by a group of 10 research centres and 13 cities in 7 European countries. Our choice fell on this method since it serves as an assessment of the situations carried out and of the project proposals as well as the possible evolution in the future, while ensuring a dialogue between the various partners of the project. On the other hand, this method does not exclude the neighbourhood analysis in its global context, namely that of the city and its inter-neighbourhood relationships.

The HQDIL method proposes a state of places which concern all the poles of SD (Economy, Environment, Social Aspects, Governance) as well as all the fields of analysis necessary for a neighbourhood, i.e. all the elements constituting the neighbourhood.

The INDI model is also a comparative tool which allows a prospective vision of a neighbourhood. In this sense, we tried to draw up a comparative profile between the development project proposed during the study of the land use plan study and the initial state of the district to assess the expected evolution of the latter and improve the project by identifying insufficiently treated targets.

Our objective through this article is to deduce the essential parameters which ensure the intervention on an existing neighbourhood to raise it to the rank of eco-neighbourhood, Thus to develop a new methodology to promote sustainable development and quality of life in the districts of Algerian cities.

## 2. Method and Materials

### *2.1 Description of Study Area*

The district chosen for the case study is “Beach” formerly called "Casino". It is located east of the city centre of Jijel City (Figure 1). It covers an area of 45 hectares with a population of 3400 inhabitants. This area is marked by a variety of collective and individual housing, as well as, tourist and bathing establishments. It contains some European style individual inhabitations dated from the colonial period that is qualified as urban heritage. In addition, it is considered as the main source of animation and attraction for the entire local population as well as for tourists from outside the city of Jijel, which clearly justifies our choice. is bordered on the north by the Mediterranean Sea. This district was chosen with the objective to identify the conditions of sustainable development in the context of the environmental qualities of the urban areas. The field investigation was based on a survey of sustainability judgements from a randomly chosen sample within the district.


**Figure 1** Aerial view of "Beach" district taken in 2020 (Source: World image altered with ArcGIS)

## 2.2 *The HQE²R approach and its tools:*

The HQE²R project has been materialized as an approach to sustainable development at the neighbourhood level (C Charlot-Valdieu & Outrequin, 2004). It is a tool to help project owners to integrate sustainable development into their work and to see the city from another perspective. This approach addresses the neighbourhood in connection with the city. This is because the neighbourhood cannot be analysed away of its framework.

The HQE²R approach as well as other international tools such as the SDGs, the city prosperity index, etc., is inspired by sustainable development in its logic. The specificity of this approach lies in the fact that it approaches the district level and goes up to the specifications of buildings and non-built elements while putting the citizen at the centre of the decision-making process. No scale is independent of the others, which justifies the choice of the HQE²R method, which is based on multi-scalar reasoning. The HQE²R approach is structured around the breakdown of an urban project into four phases: decision, analysis of the neighbourhood, development of the action plan, action and evaluation. For each of these phases, HQE²R suggests methods, tools or operational procedures to integrate the concept of sustainable development (Figure 2). This article sheds light more particularly on the second and third phases for which a system of indicators is applied. The analysis phase includes the preliminary inventory of fixtures, the collection of data, the carrying out of the diagnosis and then the determination of the development issues and the priorities of the action plan.

In this phase analysis, the HQDIL method is used to develop a shared diagnosis for the sustainable development of the neighbourhood together with the INDI model to complete the HQDIL diagnosis and graphically present the quality of life in the neighbourhood.

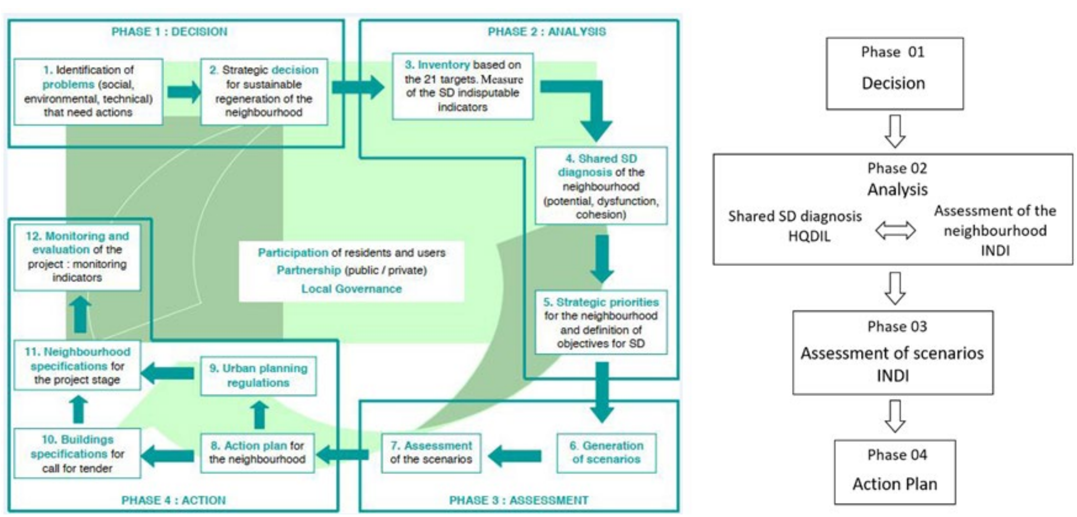



**Figure 2** HQE²R phases and integrated tools

### 2.2.1 The HQDIL method

The HQDIL (Heritage, Environmental Quality, Diversity, Integration, Social Link) method goes beyond the built environment and crosses four categories; residential buildings, non-residential buildings, building-free spaces and infrastructure with each of the 5 objectives and each of the 21 targets of the ISDIS (Integrated Sustainable Development Indicators System), in order to develop a shared diagnosis of sustainable development. This method is the tool for the HQE2R approach in the second phase of an urban project. It can be applied to any development or neighbourhood renewal project.

This analysis highlights the potentialities and strengths as well as the dysfunctions and weaknesses of the neighbourhood. The diagnosis should focus on the relationship between the neighbourhood and the rest of the city. The sustainable development of the city can only be guaranteed if that of each of the districts is ensured.

### 2.2.2 The INDI model

The INDI (INDicators Impacts) model was developed in 2002 by the ISDIS system of sustainable development indicators as part of the European HQE²R project of Philippe Outrequin , La Calade, in partnership with the project's various research teams. In 2005, within the framework of the European SUSI-Man project, an INDI vintage was developed for the French context (C Charlot-Valdieu & Outrequin, 2005). Since then, this reference system has been regularly improved for various development projects. The neighbourhood like the city as a complex system, it requires in its assessment a system of indicators. Accordingly , INDI is a system of indicators and not a set of indicators (Catherine Charlot-Valdieu & Outrequin, 2012). This means that the set of indicators constitutes a one-to-one coherent system. In other words, insofar as this selection of indicators forms an inseparable whole, although it can be completed by depending on the local context. The objective of the INDI model is to help project owners in the evaluation of a territory, a renewal or development project, by integrating sustainable development criteria and objectives. Although it is designed for urban renewal projects, INDI currently can be used for any urban project, in order to improve the decision-making process, to improve the quality of life of the inhabitants and to present it graphically.

The ISDIS system includes 61 indicators that aim to meet the sustainable development objectives of a district. According to C Charlot-Valdieu and Outrequin (2005), each indicator is evaluated individually for a district, in relation to the initial situation and the evolution envisioned within the framework of a project or scenario. This number of indicators appears to be a compromise between a detailed description of the neighbourhood and the project and a capacity to constitute a decision-making tool. That is also a tool for dialogue and even consultation. This model can be adjusted to the context of the application. For our case, the French example, which contains 73 indicators, is the nearest to our context.

This model allows an assessment in two parts. The first consists of an analysis with regard to the 21 sustainability targets and 73 sub-targets. The second is based on the 5 sustainability objectives (table 1). Indicators are tools for analysis, evaluation and monitoring that can be useful during the different phases of an urban project.

**Table 1** 5 objectives, 21 targets and 73 indicators

| SD Objectives | SD Targets | Indicators |
|---|---|---|
| To preserve and enhance Heritage and conserve resources | Energy | 1A - 1B -1C- 1D - 1E - 1F - 1G - 1H |
| | Water | 2A- 2B - 2C- 2D - 2E |
| | Urban space | 3A - 3B - 3C - 3D |
| | Materials | 4A - 4B |
| | Heritage | 5A - 5B |
| To improve the Quality of the local environment | Landscape and visual quality | 6A - 6B |
| | Built quality and spaces | 7A - 7B - 7C - 7D |
| | Hygiene and health | 8A - 8B - 8C- 8D |
| | Security and risks | 9A - 9B - 9C - 9D |
| | Air quality | 10A - 10B - 10C |
| | Noise | 11A - 11B - 11C |
| | Waste | 12A - 12B |
| To ensure Diversity | Diversity | 13A - 13B - 13C |
| | Urban mixity | 14A - 14B - 14C |
| | Housing diversity | 15A - 15B – 15C |
| To improve Integration | Education | 16A - 16B – 16C |
| | Accessibility | 17A – 17B – 17C |
| | Integration | 18A – 18B – 18C |
| | Mobility | 19A - 19B- 19C- 19D- 19E - 19F |
| To reinforce social Link | Participation | 20A – 20B |
| | Social capital | 21A - 21B - 21C - 21D |

The INDI model uses excel as a tool for assessment based on quantitative and qualitative parameters. The software encompasses four pages: « inputs », «calculation », «analysis» and « results » (figure 3). The indicators are grouped in targets and then into sustainable development objectives. The first page of inputs is presented in the form of a questionnaire concerning the 73 indicators of the model. The exhaustive definition of these indicators is presented in an assessment guide. For each indicator, a quantitative or a qualitative assessment is requested. In the absence of quantitative information a comment is required in order to provide a qualitative response in all cases (Braulio-Gonzalo, Bovea, & Ruá, 2015; Chaguetmi & Derradji, 2019).

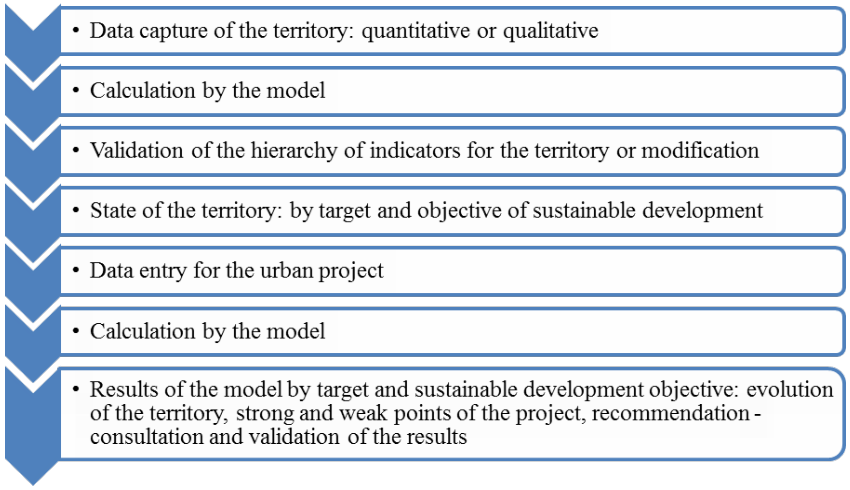



**Figure 3** Steps in using the INDI model. (Source : www.crdd-lacalade.com)

**Table 2** Calculation process of the INDI model (Target 3)

| Objectives | targets | N | Benchmark Unit | Meaning of sustainability | Weighting Coefficient | Site Data | Sustaina bility Weight | Measure ment source |
|---|---|---|---|---|---|---|---|---|
| H | 3A | 1 | a/m/mf | / | 3 | m | 4 | calculation |
| | 3B | 2 | 40m² | increasing | 3 | 6m² | 0 | Calculation and diagnosis |
| | 3C | 3 | 0% | descending | 3 | 0 | 10 | diagnosis |
| | 3D | 4 | 18 | increasing | 2 | 0 | 0 | diagnosis |
| | Sustainability Index Target 3 = 3.81 | | | | | | | |

Following this entry, each indicator is assigned a sustainability function ranging from 0 to 10. The lower value (0) is assigned to the worse situation and the higher (10) to the ideal situation (Figure 4). The development of the sustainability function is defined by a curve and depends on the definition of "benchmark" or target values that allow an indicator to be considered as moving or not towards sustainability. This multitude of indicators refers to the fact that the city is a complex system that should not be reduced to a grid of streets or built elements. The weighting given to each indicator depends on its importance in relation to the previously outlined and targeted objectives. Indicators must be measured using effective and reliable information (Table 2).

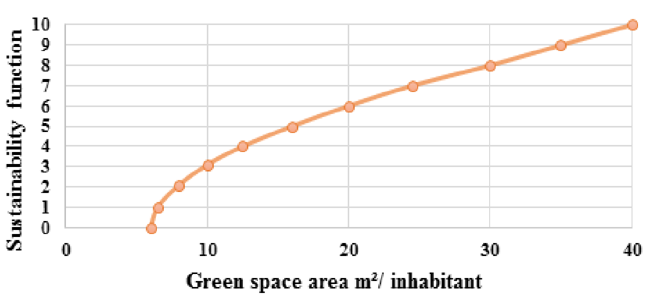



**Figure 4** An example of how to determine indicator value (3B) on the sustainability scale. (Source: www.crd-lacalade.com)

We choose weighting by the scoring method: distribution of 3 points:

- Three points: Situations believed critical
- Two points: Urgent situations requiring short and medium-term interventions;
- One point: situations requiring improvement over time.

$$\text{Sustainability Index Target} = \frac{\sum(\text{Sustainability Weight} \times \text{Weighting Coefficient})}{\sum \text{Weighting Coefficient}}$$

$$\text{Sustainability Index objective} = \frac{\sum(\text{Sustainability Index Target})}{\text{nombre of target}}$$

#### 2.2.3 The Questionnaire

From a sustainable development perspective, an inventory of fixtures or a shared diagnosis must be carried out by seeking the participation of the inhabitants and users of the district. This stage fully participates in a good evaluation of the existing situation and the definition of an action plan and priority targets for intervention.

Some indicators calculation of the INDI model requires a survey among the inhabitants and visitors of "Beach" district in Jijel City. For this purpose, we have chosen to base our survey on a questionnaire which is subdivided into 3 aspects: form, function and ecology. A population of 250 persons is randomly selected from a total population of 3400 inhabitants of the neighbourhood in question. A confidence level of 95% and a margin of error of 6% is considered. The questions asked concern the following indicators: part of trips made by public transport, part of walking and cycling, part of the population committed to sustainable development initiatives in the district, part of the population participating in community activities or solidarity and presence of activities in the field of the local economy. The responses to the questionnaire were then transferred into the SPSS software for statistical analysis. These results are then translated to a durability weight that varies between 0 and 10 depending on a benchmark value (ideal value provided by the INDI model)

## 3. Results and Discussion

### *3.1 Results of HQDIL Analysis*

The current situation analysis of the neighbourhood was made by crossing four categories namely: Residential space: (habitat), non-residential space: (public facilities, services and activities), non-built space (green spaces, woods and all natural areas), Infrastructures and networks (roads, streets, sidewalks and networks) with physical structures of the neighbourhood and their uses. The results obtained through the application of the HQDIL analysis grid are presented in the table 3.

**Table 3** Casino neighbourhood analysis by HQDIL method

| Element of district | Structure | Use |
|---|---|---|
| Residential space | -Housing Park: composed of 20% individual housing and 80% collective housing.<br>-The condition of the built environment: in good condition (bad 5%)<br>-The built environment of the site houses a layout of the French colonial period of individual housing type. | -The population of the neighbourhood is characterized by extreme youth and a more or less high birth rate<br>-The sex ratio is more or less balanced with a slight advantage for the male sex<br>-A resident population with a diverse social level<br>-Profession: 68.2% public sector and 32.4% private sector<br>-Drinking water consumption of 93 l/day/inhabitant |
| Non-residential Space | -The neighbourhood gathers a diversity of cultural, educational, administrative and other sports facilities.<br>-Presence of communal equipment: stadium, railway station and clinic | -The diversity of equipment has resulted in a diversity of uses and visitors<br>-The diversity of equipment contributes to social cohesion and provides a flow of capital and information<br>- This diversity is mainly aimed at satisfying the needs of the inhabitants but also to meet the needs of the population of the whole city |
| Non-built space | -Green space area: 6m²/inhabitant<br>-Lack of relaxation areas for young and old people | Use: low utilization<br>Cleanliness: degraded condition, poorly maintained<br>Security: more or less ensured |
| Infrastructure | -Good public transport service<br>-Good road conditions | -Mechanical mobility: strong dependence on the private car<br>-Mild mobility: low |

### *3.2 Results of the Application Of The INDI System*

Table 4 and figure 5 show the results of the assessment of the sustainability of the "Beach" district with the INDI model in relation to 73 indicators. This allowed us to assess the current situation of the site in relation to the different dimensions of sustainable development. In this graph we can see those indicators: 2A, 3C, 8D, 9A, 10B, 10C,.19D are located in the range of strong sustainability (exceed the average) with scores above the reference value. Whereas, the indicators: 2E, 3A, 8A, 19C, 19F are sustainability averages lying between 4 and 6. The situation of the latter is not considered critical, while indicators 1A, 1B, 1C, 2C, etc. are of low sustainability (or non-sustainability situation). Urgent actions must be taken to address these. Table 4 shows the sustainability level of "Beach" district using INDI model with reference to 73 indicators.

**Table 4** Sustainability level of "Beach" district using INDI model according to 73 indicators.

| | |
|---|---|
| High sustainability | 2A, 3C, 8D, 9A, 10B, 10C, 11A, 13A, ,13C, 14B, 14C, 16A, 16B, 16C, 17A,18A, 18B,19B, 19D |
| Medium | 2E, 3A, 3B, 8A, 8B, 11B, 13B, 14A, 18C, 19C, 19F |
| Low sustainability | 1A, 1B, 1C, 1D, 1E, 1F, 1G, 1H, 2B, 2C, 2D,3D,4A,4B,5A,5B,6A,6B,7A,7B,7C,7D,8C,9C,9D,10A,11C,12A,12B, 17B,17C,19A,19E,20A,20B,21A,21B,21C,21D |

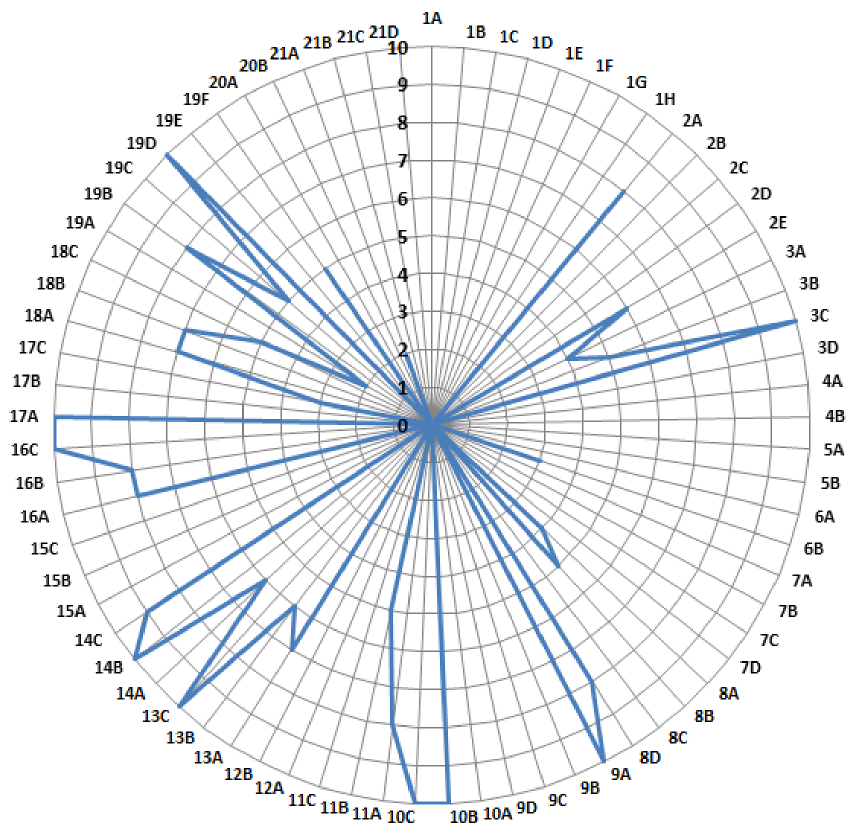



**Figure 5** Radar diagram for the analysis of the "Beach" district in relation to the 73 indicators.

It should be noted that if certain indicators are not taken into consideration in the evaluation, it is because they may not be an object of thinking. Figure 6 shows the sustainability profile of the neighbourhood by the 21 INDI model targets. It can be noted that the targets: energy management, water management, space management, materials management, heritage preservation, landscape preservation, housing quality, hygiene and health, safety, waste management, employment, social cohesion, solidarity, are low sustainability targets (less than 4). Therefore, we must act on them. While the targets for medium sustainability between (4-6) are: noise pollution and mobility. On the other hand, the targets: air quality, population diversity, function diversity, education and attractiveness are of high sustainability.

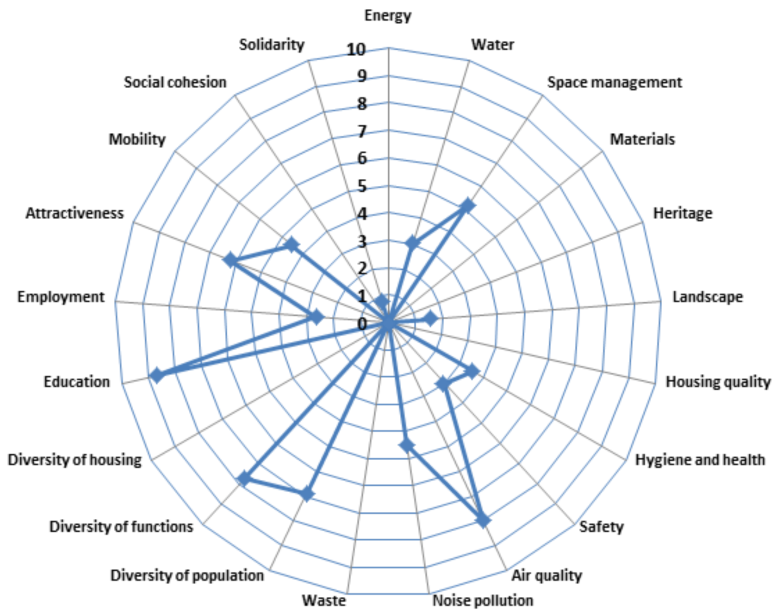



**Figure 6** Radar diagram of the "Beach" district analysis with respect to the 21 SD targets.

Figure 7 and table 5 show the assessment of the neighbourhood in relation to the five objectives of sustainable development. It is noticeable that social cohesion is the first objective to be achieved. To achieve this, social cohesion must be strengthened by involving the population in the management of their district. The second objective is to preserve and enhance the heritage and conserve resources. Therefore, it is necessary to carry out actions for the preservation of the historic built heritage of the district. The third objective is to improve the quality of the local environment, since the neighbourhood does not perform sufficiently well in terms of environmental resources and does not meet urban management criteria.

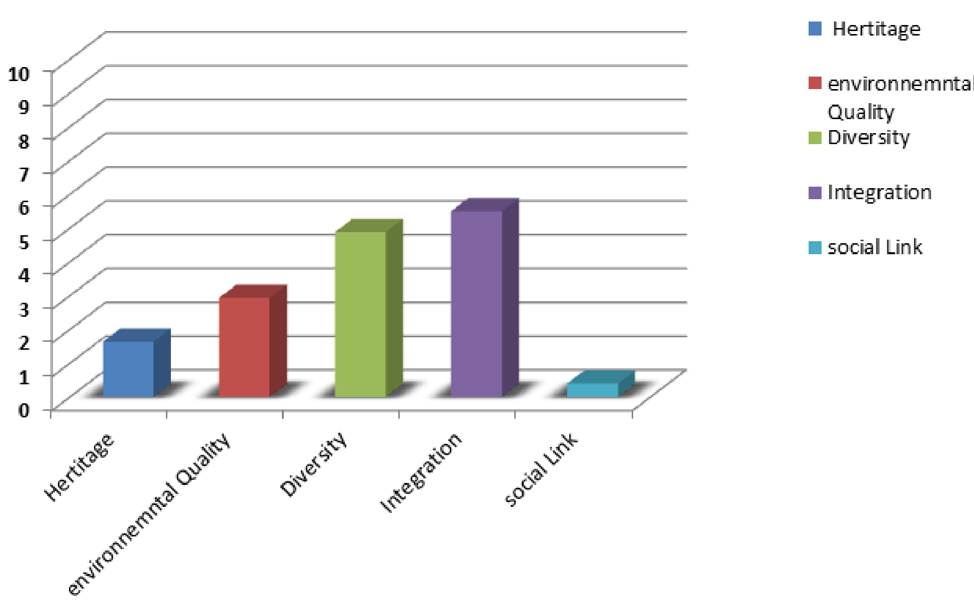



**Figure 7** Analysis of the "Beach" district with regard to the 5 objectives of sustainable development.

**Table 5** Weaknesses and potentialities of the" Beach" district according to the 5 aspects of SD

| Aspect | Weaknesses | Potentialities |
|---|---|---|
| Resources | -Total lack of use of renewable energy sources<br>-High residential water consumption and poor storm-water management.<br>-Insufficient surface area of public green spaces for inhabitants<br>-Absence of an environmental quality approach for building materials<br>-Natural and architectural heritage set aside | Programming the use of solar energy for educational buildings |
| Environmental | -Poor visual quality and maritime pollution caused by *the wadi el kantara* flowing directly into the sea.<br>-Existing housing stock of poor quality<br>-Neglect of PMKs in neighbourhood developments<br>-Public space poorly maintained<br>-Noise pollution during the summer season (RN43 and avenue Benboulaid)<br>-Poor waste management and lack of selective sorting | -Good accessibility to the site from several entrances.<br>- The proximity of our study area to the city and its opening to the sea (attractiveness)<br>- Security and medical supply |
| Diversity | -Low employment rate | -Presence of commercial activity<br>-Good distribution of equipment and utilities |
| Integration | -High unemployment rate<br>-Modes of transport not compatible with social and environmental concerns | -Population diversity by age groups<br>-Presence of equipment of communal interest<br>-Use of public transport |
| Social | -A lack of coordination and consultation between the authorities and the inhabitants.<br>- Lack of involvement of residents in community activities<br>-No solidarity association in the district | -A strong willingness on the part of the inhabitants to commit to sustainable development initiatives. |

### *3.3 Comparative Study of The Proposed Development Project with The Neighbourhood Situation*

Figure 8 illustrates the results of a comparative study of the proposed development project (in the land use plan study) with the neighbourhood situation, on the one hand, and with the sustainable development targets on the other.

From an initial coverage of sustainable development targets in the "Beach" district expressed by a blue line, the red surface corresponds to the expected impacts of a proposed development project for the district. This has enabled us to demonstrate the project's contribution to the expected improvement of the neighbourhood (comparison between the initial state and the proposed project) in order to have a prospective vision of the later.

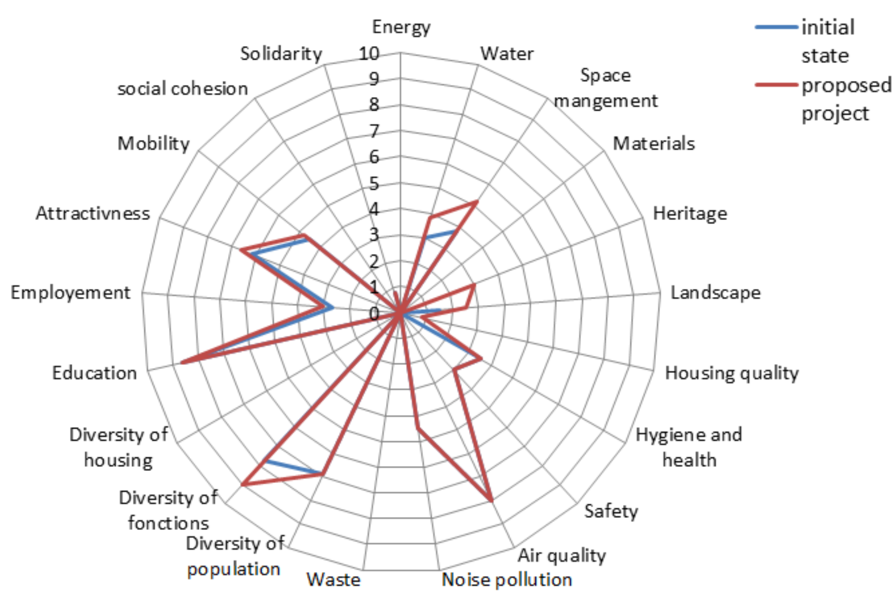



**Figure 8** Assessment of the project with regard to the 21 sustainable development targets

In addition to the previous figure, figure 9 illustrates the improvements expected for the neighbourhood thanks to the project for each of the 21 sustainable development targets: for the buildings in the neighbourhood as well as for the development of the district. Project gains or expected improvements concern the following targets: water, land management, heritage, landscape, quality of housing, diversity of functions, employment; attractiveness and mobility.

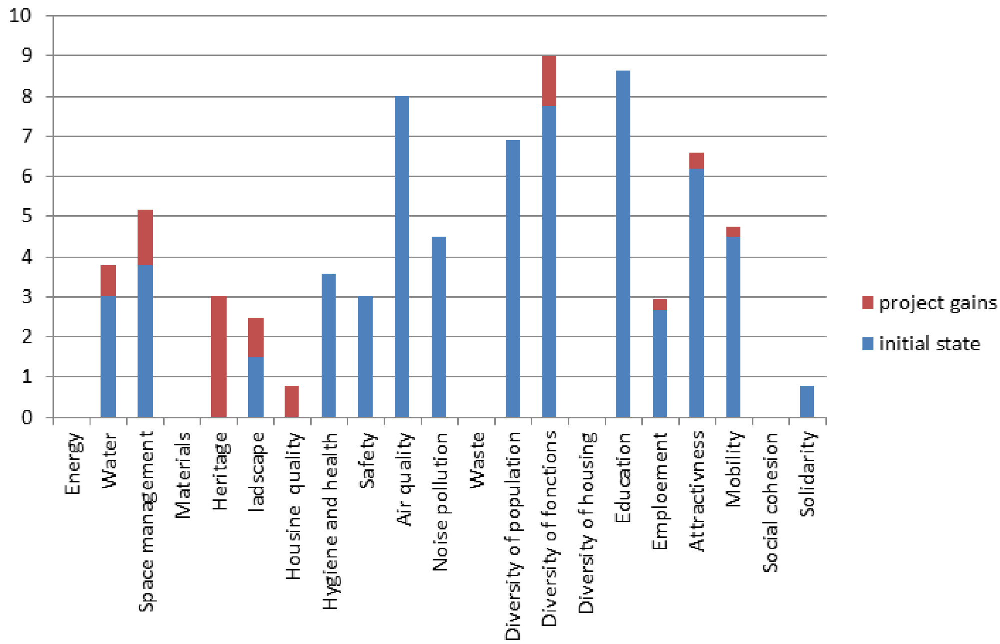



**Figure 9** The gains of the improvement project for each of the sustainable development targets

Figure 10 is a representation of the results of a comparative study of the proposed development project (in the land use plan study) with the neighbourhood situation, on the one hand, and with the objective of sustainable development on the other.

In terms of sustainable development objectives, the project proposed during the revision of the land use plan study does not really bring a significant improvement. The planned actions remain one-off and only bring superficial gains.

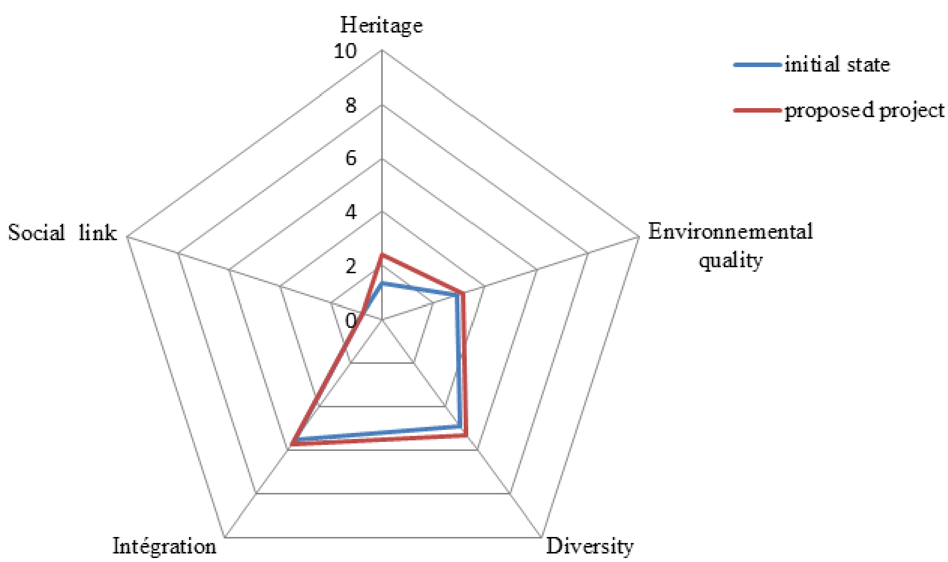



**Figure 10** Analysis of the improvement project with regard to the 5 objectives of sustainable development

## 4. Stakes and Actions

After having established a shared diagnosis of the neighbourhood and defining the local issues in order of priority, the next phase (phase 4 of the HQE²R approach) consists in establishing a program or an action plan with the strategic orientations and the measures to be taken, as well as the constraints to be respected. Then, specific recommendations will be proposed in order to take into account sustainable development in urban planning.

### *4.1. Preserve And Enhance The Heritage And Resources*

#### 4.1.1. Moving Towards Renewable Energies

The aim here is to preserve exhaustible resources and reduce greenhouse gas emissions by using renewable energy sources such as solar, wind, etc. These ambitious objectives require a solid reflection towards a policy of energy efficiency and a bioclimatic approach during development and renovation.

#### 4.1.2. Sustainable Management Of Water Resources

Sustainable management of potable water at the neighbourhood level involves a number of techniques: individual metering, double water meters (rainwater meters), and water-saving devices, use of a separate system for rainwater and household water… etc.

Rainwater harvesting present also a growing interest to cope with increasing soil sealing and flooding problems. Potholes, ditches, vegetated flat roofs; drainage and infiltration trenches; basins, underground tanks, porous materials (concrete paving, grass slabs);.Etc. are all techniques available today to promote rainwater collection and preserve the permeability of the soil in relation to the characteristics of the site and its potential on the environmental level..

#### 4.1.3. Reconciling Density And Quality Of Life

Density should be studied at the neighbourhood level in order to reduce space, and energy consumption. Indeed, better density refers to a controlled architectural design, social mix, functional diversity, and enhancement of public or private outdoor space.

#### 4.1.4. Differentiated Management Of Green Spaces

Within a district, the vegetation of residual areas and the implementation of facilities that are favourable to the fauna and the flora improve the living environment of the occupants. In addition, preserving existing natural areas and linking them together by ecological corridors allow different biotopes to develop and maintains biodiversity and landscape quality.

The majority of the roofs in the "Beach" district favour the use of vegetation. In this context, roof vegetation should be considered for any non-accessible flat roof of more than 50 m². Thanks to their composition, green roofs make it possible to delay rainwater runoff and reduce ventilation needs by 20% to 30%.

#### 4.1.5. Ecomaterials

An eco-construction also aims to integrate and optimize the use of local and renewable materials throughout the life cycle of the building while respecting the environment and public health. Materials that require a minimum of exhaustible resources and generate the least amount of waste are preferred.

#### 4.1.6. Preserving the Built And Natural Heritage

A process of a redevelopment or urban renewals of an old neighbourhood must take into account the particularities and specificities of the existing heritage. Indeed, the urban layout of the colonial period in the northern region is an added value for the district, thus improving its attractiveness. This includes: improving the technical quality of historic buildings, rehabilitating the built and natural heritage with tourist and cultural attributes, and improving the visual quality of the facades and the urban landscape.

### *4.2. Improving the Quality Of The Local Environment*

#### 4.2.1. Improving the Quality Of Housing:

The quality of housing depends largely on: the choice of non-polluting and ecological materials, the thermal and acoustic comfort of the buildings, the energy performance and insulation of facades, etc.

#### 4.2.2. Fight Pollution

The challenge is to combat pollution without compromising the pursuit of economic and social development. This problem goes well beyond the boundaries of the district, since its impact is on a larger scale, but the solutions begin with the ordinary citizen, the person primarily responsible for the pollution.

#### 4.2.3. Sustainable Waste Management

The aim is to reduce the amount of waste produced within the neighbourhood and to ensure better waste management by raising awareness among the population. At this level, waste must be thought of in terms of selective collection, sorting, treatment and recycling.

### *4.3. Improving Diversity*

#### 4.3.1. Diversity of Functions

The mix of functions (housing, work, entertainment, etc.) at the district level clearly justifies the concern of the density and for limiting transportation needs, on the one hand, and reducing energy consumption on the other. This implies strengthening local services and linking the centres around soft modes of transport.

#### 4.3.2. Quality of Equipment

Ensuring a balanced supply of local facilities is a prerequisite for maintaining social cohesion. Moreover, the quality of facilities within a neighbourhood goes hand in hand with meeting the needs of its inhabitants.

#### 4.3.3. Housing Diversity

Offering a varied typology of housing in terms of size, use and occupation contribute strongly to the development of social links and solidarity between the inhabitants. Of course, a balanced housing offer must be able to address all social categories and meet their needs and aspirations.

### *4.4. Improving Integration*

#### 4.4.1. Unemployment and Employment

Like the environmental aspect, social and economic issues need to be given special attention at the district level. Providing employment for people in difficulty is an indicator of better integration of the neighbourhood into the dynamics of the city. The aim here is to ensure social reintegration with a view to an appropriate distribution between the active and inactive populations.

#### 4.4.2. Quality Public Spaces

The challenge in the design of public spaces is to offer places for sharing and social mixing by excellence. The district's public spaces must offer a multiplicity of uses, quality, comfort, and attractiveness while taking into consideration the needs of the inhabitants and particular modes of appropriation.

#### 4.4.3. Encouraging Soft Mobility

The need to control individual motorized travel and to promote soft modes of transport is no longer in evidence. Admittedly, the organization of the neighbourhood must be based on a global transport policy favouring urban renewal, the diversification of functions, and a good interconnection of non-polluting means of transport (alternative fuel vehicles), although this implies greater coordination of the actors involved in planning and transport service.

### *4.5. Strengthening Social Bond*

#### 4.5.1. Promoting "Living Together"

Based on the design of collective spaces, green spaces, meeting spaces, etc., we must take into account ensuring social cohesion, symbolic meaning, local identity, and urbanity while promoting "living together" between the individual and others.

#### 4.5.2. Participation and Local Governance

The success and the acceptance of a sustainable development project by its inhabitants refer to the integration of the latter in all the studies and design stages as well as in the process of post-occupational management. Certainly, the development of a culture of participation and co-decision are the conditions for the establishment of a climate of trust between the inhabitants and the decision-making sphere.
The sustainability of this approach is encouraged by the creation of a "participation plan" for associations, training, information, and awareness workshops.

## 5. Conclusion

The assessment of urban sustainability is a key element upstream of any urban development or renewal operation. In addition, ensuring the effectiveness of the implementation of urban policies at the district level must be supported by sustainability assessment tools. The main objective of our work was to assess the "Beach" district in terms of sustainability by defining its weak points, its strengths and the action plan to be taken into account during a sustainable intervention. The results showed that the degree of sustainability of our case study is relatively low. Of the 21 Sustainable Development Goals, 13 are considered unsustainable. On the other hand, the evaluation of the scenario of the proposed project against its current state brought only superficial gains. On the basis of these results, we are able to identify the priority action areas and recommendations for urban actors in order to contribute to the decisions taken for each urban development or renewal project. This study outlines the urban policies that should be applied. These results have vast advantages for the development of reflections on the integration of the principles of sustainable development and assessment tools in the urban domain. From an empirical point of view, the contribution of this study is to pay particular attention to the future of Algerian cities and their districts, in order to solicit the thought to find adequate alternatives. It is important to review and rethink the current planning policy in concrete terms in order to come up with new forms of "living differently", which is part of a logic of continuous improvement; open to evolution and local democracy.

## References

Augiseau, V. (2009). Outils au service des projets de quartiers durables. *Rapport de l'action de recherche A, 18:* 11-15.

Ben Cheikh, H., & Bouchair, A. (2004). Passive cooling by evapo-reflective roof for hot dry climates. *Renewable Energy, 29*(11): 1877-1886.

Bourdin, A. (2003). *Urbanisme et quartier. Ce que nous apprend Paris Rive Gauche*: Association Terrain.

Braulio-Gonzalo, M., Bovea, M. D., & Ruá, M. J. (2015). Sustainability on the urban scale: Proposal of a structure of indicators for the Spanish context. *Environmental Impact Assessment Review, 53*: 16-30.

Catherine, C.-V., & OUTREQUIN, P. (2009a). Ecoquartier: Mode d'emploie. *Editons Eyrolles*. Paris, France.

Catherine, C.-V., & OUTREQUIN, P. (2009b). L'urbanisme durable. *Concevoir un écoquartier, Paris, Le Moniteur*. France

Chaguetmi, F., & Derradji, M. (2019). Assessment of the environmental quality of districts in the context of sustainable development: case of the Plain West in Annaba, Algeria. *Environment, Development and Sustainability*, 1-26.

Charlot-Valdieu, C., & Outrequin, P. (2004). Synthèse sur la démarche HQE²R de transformation durable d'un quartier, et Les outils de la démarche HQE²R, Volume HQE²R n 2. La Calade, France.

Charlot-Valdieu, C., & Outrequin, P. (2005). Des indicateurs de developpement Durable pour l'evaluation des Projets de renouvellement urbain: Le modele INDI-RU. *RU-2005, Ed. La Calade*.

Charlot-Valdieu, C., & Outrequin, P. (2007). La démarche HQE2R: des outils d'analyse pour des projets de quartiers durables. *Urbia, Les Cahiers du développement urbain durable.* (4): 193-209.

Charlot-Valdieu, C., & Outrequin, P. (2012). *Concevoir et évaluer un projet d'éco-quartier: avec le référentiel INDI.* Le Moniteur, Paris.

Cherqui, F. (2005). *Méthodologie d'évaluation d'un projet d'aménagement durable d'un quartier-méthode ADEQUA.* Université de La Rochelle, France.

Da Cunha, A. (2005). Régime d'urbanisation, écologie urbaine et développement urbain durable: vers un nouvel urbanisme. *Enjeux du développement urbain durable: transformations urbaines, gestion des ressources et gouvernance*, 12-38.

Da Cunha, A. (2011). Les écoquartiers, un laboratoire pour la ville durable: entre modernisations écologiques et justice urbaine. *Espaces et sociétés.* (1): 193-200.

Dahl, A. L. (2008). Overview of environmental assessment landscape at national level: State of state-of-the-environment reporting: Note by the Executive Director. UNEP/GC. *UNEP/GC, 25*.

Dind, J.-P., Thomann, M., & Bonard, Y. (2007). Structures de la ville, quartiers durables et projet urbain: quelles articulations? *Urbia, 4*: 49-75.

Emelianoff, C. (2007). Les quartiers durables en Europe: un tournant urbanistique? *Urbia–Les cahiers du développement durable, 4*: 11-30.

Gagnon, C. (2012). CHARLOT-VALDIEU, Catherine et OUTREQUIN, Philippe (2011) L'urbanisme durable. Concevoir un écoquartier (2e édition). Paris, Éditions Le Moniteur, 312 p.(ISBN 978-2-281-19501-9). *Cahiers de géographie du Québec, 56*(157): 247-248.

Godard, O. (1996). Le développement durable et le devenir des villes: bonnes intentions et fausses bonnes idées. *Futuribles*(209): 29-35.

Kaoula, D., & Bouchair, A. (2018). Evaluation of environmental impacts of hotel buildings having different envelopes using a life cycle analysis approach. *Indoor and Built environment, 27*(4): 561-580.

Kaoula, D., & Bouchair, A. (2019). The pinpointing of the most prominent parameters on the energy performance for optimal passive strategies in ecological buildings based on bioclimatic, sensitivity and uncertainty analyses. *International Journal of Ambient Energy*, 1-28.

Kaoula, D., & Bouchair, A. (2020). Identification of the best material-energy-climate compatibility for five ecological houses and the contribution of their impact sources to the overall balance. *Sustainable Cities and Society, 52*: 101781.

Marconot, J.-M. (2003). La fin des villes, la durée des quartiers. *Natures Sciences Sociétés, 11*(3): 266-275.

Yepez-Salmon, G. (2011). Construction d'un outil d'évaluation environnementale des écoquartiers: vers une méthode systémique de mise en oeuvre de la ville durable. Thése de Doctorat. *Université Bordeaux, 1*. France.

UTM UNIVERSITI TEKNOLOGI MALAYSIA

IJBES

**International Journal of Built Environment and Sustainability**
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 77-92

# Assessing The Thermal Comfort Conditions In Open Spaces: A Transversal Field Survey On The University Campus In India

**Pardeep Kumar**
Department of Mechanical Engineering, Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonepat-India

**Amit Sharma**
Department of Mechanical Engineering, Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonepat-India

**ABSTRACT**

Outdoor thermal comfort (OTC) promotes the usage frequency of public places, recreational activities, and people's wellbeing. Despite the increased interest in OTC research in the past decade, less attention has been paid to OTC research in cold weather, especially in arid regions. The present study investigates the OTC conditions in open spaces at the campus area in the arid region. The study was conducted by using subjective surveys(questionnaire) and onsite monitoring (microclimate parameters). The study was conducted at the Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Haryana-India campus during the cold season of 2019. The timings of surveys were between 9:00 and 17:00 hours. The authors processed the 185 valid questionnaire responses of the respondents to analyze OTC conditions. Only 8.6% of the respondents marked their perceived sensation "Neutral." Regression analysis was applied between respondents' thermal sensations and microclimate parameters to develop the empirical thermal sensation model. The air temperature was the most dominant parameter affecting the sensations of the respondents. The empirical model indicated that by increasing air temperature, relative humidity, and solar radiation, the thermal sensations also increased while wind speed had an opposite effect. Physiological equivalent temperature (PET) was applied for assessing the OTC conditions; the neutral PET range was found to be 18.42-25.37°C with a neutral temperature of 21.89°C. The preferred temperature was 21.99 °C by applying Probit analysis. The study's findings could provide valuable information in designing and planning outdoor spaces for educational institutions in India's arid regions.

**Article History**

Received: 02 March 2021
Received in revised form: 27 June 2021
Accepted: 28 June 2021
Published Online: 31 August 2021

**Keywords:**

Outdoor thermal comfort, PET, Thermal sensation vote model, Cold season, Thermal stress

**Corresponding Author Contact:**

amitsharma.me@dcrustm.org

**DOI:** 10.11113/ijbes. v8. n3.786



## 1. Introduction

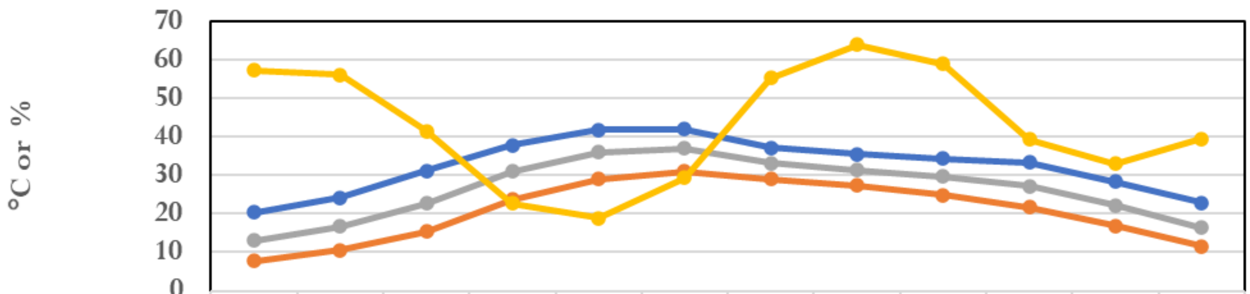
With climate change, the globe's population suffers from extreme weather events(Li & Zha, 2020). The availability of conducive OTC conditions is necessary to be a sustainable, liveable outdoor space (Altunkasa & Uslu, 2020). Urban livability relates to the early 1980s due to climate change and growing competition among the world's economies to attract investors and tourists (Kashef, 2016). Climate change negatively impacts cities' livability status (Fong, Aghamohammadi, Ramakreshnan, Sulaiman, & Mohammadi, 2019; Nazarian, Sin, & Norford, 2018) as urbanization is increasing rapidly, which causes a reduction in urban green spaces and changes in microclimate. So, the population can experience harsh weather conditions in open urban areas (Ketterer & Matzarakis, 2014; Kong et al., 2017). Due to this, the urban population prefers to stay indoors and is bound to opt for sedentary lifestyles (Salata et al., 2018). Urban planners have a big task to encourage people to use outdoor spaces, which are essential from social, environmental, and health perspective (Shooshtarian & Ridley, 2016). The urban areas' microclimate impacts the open spaces' usability frequency (Ali & Patnaik, 2018). The outdoor thermal environment's development promotes public places and ultimately improves life quality (Smith & Henríquez, 2019). Physiological and psychological health is directly linked to outdoor activities (Jianlei Niu et al., 2015; Yao, Yang, Zhuang, Shao, & Yuan, 2018). In the last decade, outdoor thermal comfort gaining more attention through microclimate studies conducted in many parts of the world; this gain is happening even though there are complex unsteady outdoor conditions. However, outdoor thermal comfort studies are still far less than indoor studies (Amindeldar, Heidari, & Khalili, 2017). Over the century, researchers were developed thermal comfort indices to evaluate the thermal environment(both indoor and outdoor) (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016; de Freitas & Grigorieva, 2017; Johansson, Thorsson, Emmanuel, & Krüger, 2014; Pardeep Kumar & Sharma, 2020; Potchter, Cohen, Lin, & Matzarakis, 2018). Although thermal comfort indices are used to evaluate the thermal environment, ultimately, it relates to the impact on the human occupant (Kumar and Sharma., 2020).

Thermal comfort indices were developed based on a single node, two-node, and multiple node models to determine comfort conditions. One node model is based on the heat balance equation. It can be calculated by giving input of six basic parameters, i.e., air temperature, mean radiant temperature, relative humidity, wind speed, clothing, and metabolic rate. The two-node model includes the effects of skin temperature and core temperature on the heat balance. In the multi-node model, the whole human body was divided into many sections to consider the effect of skin temperature, core temperature, and rate of change of skin temperature on heat balance (Fang, Feng, et al., 2019).The use of thermal indices is essential to assess human thermal comfort conditions (Coccolo et al., 2016; Hirashima, Katzschner, Ferreira, Assis, & Katzschner, 2018). Several thermal comfort indices were developed intended for the outdoor environment (Coccolo et al., 2016; de Freitas & Grigorieva, 2017; Johansson et al., 2014; Pardeep Kumar & Sharma, 2020; Potchter et al., 2018). PET is the most frequently used thermal index to evaluate the OTC conditions (Kumar and Sharma., 2020). PET was developed based on the two-node model, which includes skin and core temperature of the human body(Höppe, 1999).In the previous studies, the study area selected was public open or semi-open outdoor spaces. According to the study of (Canan, Golasi, Ciancio, Coppi, & Salata, 2019), university campuses have always played a significant role in investigating outdoor thermal comfort conditions for various landscapes because of the availability of plenty of open spaces and semi-open spaces that provide ample space for outdoor activities. In the past decade, several researchers carried out OTC studies to examine the university campus's comfort conditions in different climate zones globally; those studies are given in Table 1. It was inferred from the literature survey that none of the studies (to the best of the author's belief) investigated the hot semi-arid(Bsh) climate zone in the winter season at the campus area.

**Table 1** OTC studies carried out at various university campus

| Source | Location | Climate | Season | Sample size |
|---|---|---|---|---|
| Xi et al.,(2012) | Guangzhou, China | Humid subtropical (Cfa) | Summer | 114 |
| Makaremi et al., (2012) | Malaysia | Tropical rainforest(Af) | Spring | 200 |
| Liu et al., (2016) | Changsha, China | Humid subtropical (Cfa) | Summer& Winter | 7851 |
| Zhao et al., (2016) | Guangzhou, China | Humid subtropical (Cfa) | Summer | 1582 |
| Salata et al., (2016) | Rome, Italy | Hot-summer Mediterranean (Csa) | All seasons | 941 |
| Wang et al., (2017) | Groningen, Netherlands | Temperate oceanic (Cfb) | Spring & summer | 387 |
| Canan et al.,(2019) | Konya, Turkey | Cold semi-arid(Bsk) | Summer | 315 |
| Huang et al., (2019) | Sichuan, China | Monsoon-influenced humid subtropical (Cwa) | Summer &Winter | 523 |
| Fang et al., (2019) | Guangzhou, China | Humid subtropical (Cfa) | Summer | 1100 |
| Niu et al.,(2020) | Xi'an, China | Monsoon-influenced Humid subtropical(Cwa) | Summer | 54 |
| He et al.,(2020) | Xi'an, China | Monsoon-influenced Humid subtropical(Cwa) | Winter, Spring, and summer | 1691 |

The majority of OTC studies were carried out in tropical and temperate climate zone regions(Kumar and Sharma.,2020), with less focus on the cold weather conditions (Xu, Hong, Mi, & Yan, 2018). Thermal comfort conditions need to be improved to promote the usage frequency of outdoor spaces in cold-weather regions. In the arid regions, mild winter can be experienced by the people. People in the campus area are not provided with a recreational place where people can relax, social interact, and come close to nature, etc., in extreme weather conditions. People mostly preferred spending time indoor. They came outside only for some urgent work. Outdoor activities are prevalent only in transition season/weather. This kind of lifestyle is harmful to wellbeing. The present study was carried out to determine the outdoor thermal comfort conditions at the campus area so that campus areas can be developed to provide comfortable outdoor places in cold weather. The monthly variation of air temperature and relative humidity over a period of 10 years is shown in Figure 1. The Bsh climate of Northern plains of India includes parts of states like Punjab, Haryana, New Delhi, and Utter Pradesh (Britannica.com, n.d.). This study was conducted at a university campus in Sonepat, Haryana




| | Jan | Feb | Mar | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tmax(°C ) | 20.3 | 24.1 | 31.1 | 37.8 | 41.8 | 41.9 | 37.1 | 35.4 | 34.3 | 33.3 | 28.3 | 22.8 |
| Tmin(°C) | 7.7 | 10.6 | 15.4 | 23.6 | 28.9 | 30.9 | 28.9 | 27.3 | 24.9 | 21.6 | 16.9 | 11.6 |
| Tavg(°C) | 13.09 | 16.64 | 22.73 | 30.91 | 35.91 | 36.91 | 33.09 | 31.27 | 29.64 | 27.1 | 22.1 | 16.3 |
| RHavg(%) | 57.18 | 56 | 41.45 | 22.73 | 18.91 | 29.27 | 55.18 | 63.91 | 58.82 | 39.3 | 33 | 39.5 |

**Figure 1** Monthly variation of Maximum temperature, Minimum temperature, Average temperature, and average relative humidity from 2010-19(WWO, 2020)

The present study's driving force targets the research question: What is the cold season's influence on the people's perceptions at the university campus? What are the microclimate parameters which are significantly affecting thermal perceptions at campus? What is the neutral and preferred temperature at campus area? Based on the research question, the objectives of the present study are-

1. To investigate the OTC conditions during winters based on the transversal field surveys.
2. To develop the empirical TSV model based on thermal sensations of the people and meteorological parameters.
3. To determine the neutral temperature range, neutral temperature, and preferred temperature for the study area.

## 2. Methodology

### *2.1 Description of Study Area*

The authors conducted this study at the campus of Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonepat-India, which spreads across 273 acres of land and falls in the northern plains of India. This campus is a governmental university, and the majority of the people from different locations of Haryana and India's national capital region are studying and staying at the campus. The geographical location of the investigated site is shown in Figure 2. The authors selected the mentioned site for investigation because of the usage frequency of the sites. People visit the investigated sites for relaxing/taking a break from their academic activities/studies. The usage frequency of outdoor spaces is directly linked with the OTC conditions, and the microclimate of the site has a direct impact on the thermal comfort conditions(Lai, Guo, Hou, Lin, & Chen, 2014).Sonepat (28.99°N, 77.01° E) is characterized as the hot semi-arid climate (Bsh) zone as per Köppen climate classification(Peel, Finlayson, & Mcmahon, 2007) at the altitude of 219m from sea level. The air temperature varies from 45°C in summers to 4°C in winters. Relative humidity in the region range from 20-50% in summers and 50-90% in winters(Parveen Kumar, 2014).

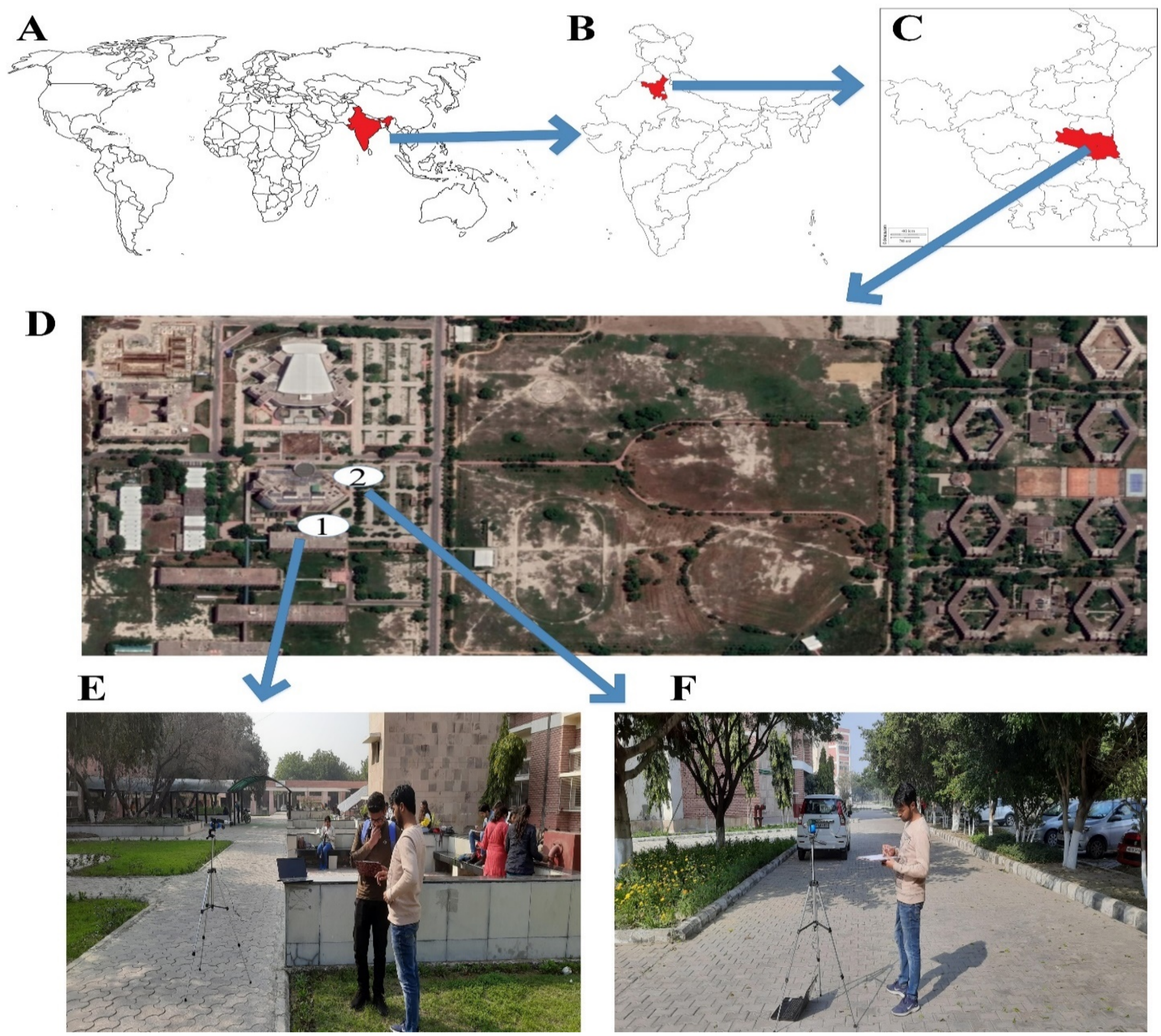



**Figure 2** Geographical location of the study area A) India's location in world map B) Haryana's location in India map C) Sonepat's location in Haryana map D) Satellite image of the university campus in Sonepat E&F) Sites investigated in the present study

### *2.2 Field Survey*

In this investigation, the authors conducted a field survey in the winter season during the five typical days from December 23, 2019, to December 31, 2019, that involved subjective surveys and objective measurements between 9:00 and 17:00 hours. During the field survey, the respondents were asked to stay at the investigated sites for 10 to 15 minutes so that they could adapt to the thermal environment. The questionnaire was designed as per ISO 10551 (ISO, 2001) and used to record subjective data like- personal information, current activity, clothing type, thermal sensation scale, thermal preference with regards to microclimate parameters, and overall preference. The authors used the ASHRAE Seven-point sensation scale(ANSI/ASHRAE Standard 55, 2010) to record the respondents' thermal sensations. The overall comfort of the respondents was recorded on the three-point scale, i.e., Uncomfortable (-1), Acceptable (0), and Comfortable (+1). The overall preference of the respondents was recorded on the three-point scale, i.e., Cooler (-1), Neutral (0), and Warmer (+1). The preference of the meteorological parameters Air temperature ($T_a$), Relative humidity (RH), Wind Speed (Ws), and Global solar radiation(G) were recorded on the three-point scale, i.e., $T_a$ preference: Higher (+1), Unchanged (0), Lower (-1); RH preference: Damper (+1), Unchanged (0), Drier (-1); Ws preference: Stronger (+1), Unchanged (0), Slower (-1); G preference: Stronger (+1), Unchanged (0), Weaker (-1). The authors presented a demonstration about the purpose of the investigation and questions in the questionnaire to each respondent before recording their responses. A total of 209 questionnaires were filled by the respondents by the transversal survey. Due to some left out questions from the respondents, 185 valid questionnaires were processed.

### *2.3 Physical Measurement*

The Onsite monitoring was conducted in parallel with the subjective survey to record the meteorological parameters. The sensors used in the present study are given in Table 2. All the instruments used were compiled with ISO 7726(ISO 7726, 1998). The global solar radiation (G) data were retrieved from the meteorological observatory center located at the university campus.

**Table 2** The sensor used in the present study for onsite monitoring of meteorological parameters

| Meteorological Parameters | Sensor | Range | Accuracy |
|---|---|---|---|
| $T_a$ | Extech HT30 WBGT meter | 0 to 50°C | ±1.8°F/1.0°C |
| RH | Extech HT30 WBGT meter | 0 to 100%RH | ±3%RH |
| Ws | Meterevi Digital anemometer (AVM-01) | 0 - 30m/s | ±(5%rdg+0.5) |

### *2.4 Thermal Comfort Index*

In the present investigation, the PET was applied to investigate the thermal comfort conditions. Several studies in the literature have used PET to determine the neutral temperature and neutral temperature range(Kumar & Sharma, 2020). It is based on the Munich Energy-balance Model for Individuals (MEMI), which models the human body's thermal needs physiologically. It is defined as the physiological equivalent temperature at any given place (outdoors or indoors) and equivalent to the air temperature at which, in a typical indoor setting (without wind and solar radiation), the human body's heat balance is maintained with core and skin temperatures equal to those under the conditions being assessed. This way, PET enables a layperson to compare the integral effects of complex thermal conditions outside with their own experience indoors(Höppe, 1999). The heat balance of the PET is given in Eq.1 :

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \quad (1)$$

Where M: Metabolic rate
W: Physical work output
R: Net radiation of the body
C: Convective heat flow
$E_D$: Latent heat flow to evaporate water into water vapor diffusing through the skin
$E_{Re}$: Sum of heat flows for heating and humidifying the inspired air
$E_{Sw}$: Heat flow due to evaporation of sweat
S: Storage heat flow for heating or cooling the body mass
Watt is the unit for all heat flow.

**Table 3** Description of physiological stress based on PET (Matzarakis & Mayer, 1996)

| PET(°C) | Thermal Sensation | Grade of physiological stress |
|---|---|---|
| <4°C | Very cold | Extreme cold stress |
| 4-8°C | Cold | Strong cold stress |
| 8-13°C | Cool | Moderate cold stress |
| 13-18°C | Slightly cool | Slight cold stress |
| 18-23°C | Comfortable | No thermal stress |
| 23-29°C | Slightly warm | Slight heat stress |
| 29-35°C | Warm | Moderate heat stress |
| 35-41°C | Hot | Strong heat stress |
| >41°C | Very hot | Extreme heat stress |

A user-friendly software package RayMan Pro 3.1 (Matzarakis, Rutz, & Mayer, 2007, 2010) was used to calculate PET's value based on MEMI. The mean radiant temperature (Tmrt) was also calculated by using RayMan. For calculation of PET, RayMan requires the input of the meteorological parameters (air temperature, relative humidity, wind speed, and Tmrt), personal data (Height, Weight, Age, Gender, clothing insulation, and metabolic rate), and geographic data (latitude, longitude, and altitude), date and time of filling the questionnaire. The description of the physiological stress based on the PET is given in Table 3. The correlation was established between the respondents' thermal sensations and PET to determine the neutral temperature and neutral temperature range. Thermal sensation votes differ amongst the individual respondents' even when they are exposed to the same thermal environment(Lin & Matzarakis, 2008). For balancing these individual differences in thermal sensations, a method was developed by (Richard J. de Dear & Gail Schiller Brager, 1998) to calculate the subjective thermal sensation responses for each 1°C bin. By applying the developed method, PET was divided into a total of 14 bins with an increment of 1°C. The mean thermal sensation vote (MTSV) was calculated corresponding to each bin. By applying linear regression, a linear equation was developed between MTSV and PET. Neutral PET is determined when MTSV =0 in the linear equation(Eq.5). In this study, the neutral temperature range was determined when the comfort interval falls in the range -0.5 ≤TSV≤ +0.5 in the linear equation (Eq.5). Although the respondents' neutral temperature represents comfort temperature, this temperature may differ from the respondents' actual preference. Hence, the preferred temperature should also be determined to assess the thermal perceptions based on the respondents' thermal preference votes (TPV)(Wang et al., 2017). TPV was grouped into 14 bins for 1°C PET intervals. Probit analysis (Ballantyne, Hill, & Spencer, 1977) was applied to fit these data bins with "prefer it to be warmer" and "prefer it to be cooler" against PET. Curve fitting was done for the estimated probability for the "prefer it to be warmer" and "prefer it to be cooler" temperatures against PET. These two models' intersection point was assumed as the preferred temperature(Wang et al., 2017). The significance of fitting was checked by applying the Chi-square test in SPSS. The research methodology framework adopted in the present study is shown in Figure 3.

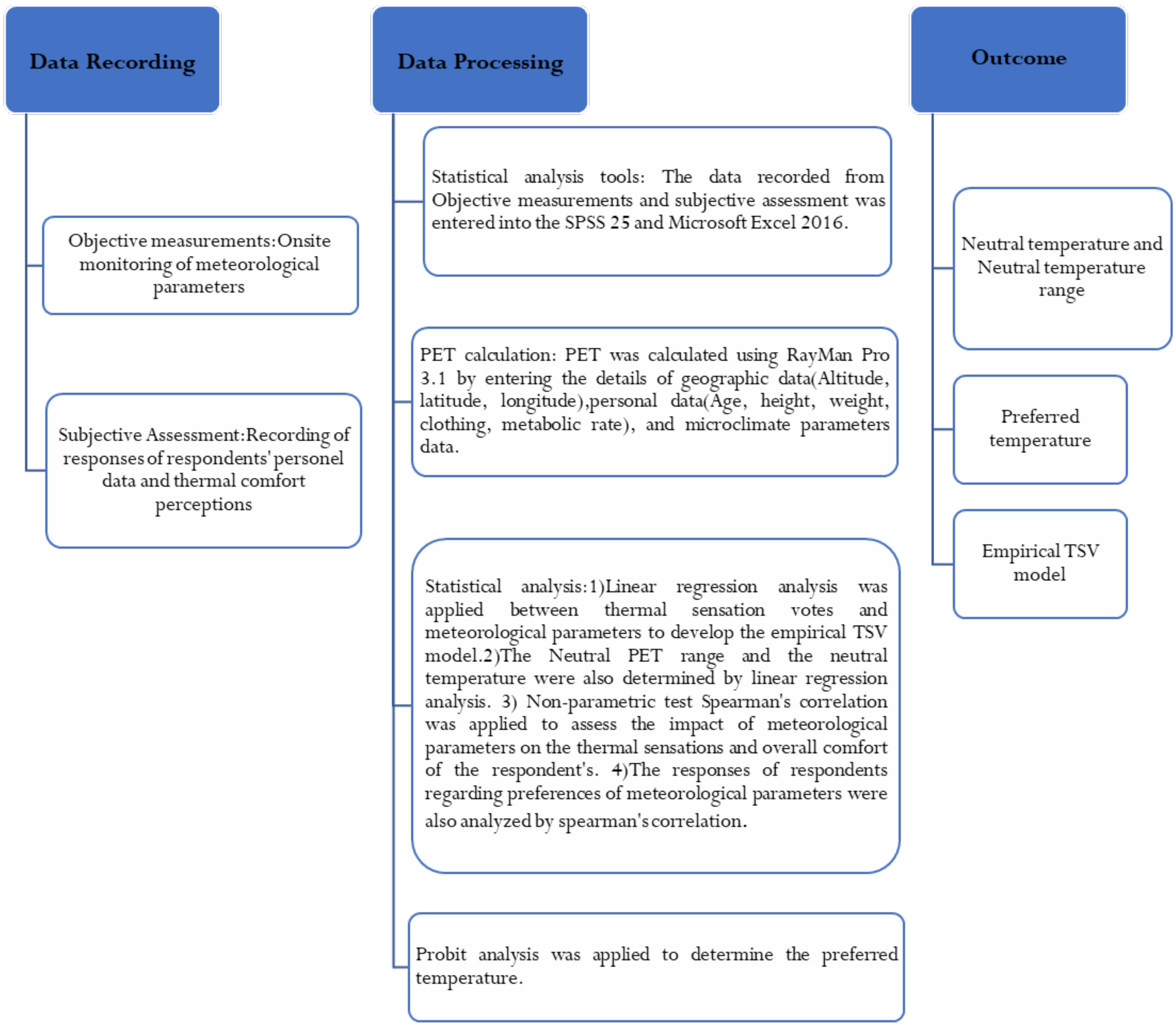



**Figure 3.** The research methodology framework adopted in the study

### *2.5 Empirical TSV model*

By referring the previous studies like (Cheng, Ng, Chan, & Givoni, 2012; Coccolo et al., 2016; Lai, Zhou, et al., 2014; Nikolopoulou, 2004), the relationship between TSV and meteorological parameters were determined by applying linear regression. The empirical TSV model can be expressed as Eq. (2)

$$\mathrm{TSV} = \mathrm{aT_a} + \mathrm{bG} + \mathrm{cRH} + \mathrm{d}V_a + \mathrm{e} \quad (2)$$

In Eq.2, Ta, G, RH, and Ws are meteorological parameters, whereas a-e is the regression coefficients.

## 3 Results

The respondents' descriptive, meteorological parameters, thermal index, and thermal sensation votes' statistics, the empirical TSV model showing the relationship between TSV and meteorological parameters, the relationship between overall comfort and thermal sensation votes, the impact of meteorological parameters on OC and TSV, respondents' preferences regarding meteorological parameters, determination of the neutral temperature range, neutral temperature, and preferred temperature are presented in this section.

### *3.1. Respondent's Statistics*

In the present study, 209 questionnaire responses were recorded from the respondents, out of which 185 valid questionnaires were selected and used for statistical analysis. Among all the respondents, females were 36.8 %(68), and males were 63.2 %(117). The respondents marked their clothing responses added all together to get one Clo value by referring to ASHRAE Standard 55. Out of 185 respondents, 85% of the respondents' clothing insulation was calculated to be 1.01Clo, and the rest 15 % of respondents clothing insulation calculated to be 1.3 Clo. The average metabolic rate (Met) of the respondents' is assumed to be 70 Watt. The Clo and Met values are according to reference (ANSI/ASHRAE Standard 55, 2010) by checking the response of respondents in the questionnaire. The descriptive statistics of the respondents can be observed in Table 4. The values of meteorological parameters and PET are given in Table 5

**Table 4** Descriptive statistics of the Gender, Age, and Activity of the respondents'

| Gender | | Age | | | | | Activity | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | >18 | 18-24 | 25-34 | 45-54 | <54 | Chatting Standing | Chatting Sitting | Exercising | Reading books | Strolling |
| Male | 63.20% | 43.5% | 42.7% | 12% | 0.9% | 0.9% | 43.8% | 35.2% | 13.5% | 4.3% | 3.2% |
| Female | 36.80% | 42.6% | 44.1% | 11.8% | 1.5% | - | 50% | 48.5% | 1.5% | - | - |

**Table 5** Meteorological parameters and thermal index data

| | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|
| $T_a$(°C) | 9.16 | 15.48 | 11.94 | 1.59 |
| RH(%) | 59.22 | 87.06 | 76.49 | 6.56 |
| $W_s$(m/s) | 0.42 | 4.93 | 1.85 | 1.08 |
| G(W/m$^2$) | 35.31 | 622.73 | 329.52 | 165.52 |
| $T_{mrt}$(°C) | 8.60 | 40.40 | 29.74 | 9.007 |
| PET(°C) | 4.6 | 22.5 | 12.99 | 4.55 |

From Figure 4, it was found that the highest TSV percentage is "Cool" (33%), followed by "Slightly cool" (30.8%) and "Cold" (19.5%). The overall mean TSV of 185 samples was -1.45, which is well below neutral, with a standard deviation of 1.20. The percentage distribution of the TSV can be observed from Figure 4

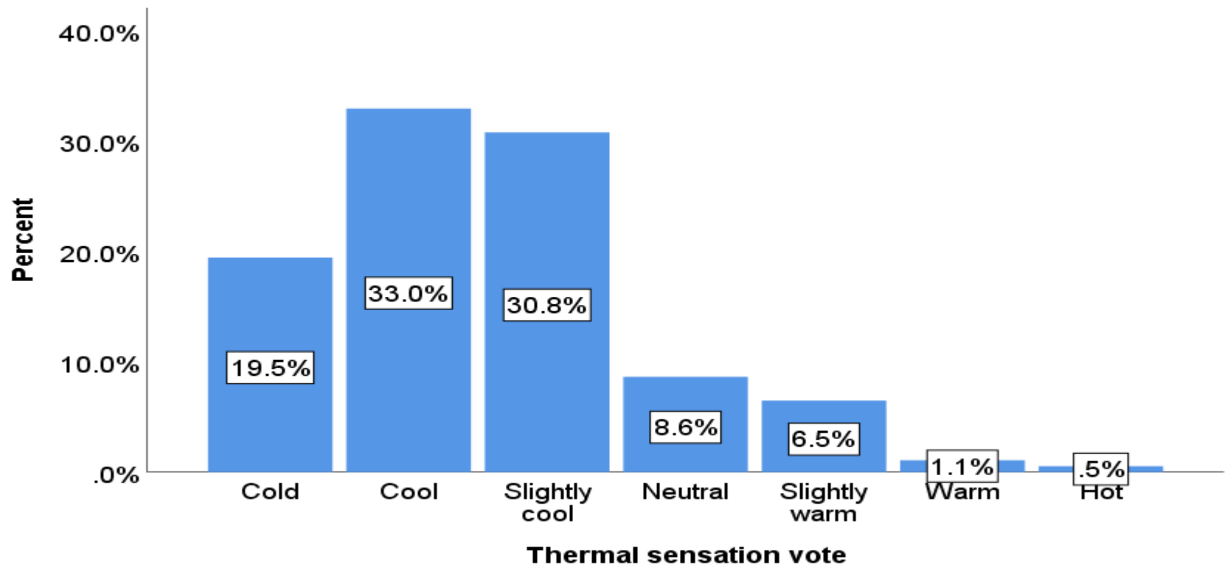



**Figure 4** The percentage distribution of the TSV during the survey

### *3.2 Development of TSV model*

In the present study, the empirical TSV model was developed by taking the effect of air temperature, relative humidity, air velocity, and solar radiation as in (Cheng et al., 2012; Coccolo et al., 2016; Lai, Zhou, et al., 2014; Nikolopoulou, 2004). Linear regression technique was applied to drive the relationship between the TSV and the meteorological parameters. The TSV model is expressed in Eq. (3).

$$TSV = 0.390Ta + 0.000431G + 0.016RH - 0.172Ws - 7.158 (R = 0.55, P < .05) \quad (3)$$

### *3.3 OTC Based On Field Survey*

#### 3.3.1 Thermal Sensation Vote And Overall Comfort

OTC may be affected by many factors like extreme weather conditions, physiology, psychology, etc. Thermal comfort is the most crucial factor which is related to the TSV of the respondents (Xu et al., 2018). The proportion of the votes of overall comfort can be observed from Figure 5

.

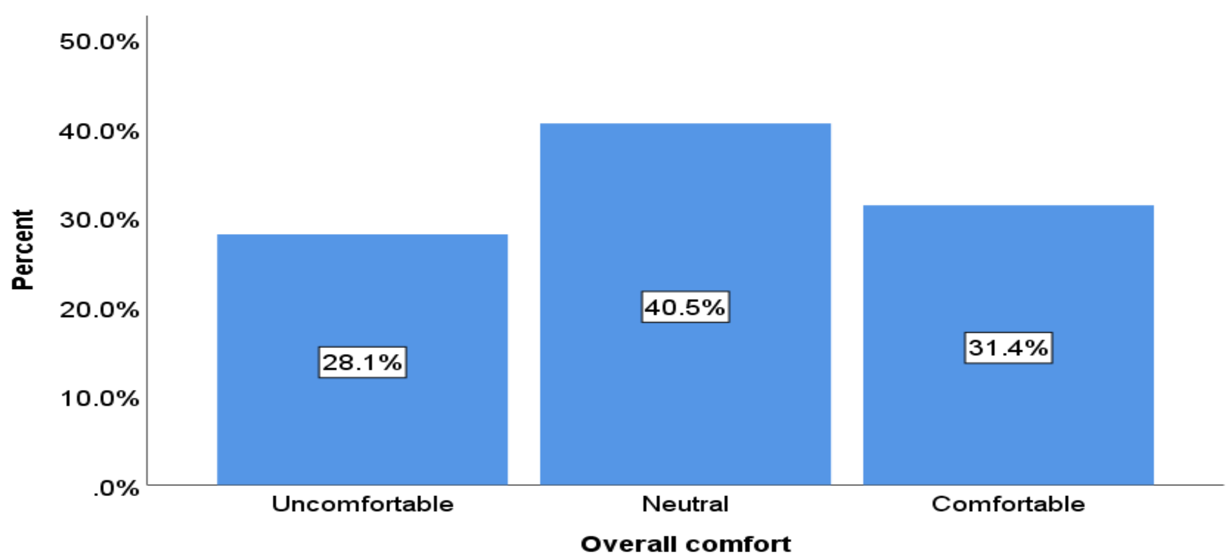



**Figure 5** Overall comfort votes during the survey

In this section, overall comfort was correlated with the thermal sensation vote. Data were sorted from the lowest to the highest value of TSV, and corresponding OC responses were sorted automatically. The data sets were separated according to various thermal sensation responses. For example, the OC responses on Cold (-3) sensation forms one data set, Cool (-2) forms secondary data set, slightly cool (-1) forms third data set, and so on. The mean values of OC and TSV of each data set were calculated, and a correlation was established between the two terms. The relationship between OC and TSV can be observed from Figure 6 and Eq. (4).

$$OC = -0.060TSV^2 + 0.110TSV + 0.421 (R^2 = 0.91), p\ value = 0.02 \quad (4)$$

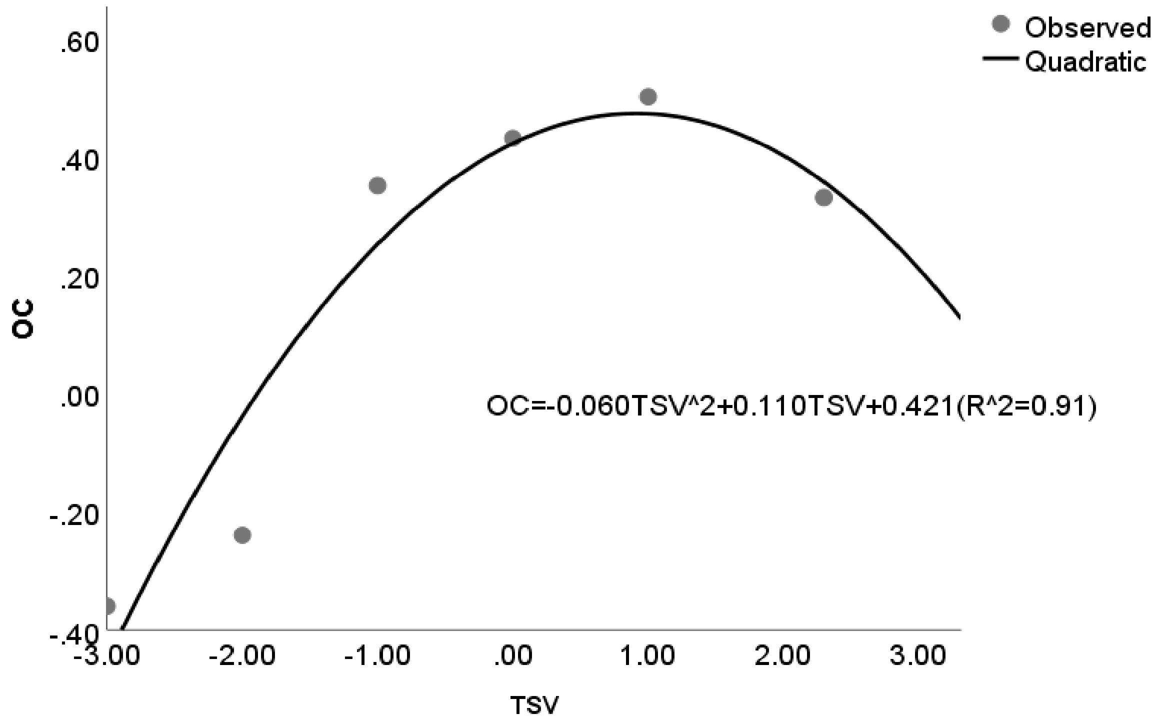



**Figure 6** Correlation between the OC and TSV

### 3.3.2 Impact Of Meteorological Parameters on TSV and OC

Meteorological parameters impact OTC conditions. The impact of microclimate parameters on TSV and OC was investigated by applying Spearman's correlation. A correlation matrix is given in Table 6

**Table 6.** Correlation of the TSV, OC, and meteorological parameters

| | TSV | Ta | RH | Ws | G | Tmrt |
|---|---|---|---|---|---|---|
| OC | .422** | .267** | -0.108 | -.248** | .148* | .179* |
| TSV | - | .524** | -.335** | -.260** | .261** | .310** |
| Ta | - | - | -.745** | -0.043 | .547** | .535** |
| RH | - | - | - | -.152* | -.727** | -.499** |
| Ws | - | - | - | - | 0.008 | -.224** |
| G | - | - | - | - | - | .844** |

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

### 3.3.3 Thermal Preference Votes

The preferences in the meteorological parameters were generally not normally distributed. So, Spearman's correlation was used to correlate the preference votes with the meteorological parameters. Solar radiation was the most significant parameter that influences the preference votes, as observed in Table 7. The proportion of the preference votes of meteorological parameters recorded from the respondents presented in Figure7

**Table 7**. Correlation between the preference votes of the meteorological parameters and meteorological parameters

| Meteorological parameters | Preferred RH | Preferred $W_s$ | Preferred G |
|---|---|---|---|
| $T_a$(°C) | -0.073 | -0.025 | 0.144* |
| RH(%) | - | 0.051 | -0.168* |
| $W_s$(m/s) | - | - | -0.431** |

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

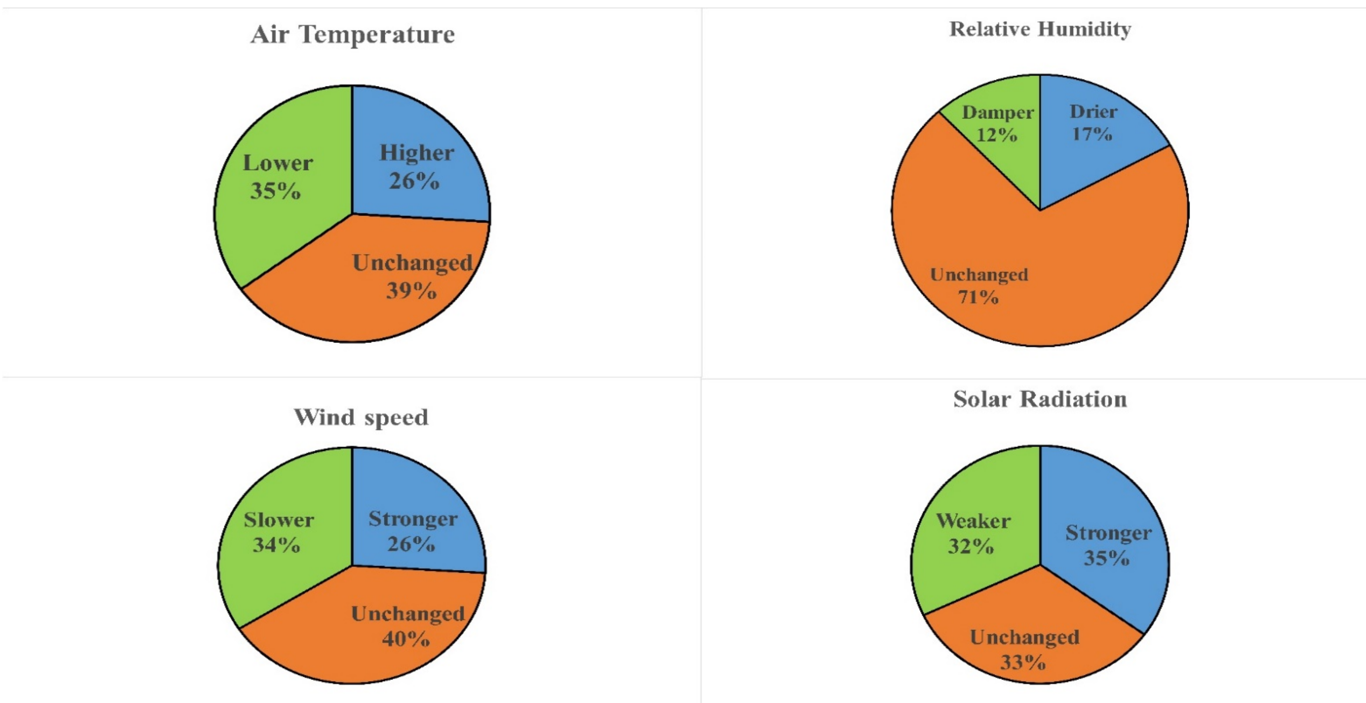



**Figure 7** Preference votes of the respondents for different meteorological parameters

### 3.3.4 Neutral Temperature

Neutral temperature can be defined as the temperature at which the respondents feel neither cool nor hot but feel comfortable(Lin, 2009). As mentioned earlier in the method section, the PET was calculated using RayMan Pro 3.1 software. Figure 8 depicts the relationship between MTSV Vs. PET. The linear relationship can be observed from Eq. (5)

$$MTSV = 0.144PET - 3.153 (R^2 = 0.65), \text{p value} = 0.0004 \qquad (5)$$

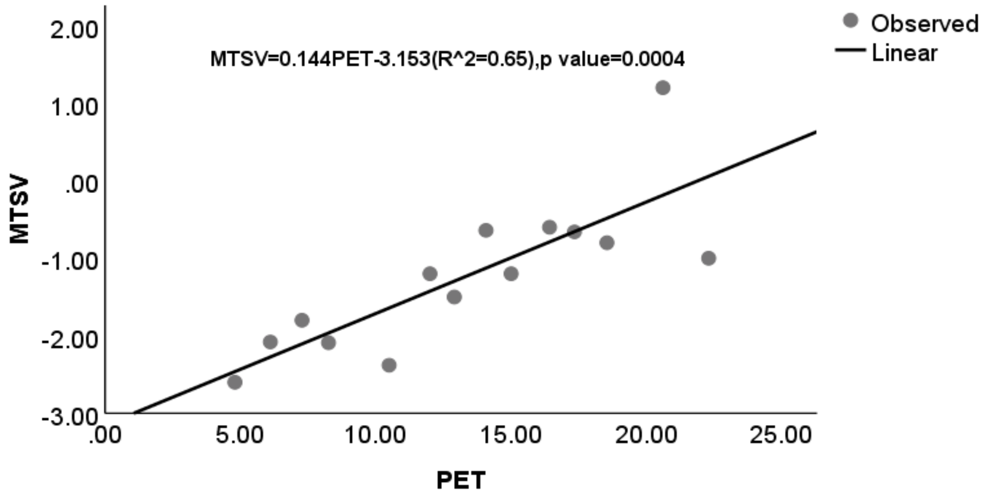



**Figure 8** Correlation between the Mean TSV and PET

Neutral PET is determined when MTSV =0 in Eq.(5). In this study, the neutral temperature range was determined when the comfort interval falls in the range -0.5 ≤MTSV≤ +0.5 on the thermal sensation scale. The neutral PET range obtained in the present study is given in Table 8. So, the neutral PET range was found to be 18.42-25.37°C with a neutral temperature of 21.89°C.

**Table 8** PET range in the present study

| Grade of physiological stress | Thermal sensations | Assumed TSV | PET range |
|---|---|---|---|
| Extreme cold stress | Very cold | <-3.5 | <-2.41°C |
| Strong cold stress | Cold | -3.5 to -2.5 | -2.41°C to 4.53°C |
| Moderate cold stress | Cool | -2.5 to -1.5 | 4.53°C to 11.47°C |
| Slight cold stress | Slightly cool | -1.5 to -0.5 | 11.47°C to 18.42°C |
| No thermal stress | Neutral | -0.5 to 0.5 | 18.42°C to 25.37°C |
| Slight heat stress | Slightly warm | 0.5 to 1.5 | 25.37°C to 32.31°C |
| Moderate heat stress | Warm | 1.5 to 2.5 | 32.31°C to 39.25°C |
| Strong heat stress | Hot | 2.5 to 3.5 | 39.25°C to 46.20°C |
| Extreme heat stress | Very hot | >3.5 | >46.20°C |

### 3.3.5 Preferred Temperature

Preferred temperature can be defined as the temperature at which the respondents feel neither cooler nor warmer in the thermal environment(Lin, De Dear, & Hwang, 2011). Probit analysis (Ballantyne et al., 1977) was applied to determine the preferred temperature, as mentioned earlier in the method section. Figure 9 shows the estimated probability for the "prefer it to be warmer" and "prefer it to be cooler" temperatures against PET. The significance of fitting was checked by applying Chi-square test; both the model was found significant (Prefer it to be warmer- $\chi 2$=62.25, df=11, Significance=0.000000004, Prefer it to be cooler-$\chi 2$=22.84, df=11, Significance=0.01). The preferred temperature was found to be 21.99°C by locating the intersection point of these models

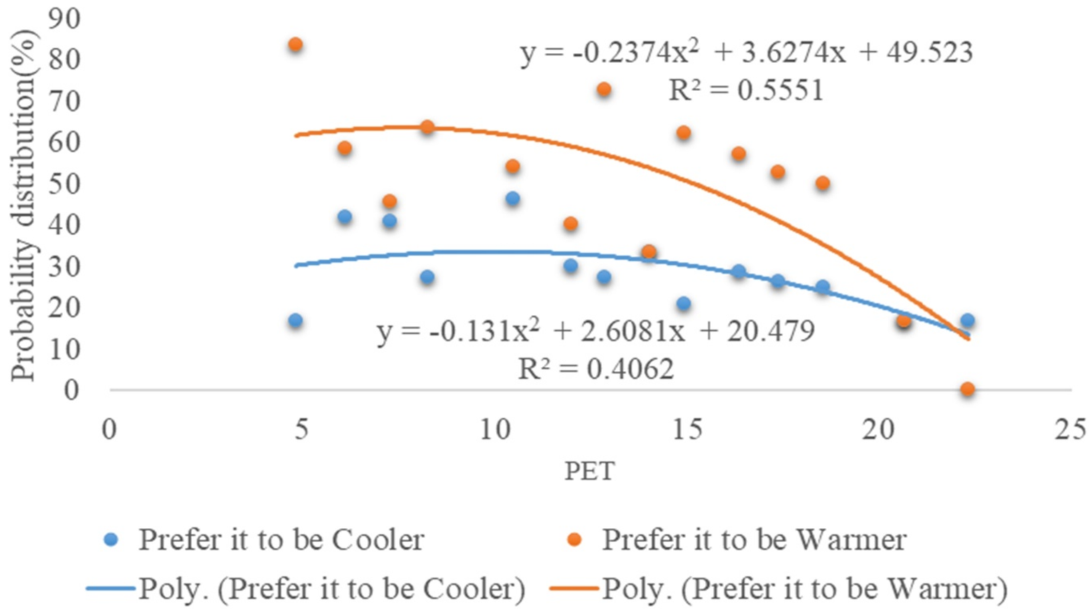



**Figure 9** Probit analysis to determine the preferred temperature

## 4 Discussion

The population's thermal comfort perceptions have a crucial role in extreme climate conditions (hot summer and mild winter) in arid climate zones. So far, less focus has been paid to the outdoor thermal comfort conditions in the cold season. This study investigated people's thermal comfort perceptions at a university campus during the cold season in the Northern plain area of India. This study is the first attempt to investigate the OTC conditions in the cold season using PET in the region.

### *4.1 Empirical TSV Model*

The empirical model in the present study indicated that by increasing air temperature, relative humidity, and solar radiation, the thermal sensations also increased while wind speed had an opposite effect. These findings are in line with investigations carried out in Thessaloniki(Greece), Kassel(Germany), and Combined model for Europe (Nikolopoulou, 2004), São Paulo, Brazil(Monteiro, 2008); Singapore and Changsha, China(Yang, Wong, & Zhang, 2013); Rome, Italy (Salata et al., 2016); Guangzhou, China(Zhao et al., 2016). Since $T_a$ and RH are tough to control in outdoor spaces, blocking Ws and allowing G is a feasible way to improve TSV and, ultimately, OTC conditions. The R-value obtained from the present study is 0.55, which is lower than 0.78 obtained in Tehran, Iran (Hadianpour, Mahdavinejad, Bemanian, & Nasrollahi, 2018), and lies in the range of 0.44-0.58 in European countries (Nikolopoulou, 2004).

### *4.2 Thermal Sensation Vote, Overall Comfort, And Thermal Preferences*

A correlation was established to determine the relationship between overall comfort and thermal sensation vote. It can be observed from Figure 6 and Eq. (4) that there is a robust and nonlinear relationship between OC and TSV; these findings are in line with the results of (Lai, Guo, et al., 2014) and (Xu et al., 2018). As observed from Eq. (4), it was found that the value of TSV is equal to -1.8 at OC =0. It means the respondents' felt overall comfortable when TSV=-1.8. Overall comfort is gradually increasing when the thermal environment approaches warmer conditions. The results indicate that the respondents are adapted to colder weather conditions but value warmer weather conditions to achieve comfort.

Further, a correlation was established among OC, TSV, and meteorological parameters to understand the impact of meteorological parameters on OC and TSV. The results demonstrated that G and $T_a$ directly impact the TSV and OC; these findings are in line with the findings of (Chen, Wen, Zhang, & Xiang, 2015) and (Xu et al., 2018). Ws was found to be inversely proportional to the TSV and OC. RH was found significantly correlated with TSV, but no significant correlation was observed between RH and OC. While analyzing the thermal preferences, it was found that the meteorological parameters' thermal choice is significantly affected by solar radiation. From Table 6, it was inferred that the option for solar radiation found a significant correlation with Tmrt(0.844) followed by RH (-0.727) and $T_a$ (0.547). The correlation coefficient's negative sign reflects the higher the G, the lower the RH. Solar radiation was found to be directly proportional to air temperature, Tmrt, and wind speed.

### *4.3 Neutral Temperature, Neutral Range, And Preferred Temperature*

The basic finding of the present study is that the neutral temperature was found to be 21.89°C. After screening the literature, it was observed that the neutral temperature was found to be more than 20 °C in hot climate zones. The neutral PET was found 28.8°C in Sydney, Australia(Spagnolo & de Dear, 2003); 23.7°C in Taiwan(Lin, 2009); 23.4°C in Damascus (Yahia & Johansson, 2013);26.5°C in Cairo, Egypt(Mahmoud, 2011); 27.85 °C in Boipara and 26.76 °C in Mallickghat (Banerjee, Middel, & Chattopadhyay, 2020).

Further, the neutral range was found to be the 18.42°C-25.37°C PET in the present study. In comparison with the previous studies, the neutral range is comparable with the neutral range in western/middle Europe (18-23°C) and Kassel/Freiburg (18-28°C). The neutral range in Glasgow, UK (9-18°C) is lower than the finding of the present study, but the neutral range in Sun Moon Lake, Taiwan(26-30°C), and Sydney, Australia (26.4-32.4°C), are higher than our finding. The neutral range obtained in various regions of the world is shown in Table 9.

**Table 9** Comparison of the Neutral range of the present study with previous studies

| Source | Location | Climate(Peel et al., 2007) | Neutral range |
|---|---|---|---|
| Lai et al.,(2014) | Tianjin, China | Dwa | 11-24°C |
| Spagnolo and de Dear,(2003) | Sydney, Australia | Cfa | 26.4-32.4°C |
| Lin and Matzarakis (2008) | Sun Moon Lake, Taiwan | Cwa | 26-30°C |
| Lin, (2009) | Taichung, Taiwan | Cwa | 21.3-28.5°C |
| Mahmoud,(2011) | Cairo, Egypt | BWh | 21.6-29°C |
| Andrade et al.,(2011) | Lisbon, Portugal | Csa | 21-23°C |
| Chen et al.,(2015) | Shanghai, China | Cfa | 15-29°C |
| Krüger et al.,(2013) | Glasgow, UK | Cfb | 9-18°C |
| Hirashima et al.,(2018) | Belo Horizonte, Brazil | Cwa | 16-30°C |
| | Kassel/Freiburg | Cfb | 18-28°C |
| Liu et al., (2016) | Changsha, China | Cfa | 15-22°C |
| Salata et al.,(2016) | Rome, Italy | Csa | 21.1-29.2°C |
| Hadianpour et al.,(2018) | Tehran, Iran | BWk | 13.9-20.5°C |
| Kenawy and Elkadi (2018) | Melbourne, Australia | Cfb | 20 -28.4°C |
| Banerjee et al., (2020) | Boipara, India | Aw | 27.8 °C - 36.8 °C |
| | Mallickghat, India | | 28 °C -32.3 °C |
| This study | Sonepat, India | Bsh | 18.42 -25.37°C |

As inferred from the results section, the preferred temperature was found to be 21.99°C. Compared to our findings, the preferred temperature is lower in Tempe (20.8°C) (Middel, Selover, Hagen, & Chhetri, 2016) and higher in Taiwan (23°C)(Lin, 2009), Sydney(30.9 °C) (Spagnolo & de Dear, 2003), and 25.5°C in Dar es Salaam (Baruti & Johansson, 2020). In addition to the current study results, there are shortcomings and future perspectives of the investigation. Firstly, the present investigation was carried out for only five typical days. Weather conditions for the whole season could be more complicated. Secondly, further research should be carried out in all seasons by examining the various campus area landscapes. Additionally, the majority of respondents were young age group people in the present study, all age group people perceptions can be explored further.

## 5 Conclusion

For healthy livability in outdoor spaces, people should visit a place without being affected by heat and cold stress. In previous studies, less attention has been paid to investigate the OTC conditions in cold weather. The present study investigated the OTC conditions during the winter season of the hot semi-arid climate of India. The investigation of the OTC conditions was conducted at a university campus in December 2019. Based on the investigation, the following conclusions were drawn from the study: In the cold weather, "Cool" was found to be the most perceived thermal sensation (33%) on the ASHRAE Seven-point sensation scale. Only 8.6% of the respondents marked their perceived sensation "Neutral." The uncomfortable votes were found to be 28.1% of the respondents. A robust and nonlinear relationship was observed between the overall comfort and thermal sensations. Overall comfort is gradually increasing when the thermal environment approaches warmer conditions

In cold weather, overall comfort is significantly affected by the air temperature followed by mean radiant temperature. The air velocity and relative humidity were found to be inversely proportional to the overall comfort. Intensification of the air temperature, mean radiant temperature, and reducing wind speed, relative humidity will improve the overall comfort.

In thermal preferences of the meteorological parameters, solar radiation was found to be the most significant parameter. Higher the value of solar radiation, the higher the value of air temperature, the lower the air velocity and relative humidity, preferred by the respondents, and vice versa.The empirical model in the present study indicated that by increasing air temperature, relative humidity, and solar radiation, the thermal sensations also increased while wind speed had an opposite effect.

The neutral PET range was 18.42-25.37°C with a neutral temperature of 21.89°C. The preferred temperature was 21.99

°C, which is slightly higher than the neutral temperature.

The present study's findings could provide a valuable reference to the urban designers to design/optimize the outdoor environment to improve the thermal comfort of people at university campuses' in the arid regions of India

## Acknowledgements

The National Project Implementation Unit (NPIU) supports this work, a unit of the Ministry of Human Resource Development, Government of India, through TEQIP-III Project at Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Haryana-India. The authors are thankful to meteorological observatory centre authorities to provide global solar radiation data. The authors are also thankful to the respondents who helped the survey completed.

## References

Ali, S. B., & Patnaik, S. (2018). Thermal comfort in urban open spaces: Objective assessment and subjective perception study in tropical city of Bhopal, India. *Urban Climate*, *24*(July): 954–967. https://doi.org/10.1016/j.uclim.2017.11.006

Altunkasa, C., & Uslu, C. (2020). Use of outdoor microclimate simulation maps for a planting design to improve thermal comfort. *Sustainable Cities and Society*, *57*: 102137. https://doi.org/10.1016/j.scs.2020.102137

Amindeldar, S., Heidari, S., & Khalili, M. (2017). The effect of personal and microclimatic variables on outdoor thermal comfort: A field study in Tehran in cold season. *Sustainable Cities and Society Journal*, *147*(June): 114–127. https://doi.org/10.1016/j.csr.2017.06.002

Andrade, H., Alcoforado, M. J., & Oliveira, S. (2011). Perception of temperature and wind by users of public outdoor spaces: Relationships with weather parameters and personal characteristics. *International Journal of Biometeorology*, *55*(5): 665–680. https://doi.org/10.1007/s00484-010-0379-0

ANSI/ASHRAE Standard 55. (2010). Thermal Environment Conditions for Human Occupancy. *ASHRAE Inc*, 42. https://doi.org/ISSN 1041-2336

Ballantyne, E. R., Hill, R. K., & Spencer, J. W. (1977). *Probit Analysis of Thermal Sensation Assessments*. *21*(I): 29–43.

Banerjee, S., Middel, A., & Chattopadhyay, S. (2020). Outdoor thermal comfort in various microentrepreneurial settings in hot humid tropical Kolkata: Human biometeorological assessment of objective and subjective parameters. *Science of the Total Environment*, *721*: 137741. https://doi.org/10.1016/j.scitotenv.2020.137741

Baruti, M. M., & Johansson, E. (2020). Urbanites' thermal perception in informal settlements of warm-humid Dar es Salaam, Tanzania. *Urban Climate*, *31*, 100564. https://doi.org/10.1016/j.uclim.2019.100564
Britannica.com. (n.d.). Britannica.com. Retrieved March 30, 2020, from https://www.britannica.com/place/India/The-Himalayas#ref487166

Canan, F., Golasi, I., Ciancio, V., Coppi, M., & Salata, F. (2019). Outdoor thermal comfort conditions during summer in a cold semi-arid climate. A transversal field survey in Central Anatolia (Turkey). *Building and Environment*, *148*(October 2018): 212–224. https://doi.org/10.1016/j.buildenv.2018.11.008

Chen, L., Wen, Y., Zhang, L., & Xiang, W. N. (2015). Studies of thermal comfort and space use in an urban park square in cool and cold seasons in Shanghai. *Building and Environment*, *94*: 644–653. https://doi.org/10.1016/j.buildenv.2015.10.020
Cheng, V., Ng, E., Chan, C., & Givoni, B. (2012). Outdoor thermal comfort study in a sub-tropical climate: A longitudinal study based in Hong Kong. *International Journal of Biometeorology*, *56*(1): 43–56. https://doi.org/10.1007/s00484-010-0396-z

Coccolo, S., Kämpf, J., Scartezzini, J. L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. *Urban Climate*, *18*: 33–57. https://doi.org/10.1016/j.uclim.2016.08.004

de Freitas, C. R., & Grigorieva, E. A. (2017). A comparison and appraisal of a comprehensive range of human thermal climate indices. *International Journal of Biometeorology*, *61*(3): 487–512. https://doi.org/10.1007/s00484-016-1228-6

Fang, Z., Feng, X., Liu, J., Lin, Z., Mak, C. M., Niu, J., … Xu, X. (2019). Investigation into the differences among several outdoor thermal comfort indices against field survey in subtropics. *Sustainable Cities and Society*, *44*(October 2018): 676–690. https://doi.org/10.1016/j.scs.2018.10.022

Fang, Z., Xu, X., Zhou, X., Deng, S., Wu, H., Liu, J., & Lin, Z. (2019). Investigation into the thermal comfort of university students conducting outdoor training. *Building and Environment*, *149*(December 2018): 26–38. https://doi.org/10.1016/j.buildenv.2018.12.003

Fong, C. S., Aghamohammadi, N., Ramakreshnan, L., Sulaiman, N. M., & Mohammadi, P. (2019). Holistic recommendations for future outdoor thermal comfort assessment in tropical Southeast Asia: A critical appraisal. *Sustainable Cities and Society*, *46*(January): 101428. https://doi.org/10.1016/j.scs.2019.101428

Hadianpour, M., Mahdavinejad, M., Bemanian, M., & Nasrollahi, F. (2018). Seasonal differences of subjective thermal sensation and neutral temperature in an outdoor shaded space in Tehran, Iran. *Sustainable Cities and Society*, *39*(March): 751–764. https://doi.org/10.1016/j.scs.2018.03.003

He, X., An, L., Hong, B., Huang, B., & Cui, X. (2020). Cross-cultural differences in thermal comfort in campus open spaces: A longitudinal field survey in China's cold region. *Building and Environment*, *172*: 106739. https://doi.org/10.1016/j.buildenv.2020.106739

Hirashima, S. Q. da S., Katzschner, A., Ferreira, D. G., Assis, E. S. de, & Katzschner, L. (2018). Thermal comfort comparison and evaluation in different climates. *Urban Climate*, *23*: 219–230. https://doi.org/10.1016/j.uclim.2016.08.007

Höppe, P. (1999). The physiological equivalent temperature - A universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, *43*(2): 71–75. https://doi.org/10.1007/s004840050118

Huang, Z., Cheng, B., Gou, Z., & Zhang, F. (2019). Outdoor thermal comfort and adaptive behaviors in a university campus in China's hot summer-cold winter climate region. *Building and Environment*, *165*(August): 106414. https://doi.org/10.1016/j.buildenv.2019.106414

ISO. (2001). *10551 Ergonomics of the thermal environment — Assessment of the influence of the thermal environment using subjective judgement scales*. Retrieved from https://www.iso.org/standard/18636.html. Retrieved date: 19 November 2019

ISO 7726. (1998). ISO 7726:1998 Ergonomics of the thermal environment — Instruments for measuring physical quantities. *ISO Standard*, *1998*: 1–56. https://doi.org/ISO 7726:1998 (E)

Johansson, E., Thorsson, S., Emmanuel, R., & Krüger, E. (2014). Instruments and methods in outdoor thermal comfort studies - The need for standardization. *Urban Climate*, *10*(P2): 346–366. https://doi.org/10.1016/j.uclim.2013.12.002

Kashef, M. (2016). Urban livability across disciplinary and professional boundaries. *Frontiers of Architectural Research*, 5: 239–253. https://doi.org/10.1016/j.foar.2016.03.003

Kenawy, I., & Elkadi, H. (2018). The outdoor thermal benchmarks in Melbourne urban climate. *Sustainable Cities and Society*, *43*(April): 587–600. https://doi.org/10.1016/j.scs.2018.09.004

Ketterer, C., & Matzarakis, A. (2014). Human-biometeorological assessment of the urban heat island in a city with complex topography - The case of Stuttgart, Germany. *Urban Climate*, *10*(P3): 573–584. https://doi.org/10.1016/j.uclim.2014.01.003

Kong, L., Lau, K. K. L., Yuan, C., Chen, Y., Xu, Y., Ren, C., & Ng, E. (2017). Regulation of outdoor thermal comfort by trees in Hong Kong. *Sustainable Cities and Society*, *31*: 12–25. https://doi.org/10.1016/j.scs.2017.01.018

Krüger, E., Drach, P., Emmanuel, R., & Corbella, O. (2013). Urban heat island and differences in outdoor comfort levels in Glasgow, UK. *Theoretical and Applied Climatology*, *112*(1–2): 127–141. https://doi.org/10.1007/s00704-012-0724-9

Kumar, P, & Sharma, A. (2020). Study on importance , procedure , and scope of outdoor thermal comfort – A review. *Sustainable Cities and Society*, *61*: 102297. https://doi.org/10.1016/j.scs.2020.102297

Kumar, Parveen. (2014). Evaluation of Thermal Comfort of Naturally Ventilated University Students' Accommodation based on Adaptive Thermal Comfort Model and Occupant Survey in Composite Climate. *International Journal of Architecture, Engineering and Construction*, *3*(4): 298–316. https://doi.org/10.7492/IJAEC.2014.024

Lai, D., Guo, D., Hou, Y., Lin, C., & Chen, Q. (2014). Studies of outdoor thermal comfort in northern China. *Building and Environment*, 77: 110–118. https://doi.org/10.1016/j.buildenv.2014.03.026

Lai, D., Zhou, C., Huang, J., Jiang, Y., Long, Z., & Chen, Q. (2014). Outdoor space quality: A field study in an urban residential community in central China. *Energy and Buildings*, *68*(PART B): 713–720. https://doi.org/10.1016/j.enbuild.2013.02.051

Li, L., & Zha, Y. (2020). Population exposure to extreme heat in China: Frequency, intensity, duration and temporal trends. *Sustainable Cities and Society*, *60*: 102282. https://doi.org/10.1016/j.scs.2020.102282

Lin, T. P. (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Building and Environment*, *44*(10): 2017–2026. https://doi.org/10.1016/j.buildenv.2009.02.004

Lin, T. P., De Dear, R., & Hwang, R. L. (2011). Effect of thermal adaptation on seasonal outdoor thermal comfort. *International Journal of Climatology*, *31*(2), 302–312. https://doi.org/10.1002/joc.2120

Lin, T. P., & Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology*, *52*(4): 281–290. https://doi.org/10.1007/s00484-007-0122-7

Liu, W., Zhang, Y., & Deng, Q. (2016). The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate. *Energy and Buildings*, *128*, 190–197. https://doi.org/10.1016/j.enbuild.2016.06.086

Mahmoud, A. H. A. (2011). Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions. *Building and Environment*, *46*(12), 2641–2656. https://doi.org/10.1016/j.buildenv.2011.06.025

Makaremi, N., Salleh, E., Jaafar, M. Z., & GhaffarianHoseini, A. (2012). Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia. *Building and Environment*, *48*(1), 7–14. https://doi.org/10.1016/j.buildenv.2011.07.024

Matzarakis, A., & Mayer, H. (1996). Another Kind of Environmental Stress: Thermal Stress. *WHO Newsletter*, Vol. 18, pp. 7–10.

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International Journal of Biometeorology*, *51*(2), 323–334. https://doi.org/10.1007/s00484-009-0261-0

Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: Basics of the RayMan model. *International Journal of Biometeorology*, *54*(2), 131–139. https://doi.org/10.1007/s00484-009-0261-0

Middel, A., Selover, N., Hagen, B., & Chhetri, N. (2016). Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. *International Journal of Biometeorology*, *60*(12), 1849–1861. https://doi.org/10.1007/s00484-016-1172-5

Monteiro, L. . (2008). *Thermal comfort predictive models: Quantification of relationships between microclimate and thermal sensation variables for outdoor spaces assessment and design*.

Nazarian, N., Sin, T., & Norford, L. (2018). Numerical modeling of outdoor thermal comfort in 3D. *Urban Climate*, *26*, 212–230. https://doi.org/10.1016/j.uclim.2018.09.001

Nikolopoulou, M. (2004). Designing Open Spaces in the Urban Environment: a Biolimatic Approach. In *Uma ética para quantos?* https://doi.org/10.1007/s13398-014-0173-7.2

Niu, Jianlei, Liu, J., Lee, T. cheung, Lin, Z., Mak, C., Tse, K. T., … Kwok, K. C. S. (2015). A new method to assess spatial variations of outdoor thermal comfort: Onsite monitoring results and implications for precinct planning. *Building and Environment*, *91*, 263–270. https://doi.org/10.1016/j.buildenv.2015.02.017

Niu, Jiaqi, Hong, B., Geng, Y., Mi, J., & He, J. (2020). Summertime physiological and thermal responses among activity levels in campus outdoor spaces in a humid subtropical city. *Science of the Total Environment*, *728*, 138757. https://doi.org/10.1016/j.scitotenv.2020.138757

Peel, M. C., Finlayson, B. L., & Mcmahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification Updated world map of the K ¨ oppen-Geiger climate classification. In *Hydrol. Earth Syst. Sci. Discuss* (Vol. 4). Retrieved from www.hydrol-earth-syst-sci-discuss.net/4/439/2007/

Potchter, O., Cohen, P., Lin, T. P., & Matzarakis, A. (2018). Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. *Science of the Total Environment*, *631–632*, 390–406. https://doi.org/10.1016/j.scitotenv.2018.02.276

Richard J. de Dear, & Gail Schiller Brager. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, *104*(1), 1–18.

Salata, F., Golasi, I., de Lieto Vollaro, R., & de Lieto Vollaro, A. (2016). Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy. *Building and Environment*, *96*, 46–61. https://doi.org/10.1016/j.buildenv.2015.11.023

Salata, F., Golasi, I., Verrusio, W., de Lieto Vollaro, E., Cacciafesta, M., & de Lieto Vollaro, A. (2018, August 1). On the necessities to analyse the thermohygrometric perception in aged people. A review about indoor thermal comfort, health and energetic aspects and a perspective for future studies. *Sustainable Cities and Society*, Vol. 41, pp. 469–480. https://doi.org/10.1016/j.scs.2018.06.003

Shooshtarian, S., & Ridley, I. (2016). the Effect of Individual and Social Environments on the Users Thermal. *Sustainable Cities and Society*, *26*, 119–133. https://doi.org/10.1016/j.scs.2016.06.005

Smith, P., & Henríquez, C. (2019). Perception of thermal comfort in outdoor public spaces in the medium-sized city of Chillán, Chile, during a warm summer. *Urban Climate*, *30*, 100525. https://doi.org/10.1016/j.uclim.2019.100525

Spagnolo, J., & de Dear, R. (2003). A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment*, *38*(5), 721–738. https://doi.org/10.1016/S0360-1323(02)00209-3

Wang, Y., de Groot, R., Bakker, F., Wörtche, H., & Leemans, R. (2017). Thermal comfort in urban green spaces: a survey on a Dutch university campus. *International Journal of Biometeorology*, *61*(1), 87–101. https://doi.org/10.1007/s00484-016-1193-0

WWO. (2020). World Weather Online | World Weather | Weather Forecast. Retrieved October 8, 2020, from https://www.worldweatheronline.com/

Xi, T., Li, Q., Mochida, A., & Meng, Q. (2012). Study on the outdoor thermal environment and thermal comfort around campus clusters in subtropical urban areas. *Building and Environment*, *52*(July 2007), 162–170. https://doi.org/10.1016/j.buildenv.2011.11.006

Xu, M., Hong, B., Mi, J., & Yan, S. (2018). Outdoor thermal comfort in an urban park during winter in cold regions of China. *Sustainable Cities and Society*, Vol. 43, pp. 208–220. https://doi.org/10.1016/j.scs.2018.08.034

Yahia, M. W., & Johansson, E. (2013). Evaluating the behaviour of different thermal indices by investigating various outdoor urban environments in the hot dry city of Damascus, Syria. *International Journal of Biometeorology*, *57*(4), 615–630. https://doi.org/10.1007/s00484-012-0589-8

Yang, W., Wong, N. H., & Zhang, G. (2013). A comparative analysis of human thermal conditions in outdoor urban spaces in the summer season in Singapore and Changsha, China. *International Journal of Biometeorology*, *57*(6), 895–907. https://doi.org/10.1007/s00484-012-0616-9

Yao, J., Yang, F., Zhuang, Z., Shao, Y., & Yuan, P. F. (2018). The effect of personal and microclimatic variables on outdoor thermal comfort: A field study in a cold season in Lujiazui CBD, Shanghai. *Sustainable Cities and Society*, *39*, 181–188. https://doi.org/10.1016/j.scs.2018.02.025

Zhao, L., Zhou, X., Li, L., He, S., & Chen, R. (2016). Study on outdoor thermal comfort on a campus in a subtropical urban area in summer. *Sustainable Cities and Society*, *22*, 164–170. https://doi.org/10.1016/j.scs.2016.02.009

IJBES

International Journal of Built Environment and Sustainability
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 93-106

# The Value of *Gotong-royong* in the Mountainous Settlement of Kepuharjo Village at Pagerjurang Permanent Shelter in Yogyakarta, Indonesia

**Freddy Marihot Rotua Nainggolan**
Faculty of Architecture and Design, Duta Wacana Christian University, Special Region of Yogyakarta 55224, Indonesia

**Tarcicius Yoyok Wahyu Subroto, Agam Marsoyo**
Department of Architecture and Planning, Faculty of Engineering, Universitas Gadjah Mada, Special Region of Yogyakarta 55281, Indonesia

**ABSTRACT**

Providing housing for refugees due to disasters is a common problem in countries prone to natural disasters. The eruption of Mount Merapi in Yogyakarta in 2010 has displaced the people of Kepuharjo Village to a new settlement in Pagerjurang permanent shelter. However, the process of settling in a new settlement requires adjustments because the people of Kepuharjo Village have been living on the slopes of Mount Merapi for generations. This research is a qualitative research which aims to find a reflection of the space-occupancy value system that occurs in the village of Kepuharjo at the Pagerjurang permanent shelter. The results of observations and interviews with 29 units show that the description of the activities and arrangement of the residential space in the Pagerjurang permanent shelter. The results showed that the motivation for the development of residential spaces is closely related to kinship and socio-cultural values in the daily life of the occupants. The socio-cultural reflection on the residential space of the Kepuharjo community in the Pagerjurang permanent shelter is in line with the social principles of mutual-cooperation (*gotong-royong*). *Gotong-royong* is expressed in the strengthening of space, expansion of space, and agreement of space.

**Article History**

Received: 24 June 2021
Received in revised form: 15 August 2021
Accepted: 17 August 2021
Published Online: 31 August 2021

**Keywords:**

Dwelling Space; Gotong Royong; Housing; Socio-cultural; Value

**Corresponding Author Contact:**

freddynainggolan@staff.ukdw.ac.id

**DOI:** 10.11113/ijbes. v8. n3.822



## 1. Introduction

Providing housing for refugees due to disasters is a common problem in countries prone to natural disasters. Interest in community-based housing solutions has revived in many countries in recent years (Fromm, Tummers in Mullins, 2018). For this reason, *Rekompak* [1] participated in building new community-based settlements to provide new settlements for disaster victims in Java, Indonesia. Community-based implementation has become part of existing development programs, which ultimately means that working in groups is also part of the local culture of life (Maly et al., 2015). However, community-based residential space development has limited space and funds. In the case of resettlement in Yogyakarta, the provision of houses in the form of core houses that require their own development by the occupants.

The eruption of Mount Merapi in 2010 had buried Kepuharjo Village. As a result, the people of Kepuharjo Village need new settlements. For this reason, Pagerjurang permanent shelter is one of the post-Merapi relocations built by the Government and *Rekompak* to meet the needs of the victims of the eruption (Setiadi et al., 2020). The sudden movement of people due to the disaster to the Pagerjurang permanent shelter caused the Kepuharjo community to require adjustments to their housing patterns in new settlements. This is due to the fact that the people of Kepuharjo Village who have lived on the slopes of Mount Merapi for generations have a way of life in harmony with nature. That is, their culture of life proves that society has viewed nature for the benefit of the future. For example, the act of willingness and seriousness in seeing natural disasters and mutual-cooperation (*gotong-royong*) is seen as social capital for disaster management during the eruption of Mount Merapi (Gunawan, 2015). The closeness of society to nature is also reflected in the ethics of interacting with nature, such as the ethics of farming, raising livestock and living (Fatkhan, 2006).

In the context of housing, Hatuka and Bar in Handel (2019) found that housing is a socio-cultural process, seeing homes and houses as representations of broader sociological and cultural phenomena. Rapoport in Atık & Erdoğan (2017) states that buildings, especially houses, are physical and cultural artifacts. In traditional Javanese, the house is often called *omah*[2]. Meanwhile, Darmanto-Jatman in Santosa (1997:2) "*formulates Omah as comprising O and mah, which extend the meaning of Omah as the meeting point between the o-ness of space-sky-male and mah-ness of ground-earth-earth-female*." *Omah* is a reflection of Javanese people who are still bounded by the concept of life in which there are routine and ritual activities. *Omah* is also the life of a cultural group (Santosa, 2000). The meaning of *omah* is similar to the meaning of the life of a Javanese cultural group. Tjahjono (1989) states that *Omah* is considered a place to calm the mind. Ronald (2005:8) stated that in the life of the Javanese people, it is also known about such the terms of space and place as *longkangan* (space), *panggonan* (place), *panepen* (residence /"settlement"), and *palungguhan* (seating for interacting). Javanese people use the term place (*panggonan*) to indicate the space in a traditional Javanese house. For Javanese, the term of place refers to the value and meaning of the activities which is carried out. This is conducted due to the understanding that every activity which is carried out is associated with the value and meaning in where the activity is carried out. It shows that the Javanese need for space (*longkang*), a place to live (*panggonan*), a place to contemplate (*panepen*), and a place to interact (*palungguhan*).

Subroto (1995) describes that the spaces of the Javanese house is divided into 3 (three) as : 1. the front space (*Pendopo* as the public domain), 2. the middle space (*Dalem* as central space and *Gandok* as female domain area) and 3. the rear space (*Pawon* or kitchen as service domain) (Figure 1). The front space as mentioned above is represented by the pendopo pavilion). The outer part of *omah* (house) is *emperan* (verandah).

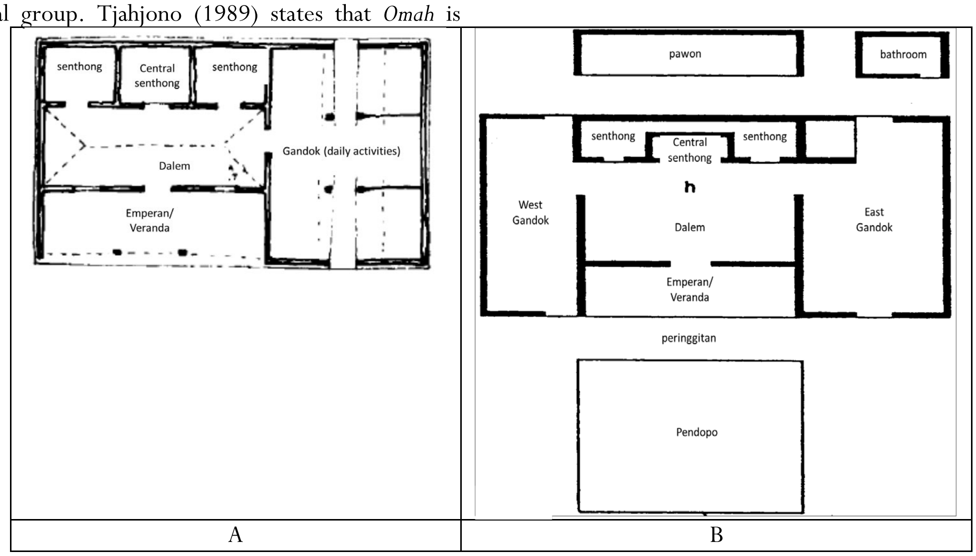



**Figure 1** Javanese Traditional House Plans (Tjahjono, 1989:101; Subroto, 1995:28)
*A. Simple House (Omah).* *B. Ideal House (Joglo).*

Furthermore, the *pendopo* is bright and open. The space between the *pendopo* and the *omah* has a *peringgitan*, which is an empty intermediate space. Thus, the division and value of space are fundamental in Javanese culture.

There are many concepts about residential space which have been published. As a bipolar space concept, many residential spaces are expressed in contradictions such as public and private, day and night, or front and back (Tjahjono, 1989). As a system, the artificial environment is formed through several subsystems. It is indicated that each subsystem consists of fixed feature, semi-fixed feature, and variable feature elements. The relationship between activities and settings is an important factor in identifying residential spaces (Rapoport, 1982). In addition, the need for shelter is a basic human need. Abraham Maslow classified the need for residential space at the two lowest levels of human needs, namely physiological and security (Jerome, 2013). A house is purified by ritual processions and is still considered the dividing line between the sacred and profane worlds (Eliade, 1959). Residential space plays an essential role as capital for low-income households in urban areas (Marsoyo, 2012). Residential space creates a relationship between cultural and social values. For example: gender relations, social uniqueness, religious, and historical context in traditional houses in Jeddah (Al-Ban, 2016); application of vernacular spaces into contemporary houses in Yogyakarta and Surabaya (Subroto, 1995); interplay of interactions of social structure, economic and cultural life of residents in the transformation of the domestic architecture of Madurese housing in Surabaya and Madura (Faqih, 2005); the evolution of housing in terms of form and culture in Seoul (Seo, 2005); the relationship between culture and architectural forms in vernacular Hakka dwellings in Meizhou (Tao et al., 2018); and the transformation of the Javanese house in Kotagede Yogyakarta (Ju et al., 2018). Other examples include changes in spatial organization as a consequence of social change, such as temporary middle class housing in Sri Lanka (Paranagamage, 2006); social-spatial relations in rural Pakistan (Mughal, 2013); a dwelling transformation in Bali (Agusintadewi, 2014); and traditional houses in Phrapradaeng District (Wongphyat and Suzuki, 2018). Several studies that have been carried out have confirmed the existence of values in residential spaces that are generated by social and cultural aspects in society.

This study is important because of the following interests: (1) the people of Kepuharjo have lived in spiritual, cultural, and social values for generations, (2) the displacement of the inhabitants of the slopes of Mount Merapi due to the eruption of the mountain needs a new settlement, and (3) new settlements, namely in Pagerjurang permanent shelter which was established by agreement and discussion involving all residents which shows the interrelation from old space to the new space. For this reason, this study aims to find a reflection of the space-occupancy value system for the people of Kepuharjo who live in Pagerjurang permanent shelter. It is hoped that this study can become part of the spatial reference pattern for the provision of new relocation residential spaces as a built environment, especially for rural refugees damaged by the disaster by taking into account the values of the old residential space.

## 2. Methodology

The phenomenon in each case represents each hamlet in the Pagerjurang permanent shelter. Selection of case observations using purposive sampling method. Apart from that, the snowball technique was also used to determine the most appropriate cases. The house was chosen purposively based on existing phenomena. Each case represents a category, namely the name of the hamlet, the level of the story, the number of bedrooms, the number of families in one house, the number of residents, and the direction of the house so that there were 29 cases representing the five hamlets.

Data collection was carried out through observation and interviews. Observations were focused on activities and settings in the Pagerjurang permanent shelter unit. Interviews were conducted with residents and the village head. The interviews were conducted with the 29 heads of households.

**Table 1** Observation checklist (Author)

| concepts | | elements |
|---|---|---|
| Fixed feature elements | Houses elements | Walls |
| | | Floor |
| Semi-fixed feature elements | Room Furniture | Furniture layout |
| | | Furniture types |
| Variable feature elements | Activities | Spiritual activities |
| | | Cultural activities |
| | | Social activities |
| | | Economic activities |

As shown in Table 1, the observation guidelines is formulated based on Rapoport (1982) which refer to 3 (three) features as 1. Fixed feature: the partition (walls) as the permanent element, 2. Semi-fixed feature: layout and types of furnitures), and 3. Non-fixed feature : activities that occur in the space. This observation aims to see the spatial organization and the space usage.

The analysis carried out was the spatial reconstruction of the residential space in the Kepuharjo Village and the Pagerjurang permanent shelter. The spatial arrangement of the Pagerjurang permanent shelter is equipped with furniture layout. The selection of furniture in each room has provided information about the character of the room. Thus, the traditional Javanese residential space pattern acts as a reference to understand the similarities between the residential space in Kepuharjo Village and the Pagerjurang permanent shelter. This is because topological distances (Hillier & Hanson, 1984) and access charts are used in this stage to determine the spatial depth and spatial connectivity of the living space. Reflections on the relationship between activities and residential space settings in Kepuharjo Village in Pagerjurang permanent shelter were found through the depth of the residential space, the connectedness of space, and the principles of Javanese house layout.

## 3. Result and Discussion

### *3.1 Utilization Strategy of Space*

#### 3.1.1 The Characteristics of Pagerjurang Permanent Shelter

Pagerjurang Housing has been inhabited since 2012. This is a new settlement for the people of Kepuharjo Village which was destroyed by a volcanic eruption. Pagerjurang permanent shelter is a permanent settlement with the largest number of units in Sleman Yogyakarta. The community consists of five hamlets on the slopes of Mount Merapi, namely Kaliadem, Petung, Manggong, Pagerjurang, and Kepuh, totaling 301 housing units. The research location is shown in (Figure 2).

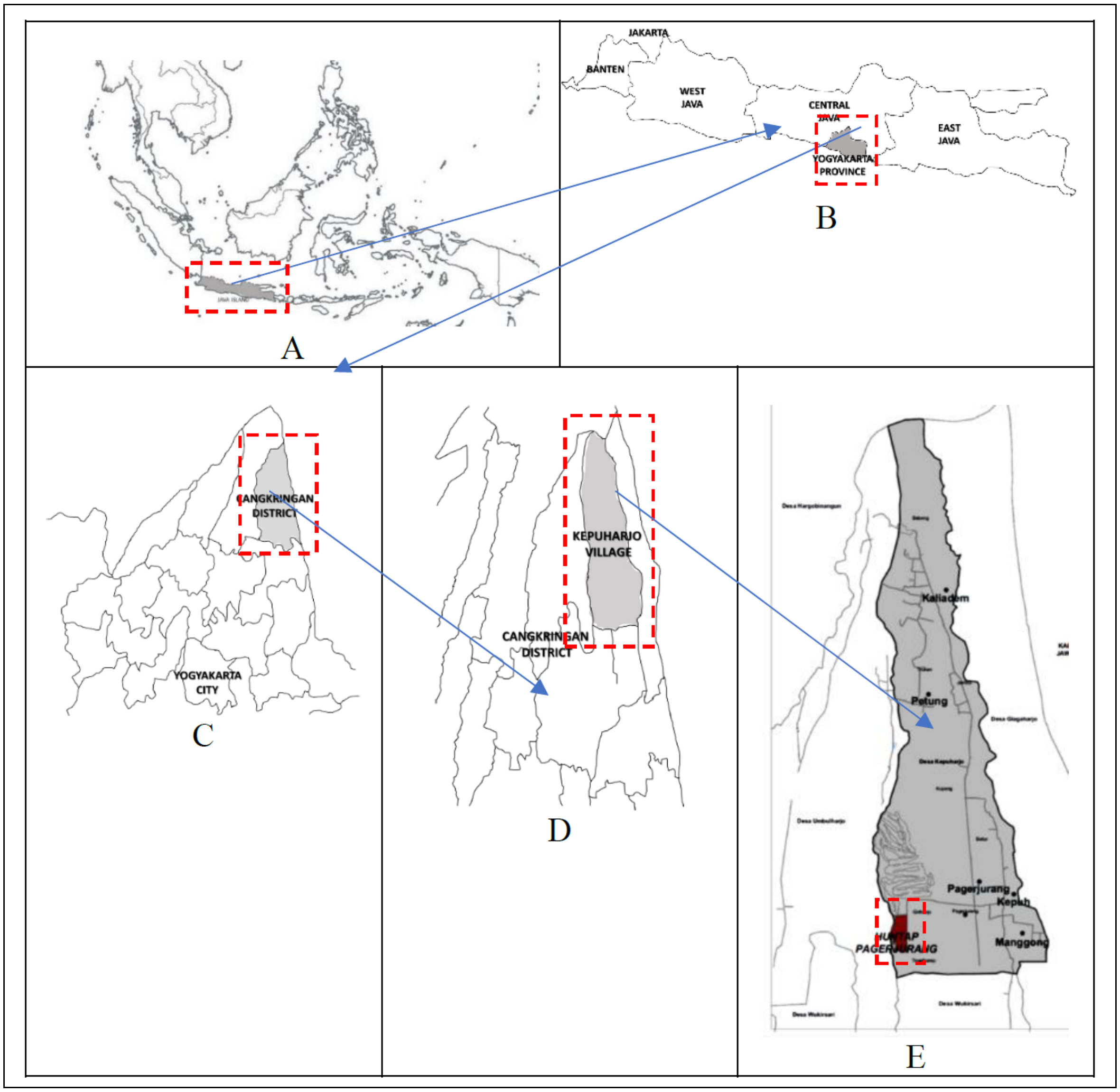



**Figure 2.** Research location (Author)

*A. Position of Java Island in Indonesia. B. Position of Yogyakarta Province in Java Island. C. Position of the cangkringan district in Yogyakarta Province. D. Position of Kepuharjo village in Cangkringan District. E. Position Pagerjurang permanent housing and the hamlets in Kepuharjo Village.*

The process of placing the housing units in the Pagerjurang permanent shelter is carried out by deliberation between the Head of Kepuharjo Village, the residents, and the Rekompak. The standard unit concept is called the core house[3]. The core house measures 36 square meters, with a total parcel area of 100 square meters. Each housing unit with a grant of IDR 30,000,000 and Rekompak applies the concept of a core house as a solution for providing housing in Java. However, residents were allowed to build the finishing unit independently. For construction purposes, as protection from recurring disasters, Rekompak applies high compliance with earthquake resistance requirements (Multi Donor Fund for Aceh and Nias, 2012).

This phenomenon shows that there was an agreement among residents to live a new life in the Pagerjurang permanent shelter based on life in Kepuharjo Village before the eruption. Firstly, the name of the hamlet in Pagerjurang permanent shelter is based on the name of the previous hamlet in Kepuharjo Village. Secondly, each hamlet runs independently as before because it is still led by the previous hamlet head. In addition, there are mosques in every hamlet, and socio-religious activities and cultural traditions are carried out as previously done in Kepuharjo village. Thirdly, the arrangement of the units for each family is carried out through deliberation. Thus, each family has the right to one housing unit and chooses its position by considering its neighbors when living in the village of Kepuharjo. Fourthly, the economic life by raising livestock is still carried out in Pagerjurang permanent shelter. Every livestock that died as a result of the eruption of Mount Merapi in 2010 has been compensated by the government. It should be added that a communal cattle pen is provided for raising livestock on the west side of the Pagerjurang permanent shelter.

### 3.1.2 Activities and Setting in Dwelling Spaces

Activities carried out by the occupants are shown in Table 3. These activities are grouped into four categories: (1) spiritual, (2) cultural, (3) social, and (4) economic. These categories are arranged in two poles, namely sacred and profane. All activities carried out at Pagerjurang permanent shelter are guided by all daily activities and rituals carried out in Kepuharjo Village. The author organizes activities and settings in residential spaces in group spaces, as shown in Table 2.

**Table 2.** Category of Space and Activity in Dwelling Spaces (Author)

| Category | Activities |
|---|---|
| O | Activities carried out outside dwelling space |
| A | *Emperan* is transitional spaces between inner space and outer space. |
| B | Space to receive guests formally |
| C | Shared space for all family members |
| D | Bedroom, space used for sleeping |
| E | *Pawon,* space used for cooking |
| F | *Bathroom,* which is used for bathing, washing, and toilet |
| G | Space used for storing equipment and vehicle |
| H | *Kandang,* Cage, space used for animals, livestock |
| I | Space used for business and selling |

The category of space in the residential space in Kepuharjo Village and Pagerjurang permanent shelter obtained from interviews and observations turns out to be permanent, semi-permanent, and non-permanent. The permanent elements are the walls and structure of the unit. Semi-permanent parts are dividers and furniture which are easy to move. The non-permanent part is the activity of the residents themselves. Based on these elements, the floor plan and space category are described accordingly.

### 3.1.3 Expansion of Dwelling Space in Pagerjurang Permanent Shelter

The government provides an initial fund of IDR 30,000,000 for each family to build a core house with the basic structure. Through dialogue between the community and Rekompak, three patterns of the core houses were obtained. The three patterns provide three spaces with a function: common room, bedroom, and bathroom. Patterns A and B have the same amount of space, namely one bedroom, one gathering room, and one bathroom, but the different ones were arranged from the entrance. Pattern C has two bedrooms, one meeting room and one bathroom. The pattern division is as follows: (1) pattern A consists of 12 units, (2) pattern B consists of 10 units, and (3) pattern C consists of seven units.

From 2012 to 2018 there has been a change in the position and size of space, as well as the shape of the unit. Firstly, a change in construction. For example, four units make up a two-story structure (Figure 3).

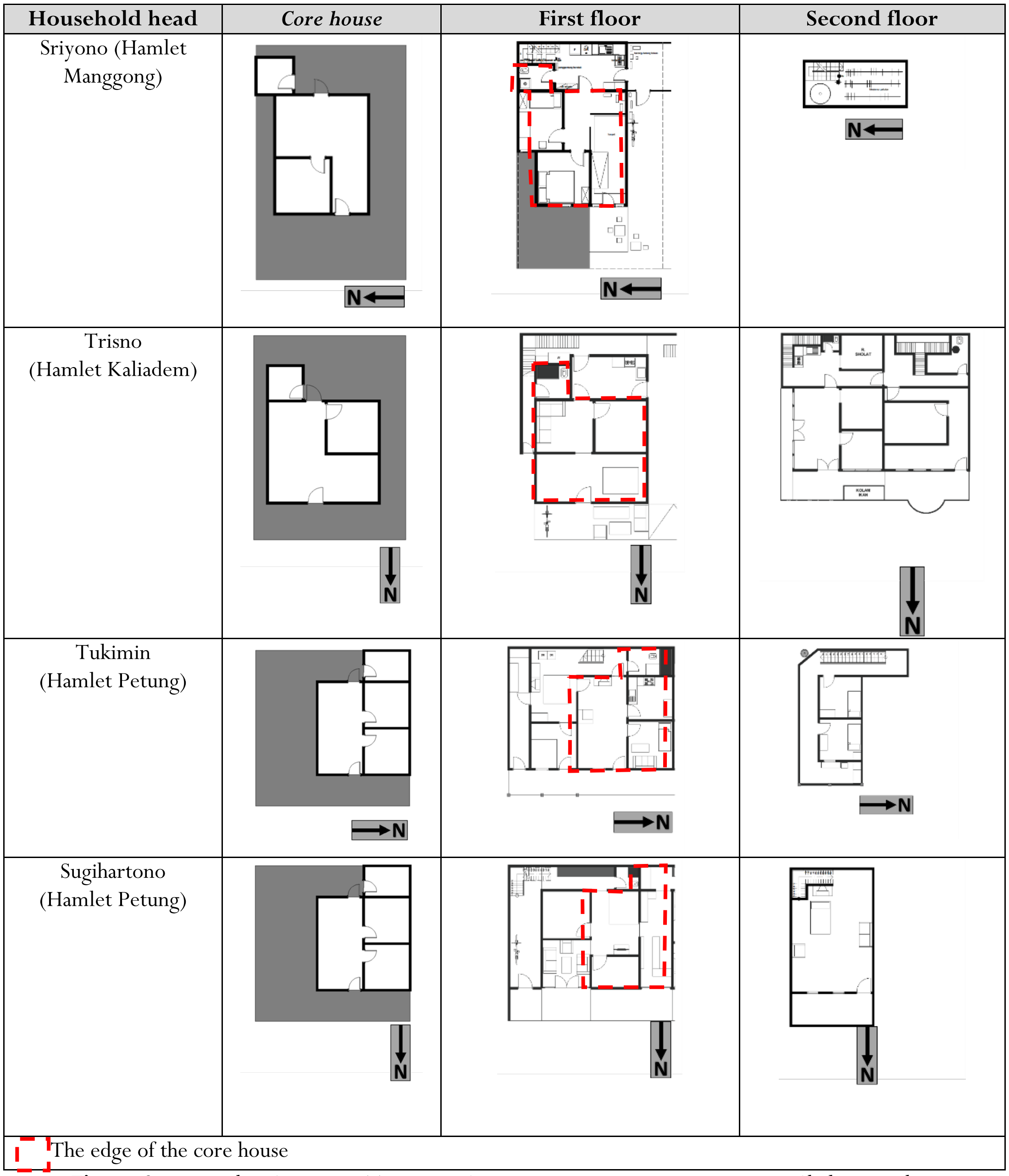



**Figure 3** Houses that Grow into Two-story Structures in Pagerjurang Permanent Shelter (Author)

In addition, the construction of the upper floors is based on the need for additional bedroom. Currently, the upper floors are widely used for storage, bedroom, living room. Secondly, the expansion is based on the needs of the bedroom. Five one-bedroom houses have made improvements to the shape of the rooms. However, not a single house unit that changed construction, for example Pak Heri's house from Manggong, was rented; therefore, construction changes are not allowed by the unit owner. It should be added that the two bedroom units have the most preference, which is 18 units. Four units have three bedrooms, one unit has four bedrooms (for example Pak Sardi's house from Kaliadem), and one unit has five bedrooms (Pak Trisno's house from Kaliadem). Thirdly, expansion of space due to changes in new family status. The number of families living in one unit is divided into two cases, namely: one family and two families. The occupants of the chosen unit are generally one family. Initially the local government provided one house for one family. However, there are several cases where there has been an increase in the number of families following the transition process. Hence, there are three units occupied by two families. The increase in the number of families forced the addition of residential space to accommodate newly married couples.

After residents have occupied the main house since 2012, it turns out that they have added rooms in the house. These data represent additional space that accommodates the functions of the family room, *pawon*[4], *tretepan*[5], warehouse, and garage. The next level is the addition of a bedroom and living room. This data shows the trend of adding and developing space to accommodate activities with categories C (family room), E (pawon), A (tretepan), G (storage room), B (living room), and D (bedroom). Rooms with categories C, E, A, G, B, and D, for spiritual, cultural and social activities.

### 3.1.4 Connecting Spaces Between Units

Limited space and cost are important factors that must be adjusted by residents. For this reason, the head of the household chooses a location by considering family relationships (Figure 4).

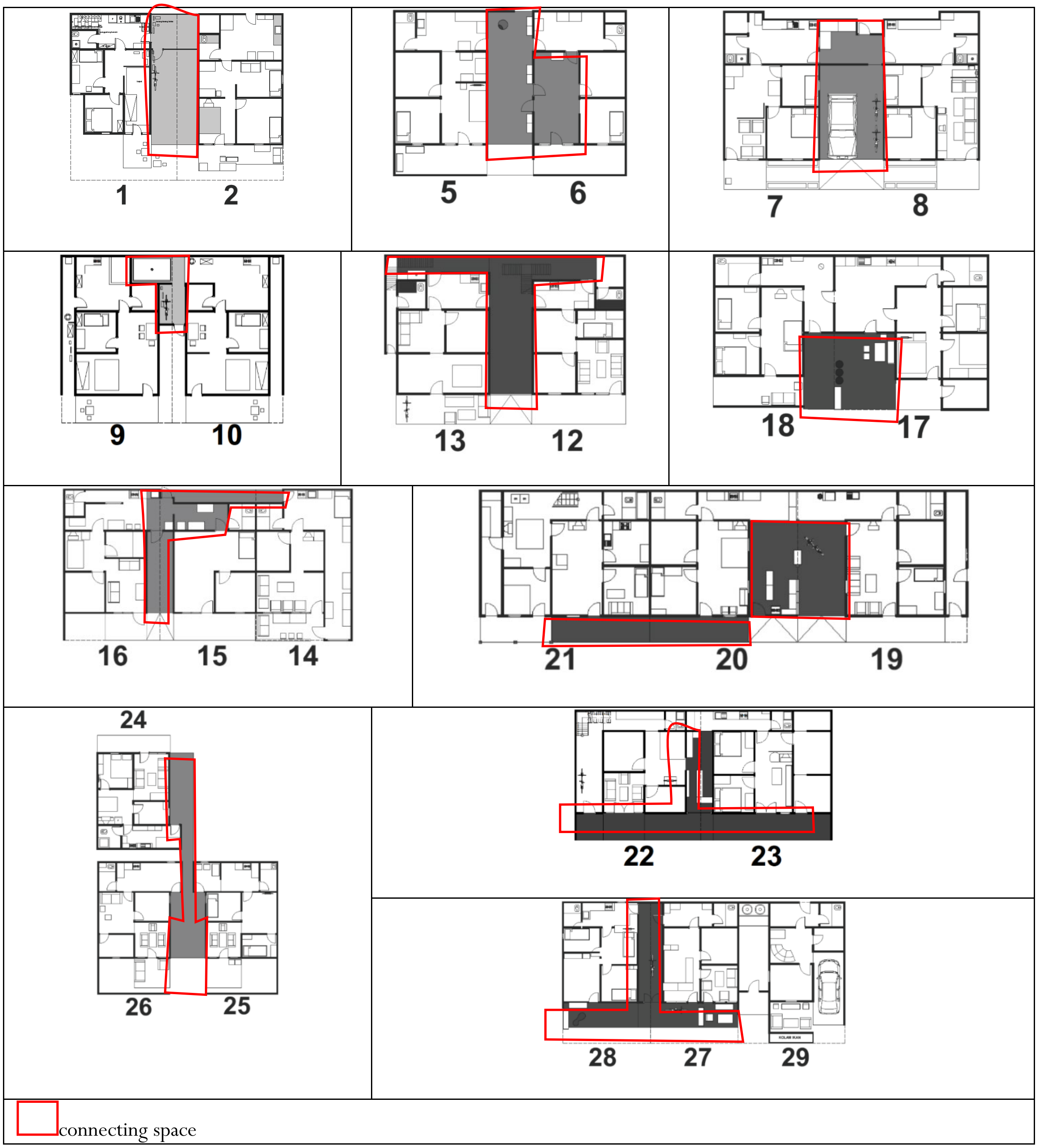



**Figure 4** Connecting space between houses in Pagerjurang permanent shelter (Author)

In the case of units 1 and 2, the connecting spaces are shared for social activities, such as meetings and household purposes, such as storage areas. Meanwhile, for units 5 and 6, the connected space is used for household activities, such as cooking and the garage. Likewise for units 7 and 8, the connected space is used for household activities, such as cooking, which uses fire and the garage. In contrast to units 9 and 10, the connected space is used for household activities, such as cooking, washing and bathing. Likewise for units 12 and 13, the connected space is used for domestic activities, such as storing goods and vehicles. For units

14, 15 and 16, the connecting space is used for household activities, such as cooking and socio-cultural activities. Meanwhile, units 17 and 18, connected spaces are used for household activities, such as cooking, storing goods and vehicles, and for social activities, such as informal gatherings. Units 19, 20 and 21, connecting spaces are used for household activities, such as cooking and social activities. Likewise in units 22 and 23, the connected space is used for economic activities, such as selling goods and food for social activities, informal gatherings and cultural activities. For units 24, 25, and 26, the connecting space is used for domestic activities using connecting corridors, for social activities, such as formal and informal meetings, and cultural activities. Finally, for units 27, 28, and 29, the connecting space is used for domestic activities, such as selling goods for social activities such as formal and informal gatherings.

Referring to Figure 4, the connected spaces are categories O (outside), A (*tretepan*), E (*pawon*), F (bathroom), and G (storage space). It can be seen that the main function of the connecting space between units in the house is used for domestic and social activities. This connecting space also shows that the dividers between residential spaces are not essential, especially in units occupied by owners who have family relations. It can be seen physically that there is still a separation of space, but access between residential areas is very open. The data show that the spaces are mostly connected at spatial depth levels of 1 (26%) and 5 (33%). The spatial depth indicates that the connected spaces actually occur in the front and rear rooms of the unit.

## *3.2 Relationship between Activities and Setting in Dwelling Space*

### 3.2.1 The Spatial Depth in a Dwelling Space

By using the spatial morphology graphic method, the level of control and space accessibility can be described. This will indicate the depth of the room. The value of spatial connectivity can be obtained through the depth of field. Connectivity is a dimension that measures spatial relationships by counting the amount of space that is directly connected in a spatial configuration. Measurement of spatial connectivity reveals the level of interaction of a room with other spaces around it (Hillier et al. in Siregar, 2014). The spatial depth of each unit in Kepuharjo Village and Pagerjurang permanent shelter is depicted by the depth of space for each unit (Figure 5).

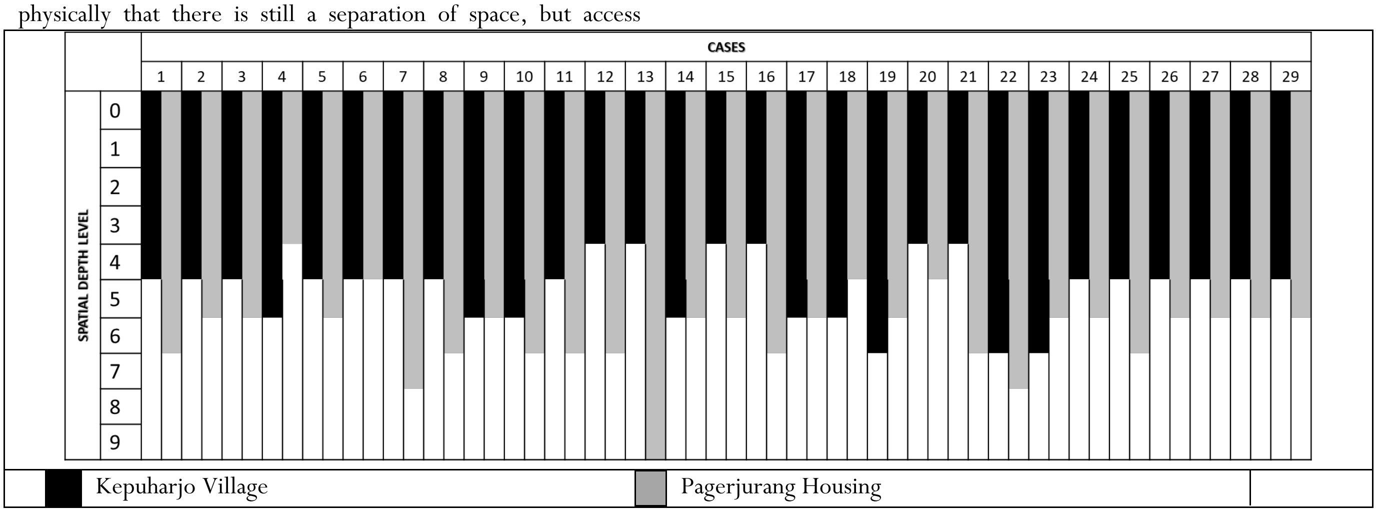



**Figure 5** Spatial depth level of each case unit in Kepuharjo village and Pagerjurang permanent shelter (Author)

Figure 5 shows a black block that shows the level of spatial depth of the residential space in Kepuharjo Village. Meanwhile, the gray block shows the level of spatial depth in the Pagerjurang permanent shelter. From that figure, it can be seen that the spatial depth in the Pagerjurang permanent shelter is much deeper than in Kepuharjo Village. This indicates that the spatial depth is caused by the need for a large residential space, but the available space is limited. Providing additional space is done by providing fixed elements and semi-fixed elements as space dividers. On the other hand, Figure 6 shows the room divider by *gedhek*[6] (6A), curtains (6B), and wood panels (6C, 6D).


**Figure 6.** Architectural elements as the space divider in Pagerjurang permanent shelter (Author)

*a. Space divider in Heri's house with a gedhek*
*b. Space divider in Harjono's house with a curtain*
*c. Space divider in Sriyono's house with a wood panel*
*d. space divider in Mitrowiyono's house with a wood panel*

### 3.2.2 Sacred and Profane Activities

Javanese life is inseparable from the belief that there is a spirit that can bring success, happiness, peace, or safety. But on the other hand, it can also cause mental and health problems and even death (Koentjaraningrat, 1993). Therefore, sacred activities must be carried out by the Javanese people to influence the universe. Activities carried out take the form of humble living, fasting, abstaining from exercising certain deeds or eating certain foods, practicing salvation, and offerings. Dualism in the life of Javanese society is essential and can occur in public and private spaces, men's and women's spaces, spaces for gods and humans, because sacred and profane activities always occur in Javanese society. For the community of Kepuharjo Village, these rituals are still carried out after they resettled in a Pagerjurang permanent shelter, as shown in Table 3.

**Table 3** The Activities of the Pagerjurang Permanent Shelter Occupants (analysis by Author)

| *Sacred Communal/Individual Activities* | | *Profane Communal/Individual Activities* | |
|---|---|---|---|
| ***Spiritual*** | ***Cultural*** | ***Social*** | ***Economic*** |
| Praying (CNP) | *Dandan kali* (ceremony aims to pray for rain to the Almighty) (COP) | Formal/informal chatting (CND) (IND) | *Ngobor* (feeding cattle) (IOD) |
| *Yasinan* (read scriptures) (CNP) | *Malam 1 Syawal* (religious ritual for new year) (COP) | *Merti Dusun* (village cleaning ceremony) (COP) | Taking fodder (IOD) |
| *Pengajian* (a tradition to offer prayers )(CNP) | *Tahlilan* (ritual/ceremony to commemorate and pray for the dead)(COP) | *Ronda (*Neighborhood guarding) (COP) | food stalling (IOD) |

| | | | |
|---|---|---|---|
| | *Brokohan* (the Javanese traditional ceremonies to welcome baby birth) (CNP) | meeting of occupants (CNP) | *Milah sampah* (sorting garbage) (COP) |
| | *Selapanan* (the ritual of a 35-day-old baby) (CNP) | *Arisan (*rotate saving club) (CNP) | |
| | *Selamatan* (gathering ceremony to ask for blessing) (CNP) | taking a nap (IND) | |
| | *Kenduri* (CNP) | Eating (IND) | |
| | *Malam 17 Agustus (*ritual of Independence Day*)* (COP) | Cooking (IND) | |
| | | Bathing (IND) | |
| | | Washing clothes (IND) | |
| | | Drying clothes (IND) | |
| | | Relaxing (IND) | |
| | | Storing goods (IND) | |

*C: CommunalI: Individually O: Outside house N: Inside house P: Periodically D: Daily*

The categories of activities are carried out communal (C), individual (I), indoors (N), outdoors (O), periodic (P), and daily (D). The whole activities can be divided into two broad categories, namely sacred and profane. Cultural activities are conducted communal, inside and outside the house, and are carried out periodically. While, for social activities, they are communal and can be done inside and outside the house, which can be done daily. Economic activities are individual in nature, are carried out outside the house, and are carried out on a daily basis. Meanwhile, domestic activities are individual in nature, carried out daily in their house. It can be concluded that sacred activities require community involvement, where the implementation is carried out periodically in the house. In contrast, profane activities are carried out individually and need to involve the community, carried out daily in the house. Hence, there is a sharp contradiction between sacred and profane activities, especially with the individuals involved and the timing of their implementation.

### 3.2.3 Shared Spaces for Cultural and Social Activities

Data obtained through observations and interviews with a focus on permanent, semi-permanent, and non-permanent elements. Data obtained through photographs, sketches of residential space reconstruction in Kepuharjo Village, sketches of the spatial unit of the Pagerjurang permanent shelter, and the daily activities of the residents. The activities in these 29 units can be categorized into two main groups. The large group of activities consists of sacred and profane activities. Topological distance access charts are used to describe the relationship between the level of spatial depth and the category of residential space in Kepuharjo Village and Pagerjurang permanent shelter. The results of the access graph are illustrated in a matrix of the relationship between spatial categories, activity categories, and spatial depths that show the relationship between cultural and profane activities in the spatial category and spatial depth. The dominant common space occurs at spatial depth levels 0, 1, and 2. The data shows that in Kepuharjo Village, the dominant cultural activities occur at the spatial depth level 2 (Table 4).

**Table 4**The Proportion of Sacred and Profane Space to the Spatial Depth Level (analysis by the author)

| Spatial depth level | Sacred | | Profane | |
|---|---|---|---|---|
| | Kepuharjo | Pagerjurang | Kepuharjo | Pagerjurang |
| 0 | | 39% | 9% | 19% |
| 1 | 3% | 23% | 29% | 11% |
| 2 | 94% | 30% | 19% | 17% |
| 3 | | 8% | 19% | 16% |
| 4 | 3% | | 16% | 20% |
| 5 | | | 6% | 12% |
| 6 | | | 2% | 3% |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | 2% |

Based on the spatial depth analysis, it is found that the use of residential space is for cultural, economic and social activities. Figure 2 shows a common space for cultural and soci al activities. Socio-cultural activities occur at spatial depth levels of 0, 1, and 2 after resettlement to Pagerjurang permanent shelter.

The twenty-nine units have a unique pattern in the residential space in Kepuharjo Village and Pagerjurang permanent shelter. The position of space for cultural activities lies in the category O, A, B, C, D, G. The dominant positions are in A (emperan), B (living room), and C (family gathering room) (categories shown in Table 2). The dominant cultural activities are at level 2 in the village of Kepuharjo. After being relocated to Pagerjurang permanent shelter, cultural activities were spread out at spatial depth levels of 0, 1, and 2. Economic activities take place in living quarters, communal livestock sheds, and outside Pagerjurang permanent shelter. In accordance with the depth of space in Pagerjurang permanent shelter, the economic activity is at the spatial depth level of 0. It can be understood that the occupants' economic activities occur outside the home. In addition, the communal livestock pen serves as a source of income. Breeding dairy cows and cows is the livelihood of most residents. After being relocated, the room category H (cage) was not in the unit but was placed in another location: the communal pen on the west side of the Pagerjurang permanent shelter and another warehouse outside the Pagerjurang permanent shelter. This proves that the communal sheds are still preserved as the primary working location.

Social activities in Kepuharjo Village and Pagerjurang permanent shelter can also be explained. Most social activities in Kepuharjo Village occur at spatial depths at levels 1 and 2. After resettlement, social activities reach almost evenly at spatial depths at levels 0, 1, and 2. The similarity of activities from Kepuharjo Village to Pagerjurang permanent shelter is reduced at the depths of space level 1 and 2. The level 1 spatial depth in Kepuharjo Village is shown as a *tretepan*. The level 2 spatial depth is a formal meeting room, namely the living room (category B).

Domestic activities that occur in Kepuharjo Village and Pagerjurang permanent shelter are scattered at different spatial depth levels. Activities such as sleeping in Kepuharjo Village occur mainly at spatial depths at levels 3 and 4. After relocation, domestic activities also occur, especially at spatial depth levels 3 and 4. Cooking activities in Kepuharjo Village are dominant at spatial depth levels 3 and 4. In Pagerjurang permanent shelter, cooking activities mostly occur at level 4 depth. Bathing and washing activities in Kepuharjo Village occur at level 1 spatial depth, while in Pagerjurang permanent shelter it occurs at level 5. Informal family gatherings in Kepuharjo Village mainly occur at level 2 spatial depth. However, in Pagerjurang permanent shelter, family gatherings are more dominant at spatial depths 2 and 3. The main activities of these domestic activities indicate that domestic activities occur at spatial depths of levels 1, 2, 3, 4, and 5. Based on the spatial depth mapping of Pagerjurang permanent shelter, there is a common space between cultural and social activities, which occurs at the spatial depth level: 0 , 1, and 2.

### 3.2.4 Value of Space Connectivity for Cultural and Social Activities

The value of space connectivity shows the position of the room with other rooms. The room with the highest connectivity value indicates that space is associated with many different spaces. It is revealed that the balance between the contradictory elements of activity and space in Javanese society occurs in the middle of the residential space (Ju et al., 2018). The middle part of the living space is represented in *senthong tengah*[7] (the middle room in the house of common people) or *krobongan* (the middle room in the upper-class houses). The analysis revealed that the reflection of the spatial connectivity of Kepuharjo Village and Pagerjurang permanent shelter occurs at spatial depths level 2 and 3. The dominant position at level 2 spatial depth in Kepuharjo Village shifted to level 3 spatial depth after being resettled to spatial depth level 2. The data analysis shows that the connectivity space occurs in the category B and C, namely the categories of formal and informal gathering spaces for guests and family members. Spaces with high connectivity values are at spatial depth levels 2 and 3. This position reflects the value of spatial connectivity that also occurs at spatial depth levels 2 and 3 in Kepuharjo Village. The value of spatial connectivity that occurs at spatial depths 2 and 3 indicates that this is also the center of the residential space of the Pagerjurang permanent shelter. The center of residential space is also a shared space for cultural and social activities for the community of Kepuharjo Village.

## *3.3 Transformation of Dwelling Space and "Gotong Royong"*

In Javanese upper-class houses, cultural space is a private domain within the house. The *Pendopo* represents social space as a public space. Cultural activities and social activities have strict limits. Subroto (1995) mentions that the three parts of the Javanese traditional house are often referred to as *omah ngarep* (front house), *omah jero* (inner house), and *omah mburi*[8] (rear house). Social activities are in *Omah Ngarep*, while cultural activities are in *Omah jero*. The houses in Kepuharjo Village have a village house spatial pattern. In this village house pattern, cultural and social activities use shared space. Cost-related factors determine the integration of cultural and social spaces. Despite it has limited costs, each residence has unlimited space.

After moving to Pagerjurang permanent shelter, sacred and profane activities were carried out in cultural and social activities. Referring to Table 6, the shared space between cultural and social activities is dominant at the spatial depth levels 1 and 2. The space categories at the spatial depth levels 1 and 2 are A, B, and C. Activities that occur in Category A, B, and C are in *tretepan* as informal gathering space, living room as formal gathering space, and family room as informal gathering space for families. These activities are related to social activities and are carried out daily (Table 5). These social activities can occur periodically between residents and the community and between individual residents. Periodically refers to the time chosen based on sacred events.

Tjahjono (1989:100) states that the omah is divided into the outer and the inner part. *Emperan* (verandah or porch) is the outer part. On its east side stands usually an *amben* (bamboo bed), its west side is reserved for receiving guest(s). In Pagerjurang permanent shelter, when profane activity occurs, the verandah/porch is a place for receiving guests. However, emperan (verandah/ porch) was an extension of the living room during cultural activities, while the layout of furniture was changed by moving the *amben* and rolling out mats.

Limited funds and space are factors in the occurrence of common space for cultural and social activities. Due to limitations, cultural activities require community support, which in the end, cultural activities as a private sphere in Javanese culture becomes public. The space used is also a space that is easily accessible by the community. Table 4 confirms that the inner space used is at the spatial depth levels 1 and 2. Besides that, due to limited space in Pagerjurang permanent shelter, some cultural activities require additional space. There is an expansion of space where communal space and public space get permission from the occupants to be used as additional space for cultural activities. The use of public space as a shared space is expressed through various cultural events. The *dandan kali* or *becekan* ritual[9] is performed by residents of Manggong, Kepuh, and Pagerjurang hamlets on the Gendol River [Figures 7a, b, c]. Rituals are performed at the end of the dry season to pray for rain and are performed as part of *gotong royong* (mutual-cooperation) by men, including cooking, providing a goat to be sacrificed, and space for *kenduri*[10] (feast). The highlight of the *becekan* activity is *kenduri* which is done by sitting cross-legged and praying. The prayer is led by a *modin*[11] (cleric). The Kenduri is ended by eating together the food brought by the participants who had been prayed for [Figure 7d, e].

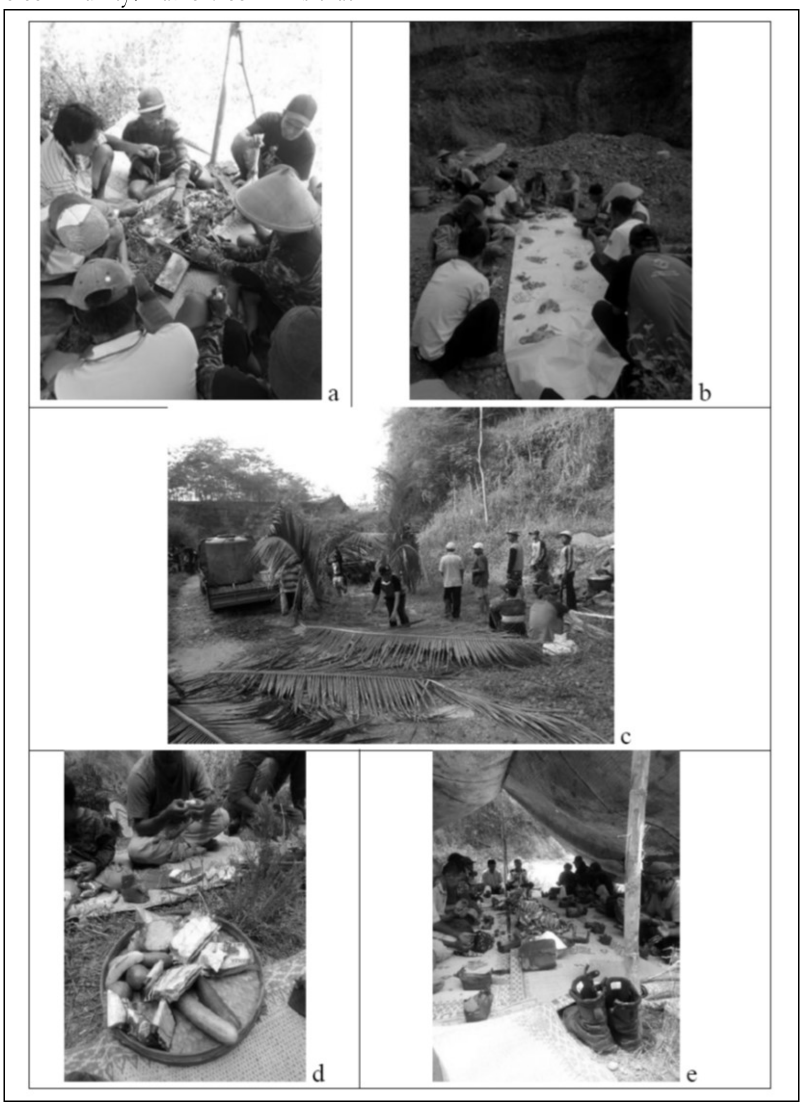



**Figure 7.** Ritual *Dandan Kali* (*becekan*)(photograph by Author)

*a.Preparing the ritual of dandan kali by a community of the manggong hamlet b.The ritual of dandan kali by a community of the pagerjurang hamlet c.Preparing the ritual of dandan kali by a community of the Kepuh hamlet d.Food in the tray for the kenduri e.Implementation of the kenduri led by a modin*

The need for additional development space was marked by the construction of a meeting hall in each hamlet in Pagerjurang permanent shelter. The meeting hall is a representation of the hamlet hall in Kepuharjo Village. The halls are also used for cultural ritual activities that invite many residents. Cultural rituals carried out in the meeting hall can be either individual or communal cultural activities. One of the communal cultural activities featured is the festive night of Indonesia's Independence Day on August 17th. The night of *kenduri* on August 17 is a tradition carried out by the people of Petung Hamlet to be grateful for the independence of the Republic of Indonesia.

The development of spatial planning is also demonstrated by the use of public spaces together, such as roads and residential spaces for local residents. Cultural activities involve the collaboration of all residents in the use of public spaces and residences. One example is the preparation for marriage by residents of the Petung hamlet in Pagerjurang permanent shelter. In preparation for the wedding ceremony of Pak Paing's daughter, it is called *rewang*[12], a tradition in which residents cook together and prepare a shared room for the wedding ceremony. The residences of the neighbors around Pak Paing's house were used for additional preparation space.

## 4. Conclusion

This study found that a reflection of the cultural and social life of the people of Kepuharjo Village in a residence after being resettled in Pagerjurang permanent shelter. Firstly, the people of Kepuharjo Village who live in Pagerjurang permanent shelter gradually develop their houses. This development is highly motivated by family values. For example, increasing the number of rooms to provide private space for newly married family members and the formation of connecting rooms that extend and connect residential spaces where the owner has a family relationship. Secondly, the socio-cultural values in the life of the people of Kepuharjo Village who resettled at the Pagerjurang permanent shelter greatly influenced the development of the depth of space. Thirdly, in terms of limited funds and space, socio-cultural activities are attached to one another so that the socio-cultural space is merged. Fourthly, the common space between cultural and social activities at Pagerjurang permanent shelter has become the core space which is the center of the residential space.

These findings also reveal the process of reviving the social and cultural values of the people of Kepuharjo Village. This is because the relocation process must be carried out suddenly by the community. Private cultural activities require validation to involve public social activities. Limited funds and space are resolved through overlapping spaces involving cultural and social activities. The positioning of the space is located without difficulty both visually and its accessibility.

Finally, the findings of this study confirm that socio-cultural values cannot be separated from the life of the people of Kepuharjo Village. Socio-cultural values are still applied in adapting to changes in the shape and dimensions of space. The socio-cultural reflection on the residential space of the Kepuharjo Village community at Pagerjurang permanent shelter is in line with the social principles of *gotong-royong*[13]. *Gotong-royong* takes place in three aspects, namely: *gotong-royong* of space, *gotong-royong* of human power, and *gotong-royong* of resources. Gotong royong has eliminated the boundaries of residential space and supports spatial development. Gotong royong is expressed in the strengthening of space, expansion of space, and agreement on space. This is important because many countries in Asia are threatened by natural disasters. In Indonesia, many settlements were damaged by volcanic disasters. This study can be part of a spatial reference pattern for the provision of new relocation residential spaces, especially for rural refugees damaged by the disaster.

## Acknowledgement

We would like to appreciate The Indonesian Ministry of Education and Indonesian Endowment Fund for Education for the awarded of BUDI-DN Scholarship. We also would like to appreciate The Doctoral Program of Architecture, Universitas Gadjah Mada, for all the research assistance.

## References

Agusintadewi, N. K. (2014). *Transforming Domestic Architecture: A Spatio-temporal Analysis of Urban Dwellings in Bali*. Newcastle University.

Al-Ban, A. Z. G. (2016). *Architecture And Cultural Identity In The Traditional Homes Of Jeddah*. The University of Colorado at Denver. Retrieved from https://search.proquest.com.ezproxy.ugm.ac.id/docview/1795077484?accountid=13771 Retrieved onJune 2017

Atık, D., & Erdoğan, N. (2017). A model suggestion for determining physical and socio-cultural changes of traditional settlements in Turkey. *A/Z ITU Journal of the Faculty of Architecture*, *14*(2): 81–93. https://doi.org/10.5505/itujfa.2017.62534

Eliade, M. (1959). *The Sacred and the Profane: the Nature of Religion*. Chicago: Harcourt Brace and World.

Faqih, M. (2005). *Domestic Architecture and Culture Change. Re-ordering the use of space in Madurese housing*. unpublished PhD Thesis. Faculty of Humanities and Social Sciences, University of Newcastle Upon Tyne.

Fatkhan, M. (2006). Kearifan lingkungan masyarakat lereng gunung merapi. *Aplikasia. Jurnal Aplikasi Llmu-Ilmu Agama*, 7(2): 107–121. Retrieved from http://digilib.uin-suka.ac.id/id/eprint/8328

Gunawan. (2015). Kearifan Masyarakat Lereng Merapi Bagian Selatan, Kabupaten Sleman – Daerah Istimewa Yogyakarta. *Sosio Informa*, *1*(02): 189–212. https://doi.org/10.33007/inf.v1i2.148

Handel, A. (2019). What's in a home? Toward a critical theory of housing/dwelling. *Environment and Planning C: Politics and Space*, *37*(6): 1045–1062. https://doi.org/10.1177/2399654418819104

Hillier, B., & Hanson, J. (1984). *The social logic of space*. Cambridge: Cambridge University Press.

Jerome, N. (2013). Application of the Maslow's hierarchy of need theory; impacts and implications on organizational culture, human resource and employee's performance. *International Journal of Business and Management Invention*, *2*(3): 39–45.

Ju, S. R., Kim, D. Y., & Santosa, R. B. (2018). Dualism in the Javanese House and Transformation With focus on the houses of. *Journal of Asian Architecture and Building Engineering*, *7581*(17:1), 71–78. https://doi.org/10.3130/jaabe.17.71

Koentjaraningrat. (1993). *Manusia dan Kebudayaan di Indonesia*. Jakarta: Penerbit Djambatan.

Maly, E., Iuchi, K., & Nareswari, A. (2015). Community-Based Housing Reconstruction and Relocation: REKOMPAK Program after the 2010 Eruption of Mt. Merapi, Indonesia. *Journal of Social Safety Science*, *27*(27): 205–214. https://doi.org/10.11314/jisss.27.205

Marsoyo, A. (2012). *Constructing Spatial Capital. Household Adaptation Strategies in Home-Based Enterprises in Yogyakarta*. Faculty of Humanities and Social Sciences-University of Newcastle upon Tyne. Retrieved from https://theses.ncl.ac.uk/jspui/handle/10443/1452 Retrieved on December 2017

Mughal, M. A. Z. (2013). Domestic space and socio-spatial relationship in rural pakistan. *South Asia Research*, *35*(2): 214–234. https://doi.org/10.1177/0262728015581287

Mullins, D. (2018). Achieving policy recognition for community-based housing solutions: the case of self-help housing in England. *International Journal of Housing Policy*, *18*(1): 143–155. https://doi.org/10.1080/19491247.2017.1384692

Multi Donor Fund for Aceh and Nias, & J. R. F. (2012). *Rekompak. Membangun Kembali Masyarakat Indonesia Pascabencana*. Jakarta: Sekeretariat Multi Donor Fund untuk Aceh dan Nias dan Java Reconstruction Fund. Retrieved from https://www.scribd.com/document/397844721/Membangun-Kembali-Masyarakat-Indonesia-Pasca-Bencana Retrieved date: Februrary 2017

Paranagamage, I. P. D. H. (2006). *Changing boundaries and meanings of the home: a case study of middle class houses in Sri Lanka*. University of London, University College London (United Kingdom). Retrieved fromhttps://search.proquest.com.ezproxy.ugm.ac.id/docview/1427931075?accountid=13771 Retrieved date: June 2017

Rapoport, A. (1982). *The meaning of the built environment : A nonverbal communication approach*. California: The University of Arizona Press.

Ronald, A. (2005). *Nilai-nilai arsitektur rumah tradisional Jawa: Sebuah akumulasi karya tulis yang diungkapkan karena rasa bangga menjadi orang Jawa yang harus penuh tenggang rasa*. Bulaksumur, Yogyakarta: Gadjah Mada University Press

Santosa, R. B.(1997). Omah: The construction of meanings in Javanese domestic settings. *ProQuest Dissertations and Theses*, 115-115. Retrieved fromhttp://search.proquest.com/docview/304410596?accountid=13771 Retrieved on August, 2016

Santosa, R. B. (2000). *Omah. Membaca makna rumah Jawa.* Yogyakarta: Yayasan Bentang Budaya.

Seo, K. W. (2005). *Spatial interpretation of housing*. University of London, University College London (United Kingdom), ProQuest Dissertations Publishing, 2005. U602414. Retrieved from https://search.proquest.com/docview/1501974154?accountid=1371 Retrieved date: June 2017

Setiadi, A., Andriessen, A., & Anisa, R. (2020). Post-occupancy evaluation of Pagerjurang permanent housing after the Merapi volcanic eruption. *Journal of Architecture and Urbanism*, *44*(2): 145–151. https://doi.org/10.3846/jau.2020.11265

Siregar, J. P. (2014). *Metodologi dasar space syntax dalam analisis konfigurasi ruang*. Retrieved from https://docobook.com/queue/metodologi-dasar-space-syntax-dalam-analisis-konfigurasi-rua.html Retrieved date: April 2019

Subroto, T. Y. W.(1995). *A study on the spatial linkage in urban settlement as an alternative tool for improving living environment in the cities of Java: An attempt to interpret and implement the vernacular space order into contemporary housing planning*. unpublished PhD Thesis. The Course of Environmental Engineering, Graduate School of Engineering, Osaka University.

Tao, J., Chen, H., Zhang, S., & Xiao, D. (2018). Space and Culture : Isomerism in Vernacular Dwellings in Meizhou , Guangdong Province , China. *Journal of Asian Architecture and Building Engineering*, 17(1): 15–22. https://doi.org/10.3130/jaabe.17.15

Tjahjono, G.(1989). Cosmos, center, and duality in Javanese architectural tradition: The symbolic dimensions of house shapes in Kota Gede and surroundings. *ProQuest Dissertations and Theses*, 389-389 Retrieved from http://search.proquest.com/docview/303682297?accountid=13771 Retrieved on August 2016

Wongphyat, W., & Suzuki, H. (2018). Spatial Analysis of Traditional Thai Dwellings in the Phrapradaeng District. *Journal of Asian Architecture and Building Engineering*, 7(2): 225–232. https://doi.org/10.3130/jaabe.7.225

## Notes

[1] *Rekompak* is the name of a community-based approach to large-scale reconstruction of homes and community infrastructure initiated in Indonesia by the MDF (Multi-Donor Fund) and JRF (Java Reconstruction Fund)
[2] *Omah* is a term used for vernacular homes in Javanese society
[3] A core house built in the basic construction and have one room for sleeping, one bathroom and a shared space for the community in the permanent house
[4] Space for cooking, eating, and resting. This space is located on the back of the house
[5] *Tretepan* is a term for the terrace of the house. It is an open building with an extended roof of the main building
[6] Plait made of bamboo planks for the walls of the house
[7] *Senthong* is a space used for resting and storing some sacred items. In Javanese houses, arranged in three parts, middle, left and right. *Krobongan* referred to central *senthong*
[8] The traditional Javanese house divided into three sections. The first section, *omah ngarep* referred to the front house. The second section, *omah jero* is central of the house. The third section, *omah mburi* referred to the service area at the back of the house
[9] *Dandan kali* ceremony also called *becekan* is a traditional ceremony of the community of Kepuharjo village. The ceremony is held for blessings and prays for rain.
[10] *Kenduri* also called *selamatan* is a gathering ceremony for asking blessings. The ceremony is carried out by the men.
[11] The man to read the prayer
[12] Participation of community for preparing the celebration
[13] *Gotong royong* is a type of mutual aid among community member in Indonesia

IJBES

**International Journal of Built Environment and Sustainability**
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 107-119

# Post Occupancy Evaluation of the Built Environment: A Case Study of Mosque Facilities

**Mohammad A. Hassanain**
Architectural Engineering Department, King Fahd University of Petroleum and Minerals, Saudi Arabia

**Mohammed Kajak**
Architectural Engineering Department, King Fahd University of Petroleum and Minerals, Saudi Arabia

**Mohammad B. Hamida**
Department of Management in the Built Environment, Delft University of Technology, Netherlands

**Ahmed M. Ibrahim**
Department of ICT and Natural Sciences, Norwegian University of Science and Technology, Norway

## ABSTRACT

Mosques are religious and cultural facilities that are used as a place of worship, social gatherings, and religious events by Islamic communities. The built environment in these facilities should meet certain technical, functional, and behavioral requirements for worshipers. Mosques could endure critical defects and inadequate performance, with gaps in knowledge, of appraisal tools for their overall performance assessment. Therefore, this research was motivated by the need to identify and purpose an exemplary systematic process upon the conduct of post-occupancy evaluation, owing to the fundamental need for satisfactory conditions that need to be met by mosque facilities. Thus, this paper presents an exemplary post-occupancy evaluation of mosque facilities in Saudi Arabia; as a religious built environment. A triangulation approach of data collection and assessment methods were followed and discussed in this research. A case study mosque was selected, following a review of literature. Interviews and walkthrough inspection identified 34 performance elements. Users' satisfaction survey data were collected and analyzed. Recommendations were proposed towards improving performance of the case study mosque as a religious built environment that demands satisfactory occupancy conditions. The findings indicated that worshipers were strongly satisfied with the conditions of the built environment in the case study facility; including acoustical comfort, spirituality, and aesthetic performance elements. This paper expands the boundaries of knowledge in terms of identification of mosques' performance elements.

**Article History**

Received: 12 June 2021
Received in revised form: 12 August 2021
Accepted: 12 August 2021
Published Online: 31 August 2021

**Keywords:**

Post-occupancy evaluation; mosques; technical; functional; behavioral; performance criteria.

**Corresponding Author Contact:**

mohhas@kfupm.edu.sa

**DOI:** 10.11113/ijbes. v8. n3.831



## 1. Introduction

A mosque is a built facility used by Islamic communities as a house of prayer, a center of cultural activities, an area for social gatherings, a courthouse, and an educational facility (Neufert and Neufert, 2012). Mosques are built to be daily occupied lively at different times, where mainly five prayers take place, at designated times. Contemporary mosques mainly have five architectural elements that distinguish its function, namely: prayers hall, dome, towers announcing call for prayers referred to as minarets, a sanctuary for the lead prayer referred to as mihrab, and an ablution space for pre-prayer wash (Alnajadah, 2017). The functional and environmental aspects of mosques are performance elements that provide a well-maintained contemporary space of worship (Asfour, 2016). Operational conditions of thermal (Al-ajmi, 2010; Asfour, 2009; Mushtaha and Helmy, 2016), acoustical (Eldien and Al Qahtani, 2012; Ismail, 2013; Kavraz, 2014; Karaman and Güzel, 2017), and illumination (Hassan and Arab, 2013; Belakeha et al., 2016; El-Darwish and El-Gendy, 2016) performance elements in mosques, must be provided and maintained to serve a satisfactory performance for its users. It is necessary to optimize the worship space design and utilization for efficiency, achieving sustainability principles, within a social and cultural context of service that is required in mosques. These aspects are among the critical dimensions, which set responsibilities for designers, contractors, and facilities managers, simultaneously. Many mosques suffer from common building defects and design problems in various built-elements, systems and components (Mustafaraj and Yardım, 2013). For example, many mosques in Malaysia faced diverse forms of structural defects, service systems, fenestrations' components, circulation, finishes and walls (Johar et al., 2013; Alauddin et al., 2018). Thus, it is important to perform an effective and systematic management and monitoring procedures for evaluation of their assets and systems, for enhancing their overall conditions, as well as reducing required maintenance and renovation costs, caused by such defects (Mohd-noor et al., 2016). This requirement necessitates to develop a holistic approach for assessing the overall performance and condition of mosques. In fact, post occupancy evaluation is one of the useful methods that provides an overall perception of a building performance and its condition (Ali and Alfalah, 2010; Pereira et al., 2016). Post occupancy evaluation is defined as "the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time" (Preiser et al., 1988). Post occupancy evaluation can be conducted over three levels of effort; namely indicative, investigative and diagnostic (Preiser et al., 1988). The motivation for this research evolved from the following research questions, in the context of post occupancy evaluation of mosques, as a common built environment in Saudi Arabia:

RQ1. How did the literature approach post occupancy evaluation of the built environment in the context of mosques?
RQ2. What are the considerations and performance elements that derive satisfactory users' occupancy at mosques?
RQ3. What are the systematic steps for indicatively assessing users' satisfaction in mosques?

In response to the research questions motivated by the researchers and the review of literature, this research aims to present an indicative post occupancy evaluation findings, by evaluating major performance elements of a built environment in a case study mosque facility, located in the Eastern Province of Saudi Arabia. This research expands the knowledge boundaries, about performance elements, in places of worship, specifically mosque facilities, and introduces a methodological assessment framework.

## 2. Research Methodology

The research is designed to conduct an indicative post occupancy evaluation, which comprised of the following activities, namely: a literature review, an indicative walkthrough, interviews with users, collection of users' satisfaction surveys and data analyses.

### *2.1 Literature Review on the Performance Considerations and Elements*

A literature review was performed on relevant sources, including previous studies, handbooks, and standards. This activity aimed at interpreting focal points of observations for carrying out an indicative walkthrough, while identifying major performance considerations and elements, in the context of mosque facilities. Several performance considerations and elements were identified under the following dimensions (Preiser et al., 1988):

- Technical elements: constitute environmental attributes, which are measurable, sensible, and physically tangible.
- The functional elements: constitute the elements affecting building activities and utilization by its users within its spaces.
- Behavioral elements: constitute the psychological and sociological well-being of occupants in response to design of buildings.

A set of 5 elements under each category except the behavioural where three elements were identified namely, technical (such as thermal comfort, fire safety, acoustical comfort, indoor air quality and visual comfort), functional (such as interior and exterior finishes, furniture quality, cleanliness, plumbing systems, and circulation effecciency) and behavioural (such as aesthetics and spirituality). On the other hand, A set of 14 technical, 16 functional and 4 behavioral performance considerations of mosques, relating to the identified performance elements, under each category were identified.

### *2.2 Selection of A Case Study Mosque*

A large mosque located in the Eastern Province of Saudi Arabia, that was constructed in 2018 was selected as a case study facility for this research. The mosque has a gross area of 800 m2 and a prayer hall of 20 prayer rows, that can accommodate up to 600 users. It has an ablution area, and toilets. Further, it provides a car parking and services for its users, including announcement screens, high quality finishes, furniture, decorations, a good utilization of daylighting and a closed-circuit television system.

### *2.3 Indicative Walkthrough*

An indicative walkthrough inspection was implemented at the case study mosque during different weekdays, at deferring times (prayers and non-prayers). This activity aimed at forming a perception about the overall condition and performance, considering variations of activities, occasions and deferring occupation levels, throughout the weekdays. The walkthrough inspection contributed to identifying and documenting the main defects in the case study mosque. These defects were discussed and considered for the succeeding research activities.

### *2.4 Users' Interviews*

In this activity, face-to-face interviews were conducted with a selected sample of five frequent worshipers at the case study mosque. The activity aimed at exploring users' perception towards the overall condition and performance of the building. Moreover, the interviews aimed at investigating users' views about observed and documented building defects that were identified during the walkthrough, as well as their performance elements that were identified from the review of literature. The interviews were qualitatively used to formulate the users' satisfaction surveys.

### *2.5 Users' Satisfaction Survey*

In this activity, a users' satisfaction survey was developed, pilot-studied, and then conducted on the permanent worshipers of the case study mosque facility. The pilot study aimed to ensure the readability and clarity of the questions asked in the surveys and the time sufficiency for collecting responses from the users, effectively. The results of the piloted surveys led to enhancement of the language and reduction of preliminary redundant questions within the surveys. This activity aimed at determining the level of users' satisfaction with the identified major mosques performance elements. The survey adopted a 4-point Likert scale, in which the respondents were asked to indicate their levels of satisfaction against each performance element by selecting among: "strongly satisfied", "satisfied", "dissatisfied" and "strongly dissatisfied". The four point Likert scale was preferred, to assure a determined negative or positive users' feedback on the performance elements; avoiding neutral opinions. In this study, 92 surveys were distributed to the permanent users of the case study facility, 35 reliable responses (which accounts for 38% response rate) were collected and analyzed. The selection of 35 users, as a representative sample size conforms to the central limit theorem, which mandates that surveys in social and practical research studies, would involve at least a minimal of 30 respondents to achieve a normal distribution of the processed data.

### *2.6 Data Analysis*

The received data from the users' satisfaction survey was sorted and analyzed, so that the findings, discussion, and conclusions were derived accordingly. The weighted mean response (Sj) was calculated for all performance elements that were included in the users' satisfaction survey, to determine the rates of satisfaction. The following formula was used to calculate the weighted mean response (Hassanain and Iftikhar, 2015):

$$S_j = \frac{(\sum_{i=1}^{4} w_{ij}\ n_i)}{(\sum_{i=1}^{4}\ n_i)}$$

Where:
$S_j$ is the weighted mean response.
$n_i$ is the number of respondents who assessed the element $j$ of performance in the survey.
$w_i$ is the assigned corresponding weight to the satisfaction level ($i$ = 1, 2, 3 or 4).

Each satisfaction level was given a corresponding weight ($W_i$), as follows: "strongly satisfied" = 4; "satisfied" = 3; "dissatisfied" = 2; and "strongly dissatisfied" = 1. In order to express the satisfaction rate of each performance element, the following calibration was adopted to calculate a weighted mean for the responses:

- "strongly satisfied" = 3.50 – 4;
- "satisfied" = 2.50 – 3.49;
- "dissatisfied" = 1.50 – 2.49;
- and "strongly dissatisfied" = 0 - 1.49.

These weights are calibrated evenly, to avoid specific bias in users' feedback. The users were informed of the calibrated ranges ahead of their feedbacks and opinions. These ranges also reflect the four-point scale deterministic objective for selection as discussed.

### *2.7 Development of Recommendations*

A set of recommendations were proposed for formulating a plan of action. This activity aimed at developing effective recommendations that have the potential to enhance the overall performance and condition of the case study facility. The recommendations were mainly stemmed from the findings and conclusions of the conducted post occupancy evaluation .

## 3. Previous Studies on Performance Considerations

The following studies were reviewed and synthesized from literature. The studies concluded that indoor environmental quality of mosques require effective maintenance up to appropriate levels of performance. Further, mosques need to have contemporary architectural elements without compromising its cultural identity and functional need, to serve as a mosque facility. The following considerations were identified:

### *3.1 Thermal Performance Considerations*

Asfour (2009) studied the impacts of the architectural style on thermal comfort at mosque facilities. The study analyzed four different models of mosques that were different in terms of geometry and geographic location. An energy simulation software was used to investigate the thermal performance within the case study facilities, at two different cities from Europe and the Middle-East; Rome, Italy and Riyadh, Saudi Arabia. The study revealed that there is a direct impact of the architectural style on the thermal performance of mosques. Mushtaha and Helmy (2016) conducted an analytical examination to assess the impact of passive parameters, which are related to the thermal performance and indoor thermal comfort of mosques; in Sharjah, United Arab Emirates. The assessed passive parameters included thermal insulation, shading devices and natural ventilation. The study revealed that passive design strategies are not effective to enhance the thermal performance of mosques, alone. Moreover, it revealed that active strategies need to be considered for achieving a more efficient thermal performance.

### *3.2 Acoustical Performance Considerations*

Eldien and Al-Qahtani (2012) studied the impacts of acoustical design considerations for mosques, as a place of worship, in Saudi Arabia. Measurements were conducted on typical contemporary mosques with different architectural styles. The study revealed that many design decisions, including form and space of mosques, had a direct bearing on acoustical performance. Accordingly, the study concluded that designers must take into account the acoustical aspects at the early design phase. Karaman and Güzel (2017) conducted a case study in a mosque at Manisa, Turkey, to investigate the acoustical properties in the main prayer hall of the case study facility. Measurements were conducted at different receptive locations, within its prayer hall. The research concluded that the case study facility has satisfied the recommended levels of acoustical performance, despite the challenges of optimizing acoustical requirements due to the mosque's architectural style.

### *3.3 Illumination Performance Considerations*

Hassan and Arab (2012) analyzed illumination performance in two mosque facilities with a singular pendentive dome, one located in Turkey and other in Bosnia-Herzegovina, during summer solstice. The study revealed that the mosques had a high potential, to satisfy the recommended illumination performance levels and its indoor quality requirements. El-Darwish and El-Gendy (2016) studied daylight performance in six-historical mosques that were built in the 19th century, in Alexandria, Egypt. The study revealed that the case study mosques had a specific strategy for daylighting, utilizing fenestrations, as an autonomous medium for effectively enhancing access to daylight.

### *3.4 Architectural Elements as Functional Considerations*

Asfour (2016) studied the architectural elements that need to be utilized in contemporary mosques. The study adopted a method that enabled the identification of historical design elements which contribute to the functional role of mosques. A critical observation of several- contemporary cases revealed that modern mosques need to align cultural-architectural aspects (including main prayer hall, minaret, courtyard, ablution, and female zone) and modern treatment elements (e.g. sound systems).

### *3.5 Durability Considerations*

Johar et al. (2013) conducted a preliminary condition assessment survey and analysis of building defects, for traditional timber-built mosques in Malaysia. The study covered 52 traditional mosques, where common defects were identified at roofs due to dampness, and defects related to aesthetic elements. Further, the study found that the primary cause of defects was related to poor conduct of periodic maintenance. Alauddin et al. (2018) investigated critical defects of five heritage mosques located in Perak, Malaysia. The methodology adopted in the study was mainly based on field observations that were guided by a developed checklist. The checklist was based on a review of literature, on common defects at heritage facilities. There were four critical defects identified in the context of heritage mosque facilities, namely: cracks, peeled paint, fungus and missing broken parts.

## 4. Literature Review on The Performance Elements of Mosques

The literature review aimed to survey the relevant studies that were conducted on mosque facilities. The studies presented and described and led to identification of a set of major performance elements, as follows:

### *4.1 Technical Performance Elements*

The technical performance elements are concerned with a fundamental aim for survival of users, such as: health, safety and security (Preiser et al., 1988). Based on the review of literature, five major categories, in the context of mosque facilities were identified, namely: "thermal comfort", "acoustical comfort", "visual comfort", "indoor air quality", and "fire safety".

#### 4.1.1 Thermal Comfort

It is defined as a mental condition that expresses individuals' subjective satisfaction with their surrounding thermal environment (ASHRAE 55, 2017). Several parameters need to be considered within the context of thermal comfort assessment, due to their direct impact on users' satisfaction with thermal environment (Hassanain, 2008). There are five major parameters affecting thermal comfort, namely air temperature, air humidity, air motion, clothing insulation and metabolism (Nicol and Roaf, 2005). At mosques, satisfying thermal comfort represents an environmental challenge, because of the diversity of users' characteristics, such as: age, clothing type, activity rate, place, ethnics, color and other considerations (Al-ajmi, 2010).

#### 4.1.2 Acoustical Comfort

It is defined as the absence of unwanted sound and quality performance of acoustical propagation, that ensures clear hearing and privacy of individuals' activities and communication, without causes of acoustical abnormalities or nuisance (Rasmussen and Rindel, 2003). At mosques, acoustics are essential to be fulfilled within an appropriate level of performance (e.g. reverberation and propagation), due to the nature of individual and group formations for worships and rituals (Karaman and Güzel, 2017). Acoustics in mosques are characterized by placing an audible, intelligible, and spacious reach of sound recitations and speech (Eldien and Al Qahtani, 2012).

#### 4.1.3 Visual Comfort

It is defined as the occupants' subjective well-being of visual conditions at a built-environment (BS EN 12665, 2018). Visual comfort is a fundamental human need that has potential to influence individuals' task performance, health, safety, mood and atmosphere satisfaction (IES, 2011). In general, visual comfort can be achieved by providing three main elements including the control over glare, adequacy of illumination levels (e.g. by use of natural and artificial light) which supports tasks performance, conduct of activities, and comprehending visible aesthetics (Giarma et al., 2017). Light in mosques is a principal element that influences spiritual symbolism and adds ambiently to the tranquility of mosques' interiors and exteriors. This is by ensuring a functional adherence of individuals to sense the place of worship (Arel and Öner, 2017). Several active and passive strategies can be used to meet requirements of light performance aspects, in which daylighting techniques are considered as the most effective, and sustainable approach, that is adopted historically in mosques (El-Darwish and El-Gendy, 2016).

#### 4.1.4 Indoor Air Quality

It is defined as air quality aspects that are ensuring health and comfort of building occupants (EPA, 2018). Indoor air quality is a major element that needs to be assessed and maintained, due to its direct influence on users' performance and productivity. In mosques, indoor air quality needs to be assessed in alignment to the wider context of indoor environmental quality, as a technical performance element (Al-ajmi et al., 2017).

#### 4.1.5 Fire Safety

It is defined as a facility fire prevention and control measures, which sustain occupants' life, minimize property damages, and control against fire spread (IFC, 2018). This can be achieved by satisfying fire codes requirements, during the design process following a performance-based approach (Maluk et al., 2017). The assessment of fire safety levels in existing buildings is an essential task that must be carried out through following an inspection-based approach which assesses the compliance to fire safety requirements of all active and passive systems for the occupancy type of the building (Hassanain and Ashwal, 2004). In fact, mosques are considered as a highly occupied facilities that must provide an appropriate safety level for their occupants; to avoid risks of fire-hazard to lives (Alnabulsi and Drury, 2014).

### *4.2 Functional Performance Elements*

The functional performance elements are concerned with enablement of conditions that ensure occupants' productivity and efficiency (Preiser et al., 1988). Based on the literature review, five major categories of the functional performance elements were identified for mosques, namely: "interior and exterior finishes' systems", "furniture quality", "efficiency of circulation", "plumbing system", and "cleanliness".

#### 4.2.1 Interior and Exterior Finishes' Systems

Condition of finishing materials and building façade is among the elements that can affect users' satisfaction with their built-environment (Loftness et al., 2009). However, the deterioration of finishes, for different building elements is among the common defects that appear in existing buildings. Such defects occur due to different causes, related to design, workmanship, material, occupancy, and maintenance (Chong and Low, 2006). Finishes used in mosques are considered as one of the factors that has an impact on users' perception (Taib et al., 2016). One major element of contemporary mosques is the protection of cultural identity, in terms of style, and type of used construction materials. In addition, such materials need to be installed in a manner that is compatible with modern textures, colors, proportion, and form (Asfour, 2016). Mosque performance as a facility can be impacted by critical defects in interior and exterior elements of finishes (Alauddin et al., 2018). Consequently, efficient maintenance and assessment of defects and materials used in mosques need to be carried out periodically (Mohd-noor et al., 2016).

#### 4.2.2 Furniture Quality

Mosques are historically among the buildings that were internally furnished and decorated (Alnajadah, 2017). Poor furnishing selection causes users' discomfort (Parcells et al., 1999). They must provide a sufficient number of cabinets or shelves to store volumes of contextual books (Mokhtar, 2009). In addition, they must be furnished with suitable chairs, to ensure inclusiveness for the elderly and disabled users, who might not be able to perform worship activities easily (Daghistani, 2016). Moreover, the floors of mosques are usually covered by carpets, in which such carpets should be in an appropriate level of cleanliness and purification to satisfy the needs of worshipers and their activities.

#### 4.2.3 Circulation Efficiency and Adequacy

Circulation is the physical movement of occupants or goods through a facility, either vertically (e.g. stairs and elevators) or horizontally (e.g. entrances, corridors, walkways and lobbies) (Preiser et al., 1988). The efficiency of building circulation is a crucial aspect that needs to meet users' behavior in terms of internal and external (Lee et al., 2010). Several spatial properties define the efficiency of the circulation routes in buildings, including travel distance, dimensions of the route, security and safety measures and relation with the net area of the building and its rooms (Lee, 2011). Thus, designers and facility managers must consider circulation efficiency through assessing spatial properties (Lee and Kim, 2014). At mosques, circulation efficiency is among the elements that have a vital role in satisfactory implementation of worshipping activities. This requires a spatial organization of the passageway and corridors in a manner that is integrated with the internal and external environments of the mosque. They must satisfy wayfinding by design, and layout of separated passageways (Mustafa and Hassan, 2013).

#### 4.2.4 Plumbing Systems

Plumbing system includes water distribution, sewerage, treatment, equipment, and their appurtenances, in built facilities (IPC, 2018). At mosques, designers of plumbing systems must consider space technical requirements for ablution areas. Ablution areas accommodate a set of taps provided with platforms, used by worshipers to carry out ablution ritual prior to prayers. Such spaces must be designed and constructed in a manner that meets the requirements of location, accessibility, safety, privacy, density (number of ablution taps), dimensions, inclusiveness of the elderly and physically challenged needs, ventilation, quality of fittings and materials (Mokhtar, 2003).

#### 4.2.5 Cleanliness

Cleanability of the building spaces is a performance criteria that needs to be met in all buildings (Preiser et al., 1988). Cleanliness of the building has a direct bearing on its image, as well as its compliance with the indoor environmental quality requirements. Additionally, the level of cleanliness is important for occupants, since it affects their comfort, satisfaction, and productivity (Khalil and Husin, 2009). Consequently, it is necessary to assess and maintain the overall cleanliness, as well as the level of cleaning service provided within the facility (Frontczak et al., 2012). At mosques, cleanliness and purification is traditionally a major attention. This implies that prayer halls, furniture, ablution areas and bathrooms need to be provided with an appropriate level of cleanliness and hygiene (Mokhtar, 2009).

### *4.3 Behavioral Elements of Performance*

The behavioral performance elements are concerned with satisfactory social, psychological needs of occupants, such as: occupants' density, privacy, and social interaction (Preiser et al., 1988). Based on the literature review, two major categories of behavioral elements were identified at mosques, namely "spirituality", and "aesthetics".

#### 4.3.1 Spirituality

It is a major element in the religious life, and it is correlated with individuals' religious expression. Social and environmental surroundings influence the spirituality of religious people. This implies that built-environment has an impact on spirituality. Since spirituality is an invisible dimension, architects and designers need to consider the integration of aesthetic religious influences (Barrie et al., 2016). At mosques, the same concept is applied, in which the masses (physical design elements) must satisfy the religious design needs of spirituality.

#### 4.3.2 Aesthetics

At mosques, aesthetic elements have a direct bearing on the spiritual feelings of occupants (Asfour, 2016). Aesthetics as a performance element is concerned with provision of beauty and style, to different elements of the built-environment through environmental design and materials selection. It is influenced by philosophical, cultural, historical, and traditional aspects (Manning, 1991). Previous research indicated that the architectural aesthetics have direct impacts on morals and well-being of occupants (Grimm, 2010). In mosques, assessing aesthetic quality is critical, for addressing users' satisfaction with the built facility, specifically in this context mosques as a place of worship.

Based on the reviewed literature, a gap on assessing mosques indicatively, as addressed by the research questions has been identified. The review of literature indicated the lack of holistic studies that cover the mosque facilities in its context, through identifying all performance considerations as in this research, while implying a systematic mean of evaluation. The reviewed studies covered partially specific, and scattered performance elements, rather than collectively.

Thus, this research aims to propose a methodological framework for the assessment of mosque facilities. The followed framework in this study is meant to be indicative, to measure the users' satisfaction upon technical, functional, and behavioral performance elements. Additionally, the applied framework assists to identify the deficiencies in a case study facility as a built environment, to provide facility managers with a systematic method, that can be applied to measure the users' satisfaction and recognize the deficiencies within the built environment. The framework consists of five main stages namely: identify the case study facility, conduct an indicative walkthrough, interview the permanent users, develop a satisfaction survey, and derive recommendations for the case study-built facility. The framework is illustrated in figure 1.

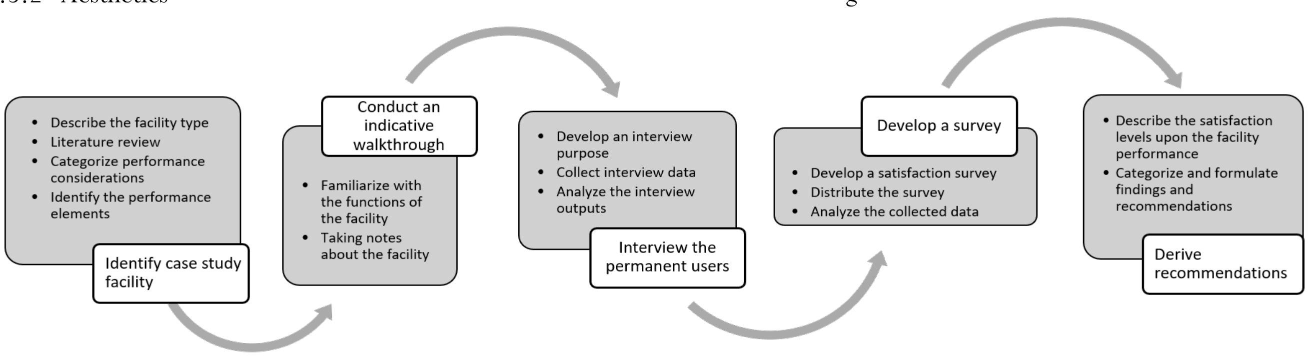



**Figure 1.** An Indicative post occupancy evaluation framework for built facilities

## 5. Findings and Discussion

The research is designed to conduct an indicative post occupancy evaluation. Accordingly, the mean rate of satisfaction for technical, functional, and behavioral elements of performance are illustrated in Figures 2, Figure 3 and Figure 4. The findings are discussed as below:

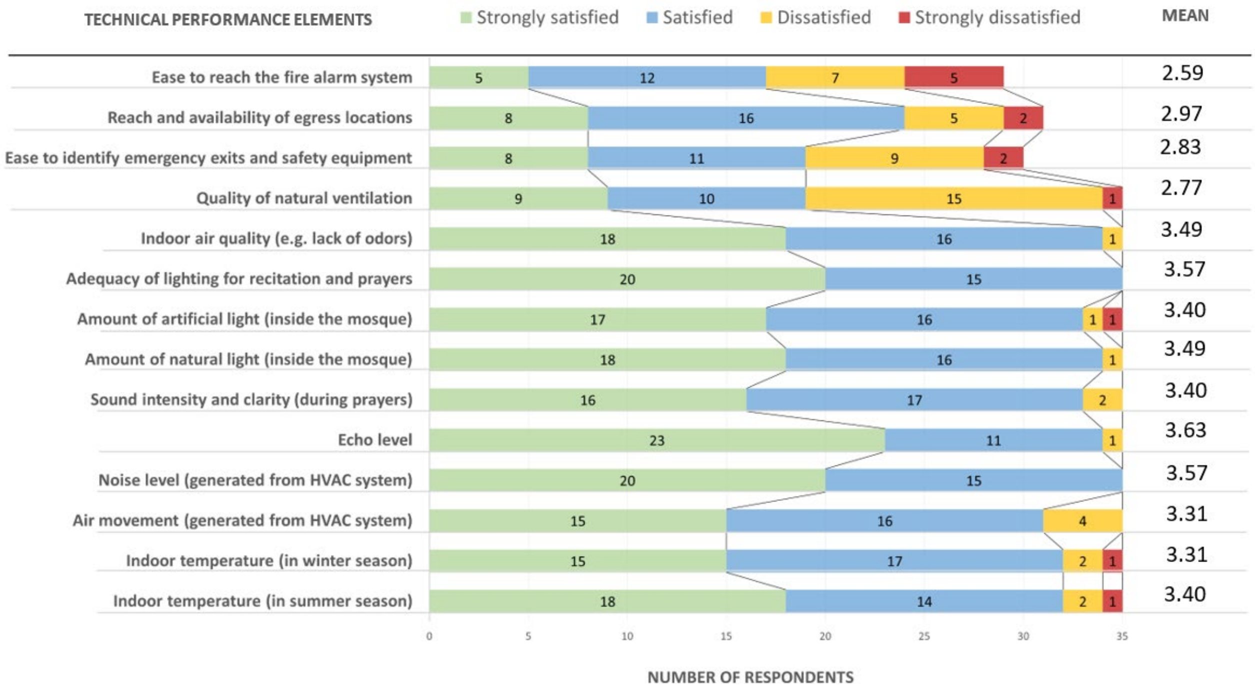



**Figure 2** Technical performance considerations

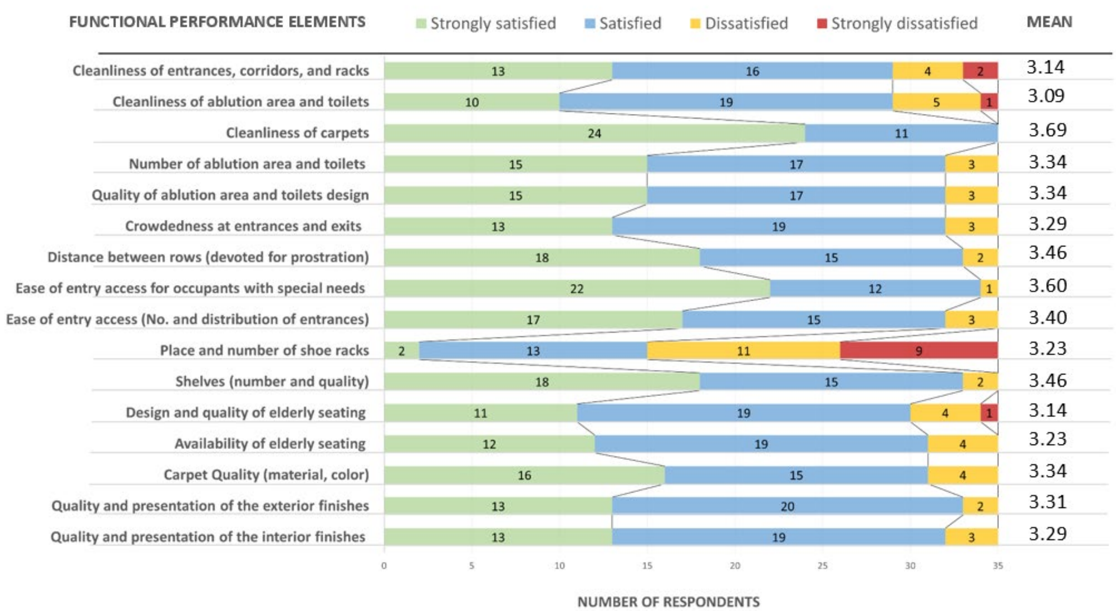



**Figure 3** Functional performance considerations

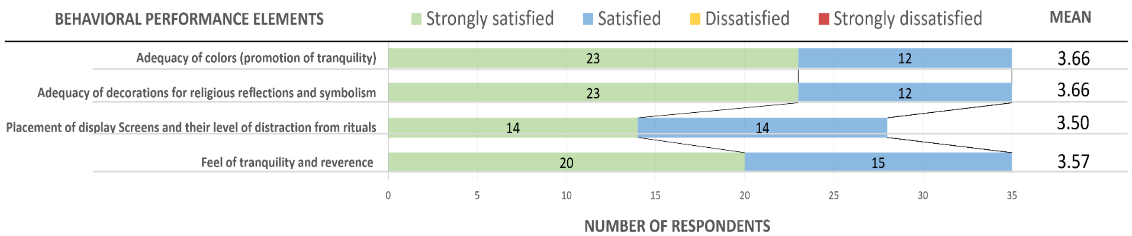



**Figure 4** Behavioral performance considerations

## *5.1 Technical Performance Elements*

The mean rates of satisfaction are illustrated in figure 5, where:

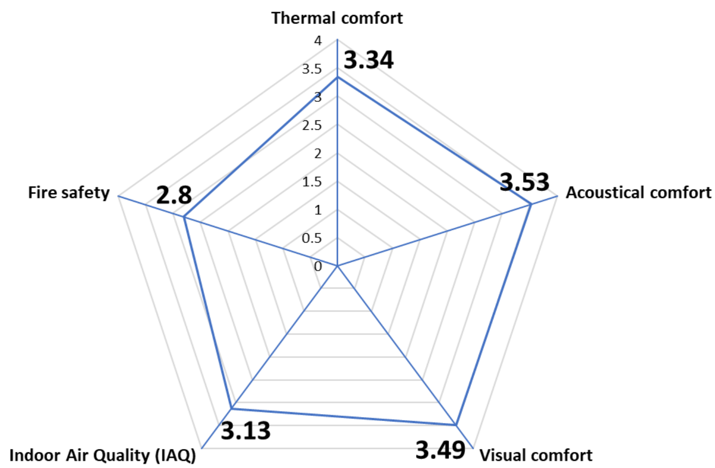



**Figure 5** Mean satisfaction by categories - Technical elements

### 5.1.1 Thermal Comfort

The walkthrough inspection indicated that the modern central air conditioning system was provided for cooling interior spaces. air conditioning inlets and outlets were distributed symmetrically throughout the prayer hall, as well as the other interior spaces of services. However, the interviews with frequent occupants indicated that air conditioning control panels are accessible, where some occupants manipulate the operation settings randomly without any coordination with the building operator. This behavior led to a fluctuation in the occupants' thermal comfort during the non-hot periods of the year. As shown in Figure 2, the average satisfaction mean of the thermal elements of performance is 3.34, which reveals that the occupants were "satisfied" with the thermal conditions in the mosque.

### 5.1.2 Acoustical Comfort

The walkthrough inspection during the prayers and non-prayers times reported that there were no sensible sources of noise, neither internally (e.g. equipment and appliances) nor externally (e.g. traffic), since the case study mosque is located in a sufficient distance away from the main roads. Interviews with frequent occupants indicated that they feel comfortable with the acoustical quality and clarity to the digital speaker system. The results revealed that the average satisfaction mean of the acoustical performance elements 3.53, which indicates that occupants were "strongly satisfied" with the acoustical environment in the mosque.

### 5.1.3 Visual Comfort

The walkthrough inspection indicated that daylighting was adequately provided during daytime, through windows and translucency of the dome. Further, sufficient artificial lighting was provided during the day through a symmetrical distribution of spot and hidden lights, across the ceiling. Interviews with frequent occupants indicated that they feel that the building illumination provides adequate light for recitation as well as conduct of religious rituals and activities. The average satisfaction mean of the visual performance element is 3.49, which indicates that worshipers were "satisfied" with the building illumination.

### 5.1.4 Indoor Air Quality

The walkthrough inspection indicated that the mosque was effectively ventilated by the air conditioning system. Further, there was no appearance of bad odors and dust in the internal air inside the mosque, as well as, in the other supporting spaces. However, it was noted that there was no consideration of the passive ventilation techniques, where windows were not operable. Interviewed occupants mentioned that windows need to be controllable in order to allow for natural ventilation during the winter and spring seasons. The indoor air quality elements of performance received an average satisfaction mean of 3.13, which indicates that occupants were "satisfied" with the indoor air quality inside the mosque and its supporting spaces.

#### 5.1.5 Fire Safety

The walkthrough inspection indicated that some of the fire safety systems and measures were provided in the mosque, namely: fire alarm system, smoke detectors and fire alarm system control panel. However, it was noted that exit signs, fire sprinklers, extinguishers and emergency exits were not provided. Interviewed occupants mentioned that there is a lack of awareness about the fire safety measures among the permanent users of the mosque. Yet, elements of performance related to fire safety received an average satisfaction mean of 2.80, which indicates that users were barely "satisfied" with the safety condition of the mosque.

### *5.2 Functional Performance Elements*

The mean rates of satisfaction are illustrated in figure 6, where:

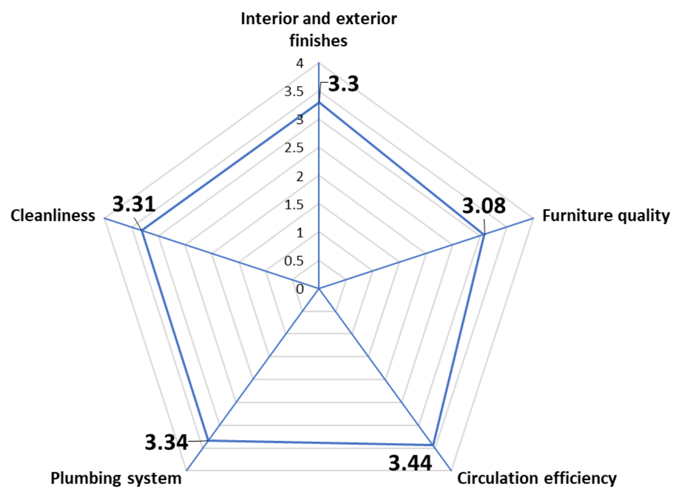



**Figure 6** Mean satisfaction by categories - Functional elements

#### 5.2.1 Interior and Exterior Finishes

The walkthrough inspection indicated that the case study mosque was constructed with luxurious selection of finishes for interior and exterior surfaces. Interviews with permanent occupants revealed that finishes and decorative elements seem to be consistent and satisfactory to the users. The results revealed that the average satisfaction mean of the performance elements related to building finishes is 3.3, which implies that occupants were "satisfied" with the quality of the mosque finishes.

#### 5.2.2 Furniture Quality

The walkthrough inspection indicated that the provided furniture elements inside the mosque were adequately distributed and manufactured by high-quality materials. Interviews with permanent worshipers indicated that chairs and shelves of the mosque were sufficiently provided. However, they mentioned that they suffer from the shortage of the adequate number of shoe racks during the Friday prayer (for being the highest occupancy time and day). However, the findings revealed that average mean response of the functional elements of performance related to furniture quality is 3.08, which indicates that worshipers were "satisfied" with the quality of the furniture of the mosque.

#### 5.2.3 Circulation Efficiency

The walkthrough inspection indicated that there were sufficient number of avenues provided for circulation around and among the occupants' rows of worship. Interviews with frequent occupants indicated that circulation means were clearly identified, through the usage of distinct flooring finishes, across the adopted avenues for occupants' movement. The results revealed that the average satisfaction mean of the elements of performance related the circulation efficiency is 3.44, which implies that occupants were "satisfied" with the building circulation.

#### 5.2.4 Plumbing System

The walkthrough inspection indicated that plumbing fixtures were adequately provided to occupants, since twelve water faucets for ablution and eight toilets were offered and distributed in two separate spaces of service. Interviews with frequent users indicated that they feel comfortable with the number, distribution and quality of the plumbing services that were provided. Elements of performance related to the plumbing systems received an average satisfaction mean of 3.34, which indicates that users were “satisfied” with the provided ablution and toilets areas.

#### 5.2.5 Cleanliness

The walkthrough inspection indicated that the mosque and its supporting facilities are operated and maintained in an appropriate level of cleanliness. Interviews with frequent occupants indicated that there are at least two cleaning shifts, conducted every day throughout the mosque, in order to maintain a satisfactory level of hygiene and cleanliness for the users. The results of the occupants’ satisfaction survey indicated functional elements of performance, related to cleanliness received an average satisfaction mean of 3.31, which implies that the worshipers are “satisfied” with the achieved purity level at the mosque and its supporting facilities.

### *5.3 Behavioral Performance Elements*

The mean rates of satisfaction are illustrated in figure 7, where:


**Figure 7.** Mean satisfaction by categories - Behavioral elements

#### 5.3.1 Spirituality

The walkthrough inspections that were conducted during prayer and non-prayer times indicated that the mosque’s design, character, and activities provide a religious environment towards spirituality. The interviewed frequent users mentioned that they feel spirituality during the prayer due to clarity, calmness and beauty of the lead prayer’s voice and tone during the prayers. The results of the survey indicated that behavioral elements of performance pertaining to spirituality received an average satisfaction mean of 3.54, which implies that users were “strongly satisfied” with the spiritual environment in the mosque.

#### 5.3.2 Aesthetics

The walkthrough inspection indicated that the building finishes provide aesthetic elements that support a religious environment for prayers. Wall finishes, ceiling decorative elements and flooring patterns were designed and installed in a context that is in line with the religious culture. Interviews with frequent occupants revealed their acceptance and appreciation to the implemented innovative design of the aesthetic elements in the mosque. The behavioral elements of performance related to the indoor aesthetics received an average satisfaction mean of 3.66, which implies that worshipers were “strongly satisfied” with indoor aesthetics of the case study mosque.

## 6. Conclusions and Recommendations

In this research, an exemplary indicative post occupancy evaluation was conducted on a place of worship, for a mosque located in the Eastern province of Saudi Arabia. The research comprised the conduct of a walkthrough across the case study building, in order to have an insight about the overall facility conditions and performance, as well as to document all apparent shortcomings and defects. A review of the relevant literature was performed to identify the technical, functional, and behavioral elements of mosques performance. Based on both activities, 34 major mosques performance considerations were identified and categorized into mainly three elements of performance, namely: technical, functional, and behavioral. Then, interviews were conducted with frequent occupants in order to get their feedback about the observed condition and shortcomings of the building, as well as to examine the adequacy of the identified elements of performance and their underlying considerations. Such interviews contributed to formulate interpretation about the observations obtained in the walkthrough inspection. The study then, conducted a users’ satisfaction survey based on a 4-points’ Likert scale, including the 34 identified performance considerations. The survey was utilized as a quantitative data collection and assessment tool. The survey was then launched, where 35 reliable responses (account for 38% response rate) of permanent users were adopted and processed for the data analysis and interpretation. Findings revealed that worshipers were strongly satisfied with the elements of performance related to “acoustical comfort”, “spirituality”, and “aesthetic”. It revealed also that worshipers were satisfied with the other elements of performance. Then the conducted post occupancy evaluation findings led to a set of recommendations, that are aimed to improve the mosque operational performance:

- Air conditioning control panels should not be accessible to all occupants in order to avoid the random adjustment of cooling controls.

- Windows should be replaced with operable type, in order to allow occupants to have natural ventilation during the winter and spring seasons of the year.
- Exit signs, fire sprinklers, extinguishers and emergency exits should adhere to the applicable building codes, in order to maintain an appropriate level of safety, that aims to protect users' lives, and assets.
- Adequate number of shoe racks should be provided to accommodate the maximum number of worshipers during Friday prayers.

This paper has a direct contribution to expanding the boundaries of knowledge about the performance elements at mosques, as well as providing methodological framework to assess such elements in a triangulated manner. The findings of this research will benefit regulators, designers, contractors, and facilities managers involved in mosques projects. The research has answered the questions introduced by investigating the relevant existing literature on the application of post occupancy evaluation as an approach to evaluate and assess users' satisfaction in the context of mosques, as a built environment. Additionally, the considerations and performance elements that derive satisfactory users' occupancy at mosques were identified and assessed. An indicative systematic framework and its underlying steps, for indicatively assessing users' satisfaction in mosques was introduced and applied. Future studies would focus on the application of data analyses could incorporate a digital mean of collection through the utilization of built environment sensors and systems, to monitor real-time feedback and provide a visually dashboard of users' satisfaction in link to the performance identified elements; this link alerts the facility managers with means to adjust the operation of the built facility and highlight recommendations for improving its qualities.

The aim of this study is to provide an exemplary means of conducting a systematic post occupancy evaluation in the context of mosque facilities, while grasping the reviewed literature by identifying critical performance elements and considerations permitting satisfactory occupation. The purpose of this study is to approach a case where the framework can be applied to present facility managers with knowledge that enable them to replicate and conduct an indicative post occupancy evaluation, not to comprehensively reflect a sample of mosques that evaluate the condition of mosques in Saudi Arabia.

The performance elements were firstly driven on the basis of the reviewed literature, then the survey questions developed were pilot tested to improve the identified considerations and elements of evaluation. The walkthrough and pilot tests are additions to the existing elements collected from the dispersed body of knowledge within this research context, to explicitly cover the post occupancy evaluation process of mosque facilities; comprehensively.

A future research direction could be linked to the application of the framework towards benchmarking several case studies of mosques either in a national or international coverage of context. Yet, the selected mosque facility is considered sufficient in terms of occupying the contextual spaces addressed, serving behavioral, functional, and technical reflections of the reviewed performance elements of mosques; to holistically convey an exemplary case study.

## Acknowledgements

The authors thank King Fahd University of Petroleum and Minerals for the support and facilities that made this research possible.

## References

Al-Ajmi, F. F. (2010). "Thermal comfort in air-conditioned mosques in the dry desert climate", *Building and Environment*, 45(11): 2407–2413.

Al-Ajmi, F. F., Al-azmi, A. S., and Alrashidi, F. A. (2017). "Indoor environmental quality in air-conditioned mosque buildings in Kuwait", *American Journal of Civil Engineering and Architecture*, 5(4): 167–173.

Alauddin, K., Ishak, M. F., Azim, M., and Wazir, M. A. M. (2018). "The critical defects of heritage mosque in Perak, Malaysia", *Proceedings of International Conference on Architecture 2017 (ICRP-AVAN), Unsyiah (Banda Aceh) and UiTM (Perak), October 18-19, 2017, Banda Aceh, Indonesia*.

Alnabulsi, H., and Drury, J. (2014). "Social identification moderates the effect of crowd density on safety at the Hajj", *Proceedings of the National Academy of Sciences (PNAS)*, 111(25): 9091–9096.

Alnajadah, A. S. (2017). "Islamic architecture and interiors: Challenges versus opportunities", *Journal of Researches in Science and Specific Arts*, 2(7): 6.

Arel, H. S., and Öner, M. (2017). "Use of daylight in mosques: Meaning and practice in three different cases", *International Journal of Heritage Architecture*, 1(3): 421–429.

Asfour, O. S. (2009). "Effect of mosque architectural style on its thermal performance", *The Islamic University Journal (Series of Natural Studies and Engineering)*, 17(2): 61–74.

Asfour, O. S. (2016). "Bridging the gap between the Past and the Present: A Reconsideration of Mosque Architectural Elements", *Journal of Islamic Architecture*, 4(2): 77–85.

ASHRAE 55. (2017). *Thermal Environmental Conditions for Human Occupancy*. Northeast Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Barrie, T., Bermudez, J., and Tabb, P. J. (2016). *Architecture, Culture, and Spirituality*. New York, USA: Routledge.

BS EN 12665. (2018). *Light and lighting. Basic terms and criteria for specifying lighting requirements*. London: BSI.

Chong, W.-K., and Low, S.-P. (2006). Latent building defects: Causes and design strategies to prevent them", *Journal of Performance of Constructed Facilities*, 20(3): 213–221.

Daghistani, F. (2016). "Conceptual design of congregational prayer chair", *Jordan Journal of Mechanical and Industrial Engineering*, 10(2): 133–140.

El-Darwish, I. I., and El-Gendy, R. A. (2016). "The role of fenestration in promoting daylight performance: The mosques of Alexandria since the 19th century", *Alexandria Engineering Journal*, 55(4): 3185–3193.

Eldien, H. H., and Al Qahtani, H. (2012). The acoustical performance of mosques main prayer hall geometry in the eastern province, Saudi Arabia. In *Acoustics 2012*. 949–955. Retrieved from https://hal.archives-ouvertes.fr/hal-00810652 Retrieved July 30, 2019

EPA. (2018). Introduction to Indoor Air Quality. Retrieved July 30, 2019, from https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality

Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H., and Wargocki, P. (2012). "Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design", *Indoor Air*, 22(2): 119–131.

Giarma, C., Tsikaloudaki, K., and Aravantinos, D. (2017). "Daylighting and visual comfort in buildings' environmental performance assessment tools: A critical review", *Procedia Environmental Sciences*, 38: 522–529.

Grimm, S. R. (2010). *Architeotute and Spiritualit; An Architectute-Genteteil Aesthetic Experience*. University of Hawai'i at Mañoa.

Hassan, A. S., and Arab, Y. (2012). "Lighting analysis of single pendentive dome mosque design in Sarajevo and Istanbul during summer solstice", *The Arab World Geographer*, 15(2): 163–179.

Hassan, A. S., and Arab, Y. (2013). "Analysis of lighting performance between single dome and pyramid roof mosque in Mostar, Bosnia Herzegovina", *Procedia Social and Behavioral Sciences*, 91: 1–12.

Hassanain, M. A. (2008). "On the performance evaluation of sustainable student housing facilities", *Journal of Facilities Management*, 6(3): 212–225.

Hassanain, M. A., and Ashwal, N. Al. (2004). "An approach to assess fire safety requirements in library facilities", *Facilities*, 23(5), 239–252.
Hassanain, M. A., and Iftikhar, A. (2015). "Framework model for post-occupancy evaluation of school facilities", Structural Survey, 33(4): 322–336.

IES. (2011). *The Lighting Handbook,* 10th Ed., New York: Illuminating Engineering Society (IES).

IFC. (2018). *International Fire Code*. New Jersey, USA: International Code Council.

IPC. (2018). *International Plumbing Code*. Country Club Hills: International Code Council.

Ismail, M. R. (2013). "A parametric investigation of the acoustical performance of contemporary mosques", *Frontiers of Architectural Research*, 2(1): 30–41.

Johar, S., Che-Ani, A. I., Tawil, N. M., Surat, M., and Kamaruzzaman, S. N. (2013). "Preliminary survey and defects analysis of traditional timber mosques in Malaysia", *WSEAS Transactions on Environment and Development*, 9(1): 119–129.

Karaman, Ö. Y., and Güzel, N. O. (2017). "Acoustical Properties of Contemporary Mosques: Case Study of "Bedirye Tiryaki Mencik Mosque", Manisa", *YBL Journal of Built Environment*, 5(1): 14–30.

Kavraz, M. (2014). "The acoustic characteristics of the Çarşı Mosque in Trabzon, Turkey", *Indoor and Built Environment*, 25(1): 128–136.

Khalil, N., and Husin, H. N. (2009). "Post occupancy evaluation towards indoor environment improvement in Malaysia's office buildings", *Journal of Sustainable Development*, 2(1): 186–191.

Lee, J. K. (2011). *Building Environment Rule and Analysis (BERA) Language And its Application for Evaluating Building Circulation and Spatial Program*. Georgia Institute of Technology.

Lee, J. K., and Kim, M. J. (2014). "BIM-enabled conceptual modelling and representation of building circulation", *International Journal of Advanced Robotic Systems*, 11(8): 127.

Lee, J. K., Eastman, C. M., Lee, J. M., Kannala, M., and Jeong, Y. (2010). "Computing walking distances within buildings using the universal circulation network", *Environment and Planning B: Planning and Design*, 37(4): 628–645.

Loftness, V., Aziz, A., Choi, J., Kampschroer, K., Powell, K., Atkinson, M., and Heerwagen, J. (2009). "The value of post-occupancy evaluation for building occupants and facility managers", *Intelligent Buildings International*, 1(4): 249–268.

Maluk, C., Woodrow, M., and Torero, J. L. (2017). "The potential of integrating fire safety in modern building design", *Fire Safety Journal*, 88: 104–112.

Manning, P. (1991). Environmental aesthetic design: Identifying and achieving desired environmental effects, particularly "image" and "atmosphere." *Building and Environment*, 26(4): 331–340.

Mokhtar, A. (2003). "Challenges of designing ablution spaces in mosques", *Journal of Architectural Engineering*, 9(2): 55–61.

Mokhtar, A. (2009). "Design standards for Muslim prayer facilities within public buildings", *Proceedings of the Annual Research Conference of the Architectural Research Centers Consortium (ARCC): Leadership in Architectural Research, Between Academia and the Profession* 163–169. San Antonio, Texas, USA: Architectural Research Centers Consortium (ARCC).

Mushtaha, E., and Helmy, O. (2016). Impact of building forms on thermal performance and thermal comfort conditions in religious buildings in hot climates: a case study in Sharjah city. *International Journal of Sustainable Energy*, 36(10): 926–944.

Mustafa, F. A., and Hassan, A. S. (2013). "Mosque layout design: An analytical study of mosque layouts in the early Ottoman period", *Frontiers of Architectural Research*, 2(4): 445–456.

Mustafaraj, E., and Yardım, Y. (2013). Repair and strengthening of historical structures: Naziresha's Mosque in Elbasan. In *3rd Annual International Conference on Civil Engineering*.

Neufert, E., and Neufert, P. (2012). *Neufert's Architects' Data* (4th ed.). Chichester,West Sussex,UK: Wiley-Blackwell.

Nicol, F., and Roaf, S. (2005). Post-occupancy evaluation and field studies of thermal comfort. *Building Research & Information*, 33(4): 338–346.

Parcells, C., Stommel, M., and Hubbard, R. P. (1999). "Mismatch of classroom furniture and student body dimensions: Empirical findings and health implications", *Journal of Adolescent Health*, 24(4): 265–273.

Pereira, N. B., Rodrigues, R. C., and Rocha, P. F. (2016). "Post-occupancy evaluation data support for planning and management of building maintenance plans", *Buildings*, 6(4): 45.

Preiser, W. F. E., Rabinowitz, H. Z., and White, E. (1988). *Post Occupancy Evaluation*. New York: Van Nostrand Reinhold.

Rasmussen, B., and Rindel, J. H. (2003). "Sound insulation of dwellings - Legal requirements in Europe and subjective evaluation of acoustical comfort", *Proceedings of the DAGA 2003 Deutsche Gesellschaft für Akustik*, Aachen, 118–121.

Taib, M. Z. M., Ismail, Z., Ahmad, S., and Rasdi, T. (2016). Mosque development in Malaysia: Is it the product of evolution and social behaviour? *Environment-Behaviour Proceedings Journal*, 1(1): 36–43.

UTM UNIVERSITI TEKNOLOGI MALAYSIA

IJBES

**International Journal of Built Environment and Sustainability**
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 121-133

# Window Ventilation Behavior for Overheating Evaluation: Residents' Survey and Derived Ventilation Profiles

**David Schiela**
Leibniz Institute of Ecological Urban and Regional Development, Weberplatz 1, 01217 Dresden, Germany

**Christoph Schünemann**
Leibniz Institute of Ecological Urban and Regional Development, Weberplatz 1, 01217 Dresden, Germany

## ABSTRACT

Studies have shown that night-time ventilation can greatly reduce indoor overheating during hot spells. Yet the relevant literature is largely silent on which specific time resolved window ventilation behavior can be applied for investigations with building performance simulations. The aim of this article is to close this gap in knowledge. Specifically, a survey was carried out in two German cities Dresden and Erfurt regarding window ventilation behavior on hot (outside temperature > 30 °C) and average summer days to determine how, when and for how long ventilation is actually implemented in residential buildings. The results show that approximately 80 % of respondents ventilate their living rooms and bedrooms mainly at night and/or in the early morning on both hot and average summer days – although the individual window ventilation behavior may vary significantly. The details provided by the respondents were processed to create characteristic window ventilation profiles in order to reflect the individual user behavior more realistically in future studies, especially for overheating evaluations by building performance simulation.

**Article History**

Received: 23 July 2021
Received in revised form: 10 August 2021
Accepted: 13 August 2021
Published Online: 31 August 2021

**Keywords:**

Overheating, heat resilience, residential buildings, window ventilation behavior, questionnaire

**Corresponding Author Contact:**

d.schiela@ioer.de

**DOI:** 10.11113/ijbes. v8. n3.852



## 1. Introduction

Forecasts confirm that, in particular, the duration and intensity of heatwaves will continue to increase (Intergovernmental Panel on Climate Change (IPCC), 2014). To analyze the thermal comfort of buildings under these climate changes the building performance simulation is a suitable tool (Deutsches Institut für Normung e. V. (DIN), 2013; The Chartered Institution of Building Services Engineers (CIBSE), 2017).

Studies have shown that the natural air exchange due to window ventilation and, above all, night-time cooling via open windows have a significant influence on the heat resilience of buildings and the effectiveness of heat adaptation measures (Rijal et al., 2008; Fabi et al., 2012; Porritt et al., 2013; Ferk et al., 2016; Vellei et al., 2017; Fosas et al., 2018; Ivankovic et al., 2019; Schünemann et al., 2020; Hoffmann and Kheybari, 2021). However, the question arises which time-resolved window ventilation profiles can be taken as representative and realistic in building performance simulations to reflect the individual user behavior and accordingly the reality in an accurate manner.

In general, the influence of the window ventilation on the heat resilience of buildings depends on a variety of boundary conditions. Accordingly, structural conditions (e. g. room volume, window opening area, window orientation), weather conditions, type of room use and occupant behavior can affect the window ventilation. For example, Hall et al. conducted measurements in a model room in a laboratory to determine the air exchange rate depending on the window opening area as well as the reveal depth and arrangement of a bottom-hung window. The results showed that the air exchange is highest without an outside and inside reveal. However, these investigations were designed for winter weather conditions (Hall, 2004). In contrast, Schünemann et al. performed building performance simulations for attic apartments of two multi-residential buildings located in Germany. They concluded that the effect of window ventilation also depends on the building physics of a room (Schünemann et al., 2021). Mavrogianni et al. also performed building performance simulations for residential buildings in London under various boundary conditions (e. g. occupant profiles, building geometry and orientation, insulation level, shading) and found that the effect of window ventilation is associated with the insulation level of a building and window shading (Mavrogianni et al., 2014).

Further studies investigated the influence of external weather conditions on occupants' window ventilation behavior. For example, Fabi et al. showed that the ventilation behavior in apartments is strongly dependent on the outside temperature (linear increase in ventilation intensity as outside air temperatures rise from -10 °C to 25 °C) and wind speed (Fabi et al., 2012). However, this study did not specifically examine the ventilation behavior on summer days (outdoor temperature > 25 °C) or the impact of the ventilation behavior.

Surveys of window ventilation behavior were conducted by Mavrogianni et al. in the United Kingdom. They pointed out that 70 % of residents did not ventilate their apartment at all during the night or at most with only one open window. The main reason given for this was usually security concerns such as the risk of burglary (Mavrogianni et al., 2016). Vellei et al. combined surveys with indoor climate measurements and investigated the thermal comfort in bathrooms, kitchens and living rooms of 46 renovated residential buildings in the United Kingdom. They noted that the degree of overheating was associated with inadequate window ventilation behavior (Vellei et al., 2016).

With regard to window ventilation profiles the German standard DIN 4108-2:2013-02 (Deutsches Institut für Normung e. V. (DIN), 2013) specified boundary conditions for analyzing the summer comfort of buildings using building performance simulation. Thus, from 6 am to 11 pm a constant air exchange rate of 3 $h^{-1}$ can be assumed in residential buildings if the indoor temperature is > 23 °C and the indoor temperature also exceeds the outdoor temperature. During night-time hours, a ventilation rate of 2 $h^{-1}$ can be assumed in residential buildings if the indoor temperature is > 20 °C and at the same time exceeds the outdoor temperature (Deutsches Institut für Normung e. V. (DIN), 2013). According to the standard CIBSE TM 59 (2017), it can be assumed that the windows are open if the indoor temperature exceeds 22 °C and the room is used at the same time. It is also specified that interior doors should be open during the day and closed during sleeping time (The Chartered Institution of Building Services Engineers, 2017).

Of course, these normative approaches are important boundary conditions, but they do not adequately reflect the individual user behavior. Detailed knowledge of the time periods of window opening is needed in order to take better account of individual behavior and induced impacts on heat resilience of apartments. For example, users may be absent for most of the day. Since windows in residential buildings do not usually open and close automatically, residents have to decide when leaving their homes whether to keep the windows open or closed during the day. The question also arises whether the specified air exchange rates in the German standard DIN 4108-2:2013-02 can always be achieved by tilting and shock/cross-ventilation, especially at night when it is also necessary to take account of factors such as burglary protection or outdoor noise. In addition, cross-ventilation may be rejected due to the risk of unpleasant draughts. Furthermore, it is not always possible or desirable to open interior doors for cross-ventilation due to individual requirements for room use.

To get a more precise picture, this work presents the results of a residents' survey carried out in the summer months of the year 2019 to find out how, when and for how long ventilation is actually carried out during hot (outside temperature > 30 °C) and average summer days in residential buildings. Furthermore, characteristic window ventilation profiles will be derived from the survey results in order to more realistically represent individual window ventilation behavior in future studies, especially for investigations with building performance simulations.

## 2. Methodology

To evaluate the window ventilation behavior during summer weather conditions, the methodology of a written survey was used. For this purpose, a total of 400 questionnaires with enclosed envelopes were randomly distributed in letterboxes of multi-residential buildings in two urban districts in Germany. Studies have shown that residents of multi-residential buildings in cities are particularly affected by heat stress due to the urban densification and the associated urban heat island effect (Schünemann et al., 2020b).

The first sample district is located in the city of Dresden (district Dresden-Gorbitz) with precast large-panel housing blocks while the second is located in Erfurt (district Erfurt Oststadt) with buildings from the 19th-century (*Gründerzeit* periode). These types of multi-residential buildings are often not yet adapted to the increasing summer weather conditions (Schünemann et al., 2020). Accordingly, there is a need for action to optimize the summer comfort. In addition, the selected buildings are typical representatives of multi-residential buildings in European cities (Schünemann et al., 2020). The results of the investigations are therefore highly relevant for many urban neighborhoods.

The buildings investigated in the district of Dresden-Gorbitz are both refurbished and non-refurbished precast large-panel housing blocks, usually six storeys high. Here the apartments have a similar floor plan across all storeys. In comparison, the buildings in Erfurt's Oststadt district from the so-called *Gründerzeit* period often have attics converted into living space. These attic apartments differ significantly in floor plan and structural design from the apartments in the underlying three or four storeys. Further details on the building structures, their structural components and window properties can be found elsewhere (Schünemann et al., 2020; Kunze, 2019; Schiela and Schünemann, 2020).

From a total of 400 distributed questionnaires, 83 households had replied by 31 August 2019. The questionnaire itself contained 12 questions, most of which were mainly multiple choice. The two-page questionnaire is shown in Table A 1 (Appendix).

First, the participants were asked to assess the indoor temperatures in the individual rooms of their homes during hot summer days (maximum temperature > 30 °C). The residents were able to evaluate the indoor temperatures during summer weather conditions on a predetermined 5-point scale ("just right" to "hot"). This 5-point scale allowed a detailed gradation of the subjective heat sensation of the residents in the two multi-residential building types and also showed tendencies of the heat sensation in comparison to a 3-point scale (low, medium and high heat stress).

Subsequently, the questionnaire asked about the window ventilation behavior for each room in the apartment, i.e. living room, bedroom, children's room, study and bathroom. Here the respondents could choose between tilt and shock (fully opened) ventilation as well as combinations of these types with cross-ventilation. By means of a timeline, respondents could mark in boxes the specific times when they predominantly used these individual or combined forms of window ventilation. The ventilation behavior was recorded separately for hot summer days (maximum temperature > 30 °C) and average summer days (maximum temperature < 30 °C).

In addition, the survey also considered the obstacles to window ventilation during the day or at night and whether fans were utilized. These questions were also created as multiple choice questions with the specifications of "burglary protection", "driving rain", "outside noise", "insects" and "draught" or "yes" and "no". Additional space was provided for own comments. In the last part of the questionnaire, the participants were asked to provide details about the building, the apartment and the persons making up their household in order to determine any correlation of these factors with window ventilation behavior.

For the data analysis, the residents' responses were first digitized using the spreadsheet program Microsoft Excel. This was followed by a check of the completeness and meaningfulness of the answers. Subsequently, the data were processed into tables and individual questions were linked with filters in order to make statistical statements on window ventilation behavior under certain boundary conditions (e. g. window ventilation behavior depending on the building floor). In order to derive characteristic window ventilation profiles, the specified profiles of each household were evaluated separately and categorized into groups depending on various boundary conditions.

## 3. Results and Discussion

### *3.1 Age Structures in the Investigated Districts*

A total of 60 people live in the households surveyed in Dresden-Gorbitz and 100 in the households surveyed in Erfurt's Oststadt district. Figure 1 compares the age structure of the 160 residents in the 83 participating apartments in relation to the building floor. Here we distinguish between the ground and intermediate floors (GF+IF) and the top floor (precast large-panel housing blocks) or attic floor (*Gründerzeit* buildings). In this context, intermediate floors are those floors which cannot be classified as a ground floor, a top floor or an attic floor.

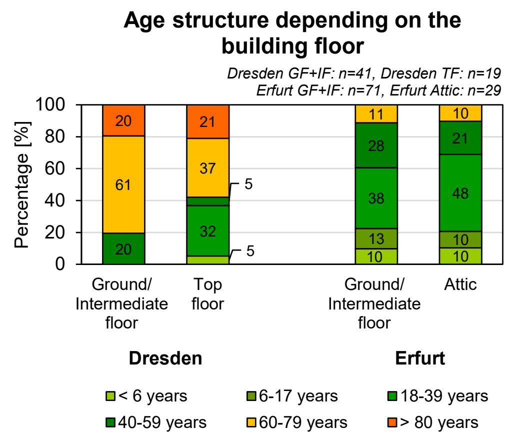



**Figure 1** Age structure of the 160 persons living in the 83 surveyed households in Dresden-Gorbitz and Erfurt Oststadt in relation to the building floor

The results show a clear difference between the age structures of the two sample districts. For example, the proportion of residents over 60 years of age is 81 % in Dresden-Gorbitz (ground floor/intermediate floor) and 58 % (top floor) while in Erfurt's Oststadt the ratio is only 11 % for the ground/intermediate floors and 10 % for attic apartments. In the *Gründerzeit* buildings in Erfurt, the majority of residents fall in the age group 18-59 years, i.e. 66 % (ground/intermediate floor) and 69 % (attic).

Age differences between floors are particularly evident in Dresden-Gorbitz. These can generally be attributed to the condition of the buildings. In unrenovated buildings, younger people generally live on the top floors and older residents on the lowest floors. However, a large proportion of residential buildings in the study area have already been upgraded for older people. Newly installed lifts mean that many apartments on the 5th floor are now also barrier free.

### *3.2 Subjective Heat Stress in Relation to The Floor*

Based on the indicated age structures, Figure 2 compares the assessment by local residents of Dresden-Gorbitz and Erfurt's Oststadt of the level of heat stress. Here we see an evaluation for the living room and bedroom on a hot summer day with outside temperatures > 30 °C. The data is broken down by floor in order to determine the subjective heat stress felt by those living on the top floor or attic floor, which are generally much hotter than underlying floors.

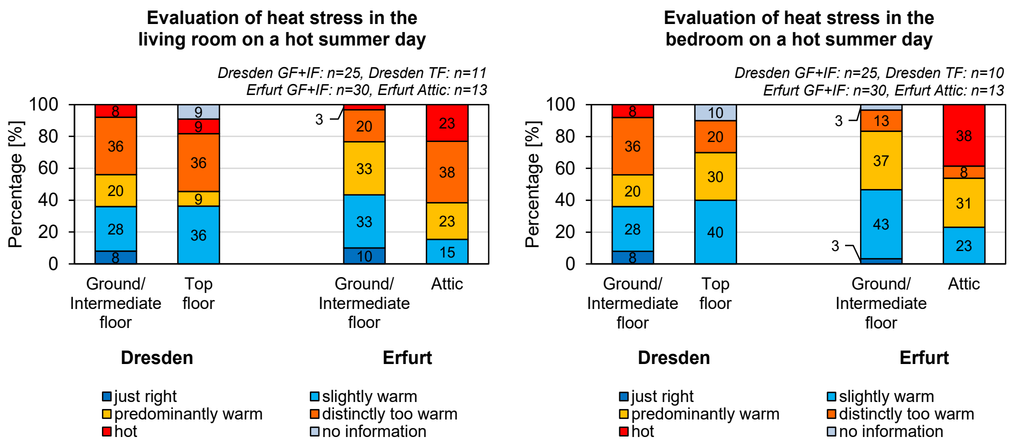



**Figure 2** Subjective assessment of heat stress in the living room and bedroom on a hot summer day in relation to the building floor

In general, we see that a similar perception of heat stress is indicated for the living room and the bedroom on each floor of residential buildings in Dresden. Regarding the living room, 64 % (ground/intermediate floor) and 54 % (top floor) of respondents rated the indoor temperature as "predominantly warm" to "hot". Regarding the bedroom, the ratios are 64 % (ground/intermediate floor) and 50 % (top floor). The similar evaluations of heat stress can be attributed to the nearly identical floor plans and interior fittings of the apartments. Furthermore, many buildings in the study area had already been refurbished, in particular, the apartments on the top floors were fitted with ceiling and façade insulation, thereby reducing the possibility of external heat reaching the interior space (Schünemann et al., 2020). In addition, the subjective assessment of the heat stress is particularly dependent on the prevailing weather conditions during the survey as well as the particular situation (floor, ventilation behavior) of each household. The summer of 2019 was one of the warmest ever recorded in Germany, with an average temperature of 19.2 °C and maximum temperatures of over 40 °C (Deutscher Wetterdienst (DWD), 2019). For this reason, the survey findings could help residents cope with the forecasted heatwaves of coming summers.

In Erfurt's *Gründerzeit* residential buildings, we observe a significantly higher perception of heat stress in the attic apartments compared to the top floors in Dresden. Here 84 % of respondents classified the interior temperature in the living room as "predominantly warm" to "hot" while 77 % gave the same evaluation for the bedroom.

The comparison of the results for the ground and intermediate floors of the two multi-residential building types shows that 64 % of the participants in Dresden evaluate the heat stress in the living room and bedroom as "predominantly warm" to "hot". For the buildings in Erfurt, these values are 56 % (living room) and 50 % (bedroom). Accordingly, it can be concluded that the heat stress on the ground and intermediate floors of the *Gründerzeit* buildings is rated lower. The noted disparity in the evaluation of heat stress in the *Gründerzeit* buildings can be attributed to the unique design and structural features of the attic apartments compared to the other residential floors.

In summary, it can be said that there is basically no correlation between the age of the respondents and the subjective assessment of heat stress. Using the methodology of table filtering, it was found that 60 % of residents in Dresden-Gorbitz, who are over 60 years and at the same time live on the ground or intermediate floor, classified the heat stress in their living rooms as "predominantly warm" to "hot". For the attic apartments, this proportion is also approximately 60 %. This shows that a high proportion of older people do not necessarily also evaluate the heat stress in the apartment as high. The decisive factors are rather the location of the apartments in the building and whether it is an attic apartment. Therefore, residents of attics in *Gründerzeit* buildings were particularly likely to indicate a high heat stress.

### *3.3 Window Ventilation Behavior In The Living Room And Bedroom In Relation To The Floor*

The first step in evaluating the window ventilation behavior was to examine the data on window opening in the living room and bedroom. The two types of window ventilation practiced by the surveyed households are here summed for each hour of the 24-hour period in order to reveal those times when the living room and bedroom are most likely to be ventilated. In view of the lack of significant differences between the responses from Dresden and Erfurt, these two datasets are here aggregated and differentiated by floor. In the histograms of Figure 3 and Figure 4, the horizontal axes represent the 24-hour period and the vertical axes the respective proportion of respondents. The indented columns show the proportion of respondents combining a tilted (red) or fully opened window (yellow) with cross-ventilation.

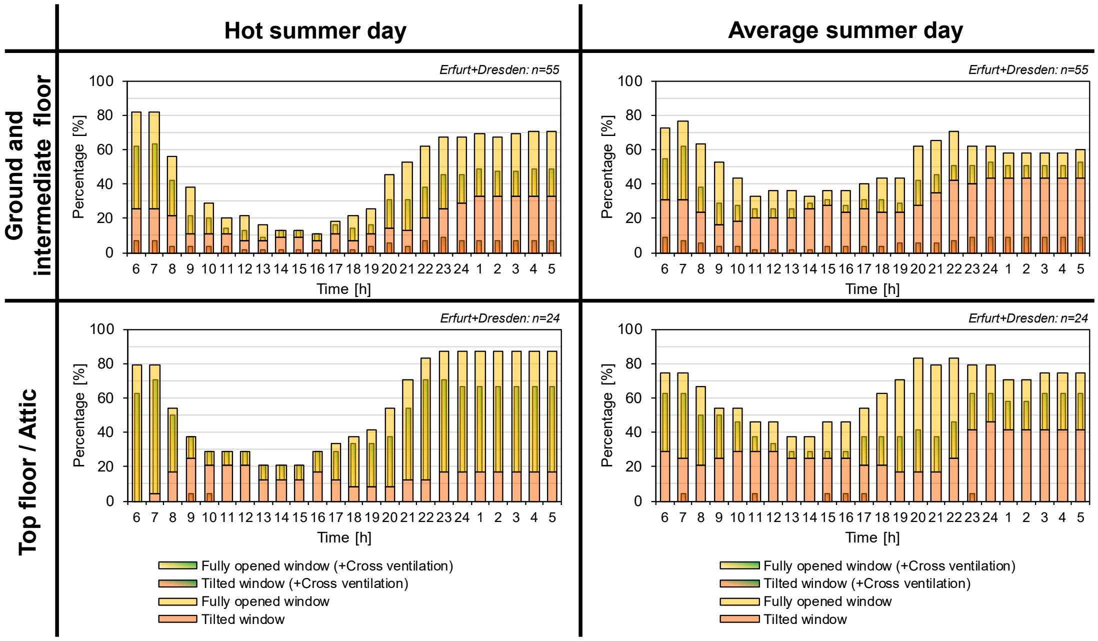



**Figure 3** Evaluation of window ventilation behavior in the living room on hot and average summer days for different floors. The indented columns show the proportion of respondents combining a tilted (red) or fully opened window (yellow) with cross-ventilation

The aggregated data for tilt and shock ventilation during hot summer temperatures shows that the majority of respondents keep their windows closed during the day, both on the ground/intermediate floors as well as on the top floors or attic space. Instead, most residents ventilate largely at night or in the early morning hours. It should also be noted that an even larger proportion of respondents living on top floors or in attic spaces will ventilate due to the higher heat loads found there than on the other floors. Specifically, the average proportion of respondents ventilating from around 10 pm to 8 am is approx. 70 % on the ground floor/intermediate floors in contrast to approx. 90 % on the top floor/attic. Furthermore, we also note a steady increase in ventilation from around 4 pm. When ventilation takes place, the window on the top floor or attic is opened completely rather than just tilted. On the ground and intermediate floors, however, the ratio between tilt and shock ventilation is relatively balanced. With regard to window ventilation combined with cross-ventilation, we see that this is much more likely to occur with a fully opened window than a tilted window. This form of combined ventilation also applies to an average summer day and results in the greatest influx of fresh air into the apartment.

Comparing a hot day with an average summer day, it can be seen that in the latter case ventilation increases during the day (primarily tilt ventilation). The proportion of tilt ventilation also increases at night, in particular, this is preferred by respondents in the ground and intermediate floors to fully opened windows. On the top floors or attic spaces, a relatively high rate of shock ventilation occurs between 7 pm and 11 pm.

In principle, the ventilation behavior already described for the living room (Figure 3) also applies to the bedroom (Figure 4): on hot summer days, ventilation is mainly in the early morning hours and at night. During night-time hours from 10 pm to 6 am, however, there is slightly increased likelihood of ventilation on the ground floor and intermediate floors (about 80 %) and lower likelihood of ventilation on the top floor or attic space (about 75 %) than in the living room. Tilt ventilation is hardly used on the top floors or attics. On average summer days, tilt ventilation also increases significantly compared to hot summer days, especially on the top floors or attics.

In summary, while we note some minor variations in window ventilation between the living room and bedroom, no significant disparities can be detected between the two rooms or between the floors. The differences that do occur are, above all, in regard to daytime window ventilation for hot vs. average summer days.

The results on window ventilation behavior during summer weather conditions show that window ventilation is used by approximately 80 % of the respondents in the living room and bedroom to cool the rooms at night. The results of Mavrogianni et al. that 70 % of the residents do not ventilate their apartment at all or only with one open window during the night could thus only be partially confirmed for the building types considered in this study (Mavrogianni et al., 2016).

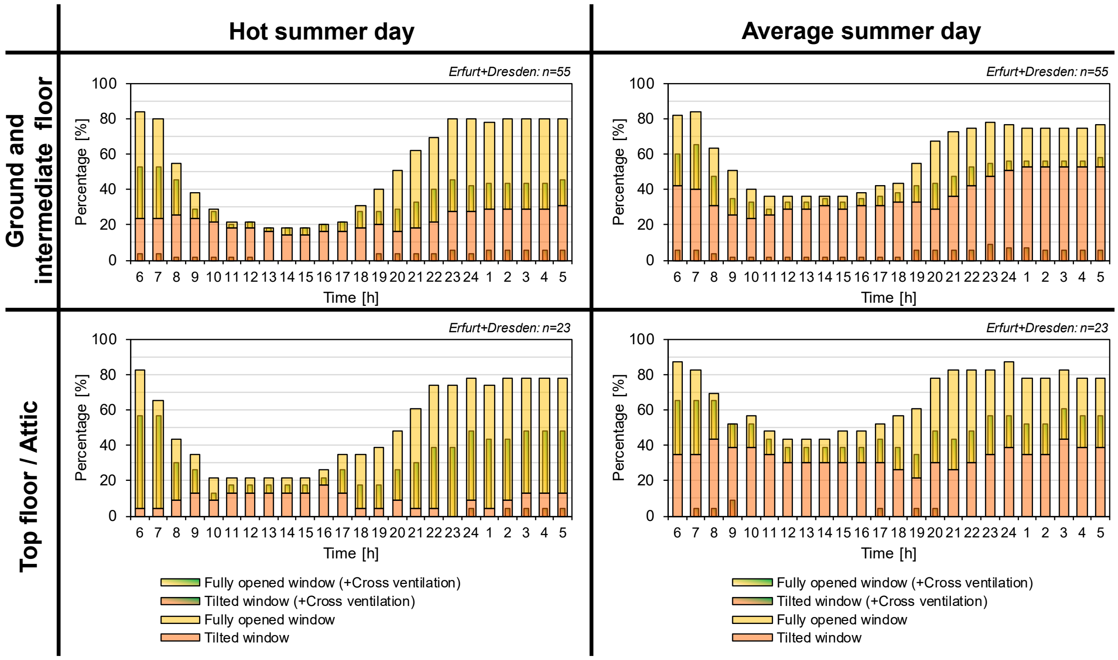



**Figure 4** Evaluation of window ventilation behavior in the bedroom on hot and average summer days for different floors. The indented columns show the proportion of respondents combining a tilted (red) or fully opened window (yellow) with cross-ventilation

### *3.4 Obstacles To Window Ventilation At Night*

Night-time ventilation has a major impact on thermal comfort during long periods of hot weather (Schünemann et al., 2021). Accordingly, adequate window ventilation can make a useful contribution to the night-time cooling of rooms. This is especially true in the Central European climate zone where outside temperatures drop significantly at night and tropical nights (minimum temperature > 20 °C) are rare. Night-time ventilation can help to release heat that has accumulated indoors over the course of the day. However, residents have a number of good reasons to keep windows closed at night. Figure 5 shows the findings of the questionnaire on these general obstacles to night-time ventilation.

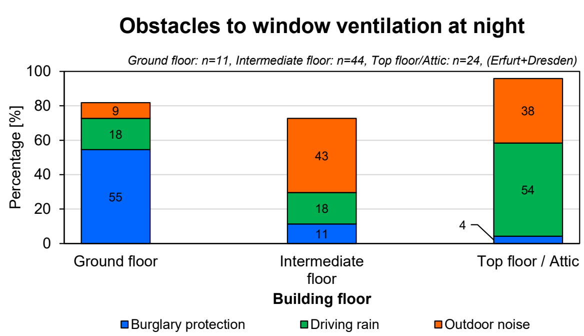



**Figure 5** Findings of the 83 surveyed households on general obstacles to night-time ventilation in relation to the building floor

The results show that, depending on the floor type, different reasons are given clear for not opening windows. For example, burglary protection is named by over 50 % of respondents living on the ground floor. The findings of Mavrogianni et al. that burglary protection plays an important role in the implementation of window ventilation could be confirmed with this survey, especially for occupants of ground floors (Mavrogianni et al., 2016). Furthermore, over 50 % of those inhabiting top floors or attics gave driving rain as the main reason. Outdoor noise also plays an important role, especially among those living on intermediate floors (43 %) and on top floors or attics (38 %). Consequently, architects and urban planners must consider special measures to ensure that users are able to exploit night-time window ventilation. This will also benefit climate protection by avoiding the use of air conditioning.

## 4. Derivation Of Characteristic Ventilation Profiles

The histograms in Figure 3 and Figure 4 give an overview of window ventilation behavior in living rooms and bedrooms over a 24-hour period. However, individual ventilation behavior cannot be deduced from these figures as, for example, it is impossible to determine whether a resident who ventilates in the morning also ventilates in the evening. For this reason, the investigations were extended to examine the questionnaires on a case-by-case basis. Here the only distinction made was between tilted and fully opened windows. For reasons of simplicity, cross-ventilation was neglected and merely recommended as an additional option to achieve a more efficient air exchange. Some individual window ventilation profiles are shown in Figure A 1 and Figure A 2 (see appendix) for the living room and bedroom. A distinction is made between hot and average summer days as well as between the top/attic floor and ground/intermediate floors. The respondents' own assessment of the heat stress on a hot summer day (outside temperature > 30 °C) is shown for the two considered rooms. While the questionnaire results confirm that many respondents ventilate mainly in the morning and at night, a wide range of individual ventilation behavior is also apparent. For example, there are households that ventilate in the morning but not at night. Some respondents also change the applied type of window ventilation over the course of a day. In other households the window is simply left open all day. The ventilation profiles for the living room and bedroom are largely the same.

The subjective assessment of heat stress reveals no or only a weak correlation between perceived heat stress and ventilation behavior. The use of night-time window ventilation to cool down the rooms does not mean that the indoor temperatures are perceived as pleasant. Nor can low window ventilation behavior at night indicate the residents do not suffer from high heat stress. Furthermore, it should be mentioned that the window ventilation behavior can also deviate on certain days from the practices stated here, leading to variations in the perceived heat stress over the course of the summer. In addition to user behavior, the physical structure of the building can also greatly determine whether rooms become overheated (Schünemann et al., 2021).

The histograms in Figure 3 and Figure 4 indicate that there are times during the course of the day when similar forms of ventilation behavior occur in the living room and bedroom or when similar ratios of ventilation behavior arise. In order to derive characteristic ventilation profiles, the authors decided to distinguish between ventilation in the morning (6 am to 8 am), ventilation during the day (8 am to 6 pm), ventilation in the evening (6 pm to 10 pm) and night-time ventilation (10 pm to 6 am). As the window can be either closed, tilted or completely open at any of the indicated time periods, there are a total of 81 (3 window ventilation variants per time period: 3 x 3 x 3 x 3) possible ventilation profiles. In our investigation, we determined (under certain boundary conditions) which variant occurs most frequently in each time period. These boundary conditions are summarized in Figure 6

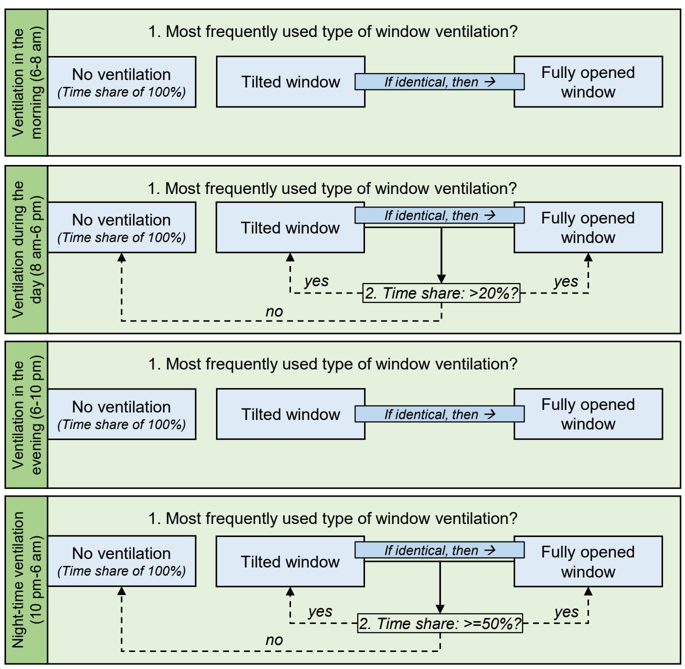



**Figure 6** Scheme to derive characteristic window ventilation profiles by setting four selected time periods and boundary conditions for each period

First, we examined how often each ventilation type occurred in the respective time period and determined the most frequently used type of ventilation. If there was no difference in the frequencies of the tilted or fully-opened window, the latter ventilation type was chosen ("if identical, then" in Figure 6). Subsequently, it was determined whether the most frequently occurring ventilation type was also effectively applied and fulfilled the named boundary conditions. For the definition of the boundary conditions, it was assumed that there must be a certain duration of window opening in the selected time periods in order to achieve an effect with regard to the indoor climate. Accordingly, only those cases of daytime ventilation (8 am to 6 pm) were considered in which the window was kept open more than 20 % of the time, thus enabling warm outdoor air to flow into the room and increase indoor temperatures. This assumption also ensures that fresh air can enter the room during the day, when residents should be at home. At night, ventilation was only deemed to occur if the window was open for at least 50 % of the time, so that the low outdoor air temperatures at night were specifically used to cool down the rooms. At the other times of the day, all households were counted that ventilated for at least one hour. Thus, the effectiveness of some ventilation profiles shown in Figure A 1 and Figure A 2 is over- or underestimated, respectively. However, these assumptions were necessary to limit the range of possible window ventilation profiles and thus to maintain the clarity of the results.

The individual questionnaires were then assigned to one of the 81 possible ventilation profiles and sorted according to frequency. Table 1 shows the identified ventilation profiles independent of the floor.

The window ventilation profiles derived from the survey on window ventilation for summertime outdoor temperatures represent a wide range of individual user behavior. The distinguishing characteristic of the most common ventilation profiles is a lack of ventilation during the day or at night. Combinations of tilt and/or shock ventilation are also employed. The profiles can therefore be used for overheating assessment by building performance simulation to take better into account of individual user behavior.

**Table 1** The most common window ventilation profiles for living rooms and bedrooms on hot summer days as determined by the questionnaires

| Profile | Ventilation in the morning (6-8 am) | Ventilation during the day (8 am-6 pm) | Ventilation in the evening (6-10 pm) | Night-time ventilation (22 pm-6 am) | Number Living room | Number Bedroom |
|---|---|---|---|---|---|---|
| 1 | Fully opened window | No ventilation | No ventilation | Fully opened window | 13 | 10 |
| 2 | Fully opened window | No ventilation | Fully opened window | Fully opened window | 11 | 15 |
| 3 | Fully opened window | No ventilation | No ventilation | No ventilation | 7 | 11 |
| 4 | Tilted window | No ventilation | No ventilation | Tilted window | 5 | 1 |
| 5 | Tilted window | Fully opened window | Fully opened window | Tilted window | 4 | - |
| 6 | Fully opened window | No ventilation | Fully opened window | No ventilation | 4 | 1 |
| 7 | Fully opened window | Fully opened window | Fully opened window | Fully opened window | 3 | 4 |

## 5. Limitations of the Study

It is important to note that the window ventilation profiles were derived from the surveys using simplified assumptions to minimize the number of possible window ventilation profiles. Accordingly, a change in the selected time periods and boundary conditions also changes the ventilation profiles in design and frequency. The results represent case examples for two multi-residential building types of two different districts in Germany. Therefore, the window ventilation behavior may vary in other German regions or countries with or without similar building structures. Due to the fact that only 83 households took part in the survey, the results presented are randomly and have to be checked for transferability. Furthermore, it must also be taken into account that some respondents may have idealized their user behavior and thus the respondents' window ventilation behavior can deviate from the practices stated in the questionnaire and does not necessarily reflect the reality.

## 6. Conclusion

Previous investigations had shown that window ventilation behavior, especially at night, has a major influence on indoor overheating. However, the question arises which window ventilation profiles are suitable to reflect the individual user behavior and accordingly the reality in a good manner.

To get a more precise picture, a residents' survey was carried out in the summer months of the year 2019 to find out how, when and for how long ventilation is actually carried out during hot (outside temperature > 30 °C) and average summer days in multi-residential buildings. Therefore, two study areas each with different representative building types were chosen located in the German cities of Dresden and Erfurt.

Of a total of 400 distributed questionnaires, 83 households took part in the survey. The questionnaire itself contained 12 questions, which were mainly multiple choice. In addition to room-specific questions regarding window ventilation behavior on hot and average summer days as well as an own assessment of the heat stress on hot summer days, an important part of the survey was to identify some general obstacles to night-time ventilation. These questions were supplemented by information on the building, the apartment and the individuals making up the household.

The following results could be derived from the answers of the questionnaires:

1. No correlation was found between the age of residents and their perception of heat stress. However, the location of the apartment in the building, specifically whether it is an attic apartment or an underlying apartment, plays a significant role.

2. Many respondents ventilate their homes mainly at night and/or early in the morning on hot as well as on average summer days. The majority of respondents keep their windows closed during the day. However, windows are opened more frequently during daytime hours when the summer weather is average rather than when it is hot.

3. The application of night-time window ventilation does not mean that the indoor temperatures in the apartment are perceived as pleasant.

4. On hot and average summer days, the ventilation behavior in the living room and bedroom differs only slightly.

To achieve the objective of characteristic window ventilation profiles, the next step was to evaluate the individual ventilation behavior of each household. For this purpose, boundary conditions were defined for four selected periods over 24 hours and the generated ventilation profiles classified by frequency. This resulted in the identification of seven ventilation profiles, which can be basically differentiated by a lack of window ventilation during the day or at night. The profiles represent a wide range of user behavior and can thus be used in a targeted manner for overheating assessment by building performance simulation to realistically represent window ventilation behavior. Different ventilation profiles and thus ventilation scenarios can thus be examined for a building. For example, it is possible to select a ventilation profile for rooms on the ground floor that only takes into account ventilation in the morning and/or evening, if night ventilation is not possible due to burglary protection. It is also possible to investigate whether ventilation in the evening and/or morning is sufficient to reduce the heat stress in the building or whether measures to support the air exchange by means of a ventilation system are necessary. For the top floors or attics that are particularly affected by heat stress, it can also be investigated whether night-time ventilation is sufficient to achieve a comfortable indoor climate during summer weather conditions or whether further measures (e. g. window shading) are required.

## Acknowledgements

The authors thank the project partners of the HeatResilientCity project for the provision of the building data, outdoor measurements, indoor measurements and coordination. The research was mainly funded by the German Federal Ministry of Education and Research (BMBF) in the joint project "HeatResilientCity" (subproject grant number: 01LR1724A). The promoter of this project is the DLR project management agency (DLR-PT).

## References

Deutscher Wetterdienst (DWD) (2019). Deutschlandwetter im Sommer 2019 - Sonnenscheinreich und niederschlagsarm - neue Temperaturrekorde, Pressemitteilung. World Wide Web: https://www.dwd.de/DE/presse/pressemitteilungen/DE/2019/20190830_deutschlandwetter_sommer2019.pdf?__blob=publicationFile&v=2. Accessed 7/19/2021.

Deutsches Institut für Normung e. V. (DIN) (2013). DIN 4108-2:2013-02 Wärmeschutz und Energie-Einsparung in Gebäuden - Teil 2: Mindestanforderungen an den Wärmeschutz. Berlin: Beuth Verlag.

Fabi, V., Andersen, R. V., Corgnati, S. and Olesen, B. W. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, 58: 188–198. https://doi.org/10.1016/j.buildenv.2012.07.009.

Ferk, H., Rüdisser, D., Riederer, G. and Majdanac, E. (2016). Sommerlicher Wärmeschutz im Klimawandel - Einfluss der Bauweise und weiterer Faktoren. Zuschnitt Attachment – Sonderthemen im Bereich Holz, Holzwerkstoff und Holzbau, 1–22.

Fosas, D., Coley, D. A., Natarajan, S., Herrera, M., Fosas de Pando, M. and Ramallo-Gonzalez, A. (2018). Mitigation versus adaptation: Does insulating dwellings increase overheating risk? *Building and Environment*, 143: 740–759. https://doi.org/10.1016/j.buildenv.2018.07.033.

Hall, M. (2004). Untersuchungen zum thermisch induzierten Luftwechselpotential von Kippfenstern. Bauphysik 26 (2004), Heft 3, 109-115. Berlin: Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG.

Hoffmann, S. and Kheybari, A. G. (2021). Untersuchungen zum sommerlichen Wärmeschutz - Teil 1: Vergleich der Nachweisverfahren unter Berücksichtigung zukünftiger Klimadaten. *Bauphysik* 43 (2021), Heft 1, 27–35.

Intergovernmental Panel on Climate Change (IPCC) (2014). Climate Change 2014 - Impacts, Adaptation and Vulnerability - Part B: Regional Aspects.

Ivankovic, G., Hafellner, H. and Kautsch, P. (2019). Berechnung des sommerlichen Wärmeschutzes. *Bauphysik* 41 (2019), Heft 1, 7–16.

Kunze, S. (2019). Sommerliche Überhitzung in Wohngebäuden – Baukonstruktive und haustechnische Anpassungsmaßnahmen. In: L. Sieber, ed., Tagungsband zum 4. BIH-Treffen 2019, Interdisziplinäre Forschung - Chancen und Herausforderungen, Fachtagung für wissenschaftlich Beschäftigte und Nachwuchskräfte an Bauingenieur-Institutionen deutscher Hochschulen, 19–28.

Mavrogianni, A., Davies, M., Taylor, J., Chalabi, Z., Biddulph, P., Oikonomou, E., Das, P. and Jones, B. M. (2014). The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments. *Building and Environment*, 78: 183–198. https://doi.org/10.1016/j.buildenv.2014.04.008.

Mavrogianni, A., Pathan, A., Oikonomou, E., Biddulph, P., Symonds, P. and Davies, M. (2016). Inhabitant actions and summer overheating risk in London dwellings. *Building Research & Information*, 45 (1-2): 119–142. https://doi.org/10.1080/09613218.2016.1208431.

Porritt, S., Cropper, P., Shao, L. and Goddier, C. I. (2013). Heat wave adaptations for UK dwellings and development of a retrofit toolkit. *International Journal of Disaster Resilience in the Build Environment*, 4 (3): 269–286. https://doi.org/10.1108/ijdrbe-08-2012-0026.

Rijal, H. B., Tuohy, P., Nicol, F., Humphreys, M., Samuel, A. and Clarke, J. A. (2008). Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. *Journal of Building Performance Simulation*, 1(1): 17–30. https://doi.org/10.1080/19401490701868448.

Schiela, D. and Schünemann, C. (2020). Strategien gegen die Überhitzung. Gebäudeenergieberater, 05 2020, 20–23.

Schünemann, C., Olfert, A., Schiela, D., Gruhler, K. and Ortlepp, R. (2020). Mitigation and adaptation of multifamily housing: overheating and climate justice. *Buildings and Cities*, 1(1): 36–55.

https://doi.org/10.5334/bc.12.

Schünemann, C., Ziemann, A., Goldberg, V. and Ortlepp, R. (2020b). Urban climate impact on indoor overheating – a model chain approach from urban climate to thermal building simulation. In: Zilahy, Gyula (Eds.): Sustainability in Transforming Societies. Proceedings of the 26th Annual Conference of the International Sustainable Development Research Society (ISDRS), 15-17 July 2020, Budapest, Hungary. Budapest: Budapest University of Technology and Economics, 723-734. http://www.isdrsconference.org/download/file/971/.

Schünemann, C., Schiela, D. and Ortlepp, R. (2021). How window ventilation behaviour affects the heat resilience in multi-residential buildings. Building and Environment, 202: 107987, ISSN 0360-1323 (Online First). https://doi.org/10.1016/j.buildenv.2021.107987.

The Chartered Institution of Building Services Engineers (CIBSE) (2017). CIBSE TM 59 (2017) Design Methodology for the Assessment of Overheating Risk in Homes. London: The Chartered Institution of Building Services Engineers.

Vellei, M., Ramallo-Gonzalez, A. P., Kaleli, D., Lee, J. and Natarajan, S. (2016). Investigating the overheating risk in refurbished social housing. In: Proceedings of 9th Windsor Conference: Making Comfort Relevant.

Vellei, M., Ramallo-Gonzalez, A. P., Coley, D., Lee, J., Gabe-Thomas, E., Lovett, T. and Natarajan, S. (2017). Overheating in vulnerable and non-vulnerable households. *Building Research & Information*, 45 (1-2): 102–118. https://doi.org/10.1080/09613218.2016.1222190.

## Appendix

**Table A1** The two-page questionnaire used to survey window ventilation behavior during hot summer weather

1. How do you evaluate the indoor temperatures in the individual rooms of your apartment during persistently hot outdoor temperatures in the summer?

| | just right | slightly warm | predominantly warm | distinctly too warm | hot |
|---|---|---|---|---|---|
| Living room | ☐ | ☐ | ☐ | ☐ | ☐ |
| Bedroom | ☐ | ☐ | ☐ | ☐ | ☐ |
| Children's room / study | ☐ | ☐ | ☐ | ☐ | ☐ |

2. How often and for how long do you usually use the following window ventilation options in your apartment during **persistently hot summer outdoor temperatures** (daytime maximum > 30 °C)? Please mark the periods in the boxes.

| Time / Window ventilation | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Living room | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |
| Bedroom | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |
| Children's room | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |
| Study | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |
| Bathroom | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |

3. How often and for how long do you usually use the following window ventilation options in your apartment during **average summer outdoor temperatures**? Please mark the periods in the boxes.

| Time / Window ventilation | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Living room | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bedroom | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |
| Children´s room | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |
| Study | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |
| Bathroom | | | | | | | | | | | | | | | | | | | | | | | | |
| Tilted window | | | | | | | | | | | | | | | | | | | | | | | | |
| Fully opened window | | | | | | | | | | | | | | | | | | | | | | | | |
| Cross ventilation | | | | | | | | | | | | | | | | | | | | | | | | |

| 4. Please give reasons why you generally do not use the following window ventilation options during the day or at night? (multiple answers possible) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Burglary protection | | Driving rain | | Outdoor noise | | Insects | | Draught if several windows are opened in the apartment | |
| Tilted window | day ☐ | night ☐ | day ☐ | night ☐ | day ☐ | night ☐ | day ☐ | night ☐ | day ☐ | night ☐ |
| Fully opened window | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cross ventilation | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Miscellaneous and comments: | | | | | | | | | | |

| 5. Do you use fans or similar in your apartment to increase thermal comfort on hot summer days? | |
|---|---|
| ☐ Yes | ☐ No |

| 6. How many floors does your building have in total? | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 or more |
| ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 7. What floor do you live on? Please also indicate whether it is an attic apartment. | | | | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 or higher |
| ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Attic? | | | ☐ Yes | | ☐ No | |

| 8. How big is your apartment? | | | | |
|---|---|---|---|---|
| ☐ less than 40 m² | ☐ 40-60 m² | ☐ 61-80 m² | ☐ 81-105 m² | ☐ more than 105 m² |

| 9. How many people in the following age groups live in your household? | | | | | | |
|---|---|---|---|---|---|---|
| | under 6 years | 6 - 17 years | 18 - 39 years | 40 - 59 years | 60 - 79 years | over 80 years |
| Number | _ pers. | __ pers. | __ pers. | __ pers. | __ pers. | __ pers. |

| 10. What kind of apartment do you live in? | | | |
|---|---|---|---|
| ☐ Rented apartment | ☐ Freehold apartment | ☐ Own house | ☐ other |

| | |
|---|---|
| 11. Please indicate the date on which you completed this questionnaire: | ___2019___. |

| 12. Do you have further notes or comments on the topic? |
|---|
| |

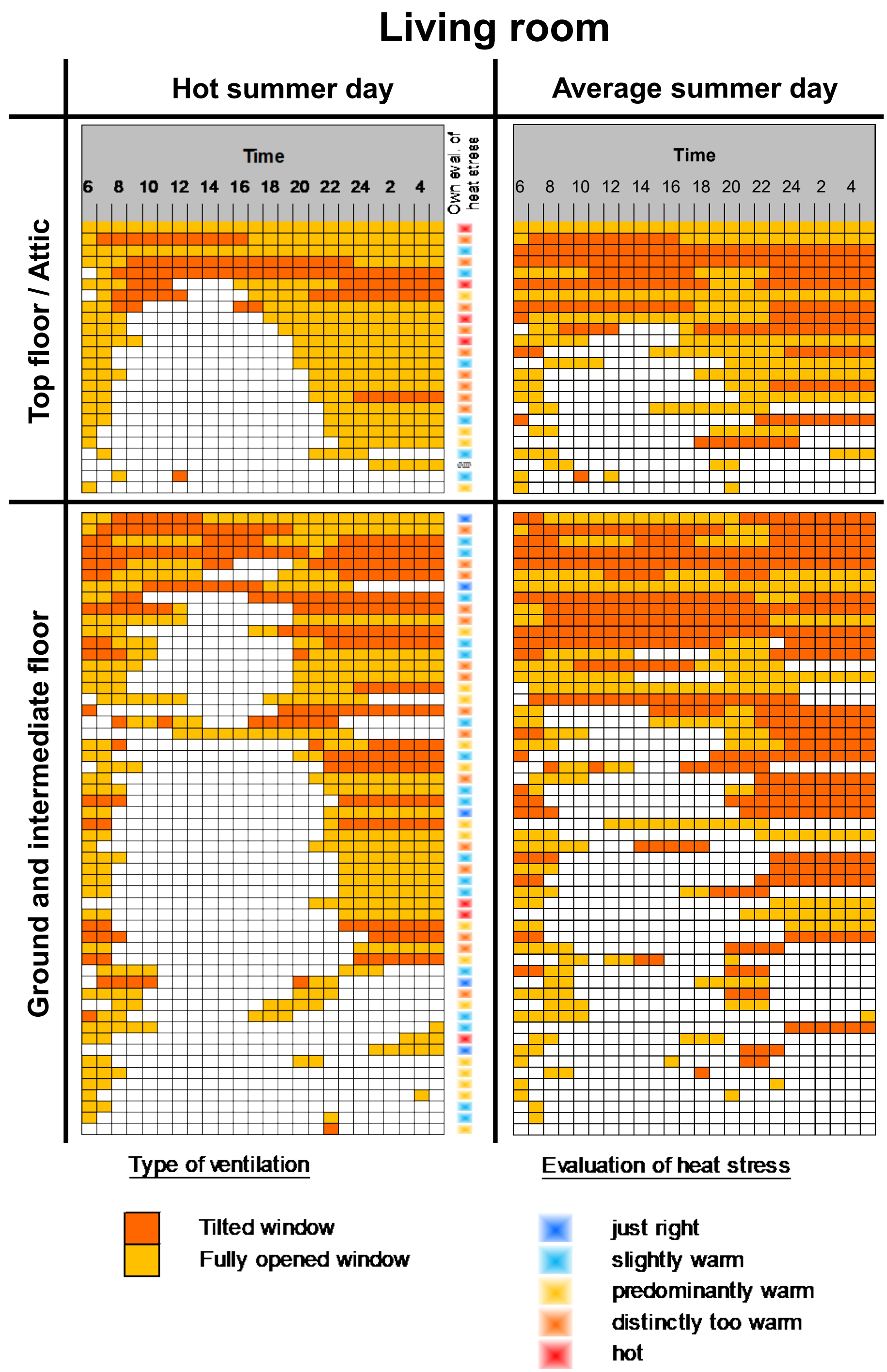



**Figure A 1** Ventilation profiles for the living rooms on hot and average summer days depending on the floor. Each row represents the individual window ventilation behavior of a surveyed household. For hot summer days with an outside temperature > 30 °C, the individual assessment of the heat stress in the living room is also shown

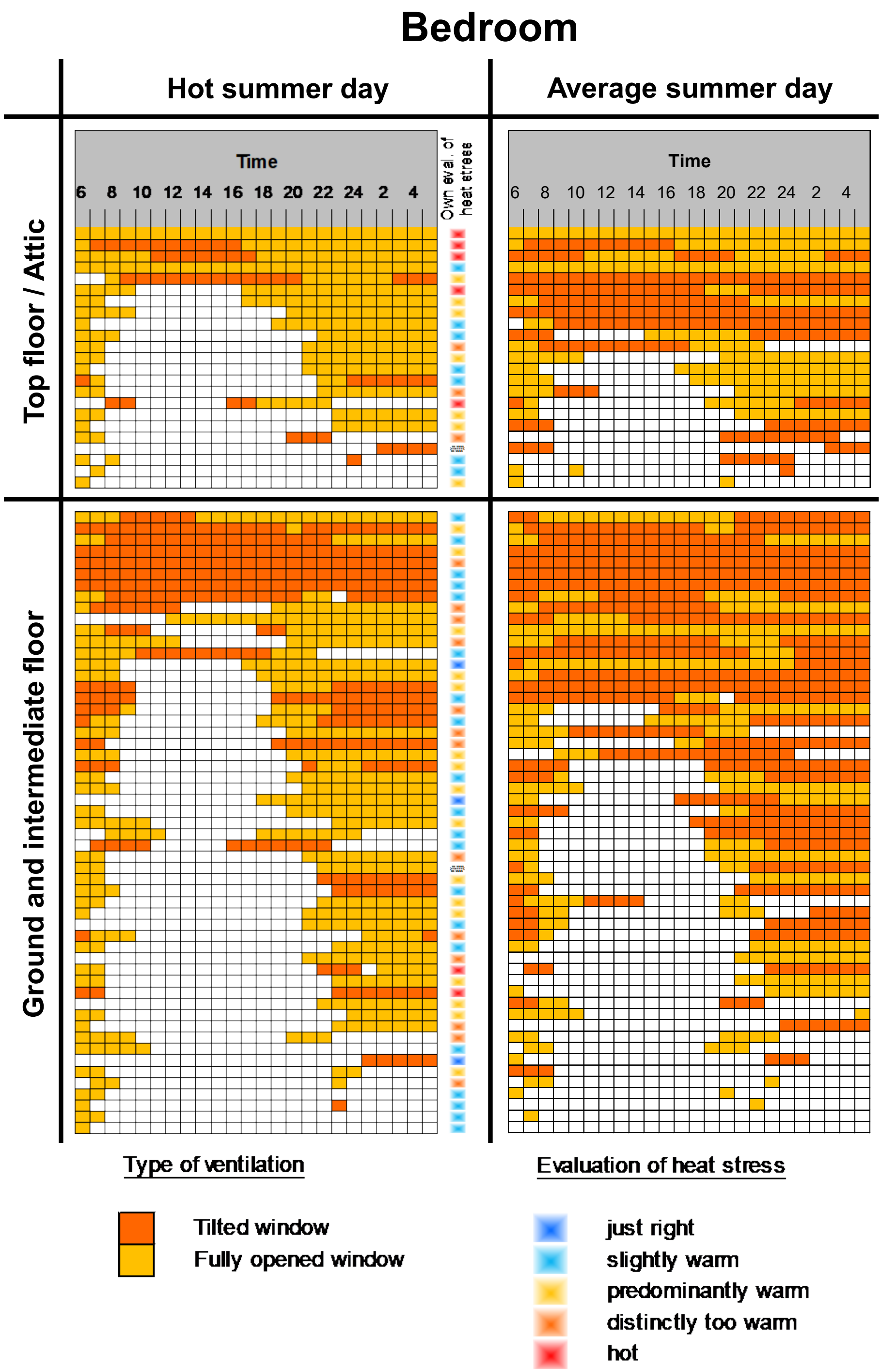



**Figure A2** Ventilation profiles for the bedrooms on hot and average summer days depending on the floor. Each row represents the individual window ventilation behavior of a surveyed household. For hot summer days with an outside temperature > 30 °C, the individual assessment of the heat stress in the bedroom is also shown

IJBES

**International Journal of Built Environment and Sustainability**
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 8(3)/2021, 135-142

# Performance Measures of a Built Environment Multidisciplinary Research Journal: IJBES Metrics in a Review

**Shamsulhadi Bandi**
Managing Editor, International Journal of Built Environment and Sustainability (IJBES), Penerbit UTM Press, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor

## ABSTRACT

An assessment of IJBES's performance since 2015 was presented in this communication using metrics data from Clarivate and the OJS Report Generator. Raw data were analyzed for the purpose of reporting to readers on the journal's performance using performance metrics available to editor. Key performance metrics such as submissions, acceptance and rejection rates, and citation trends over time were reported and presented to the reader. It has been observed that ensuring balanced content and continuously working on a niche are among the priorities of the journal. It is also necessary to attract relevant and quality manuscripts among the authors to increase citations in other publications. Despite everything, the journal, which is relatively young, was able to withstand the initial test of time and improve its visibility in the scientific community.

**Article History**

Published Online : *31 August 2021*

**Keywords:**

Citation, IJBES, Performance, Productivity, Publication

**Corresponding Author Contact:**

shamsulhadi@utm.my

**DOI:** 10.11113/ijbes.v8.n3.872



## 1. An overview on journal metrics

Scholarly publication is a staple activity among researchers in institutions around the globe. A compelling crouch to publish in highly rated journal is evident despite the pulsating experiences in the process. Butler and Spoelstra (2020) quoted that a "publication game" has become an increasingly common academic metaphor, which explained a researcher strive in making a research output known in the field. While a researcher may be able to pursue a career goal through an instrumental strategy, the objective of producing an intrinsically meaningful research may be at the expense of a journal.

While the academic circle is aware on the significance of scholarly publication to a researcher, the journal editors on the other hand is oftentimes pushed to devise a strategy which able to dislodge and shield a journal from publishing less impactful materials. One of the well-known strategies is the peer-review process (Vieira & Gomes, 2018) though much of the work to consider a material by an editor starts at the point of submission itself.

A study by Richards and Wasserman (2013), highlighted the roles of journal editors in a scholarly publication process. The study emphasised that following a plethora of complicated and vexing problems, editors had developed a range of strategies in dealing and responding to them. Over the course of commanding a journal, an editor is also expected to gradually become conversant with the materials to be published and innovative with the range of decision to be made (Petersen, 2017). This allows for a journal to bolster its presence, whilst able to attract readership and citation to the materials published.

Citation is undoubtedly at the heart of any publications and a mark of performance (Craig, Ferguson, & Finch, 2014). Aksnes, Langfeldt, and Wouters (2019) postulated that citation is often used to reflect the impact of a research and its quality. Though research quality is often considered as a multidimensional concept, common characteristics of plausibility, originality, scientific and societal value are perceived as the key characteristics (Aksnes et al., 2019; Vieira & Gomes, 2018). Having citations to watch, a journal editor has the responsibility to ensure that the characteristics are adopted in the assessment of a material for publication (Aroeira & Castanho, 2020).

The International Journal of Built Environment and Sustainability (IJBES) started in 2014 with an aim to offer readers a multidisciplinary research material within the realm of the built environment. The journal placed sustainability as its main agenda with the objective to publish a strong empirical based and original materials concerning recent development in this niche area. To align itself with other internationally recognized journal, the performance of the journal is reviewed periodically using data mined from the Online Journal System (OJS) and Clarivate. The editors of the journal are responsible to report and extract the data in evaluating the journal's performance.

This communication is presented to inform readers about the journal's standing and performance from 2014 until July 2021. The journal's footprint, publication data along with the acceptance and rejection rate, and its citation performance are presented based on the metrics data until July 2021 with a brief commentary provided to clarify.

## 2. IJBES Footprint

The inclusion of IJBES into the Emerging Source Citation Index program by Clarivate since 2015 boosted the journal's visibility among authors. This improves discoverability among researchers and allows the journal to attract good quality manuscripts from around the world. Table 1 shows the diversity of authors with at least one manuscript published on IJBES and indexed in the Web Science Database (WoS) at the same time.

IJBES currently has publications by authors from 27 countries / regions, 60% of whom live in Malaysia, followed by Nigeria (24%), India (7%) and Indonesia / Sri Lanka (3.5%). The presence of the journal in other parts of the world is also notable, with the participation of authors living in countries in the Middle East, the Pacific and Africa. There are also quite a few authors from China and European countries that have started to make their mark on IJBES.

**Table 1** IJBES author's diversity (up to July 2021)

| Countries/Regions | Record Count | % of 200 |
|---|---|---|
| Malaysia | 120 | 60.00 |
| Nigeria | 48 | 24.00 |
| India | 14 | 7.00 |
| Indonesia | 7 | 3.50 |
| Sri Lanka | 7 | 3.50 |
| Peoples R China | 4 | 2.00 |
| Australia | 3 | 1.50 |
| Saudi Arabia | 3 | 1.50 |
| South Korea | 3 | 1.50 |
| Turkey | 3 | 1.50 |
| Bangladesh | 2 | 1.00 |
| Iran | 2 | 1.00 |
| Japan | 2 | 1.00 |
| Oman | 2 | 1.00 |
| Philippines | 2 | 1.00 |
| Thailand | 2 | 1.00 |
| Algeria | 1 | 0.50 |
| Bahrain | 1 | 0.50 |
| Canada | 1 | 0.50 |
| Kuwait | 1 | 0.50 |
| Netherlands | 1 | 0.50 |
| New Zealand | 1 | 0.50 |
| Russia | 1 | 0.50 |
| Rwanda | 1 | 0.50 |
| South Africa | 1 | 0.50 |
| Sudan | 1 | 0.50 |
| USA | 1 | 0.50 |
| | $n = 27$ | |

## 3. Publication data

### *3.1 Manuscript received and published*

Since 2014, IJBES has received a total of 489 submissions from authors. Of these, 210 have been published and 200 are currently indexed in WoS. Generally, the trend of manuscript submission is increasing from year to year since 2014, however the number that made it for publication remain consistent. The overall trend of submission and publication is as shown in Figure 1.

In 2019 and 2020, IJBES received a total of 259 submission which is more than 50% of the all-time submission since 2014. This on average, equals to one new submission for every three days, or between two to three submission each week. On top of that, data shows that of all the submission received in 2020 which is 128, almost 44% was received between March until June 2020 over a duration of that four months alone. During the period, IJBES received one new submission for every 2.12 days, which is equals to one new submission for every 3.5 days.

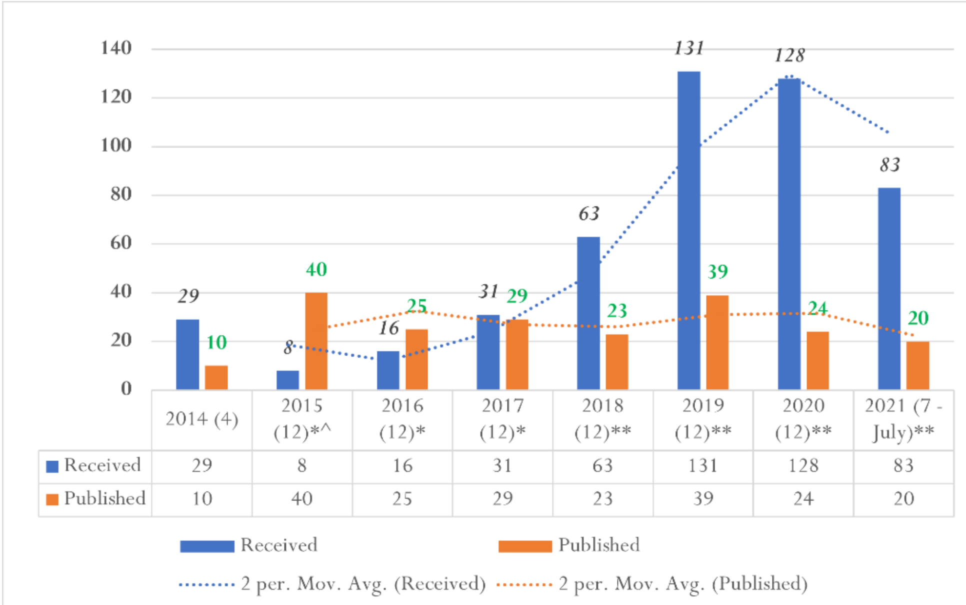



**Figure 1** Number of manuscripts received and published (2014 - July 2021)
*(**Notes:** ^ denotes the start of WoS indexing; * denotes a mix between manual and online submission; ** denotes full online submission)*

### *3.2 Acceptance and rejection rate*

Figure 2 shows the percentage of acceptance and rejection since 2018 when manuscript submission is made 100% online through the OJS. The figure shows that the gap between the acceptance and the rejection rate is gradually getting wider despite a steep increase in manuscripts submission shown in Figure 1. The overall rejection rate for all recorded period is 76%, in which 62% of rejection is determined after the first review cycle and the remaining 14% consist of desk rejection.

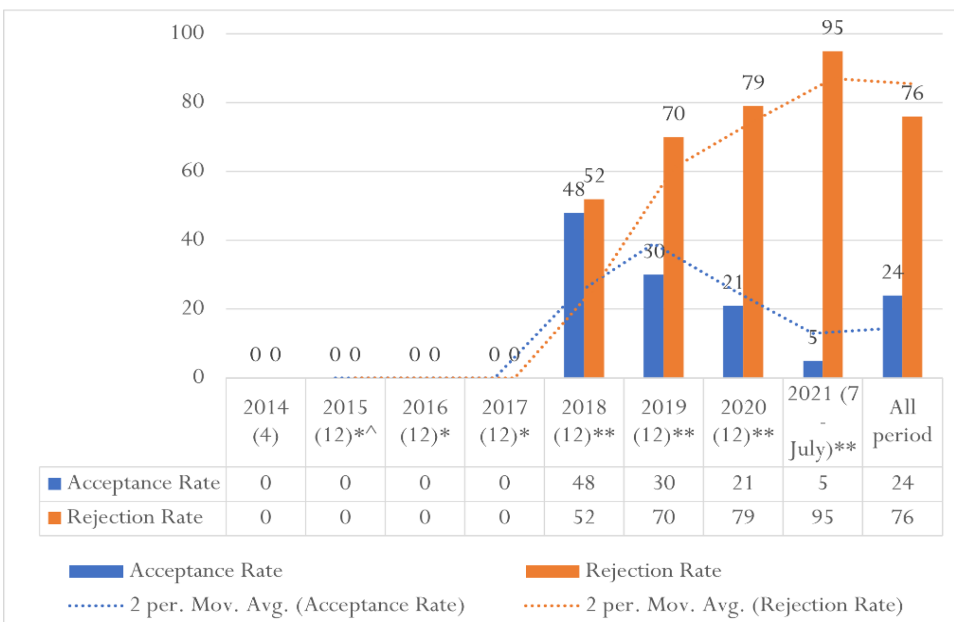



**Figure 2** Acceptance and rejection rate in % (since 2018 when submission is made 100% online via OJS)
*(**Notes:** ^ denotes the start of WoS indexing; * denotes a mix between manual and online submission; ** denotes full online submission)*

### *3.3 Citation report*

Figure 3 shows the citation trend of IJBES since 2015. There is a positive trend across materials published by IJBES since 2016. The citation momentum for IJBES started to climb in 2018 with each material published received at least one citation over the period. A positive citation record was recorded in 2019 in which for the first time, citations had exceeded the number of publications. In the year 2020, despite publishing much lesser than the year before, citations recorded an all-time-high of 83 on that year alone. The citation trend is expected to increase positively over time with the support of quality and relevant materials.

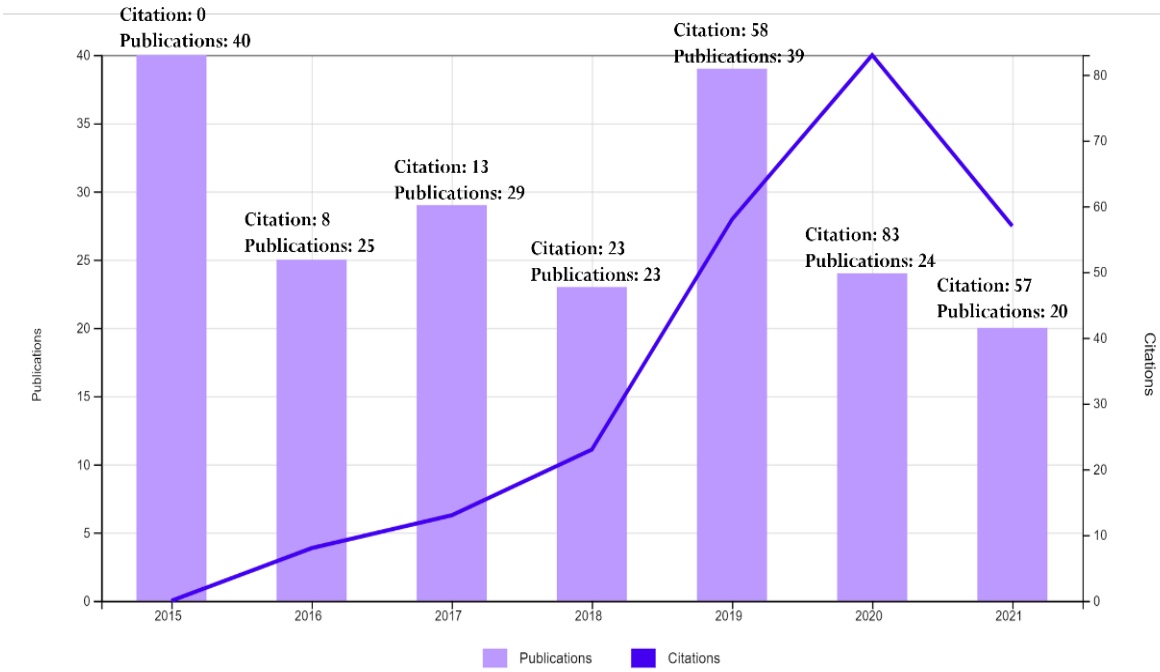



**Figure 3** Number of citations recorded (2015 – July 2021) (Clarivate, 2021)

### *3.4 Average item citation count*

Table 2 and Table 3 present item citation counts, and the yearly citations counts between two disparate timespans as shown in the tables. Since 2019 when the last citation record was reported, the sum of the times cited had increased exponentially from 46 to 242. The average citations per item stood at 1.21 and on average, IJBES recorded 40.33 citations per year.

**Table 2** Item citation counts between disparate timespan of 2015 to 2019 and 2015 to July 2021

| Criteria | IJBES (2015-2019) | IJBES (2015-July 2021) |
|---|---|---|
| Number of publications indexed by WoS | 125 | 200 |
| Sum of the Times Cited | 46 | 242 |
| Average Citations per Item | 0.37 | 1.21 |
| h-index | 3 | 7 |

**Table 3** Yearly citation counts between disparate timespan of 2015 to 2019 and 2015 to July 2021

| Yearly citation record | IJBES (2015-2019) | IJBES (2015-July 2021) |
|---|---|---|
| 2015 | 0 | 0 |
| 2016 | 5 | 8 |
| 2017 | 10 | 13 |
| 2018 | 21 | 23 |
| 2019 | 10 | 58 |
| 2020 | 0 | 83 |
| 2021 (July) | 0 | 57 |
| **Total number of citations** | **46** | **242** |
| **Average citation per year** | **11.50** | **40.33** |

### *3.5 Highly cited materials*

Table 4 shows ten highly cited materials published by IJBES since 2015 along with its most recent yearly number of citations in 2019, 2020 and up to July 2021. Data shows that review papers are likely to attract readership and translates into citation as showed in the table. Though this may be the case, original research articles continue to characterize the list of the highly cited materials.

**Table 4** 10 highly cited materials published by IJBES (since 2015)

| No. | Title of article | Vol | Issue | Year | Total citation | Average citation/ year | Yearly number of citations | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 2019 | 2020 | 2021-7 |
| 1. | Accident Causation Factors on Building Construction Sites: A Review | 5 | 1 | 2018 | 12 | 3 | 4 | 5 | 3 |
| 2. | An Appraisal into the Potential Application of Big Data in the Construction Industry | 5 | 2 | 2018 | 11 | 2.75 | 3 | 5 | 2 |
| 3. | A model to Estimate the Implicit Values of Housing Attributes by Applying the Hedonic Pricing Method | 4 | 2 | 2017 | 9 | 1.8 | 1 | 5 | 2 |
| 4. | Stakeholders Assessment of Constraints to Project Delivery in the Nigerian Construction Industry | 4 | 1 | 2017 | 8 | 1.6 | 3 | 4 | 0 |
| 5. | Mobile Augmented Reality: A Tool for Effective Tourism Interpretation in Enhancing Tourist Experience at Urban Tourism Destination | 2 | 3 | 2015 | 8 | 1.14 | 2 | 1 | 1 |
| 6. | Critical Success Factors for Malaysian Construction Projects: An Investigative Review | 4 | 2 | 2017 | 7 | 1.4 | 3 | 2 | 1 |
| 7. | Building Envelope Thermal Performance Assessment Using Visual Programming and BIM, based on ETTV requirement of Green Mark and GreenRE | 4 | 3 | 2017 | 7 | 1.4 | 2 | 4 | 1 |
| 8. | Effects of Neighborhood's Built Environment on Physical Activities in Gated Communities: A Review | 3 | 1 | 2016 | 7 | 1.17 | 2 | 1 | 0 |
| 9. | Step by step approach for qualitative data analysis | 5 | 3 | 2018 | 6 | 1.5 | 0 | 2 | 4 |
| 10. | Urban Greenery a pathway to Environmental Sustainability in Sub Saharan Africa: A Case of Northern Nigeria Cities | 4 | 3 | 2017 | 6 | 1.2 | 2 | 2 | 2 |

## 4. Citing materials

There are 224 materials citing IJBES in other publication titles indexed in WoS as in July 2021.

Data pertaining to the citing materials categories, research areas and publication titles citing IJBES is presented in the following sections.

### *4.1 Materials citing IJBES by WoS categories*

Table 5 shows the categories of materials in other publications citing IJBES. A total of 77 entries or categories are identified from the data in which the first 20 categories that appears are shown in the table. Among the categories shown, urban studies, environmental sciences, engineering and technology, and other aspects related to the built environment are dominating the categories. The data thus shows that IJBES has steered its publication to this niche aspects of the built environment which aligns with the scope of publications.

**Table 5** WoS categories of materials citing IJBES

| Web of Science Categories | # | Record Count | % Of 224 |
|---|---|---|---|
| Urban Studies | 1 | 40 | 17.857 |
| Environmental Sciences | 2 | 34 | 15.179 |
| Construction Building Technology | 3 | 25 | 11.161 |
| Engineering Civil | 4 | 24 | 10.714 |
| Environmental Studies | 5 | 24 | 10.714 |
| Green Sustainable Science Technology | 6 | 24 | 10.714 |
| Management | 7 | 19 | 8.482 |
| Engineering Multidisciplinary | 8 | 12 | 5.357 |
| Regional Urban Planning | 9 | 9 | 4.018 |
| Remote Sensing | 10 | 9 | 4.018 |
| Architecture | 11 | 7 | 3.125 |
| Energy Fuels | 12 | 7 | 3.125 |
| Hospitality Leisure Sport Tourism | 13 | 7 | 3.125 |
| Public Environmental Occupational Health | 14 | 7 | 3.125 |
| Business | 15 | 6 | 2.679 |
| Computer Science Information Systems | 16 | 6 | 2.679 |
| Engineering Electrical Electronic | 17 | 6 | 2.679 |
| Engineering Environmental | 18 | 6 | 2.679 |
| Imaging Science Photographic Technology | 19 | 6 | 2.679 |
| Engineering Industrial | 20 | 5 | 2.232 |
| ***Showing 20 out of a total of 77 entries** | | | |

### 4.2 *Materials citing IJBES by WoS research areas*

Table 6 shows the research areas of materials in other publications citing IJBES. A total of 50 entries or research areas are identified from the data in which the first 20 research areas that appears are shown in the table. Among the research areas shown, engineering, environmental sciences ecology, and urban studies are on top of the list followed by technology, business and economics, construction/building, and others.

**Table 6** WoS research areas of materials citing IJBES

| Research Areas | # | Record Count | % Of 224 |
|---|---|---|---|
| Engineering | 1 | 47 | 20.982 |
| Environmental Sciences Ecology | 2 | 41 | 18.304 |
| Urban Studies | 3 | 40 | 17.857 |
| Science Technology Other Topics | 4 | 29 | 12.946 |
| Business Economics | 5 | 27 | 12.054 |
| Construction Building Technology | 6 | 25 | 11.161 |
| Social Sciences Other Topics | 7 | 12 | 5.357 |
| Computer Science | 8 | 11 | 4.911 |
| Public Administration | 9 | 9 | 4.018 |
| Remote Sensing | 10 | 9 | 4.018 |
| Architecture | 11 | 7 | 3.125 |
| Energy Fuels | 12 | 7 | 3.125 |
| Public Environmental Occupational Health | 13 | 7 | 3.125 |
| Chemistry | 14 | 6 | 2.679 |
| Imaging Science Photographic Technology | 15 | 6 | 2.679 |
| Materials Science | 16 | 5 | 2.232 |
| Geography | 17 | 4 | 1.786 |
| Geology | 18 | 4 | 1.786 |
| Physics | 19 | 4 | 1.786 |
| Agriculture | 20 | 3 | 1.339 |
| ***Showing 20 out of a total of 50 entries** | | | |

### 4.3 *Publication titles with an Impact Factor (IF) citing materials in IJBES*

There is an indication that materials published in IJBES attract citations by authors who are publishing in publications with impact factor (IF). As shown in Table 7, the highest record count is 14 (6.25%) by Sustainability (JIF 2020 = 3.2510), followed by other well-known publications in built environment. The total entries recorded since 2015 is 168 which consist of both publications with and without impact factor (IF). The general observation suggests that the publication titles which appear in the table reflect the focus and scope of IJBES which consequently support its citations in other publication titles.

**Table 7** Materials published in publications with an Impact Factor (IF) citing materials from IJBES

| Publication Titles | Record Count | % Of 224 | JIF 2020 |
|---|---|---|---|
| Journal Of Cleaner Production | 2 | 0.893 | 9.2970 |
| Automation In Construction | 2 | 0.893 | 7.7000 |
| Sustainable Cities and Society | 2 | 0.893 | 7.5870 |
| Building And Environment | 1 | 0.446 | 6.4560 |
| Energy And Buildings | 2 | 0.893 | 5.8790 |
| Advanced Engineering Informatics | 1 | 0.446 | 5.6030 |
| Building Research and Information | 1 | 0.446 | 5.3220 |
| Urban Forestry Urban Greening | 2 | 0.893 | 4.5370 |
| Applied Geography | 1 | 0.446 | 4.2400 |
| Journal Of Construction Engineering and Management | 2 | 0.893 | 3.9510 |
| Asia Pacific Journal of Tourism Research | 1 | 0.446 | 3.6770 |
| Sensors | 2 | 0.893 | 3.5760 |
| International Journal of Environmental Research and Public Health | 3 | 1.339 | 3.3900 |
| Sustainability | 14 | 6.25 | 3.2510 |
| Applied Sciences Basel | 2 | 0.893 | 2.6790 |
| Architectural Engineering and Design Management | 2 | 0.893 | 2.6000 |
| Children's Geographies | 1 | 0.446 | 2.2910 |
| Advances In Civil Engineering | 1 | 0.446 | 1.9240 |
| Arabian Journal of Geosciences | 1 | 0.446 | 1.8270 |
| South African Journal of Economic and Management Sciences | 2 | 0.893 | 0.9910 |
| *Showing 20 out of a total of 168 entries | | | |

## 5. Observations

A review of IJBES performance since 2015 is reported in this communication using the metric data sourced from Clarivate and the OJS report generator. The raw data is analysed with an aim to report to the readers about the journal's performance using performance metrices available to the editor. Important performance indicators such as the submission data, acceptance and rejection rate and the citation trend over time are reported and presented to the readers. Despite the effort made by the editor to present the latest data, citation is nonetheless dynamic, where metrices data changes in a constant basis.

The editor wishes to stress that ensuring a balance content and continuously working on a niche area are among the journal's priority. There is also a need to attract relevant and quality manuscripts from among the authors to invite impactful citations in other publications.

Authors are advised against flooding the journal with middling manuscripts, where it will create unnecessary backlogs which put unwarranted pressure on the workflow. Notwithstanding, the journal being relatively young, has been able to stand against the initial test of time and improves its visibility among the scientific communities. The editor wishes to thank the editorial, authors, reviewers and readers for the support and assistance through every publication cycles.


## Acknowledgement

The editor wishes to thank Hairunnisa Yunos of Penerbit UTM Press for putting up the materials for every publication cycle, Universiti Teknologi Malaysia (UTM) for assistance (fund under GUP PY/2019/00597/Q.J130000.2652.16J81) and Khew Kai Ren, in formatting this communication for publication.


## References


Aksnes, D. W., Langfeldt, L., & Wouters, P. (2019). Citations, Citation Indicators, and Research Quality: An Overview of Basic Concepts and Theories. *Sage Open, 9*(1), 17. doi:10.1177/2158244019829575

Aroeira, R. I., & Castanho, M. (2020). Can citation metrics predict the true impact of scientific papers? *Febs Journal, 287*(12), 2440-2448. doi:10.1111/febs.15255

Butler, N., & Spoelstra, S. (2020). Academics at play: Why the "publication game" is more than a metaphor. *Management Learning, 51*(4), 414-430. doi:10.1177/1350507620917257

Clarivate. (2021). Result analysis and citation report. Retrieved from https://www.webofscience.com/wos/woscc/summary/fa4ae70f-2598-43bd-9f56-34268cb401e5-0516ae77/relevance/1

Craig, I. D., Ferguson, L., & Finch, A. T. (2014). *Journals ranking and impact factors: how the performance of journals is measured*. Sawston: Chandos Publ.

Petersen, J. (2017). How innovative are editors?: evidence across journals and disciplines. *Research Evaluation, 26*(3), 256-268. doi:10.1093/reseval/rvx015

Richards, I., & Wasserman, H. (2013). The heart of the matter: Journal editors and journals. *Journalism, 14*(6), 823-836. doi:10.1177/1464884913493062

Vieira, E. S., & Gomes, J. (2018). The peer-review process: The most valued dimensions according to the researcher's scientific career. *Research Evaluation, 27*(3), 246-261. doi:10.1093/reseval/rvy009