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POTENTIAL FOR URBAN GREENING WITH GREEN ROOFS: A WAY TOWARDS SMART CITIES

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ABSTRACT:

Cities are experiencing increased pressure on social, economic, and environmental sectors due to the rapid urbanisation and increasing risk owing to climate change affecting the urban environment. Solutions such as green roofs are often discussed in the context of smart and sustainable cities as they present a multi-functional and solution-oriented approach to address these challenges. Green roofs become extremely relevant in the context of highly urbanised and compact cities where impervious surfaces are abundant. Therefore, in this paper, we analyse the potential of green roofs at a city scale with the help of parameters such as area and slope of the roof and structure of the building. We also identify the priority zones based on environmental and socio-economic parameters. The study is carried out in the city of Liege, Belgium. The results suggest that around 20% (350 hectares) of the total buildings in the city have the potential for developing green roofs. Moreover, the potential of green roofs is quite significant in terms of roof area in the priority zone. Due to significant socio-economic deprivation in high priority zones, implementation of green roofs might not be affordable. Buildings with larger roof sizes are mostly owned by companies or commercial establishments, thus, making larger roofs more relevant for retrofitting green roof. Thus, our approach can act as a preliminary decision-making tool for urban planners to analyse the potential of green roofs and prioritize them in deprived areas.

1. INTRODUCTION

Unprecedented urbanisation along with the increasing climate change has led to increased pressure on social, economic and environmental sectors impacting the human life and the natural environment in the cities (Jha et al., 2012; Stephenne et al., 2016). Urban and environmental issues induced by the rapid growth of population and their consumption-driven lifestyles prove to be a challenge for urban planners (Dizdaroglu et al., 2012; Wu, et al., 2018). In such a situation, urban planners are redirected towards the frontier of sustainable cities (Sodig et al., 2019). The rapid advancements in the information and communication technologies (ICTs) have also placed the concept of smart cities in the urban planning domain (Rice, Martin, 2020). Smart city concept has been promoted as an instrument to manage various urban and environmental challenges such as environmental pollution, urban heat island, biodiversity loss and socio-economic inequalities (Yigitcanlar et al., 2019). Many researchers have indicated that the smart and sustainable cities should be intertwined to achieve the desired outcome (Bouzguenda et al., 2019; Yigitcanlar et al., 2018). As a result, it is argued that cities could not be smart without being sustainable. Therefore, in this paper, we combine the smart and sustainable city approach with a view to addressing the aforementioned urban and environmental problems.

Nature-Based Solutions (NBS) are often put forward in the context of sustainable urban development. These solutions present a multi-functional and solution-oriented approach by addressing social, economic and environmental sustainability issues simultaneously (Dorst et al., 2019). Urban Green Infrastructure (UGI) such as green roofs are one of the NBS which are highly relevant in urban areas that are abundant in impervious surfaces such as building roofs (Shafique et al., 2018). Moreover, high urban densities and compact nature of the cities make it difficult to implement other UGIs such as planting trees and developing urban green spaces. Furthermore, green roofs provide multiple urban ecosystem services such as energy efficiency, urban heat island mitigation, regulation of microclimate and provision of a better quality of life (Sharma et al., 2018; Langemeyer et al., 2020). Thus, green roofs with their multi-dimensional benefits aid in sustainable urban development.

Green roofs are a sustainable alternative to conventional roofs and are defined as the living vegetation installed on the building roofs (Guzmán-Sánchez et al., 2018; Mahdiyar et al., 2018). There are mainly of two types of green roofs, intensive and extensive (Peng, Jim, 2015). Intensive roofs are characterized by a thick layer of substrate with a diverse variety of plants whereas extensive roofs have a thinner layer of substrate which are light weight and require low level of maintenance as compared to intensive green roofs (Mahdiyar et al., 2018; Nardini et al., 2012). Most of the studies are concentrating on implementation of extensive type of green roofs as they incur lower installation and maintenance cost.

Having a potential for social acceptance (Mesimikä, 2017; Specht et al., 2016), green roofs can be incorporated at a city scale with the help of municipalities. However, due to different types of roofs and type of construction of respective buildings, not all the buildings are able to accommodate green roof strategy. Thus, identifying the potential for mobilizing the green roofs at a city scale is an essential prelude to its implementation. Apart from this, cities often witness an unequal distribution of green spaces. This not only affects the quality of life of citizens but also results in a discontinuity in green spaces affecting the
biodiversity (Braaker et al., 2014; Joimel et al., 2018). Moreover, there is a spatial variation of built-up densities which also results in different temperature in different parts of the city (Sharma et al., 2016). Additionally, socio-economic inequalities are evident in cities worldwide (UN-Habitat, 2012, 2013). Socio-economically deprived regions also experience a lower quality of life owing to the existing social, economic and environmental problems (Berhe et al., 2014). As UGIs such as green roofs are argued to have multiple benefits, it is important to prioritize their implementation accordingly.

Many studies have identified the potential of green roofs at various scales for different cities in the world. Building characteristics, for instance, building slope, area, orientation, and strength are mainly used for identifying the potential for developing green roofs (Karteris et al., 2016; Mallinis et al., 2014; Tian, Jim, 2012; Wilkinson, Reed, 2009; Santos et al., 2016). Study by Langemeyer et al. (2020), focused on identifying priority areas for implementing green roofs based on optimizing their ecosystem service provision. They include ecosystem services such as thermal regulation, runoff control, biodiversity, food production, social cohesion and recreation. A study by Herrera-Gomez et al. (2017), particularly identifies the areas where green roofs can be retrofitted in order to reduce urban heat island effect. As combining the identification of potential of green roofs with their prioritization is important, studies such as Silva et al., (2017) integrate the building characteristics with existing greens and population density to ensure urban greening in the areas where it is needed the most. A similar approach is used by Grunwald et al., (2017), where ecosystem services such as improvement of urban air quality, climate regulation, water retention and biodiversity enhancement are used to identify priority areas for developing green roofs. In this paper, we employ a similar approach of integrating the identification of potential of green roof with prioritization along with socio-economic development as an added parameter. We identify the potential of green roofs along with a prioritization based on i) lack of existing greens, ii) high temperature zones and iii) socio-economic deprivation. Altogether, we investigate whether the achieved potential of green roofs is beneficial in terms of society and environment suggesting their contribution to the sustainable smart cities.

2. MATERIALS AND METHODS

2.1 Study area and available datasets

Liege, situated in the Wallonia region of Belgium, is the third-most populous city of Belgium with a total of 195,965 inhabitants. The total area of Liege municipality is around 69 km². There are 136,170 buildings in the city, with a total area of building roofs about 10 km², which represents around 14% of the city area. There is a variety of roof and building structures in Liege, which makes the detection of the potential of green roofs challenging and crucial. This study is performed using different types of data sources (LiDAR, PICC (Projet Informatique de Cartographie Continue) data from Public Service of Wallonia (SPW)) which were analysed with the help of GIS environment (ArcMap Version 10.7.1, ESRI) and FME workbench.

2.2 Mapping potential of green roofs

In this study, we mainly consider the building characteristics such as roof slope, area of the roof and structure of the building (Figure 1). Although any roof, irrespective of the slope, can be greened, high slope roofs may require additional support to avoid slipping of vegetation materials. Moreover, maintenance of high sloped roof can be difficult. Additionally, flat rooftops require lower initial investment for retrofitting a green roof (Santos et al., 2016). Thus, we consider flat roofs to have potential for implementing green roofs.

To identify flat roofs, we used the LiDAR point cloud data obtained from SPW with a point density of 0.8 point/ m². At first, we clipped the point cloud with existing building footprints of Liege obtained from the PICC data. We then analysed the point cloud within each building footprint to obtain the information on flat roofs as follows:

Confronting the sparse nature of LiDAR data, the unsupervised interpolation of planes from point cloud could be a challenge (Cao et al., 2017). Several methods such as RANdom SAMple Consensus (RANSAC) (Schnabel et al., 2007) and the Hough transform (Ballard, 1987) allow to statistically ignore the outliers. In this methodology, we used the former as it is computationally more efficient than the Hough transform. RANSAC is currently running quicker and is better tailored for shape detection of roof planes (Tarsha-Kurdi et al., 2007).

One disadvantage of unsupervised shape detection algorithms is the definition of initial parameters. Due to the sparse point density, the non-deterministic nature of RANSAC might detect inconsistent shapes. Depending on the starting points, which are randomly determinate, the results might differ between concurrent interpolations. Given that the junctions between clusters are more detailed, this problem is less encountered in high-density point clouds. Planes detection could thus lead to false positives and/or false negatives or spurious planes (Xu et al., 2015). To avoid misidentifications, tuning parameters is often the responsibility of the expert. For this study, we need roofs that can be mobilized for greening. As building roofs/planes have obstructions such as chimneys, elevator shafts and staircases, retrofitting small sized roofs with green roof can be challenging. Therefore, we only consider planes with minimum area of 10 m² and slope between 0- 10° (Rottensteiner et al.,

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2014). Other planes are not considered as relevant. Two other limits have been set to prevent odd results: (a) the unsupervised algorithm will determine a maximum of 20 independent planes for each building. (b) the points that are more than 10 cm away from the detected shapes are considered to be outliers. These two considerations increase the robustness of the approach. The results for each building provide the number of flat planes, the percentage of flat area in a building footprint and the average height of the building.

Apart from the slope of the roofs, the building must have reserved structural capacity for accommodating a green roof. Buildings with a concrete structure have enough strength to adopt a green roof, whereas not all the buildings with a steel structure have the required reserved structural capacity. It is observed that taller buildings in Liege are made of concrete. Therefore, based on our knowledge, we assume that buildings with a height greater than or equal to 20 m have a concrete structure, whereas the buildings with height less than 20 m have a steel structure. We determine the height of building based on the average height that we computed using the LiDAR and the DEM data at 1 m resolution obtained from SPW.

To identify the buildings made of steel with adequate strength, we analysed the building standards in Europe and Belgium since 1900. Based on these standards, we determined the reserve structural capacity of the building to accommodate green roofs. The structure of the buildings was indeed according to the norms that were in force during the period of construction. The buildings constructed before 1977 have strength more than required as they were built according to old standards, which were more conservative given their lower accuracy. The Eurocode was proposed in the year 1977 after which the buildings were built with the strength and capacity due to advanced technology. It is not possible to develop green roofs on these recent buildings without major structural changes. Also, the buildings constructed before 1977 are more than 40 years old, indicating the need for in-depth renovations which can be an opportunity to develop green roofs on the top of these buildings. Therefore, we consider buildings with steel structure that are constructed before 1977 to be structurally suitable for developing green roofs.

After identifying the potential buildings that conform to the criteria explained above, we classified the potential roofs based on the area and the percentage of area of the roofs that can be mobilized for green roofs. Figure 1 shows the flow of methodology used in this study.

### 2.3 Prioritizing the areas for implementing green roofs

Green roofs are argued to provide several ecosystem services including mitigation of urban heat island effect, stormwater management and improve air quality along with improvement in the quality of life and environment. However, based on the available datasets and importance of these services, we focus on three main ecosystem services: increase in urban green areas, regulation of temperature and improving the quality of life in socio-economically deprived regions. Thus, we identified the areas with higher surface temperature, lower green areas, and socio-economically deprived regions to identify the priority zones for developing green roofs where the benefits of green roofs can be maximised.

To identify existing greens, we computed normalised difference vegetation index (NDVI). NDVI quantifies the vegetation by measuring the difference between near-infrared and red bands (Eq. 1). We used images from European Space Agency (ESA) taken by Sentinel-2 (10 m resolution) satellite on April 22nd, 2020 to compute NDVI. We used the bands that capture red (0.665 mm) and near infrared-NIR (0.842 mm) colours with band 4 and 8, respectively.

\[
NDVI = \frac{(NIR - RED)}{(NIR + RED)}
\]  

To calculate the surface temperature, we utilise LANDSAT-8 level 1 image captured on 27th June 2019. The data was procured from United states geological survey (USGS) at a resolution of 30 m and thermal band 11 was used. We computed the surface temperature (K) using equations 2 and 3 (USGS, 2019). We further converted the temperature values into degree Celsius (°C).

\[
L_\lambda = M_\lambda Q_{col} + A_L
\]

\[
T = \frac{K_2}{\ln(\frac{A_L}{L_\lambda} + 1)}
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Areas with higher NDVI values can correspond to lower land surface temperature, mainly due to the influence of humidity on ground and evapotranspiration of plants on the surface (Su et al., 2010; Yuan, Bauer, 2007). Thus, we checked the correlation between the surface temperature and NDVI values using Pearson’s correlation coefficient. For the correlation, we resampled the surface temperature rater to 10 m resolution. The correlation test suggests that the correlation between NDVI and surface temperature is significant (at 95% confidence interval), and they are negatively correlated. Figure 2 also suggests that there is a negative correlation between NDVI and surface temperature. Thus, we included only the NDVI parameter in the analysis as we have it at a finer resolution as compared to surface temperature.

Figure 2. Collinearity between NDVI and Surface Temperature
For socio-economically deprived regions, we use the socio-economic difficulty index developed by Bianchet et al. (2016) for entire Walloon region at statistical sectors level. The index was developed using Principal Component Analysis (PCA) which included a comprehensive list of indicators related to the origin of inhabitants, income, employment, and working conditions.

The socio-economic deprivation index is converted from statistical sector level and resampled to a raster of 10 m resolution. We normalised the values of NDVI and socio-economic deprivation index from 0 to 1 based on the priority. For instance, areas with lower greens or higher temperature and a higher deprivation index are considered to be 1. Thereafter, we performed a spatial multi-criteria analysis (SMCA), in which we multiplied the values of parameters giving equal weightage. We then divided the entire city into three zones namely, low, medium and high priority zones based on the scores obtained in SMCA. The threshold for categorizing the city into three categories are decided based on the interquartile range as given in table 1.

| Category | Values          |
|----------|----------------|
| Low      | <25th percentile |
| Medium   | 25th – 75th percentile |
| High     | >75th percentile |

Table 1. Categorization of SMCA score

3. RESULTS AND DISCUSSION

In this section, we present the results of the study. Firstly, we introduce the potential of green roofs in the city of Liege. For which we present the priority zones where the green roofs can be retrofitted to obtain maximum benefits.

3.1 Potential of green roofs

Our analysis suggests that around 22% (31004) of the buildings have roofs that are partially or entirely flat (0 – 10°). The total area of roofs which is flat is around 486 hectares. Out of these buildings, around 516 buildings are with a concrete structure and rest of the buildings have a steel structure. Around 26,908 (328 ha) buildings with a steel structure having flat roofs are constructed before 1977. Thus, a total of 27,424 (20%, 351 ha) buildings in Liege are having roofs that are completely or partially flat and a structure that can support roof greening. In our analysis of flat roof detection, we also identify the percentage of area that is flat in each of the building roof. Table 2 suggests that around 3425 (2%) buildings have their roofs completely flat which occupy 209.87 hectares of area. Additionally, around 19,900 (15%) buildings have roofs with more than 50% flat area. Rest of the buildings (4098, 3%) have less than 50% of their roof area as flat. As we have considered the planes greater than 10 m² for detection of flat roofs, the selected building roofs, irrespective of percentage of flat area in each roof, have a flat region greater than 10 m². Therefore, all these buildings (27,424, 20%) can be retrofitted with green roofs considering the available flat area and reserved structural capacity to support additional weight of green roof.

The distribution of potential roof sizes for roof greening in the city is as follows. We categorize the roofs in three categories as shown in Figure 3. In general, the average size of potential roofs for greening is 128 m² and around 50% of the buildings with potential for roof greening have an area greater than 41 m² which can be retrofitted with green roofs. Spatial distribution of potential of roof is shown in figure 5.

| Percentage of flat area in each roof | <50% | 50 - 100% | 100% |
|-------------------------------------|------|-----------|------|
| Number of buildings                 | 4098 | 19901     | 3425 |
| Area occupied by flat planes        | 14.56| 157.52    | 209.87|

Table 2. Number and area of building roofs classified according to percentage of area occupied by flat plane

3.2 Prioritizing the areas for green roofs

The city of Liege has substantially low green spaces in the central part which has high built-up density (Figure 4a). Thus, surface temperatures are also observed to be relatively higher in the central region (Figure 4b). Additionally, the socio-economic difficulty index is also observed to be high in the sectors near the city centre along the river and the eastern part of the city (Figure 4c). Based on these parameters, we delineated the regions with high, medium, and low priority as mentioned in section 2.3 (Figure 5).

| Priority zone | % of roof area which can be greened |
|---------------|------------------------------------|
| Low           | 67 (0.05%) 393 (0.3%) 96 (0.07%)   |
| Area (ha)     | 0.3 3.6 8.14                       |
| Medium        | 1921 (1%) 10927 (8%) 1747(1%)      |
| Area (ha)     | 6.8 82.7 98.5                      |
| High          | 2110 (2%) 8581 (6.3%) 1582 (1%)    |
| Area (ha)     | 7.4 71.1 103.1                     |

Table 3. Priority-wise percentage of total potential roofs in terms of total area of roofs and number of buildings in each category with respect to percentage of flat roof area.
Figure 4. Spatial distribution of (a) NDVI, (b) Surface temperature (c) Socio-economic deprivation index in Liege

Figure 5. Potential of green roofs in the city of Liege along with priority zones
Around 1700 hectares of the city area comes under the high priority zone, in which there are around 44% of the total buildings. Around 20% (12,273 buildings, 167 hectares) of these buildings have the potential to retrofit green roofs. Around 3423 hectares area comes under the medium priority zone, which consists of 52% of the total buildings in the city. Around 20% (14,595, 173 hectares) of these buildings have the potential for retrofitting green roofs. The low priority zone accounts for around 1700 hectares which has around 4485 buildings. Around 12% of these buildings have the potential for roof greening.

Apart from this, most of the buildings in the city of Liege have pitched roofs. The potential of roof greening is relatively lower than other cities (Biljecki, Dehbi, 2019; Silva et al., 2017), mainly due to less number of flat roofs. Building stock in Wallonia region in general and in Liege is very old (Singh et al., 2013), resulting in large number of pitched roofs. It has been argued that green roofs can also be developed on slightly pitched roofs (below 20°) (Santos et al., 2016). Thus, there may be more potential for developing green roofs than what is analysed in the paper. However, it is important to note that the installation and maintenance costs for pitched roofs are much higher as compared to flat roofs (Teotónio et al., 2018).

Additionally, our study also highlights that there are around 77% of the buildings with a roof area greater than or equal to 10 m² which are constructed before the implementation of Eurocodes. Out of these, some of the buildings have flatter roofs, however most of them are observed to have a pitched roof. Nevertheless, most of these buildings are more than 40 years old, indicating the need for in-depth renovations which can be an opportunity to develop green roofs on top of these buildings.

Apart from this, the identification of priority regions suggests that the potential of green roofs is lower in high priority region as compared to the medium priority region when analysed in terms of number of roofs, but it is quite significant when analysed in terms of total area. The roofs that are completely flat which are in high priority region account for 103 hectares of area for retrofitting green roofs. It is important to note that high priority zone which are socio-economically deprived to an extent might not be able to support the cost of implementing the green roofs, especially for smaller roofs owned by households. On the contrary, large roofs are typically owned by companies. It is essential to identify solutions to make green roofs cost effective especially for larger ones. As the built-up density is relatively higher in the high priority region, implementation of green roofs on the potential buildings can be beneficial.

### 3.4 Limitations and future scope

The present study proposes a simple approach for identifying the green roofs and prioritizing the zones for their implementation. In this study, we identified the potential of green roofs with the help of three parameters, area and slope of the roofs and structure of the building. However, more parameters such as identifying the shaded areas and the building use can enhance the analysis.

Apart from this, as mentioned earlier, roofs that are partially flat need to be further investigated. Moreover, we considered the buildings with a height greater than 20m to be made of concrete. However, a validation of roof slopes and structure is still required to fine-tune the results. Furthermore, we considered roof area greater than 10m² to have potential to develop green roofs. However, due to obstructions such as chimneys and elevator shafts, there is a need to identify the net available area on each roof for developing the green roofs.

Additionally, in this study, we also prioritized the zones where green roof implementation can yield benefits in terms of environment and socio-economic development. For this we used NDVI, surface temperature and socio-economic deprivation index. As NDVI includes all the greens in the city, it is difficult to gauge the spatial distribution of existing public green spaces in the city. Due to lack of data on existing public green spaces, parameter related to access to green spaces in the city has not

![Figure 6. Area-wise and priority-wise percentage of total potential roofs (Area and number of buildings)](image)

Table 3 shows the distribution of potential roofs with respect to percentage of flat area in a roof, in terms of total area and number of buildings in each of the priority zone. In comparison to other zones, high priority zone has the largest area of buildings with roofs that are completely flat (103 hectares). Apart from this, classification of potential roofs in terms of area of roof available for greening suggests that there is a large number of buildings with area less than 100 m² (figure 6). It is evident that although the buildings with roof area greater than 200m² are a few (figure 6), developing them can provide a larger area with green roofs. A significant number of these roofs with large areas are in priority zones. It is easier to develop green roofs in such conditions as the number of building owners is reduced and greening large areas may lead to economies of scales.

### 3.3 Discussion

Around 20% (351 hectares) of the buildings in Liege have a potential for greening. Around 12% of these buildings have complete flat roofs and rest of the buildings roofs that are partially flat. Even though partially flat, the roof sizes are above 10 m². Although there are around 20% buildings with potential of greening, around 88% of these buildings are composed of roofs which are partially flat. As per our methodology, we only identify the planes which are between 0 – 10 degrees and are greater than 10 m² area. The area values are summed up in the end to provide the area available for greening. There is a possibility that the planes are not adjacent and are away from each other. Therefore, the roofs that are reported to have a larger area for greening might have 2 small areas which are disjoint. Disjoint flat roofs, though, might not be problematic, can bring maintenance issues. Thus, further investigation for roofs that are partially flat is needed.
been considered. An approach similar to Oehrlein et al., (2019) can be used in increasing the accessibility to green spaces. Apart from this, the city of Liege is situated on the banks of river Meuse. With increase in climate change, the risk of flooding can increase. Considering a parameter related to stormwater management in prioritizing the installation of green roof can enhance the analysis. Apart from this, the ecosystem services such as biodiversity enhancement, air quality and recreation are also provided by green roofs. The SMCA including versatile ecosystem services related parameters as done by Langemeyer et al. (2020) can be integrated in our study in future.

4. CONCLUSIONS

UGIs are recognized as important instruments in addressing urban environmental problems by providing the ecosystem services. UGI such as green roofs are gaining popularity owing to their multiple benefits and their ability to provide these benefits in compact cities. In this study, we proposed a simplistic approach for identifying the potential of green roofs along with identification of priority regions in the context of Liege, Belgium.

Our analysis concludes that Liege offers a green roof potential area of about 350 hectares on 20% of the total buildings in the city. According to the analysis for priority zones, we observed that the high priority zone mainly comprises of regions in the city centre near the river and in some parts in the east. Based on the discussed benefits in the literature, developing green roofs in this zone can yield maximum benefits. We observed that the potential of green roofs in the high priority zones as compared to the moderate priority zone is low in terms of number of roofs but is significant in terms of area of roofs. Moreover, the high priority zone of Liege, especially the region in the centre of the city has significantly high built-up density, which makes green roofs implementation extremely relevant. The results also indicate the importance of cost-effective green roof solutions as high priority zones also experience socio-economic deprivation to an extent. However, owing to their multiple benefits, developing green roofs on the potential roofs can have a significant impact on the urban environment. Additionally, green roofs can be combined with other UGIs for better ecosystem services.

The methodology used in this study is straightforward but depends upon the availability and quality of datasets. Moreover, the benefits of green roofs can be analysed with the help of modelling techniques. However, our approach can act as a preliminary decision-making tool for urban planners to analyse the potential of green roofs and prioritize them in the deprived areas. Moreover, this approach can be used for other cities in Belgium and Europe with contextual modifications.

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