Geometrical Parcel Locker Network Design with Consideration of Users’ Preferences as a Solution for Sustainable Last Mile Delivery

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Abstract: Last mile logistics accounts for a small part of deliveries geographically, but generates disproportionately high costs, energy consumption, and pollutant emissions. Parcel lockers are a solution with great potential to make deliveries more sustainable. In order to use this potential, the network should be designed in such a way that users are willing to collect parcels on foot or by bicycle and to use a given number of parcel lockers to cover as much area as possible. This area is still unexplored. The purpose of this article is to present a geometric method for designing a network of parcel lockers taking into account user preferences. Authors have used methods such as literature studies, survey, and statistical analysis. The analysis conducted showed that using a triangular network allows for greater coverage than a square one with the same number of parcel lockers. The median declared distance to allow regular parcel collection by walking or cycling was 500 m. Characteristics such as gender, age, education, and type of residence did not affect this parameter. Implementing data on customer preferences into the design of a parcel locker network and using a triangular network of parcel lockers allows for deliveries to be more sustainable.

Keywords: sustainable delivery; parcel lockers; last-mile logistics; network designing; optimization

1. Introduction

Logistics companies are constantly striving to make their operations more sustainable, which is expected to translate into reduced energy consumption, costs, labor inputs, as well as negative environmental impacts. One of the key tasks is to improve last-mile logistics. Geographically, it is responsible for a negligible portion of the shipments carried out; however, it is often seen as the most expensive, least efficient, most energy-consuming, and polluting phase of logistics processes [1].

Parcel lockers are a solution with great potential in this area. They allow couriers to deliver multiple parcels in one place. However, their mere use does not mean that supplies automatically become more sustainable. Using the potential of parcel lockers in the field of sustainable deliveries requires solving two problems. Firstly, from the courier’s point of view, the greater the number of parcel lockers on their route, the less sustainable the deliveries are. In an extreme situation, their number may be equal to the number of recipients. Door-to-door delivery would then be more sustainable. Secondly, the more users travel to the parcel locker by engine vehicles, the less sustainable the delivery is. This results not in a reduction in energy consumption, pollution, and costs, but in their transfer from the courier company to the user.

Given the above, sustainable delivery requires finding a balance between the demand and supply sides of delivery. It is in the interest of couriers to have as few stop points as possible, and in the interest of users to have as many parcel lockers as possible. This would
allow them to regularly collect parcels on foot or by bicycle. Finding this balance point for
the appropriate density of the parcel locker network is possible through:

- Identifying users’ needs regarding their readiness to regularly travel to the parcel
  locker on foot or by bicycle and implementing this data into network design;
- Designing the network in such a way that a given number of parcel lockers covers as
  much area as possible.

In the literature, parcel lockers are rarely viewed from a sustainability perspective,
and the problem of the full use of their potential by taking into account users’ preferences
is unexplored. The contribution of this research is the presentation how the described
users’ needs should be recognized and implemented when designing the parcel locker
network, and how to maximize the area covered by a given number of parcel lockers using
geometric methods.

The purpose of this article is to present a geometric method for designing a network
of parcel lockers taking into account user preferences. This research was conducted based
on the preferences of residents of Lubusz Voivodeship. The following research hypotheses
were formulated:

H1. The gender of users has no effect on the distance they are willing to walk or cycle to parcel lockers.

H2. People up to 35 years old are willing to walk or cycle a greater distance to parcel lockers than
those aged 36 and over.

H3. Higher education degree has no effect on the distance users are willing to walk or cycle to
parcel lockers.

H4. Rural residents are willing to walk or cycle a greater distance to parcel lockers than residents of
cities with up to 50,000 residents and cities with more than 50,000 residents.

H5. The use of a triangular parcel locker network allows for greater coverage than a square network
with the same number of parcel lockers.

Hypotheses H1–H4 were verified through surveys and statistical analyses. Hypothesis
H5 was verified by using geometric and algebraic tools. A literature study and bibliographic
analysis were also conducted for this study.

2. Parcel Lockers and Network Design

The examined issue is interdisciplinary and can be looked at from two perspectives:
the role of parcel lockers in sustainable last-mile logistics and the design of the parcel locker
network taking into account user preferences. From the first perspective, it is important to
gain an overall idea of parcel lockers.

The interest in last mile deliveries has increased with the development of globalization
and e-commerce. Research is being carried out to make this process more sustainable. This
is usually a problem of choices regarding how to perform logistics operations. It can be
applied to the appropriate selection of third-party logistics providers [2] or the method of
delivery [3]—door-to-door or parcel locker delivery.

Parcel lockers are devices involved in e-commerce or mail-order sales, enabling the
self-delivery of shipments at a time and place convenient to the customer [4]. Deliveries
made using them have advantages, not just from the customer’s perspective. Couriers
can shorten the route traveled and reduce energy consumption and operation times by
delivering multiple shipments to a single point. Parcel lockers can be more cost efficient
and sustainable than home delivery [5] and play an important role in creating sustainable
cities [6]. As a result, recent years have seen a rapid increase in the demand, as well as
supply, of the parcel delivery service.
In addition to consumers and representatives of the B2C delivery sector, academics are also showing interest in this topic. A bibliographic analysis of the Scopus database showed that parcel lockers have appeared in the titles, abstracts, and keywords of publications 120 times in recent years. Figure 1 is a map of the co-occurrence of authors’ keywords that appeared at least three times in the mentioned publications.

Figure 1. Keywords co-occurrence map for parcel lockers.

It can be seen from the above that research on parcel lockers is most often conducted in the context of four main topic clusters:

- Last-mile delivery plus routing (light green color);
- E-commerce plus home delivery, B2C, and facility locations (blue);
- City logistics plus vehicle routing, crowdshipping, autonomous vehicles, and integer linear programming (dark green);
- Optimization, mathematical programming, parcel delivery, sustainability, automated parcel lockers, and simulation (red).

The map above helps to identify the research gap. Parcel lockers have been examined mainly from an operational and logistical perspective. In only three studies were parcel lockers connected to the concept of sustainability.

Scientists combine sustainability and parcel lockers in their research, perhaps more often than bibliometric analysis shows. For example, sustainable strategies for urban parcel delivery have been evaluated [7]. Also, parcel locker user behavior was analyzed in the context of ecology [8]. But, above all, it is also believed that the needs of parcel locker users have not yet been fully met and, at the same time, there is considerable scope for optimizing parcel lockers in terms of sustainability [9].

When it comes to the second perspective, there are studies with reference to parcel network users’ preferences, but it is not shown how to implement them in network design, which is crucial for using its potential in terms of sustainability.

Table 1 shows selected research on parcel locker networks and the preferences of their users.
Table 1. Selected research on parcel locker networks and user preferences.

<table>
<thead>
<tr>
<th>Author</th>
<th>Results Important for This Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. Lemke et al. [10]</td>
<td>40% of surveyed parcel locker users considered their location to be very good; 15% would use them more often if the location improved. Parcels were most often picked up by car (51%) and almost half (46%) of respondents had to travel an additional 1 to 5 km.</td>
</tr>
<tr>
<td>M. Giuffrida et al. [11]</td>
<td>Delivery via parcel lockers can reduce GHG emissions by two-thirds compared with door-to-door delivery. If the parcel locker is located in a city farther than 3.5 km from the recipient, only the supplier benefits economically from using parcel lockers.</td>
</tr>
<tr>
<td>J.H.R. van Duin et al. [12]</td>
<td>A parcel delivery model was described that would reduce delivery costs by 16% compared with the original delivery scheme.</td>
</tr>
<tr>
<td>S. Rohmer, B. Gendron [13]</td>
<td>The design of a network of parcel lockers consists of 3 elements: determination of their number (this depends on demand and the willingness of users to travel a certain distance), configuration (their size and the structure of the boxes), and location (determined by the desire to use a parcel locker in a specific place).</td>
</tr>
<tr>
<td>A. Niederprüm, W. van Lienden [14]</td>
<td>Comparison of business models and the use of parcel lockers in different countries. Poland has the largest number of parcel lockers in Europe, and the network is continuing to expand. In recent years, there has also been an increasing demand for collection at parcel lockers at the expense of direct delivery.</td>
</tr>
<tr>
<td>M. Schneider et al. [15]</td>
<td>From an ecological point of view, the use of parcel lockers makes more sense the fewer recipients reach them by car. If the percentage is too high, a courier delivery to the door is more ecological.</td>
</tr>
<tr>
<td>M. Schneider et al. [16]</td>
<td>Providing enough lockers throughout the whole week generated the need for twice as many lockers as are needed for 80% of the week because of variation in demand.</td>
</tr>
<tr>
<td>G. Lyu, C.-P. Teo [17]</td>
<td>The described parcel locker network located lockers not just in areas with the highest demand for parcel collection. The assumed range of a single parcel locker was 250 m.</td>
</tr>
<tr>
<td>Y.H. Lin et al. [18]</td>
<td>Consumer sensitivity to distance traveled is important in modeling the network and its profitability. Network design should also take into account the situation when a user does not have the option of using a parcel locker and seeks another delivery option.</td>
</tr>
<tr>
<td>M. Kahr [19]</td>
<td>A rectangular parcel locker network with sides of 250 and 500 m was adopted for the study. A stochastic model of parcel locker locations was proposed, according to which small and medium parcel lockers should be preferred at the expense of large ones, the expected growth from parcel locker investments was promising, parcel locker networks were able to meet the growing demand for parcels, and it was possible to plan parcel locker locations as well as their types (layout) simultaneously.</td>
</tr>
<tr>
<td>Y. Wang et al. [20]</td>
<td>In the model, 150 m was determined as the maximum distance to reach a parcel locker on foot. The location and size of parcel lockers could be determined by a single model.</td>
</tr>
<tr>
<td>M. Koszorek, M. Sobolewski [21]</td>
<td>43.75% of respondents lived within 1 km of the nearest parcel locker, 21.88% 1–2 km, 18.75% 2–5 km, and 15.60% over 5 km.</td>
</tr>
</tbody>
</table>
In the above publications, parcel locker networks were analyzed from different perspectives; however, some general conclusions can be drawn. The distance that users have to travel to a parcel locker is an important factor in meeting the demand for parcel lockers. It must be considered to realize the full potential of a parcel network, which is to reduce costs and pollution. In addition, the networks studied were not designed optimally, most often due to insufficient density of parcel lockers.

In two studies, the range of parcel lockers was arbitrarily adopted (radius of 250 m and a rectangle with sides of 250 and 500 m), and in one, it was determined by an experiment at 150 m. This is important from the perspective of this study.

3. Materials and Methods

The present study was limited to the Lubusz Voivodeship only and was divided into 2 stages. Firstly, the survey was used to examine users’ willingness to regularly walk or ride a bicycle for a specific distance to the parcel locker. The aim was to establish the maximum range of parcel lockers in the network so that it was close enough for users, but at the same time, to limit their number as much as possible. The differences in regard to the willingness to regularly walk or ride a bicycle for specific distances between different groups were also examined. The aim of this verification was to identify the features that determined the tendency to cover the distance on foot or by bicycle. This would also be important in encouraging individual user groups to be more active in this area and thus increase the range of parcel lockers.

The second part of this research presented the possibility of more effective use of a given number of parcel lockers within a range defined in the first part with the help of users. Square and triangular parcel locker networks were determined and compared with the use of the results obtained in stage 1. Networks created from other regular polygons were also taken into account during the study, but were rejected at the preliminary stage as inefficient. The more angles in a regular polygon, the larger the fields of overlapping parcel ranges owing to the increasingly unfavorable ratio of side length to the length of the segment between the polygon’s vertex and its geometric center.

A survey was the method selected for the first stage of this study due to the possibility of quickly collecting information from the entire region of the Lubusz Voivodeship, as well as anonymity, limiting the risk of distortion of declared data. The survey was conducted in March and April 2022. The authors used purposive sampling to include only people who shop via the Internet and use parcel locker delivery. The questionnaires were sent to 264 people, and 200 responses were obtained (75.76% return rate). The sample size for the studied voivodeship was sufficient because, according to the formula presented below, the minimal sample size was 196 [22,23]:

\[ n = \frac{0.25 \times Z_{\alpha/2}^2 \times N}{0.25 \times Z_{\alpha/2}^2 + (N - 1) \times d^2} \]  

where:
- \( Z_{\alpha/2}^2 \) — permissible measurement error (for a given adopted confidence coefficient);
- \( d \) — permissible result error (here ±0.05);
- \( N \) — size of the general population;
- \( n \) — size of the sample;
- \( \alpha \) — confidence factor (here 0.05).

The characteristics of the 200 respondents are shown in Table 2.
Table 2. Characteristics of the sample.

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woman</td>
<td>98</td>
<td>49%</td>
</tr>
<tr>
<td>Man</td>
<td>102</td>
<td>51%</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 35</td>
<td>172</td>
<td>86%</td>
</tr>
<tr>
<td>36 and more</td>
<td>28</td>
<td>14%</td>
</tr>
<tr>
<td><strong>Education</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher</td>
<td>52</td>
<td>26%</td>
</tr>
<tr>
<td>Other</td>
<td>148</td>
<td>74%</td>
</tr>
<tr>
<td><strong>Residence</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>63</td>
<td>31.5%</td>
</tr>
<tr>
<td>Urban pop. ≤ 50,000</td>
<td>59</td>
<td>29.5%</td>
</tr>
<tr>
<td>Urban pop. &gt; 50,000</td>
<td>78</td>
<td>39.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>200</td>
<td>100%</td>
</tr>
</tbody>
</table>

Statistical methods were used to test for differences between groups. The Shapiro–Wilk test was used to test the normality of the distribution of the groups. The test statistic was calculated using the following formula [24]:

$$W = \frac{\left(\sum_{i=1}^{n} a_i X_i\right)^2}{\sum_{i=1}^{n} (X_i + \bar{X})^2}$$  \hspace{1cm} (2)

where:
- \(a_i\)—can be found in mathematical tables;
- \(X_i\)—ith order statistic;
- \(\bar{X}\)—mean.

Owing to the fact that not all the studied groups had a distribution close to normal, they were characterized by different numbers and the Kruskal–Wallis test was used to simultaneously compare more than 2 groups. This test was to confirm or exclude the statistical significance of differences. Test statistics were calculated using the following formula [25]:

$$H_p = \frac{H}{1 - \frac{\sum_{i=1}^{t_i} \frac{1}{n_i - t_i}}{N^3 - N}}$$  \hspace{1cm} (3)

where:
- \(N\)—total number of observations;
- \(t_i\)—number of observations with ties;
- \(H\)—Kruskal–Wallis test value without correction for ties [26]:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{p} \frac{R_i^2}{n_i} - 3(N + 1)$$  \hspace{1cm} (4)

where:
- \(p\)—number of groups compared;
- \(R_i\)—sum of ranks in a group \(i\);
- \(n_i\)—number of observations in a group \(i\)
Mann–Whitney tests were performed as post hoc analysis. They were also used for comparisons between the 2 groups. The test values were calculated according to the following formula [27]:

\[ U = R_{\text{min}}(k) - \frac{n_k(n_k + 1)}{2} \]  

where:
- \( R_{\text{min}}(k) \) —the sum of the ranks in the group with lower sum;
- \( n_k \) —the number of observations in the group with the lower rank sum.

The statistics of multiple pairwise comparisons were corrected using the Bonferroni correction, which is calculated according to the formula [28]:

\[ PC_\alpha = \frac{EW_\alpha}{k} \]  

where:
- \( PC_\alpha \) —Bonferroni corrected level of significance;
- \( EW_\alpha \) —nominal level of significance;
- \( k \) —number of tests.

Outlier observations were determined using the 1.5 IQR method [29].

4. Results

4.1. Users’ Preferences

The conducted survey showed that different groups of consumers differed when it came to their preference for using parcel lockers. The place of residence and distance from the nearest parcel locker were of the greatest importance here. Figure 2 shows the distance between the respondents’ place of residence and the nearest parcel locker by the type of residence.

![Figure 2. The distance between the respondents’ place of residence and the nearest parcel locker by the type of residence.](image)

The longest distance to a parcel locker was recorded among rural residents, and the shortest in large cities. It should be noted, however, that the difference between urban groups was significantly smaller than that between rural areas and small towns. The percentage of users living within 100 m of the nearest parcel locker was similar in small and large cities. Among the respondents, there was no resident of a large city who had to travel more than 5 km to a parcel locker.

Distance is also an important factor influencing the method of parcel collection. There were two methods available in the survey: walking/cycling or using a motor vehicle. Parcel pick-up can also be done on the way to another point or by taking a route specifically for this purpose. This is shown in Figure 3.
Walking/cycling to parcel lockers was prevalent up to 500 m. Over 2 km, such a collection method was among the exceptions. Already at this stage of the analysis, it can be concluded that, in order to use the potential of parcel lockers in sustainable deliveries, it is necessary to ensure that the distance to the nearest parcel locker is no more than 500 m. The key to the study is the group of people who collect parcels from lockers using a motor vehicle, making a route specifically for this purpose. Their impact on the environment is the greatest and the negative effects caused by them are not shared with other activities, like commuting to work, shopping, etc. These people accounted for 7% of those surveyed.

However, to design a new network or optimize an existing one, it is important to remember that the distance to the parcel locker that users currently have is not the only crucial factor. In the survey, they were asked to declare the maximum distance to a parcel locker that they would regularly walk or ride a bicycle to. From the responses of all respondents, the 1.5 IQR method determined the lower limit of the declaration as 0 m and the upper limit as 1787.5 m. Accordingly, 37 observations with higher values were considered as outliers and removed from this part of the analysis. While the declaration of regularly walking or cycling 12 or 15 km to a parcel locker is more of a typing error, the actual willingness of respondents to walk five kilometers to collect a parcel cannot be ruled out. It is important to remember that the designed network of parcel lockers was intended to serve the majority of the population, not just active people with plenty of free time. Walking or cycling should also be the dominant form of collection on a daily basis, not just under favorable conditions. Table 3 shows the maximum distance for parcel collection that excluded the use of a motor vehicle.

Table 3. Declared maximum distance to the parcel locker for regular walking/cycling collection.

<table>
<thead>
<tr>
<th></th>
<th>200 (The Whole Group)</th>
<th>163 (Without Outliers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1177.36 m</td>
<td>616.34 m</td>
</tr>
<tr>
<td>Minimum</td>
<td>0 m</td>
<td>0 m</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>475 m</td>
<td>300 m</td>
</tr>
<tr>
<td>Median</td>
<td>775 m</td>
<td>500 m</td>
</tr>
<tr>
<td>Quartile 3</td>
<td>1000 m</td>
<td>1000 m</td>
</tr>
<tr>
<td>Maximum</td>
<td>15,000 m</td>
<td>1500 m</td>
</tr>
</tbody>
</table>

In the entire study group, the maximum declared distance was 15,000 m, and 1500 m after excluding outliers. The minimum was 0 m. This answer was reported only once, along with a comment that the parcel would be collected on the way from work by motor vehicle, regardless of the distance to the nearest parcel locker.
However, designing a parcel locker network requires more detailed information. Figure 4 shows the percentage of respondents who, according to their declarations, would cover a given distance to the parcel locker on a regular basis on foot or by bicycle.

![Figure 4](image-url)

**Figure 4.** Percentage of respondents who declared their willingness to regularly walk or cycle to the parcel locker for a specific distance.

The data presented in the graph above make it easy to find the right degree of network density for designers who need to consider not only customer requirements, but also capital and operating expenses. This is a kind of quasi-demand curve from which it is possible to read what density of the parcel locker network should be provided to users so that a given percentage of them travel to the parcel locker regularly on foot or by bicycle.

In addition to general research, an in-depth analysis was carried out for the entire study group, taking into account such factors as gender, age, education, and type of residence. The results are presented in Table 4. In each of these cases, outliers were omitted.

Among men, the declared average distance was over 50 m longer than that among women, but the test showed no statistical significance. The value of the medians was the same. Therefore, hypothesis H1 was confirmed.

When it comes to age, the same median of 500 m was found in both groups. Younger people were willing to walk, on average, almost 6 m more than the representatives of the second group, but the differences turned out to be statistically insignificant. Hypothesis H2 was therefore rejected.

Taking into account education, the differences between the study groups occurred both in the case of average values (71.34 m) and medians, with the tendency to cover longer distances demonstrated by people with higher education. Although, numerically, this difference was relatively high, in this case, it turned out to be statistically insignificant. Therefore, it cannot be confirmed that people with higher education have greater environmental awareness, implying a tendency to cover longer distances on foot or by bicycle. The H3 hypothesis was confirmed.

In the analysis, by the type of residence, the observed differences in means and medians were not statistically significant. It was confirmed by the results of the Kruskal–Wallis test and post hoc analysis using the Mann–Whitney method presented in Table 5.
Table 4. Declared maximum distance to the parcel locker for regular walking/cycling collection by group.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Woman</th>
<th>Man</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>80</td>
<td>83</td>
</tr>
<tr>
<td>Mean</td>
<td>590.29 m</td>
<td>641.45 m</td>
</tr>
<tr>
<td>Median</td>
<td>500 m</td>
<td>500 m</td>
</tr>
<tr>
<td>M-W test *</td>
<td></td>
<td>p = 0.6005</td>
</tr>
</tbody>
</table>

Age

<table>
<thead>
<tr>
<th>Age</th>
<th>Up to 35</th>
<th>36 and more</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>135</td>
<td>28</td>
</tr>
<tr>
<td>Mean</td>
<td>617.36 m</td>
<td>611.43 m</td>
</tr>
<tr>
<td>Median</td>
<td>500 m</td>
<td>500 m</td>
</tr>
<tr>
<td>M-W test *</td>
<td></td>
<td>p = 0.8587</td>
</tr>
</tbody>
</table>

Education

<table>
<thead>
<tr>
<th>Education</th>
<th>Higher</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>48</td>
<td>115</td>
</tr>
<tr>
<td>Mean</td>
<td>666.67 m</td>
<td>595.33 m</td>
</tr>
<tr>
<td>Median</td>
<td>600 m</td>
<td>500 m</td>
</tr>
<tr>
<td>M-W test *</td>
<td></td>
<td>p = 0.2522</td>
</tr>
</tbody>
</table>

Residence

<table>
<thead>
<tr>
<th>Residence</th>
<th>Rural</th>
<th>Urban pop. ≤ 50,000</th>
<th>Urban pop. &gt; 50,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>45</td>
<td>48</td>
<td>69</td>
</tr>
<tr>
<td>Mean</td>
<td>655.62 m</td>
<td>544.69 m</td>
<td>641.59 m</td>
</tr>
<tr>
<td>Median</td>
<td>600 m</td>
<td>500 m</td>
<td>500 m</td>
</tr>
<tr>
<td>M-W test *</td>
<td></td>
<td>p = 0.2845</td>
<td></td>
</tr>
</tbody>
</table>

* p value in Mann–Whitney test.

Table 5. p values for Mann–Whitney test (Bonferroni-corrected/incorrected) (spacja miedzy \?).

<table>
<thead>
<tr>
<th>Village</th>
<th>Urban Pop. ≤ 50,000</th>
<th>Urban Pop. &gt; 50,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Village</td>
<td>0.132</td>
<td>0.6261</td>
</tr>
<tr>
<td>Urban pop. ≤ 50,000</td>
<td>0.3959</td>
<td>0.2346</td>
</tr>
<tr>
<td>Urban pop. &gt; 50,000</td>
<td>1</td>
<td>0.7038</td>
</tr>
</tbody>
</table>

The p-values for the Mann–Whitney test, both Bonferroni-corrected and incorrected, clearly indicate no statistically significant differences between the study groups. The place of residence does not significantly affect the declared walking or cycling distance for collecting parcels from a parcel locker. Even the currently much lower density of parcel lockers in villages does not encourage their inhabitants to cover longer distances on foot or by bicycle. Hypothesis H4 was rejected.

If the present study showed differences in declarations of the distance traveled to a parcel locker on foot or by bicycle due to age, gender, or education, it would not have a direct impact on the shape and density of the parcel locker network. For people of different ages, genders, and educational backgrounds, separate networks tailored to their preferences would not be created. However, we would be dealing with an indirect influence. The identification of groups with a significantly lower declaration of willingness to cover the distance on foot or by bike would make it possible to select appropriate stimuli to activate them. For example, if statistically significant differences were observed in the declarations of inhabitants of different residential areas, it would have a direct impact on the design of parcel locker networks in villages, towns, and cities.
4.2. Square and Triangular Parcel Locker Networks

The maximum distance that users have to cover to the nearest parcel locker, determined during the design of the network, from the geometric point of view is also the radius of the parcel locker range and will be referred to as such. Figure 5 shows a schematic diagram of a square network of six parcel lockers. The ranges of parcel lockers are depicted with black circles.

![Figure 5. Square parcel locker network.](image)

Owing to such a network design, each user would be within the planned range of at least one parcel locker. From the point of view of this analysis, the problem of overcrowding of parcel lockers is negligible, but it should be noted that it could be solved in two ways. First, lockers of different sizes can be used. Second, additional parcel lockers can be located in areas with the greatest demand.

Knowing the formula for the area of a circle, the area of a sector, and the area of a segment, and using the notations adopted in this article, one can determine:

- The range of a single parcel locker as a circle area—πr², where r is the radius of the parcel locker;
- The length of the side of the square forming the network of parcel lockers a = r√2;
- The area where the ranges of parcel lockers overlap (marked in blue in Figure 5), as the area of two circle segments is the difference in the area of a circle sector with the angle of 90°, radius r and the area of the triangle with side r and height r which is:

\[
2 \left( \frac{\pi r^2}{4} - \frac{r^2}{2} \right) = \frac{r^2(\pi - 2)}{2} \tag{7} \]

Further, it should be noted that the number of areas where the ranges of parcel lockers overlap increases linearly with subsequent parcel lockers; however, the function looks different for even and odd numbers of parcel lockers. By adding an odd parcel locker, it has only one part of the range in common with the already existing ones. When we add an even number to the network, we get two new common fields. Hence, the linear function of the number of common coverage areas depending on the number of parcel lockers is as follows:

- 1.5n − 2.5 for odd;
- 1.5n − 2 for even.

Therefore, for a square network, there are two formulas for the area of a parcel locker network, depending on their number and range. For an odd number:

\[
P = n\pi r^2 - \left[ (1.5n - 2.5) \left( \frac{r^2(\pi - 2)}{2} \right) \right] \tag{8} \]
For an even number:

\[
P = n\pi r^2 - \left[ (1.5n - 2) \left( \frac{r^2(\pi - 2)}{2} \right) \right]_{\forall n \in \mathbb{N} \land n \geq 2 \land \forall r > 0}
\]  

(9)

However, the grid lines do not have to cross at right-angles to form squares. This is probably the most popular form of network, and in many applications, also the most optimal, but it is not a rule. In the case of the problem discussed in this study, the grid composed of equilateral triangles, which is presented in Figure 6, is more effective.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure6.png}
\caption{Triangular parcel locker network.}
\end{figure}

Compared with the square network, there are more parts of common ranges of parcel lockers, but their area is smaller. In this case, the calculations are similar to those used for the square grid; the difference lies in the number and area of common areas of parcel locker ranges. We can set:

- The range of a single parcel locker as a circle area—\( \pi r^2 \);
- The length of the side of the equilateral triangle forming the network \( a = r \sqrt{3} \);
- The area where the ranges of parcel lockers overlap (marked blue in Figure 6), as the area of two circle segments is the difference in the area of a circle sector with the angle \( 60^\circ \), radius \( r \), and the area of a triangle with side \( r \) and height \( \frac{\sqrt{3}}{2} \):

\[
2 \left( \frac{\pi r^2}{6} - \frac{r^2 \sqrt{3}}{4} \right) = \frac{r^2(2\pi - 3\sqrt{3})}{6}
\]  

(10)

Further, it should be noted that the number of fields where the ranges of parcel lockers overlap increases linearly with subsequent parcel lockers according to the function: \( 2n - 3 \). Then, one can determine the final formula for the area of the network:

\[
P = n\pi r^2 - \left[ (2n - 3) \left( \frac{r^2(2\pi - 3\sqrt{3})}{6} \right) \right]_{\forall n \in \mathbb{N} \land n \geq 2 \land \forall r > 0}
\]  

(11)

where \( n \) is the number of parcel lockers.

This equation could be simplified through rounding, which will make it easier to use in practice. We can assume that \( \pi \) is 3.14159 and \( \sqrt{3} \) is 1.73205, and use the following formula:

\[
P = r^2(2.77923n + 0.54354)_{\forall n \in \mathbb{N} \land n \geq 2 \land \forall r > 0}
\]  

(12)
In this case, the calculation error resulting from the rounding of the parameter values is less than 0.05%.

The practical application of the above information may more often take the opposite form. Knowing the size of a given area, it is possible to establish what number of parcel lockers will be sufficient to service it. In this case, the calculation result will be approximate and, in order to obtain a 100% coverage of the area with parcel lockers, it should be rounded up. The formula should be derived from Equation (11) as follows:

\[
P = n\pi r^2 - \frac{2n r^2 (2\pi - 3\sqrt{3})}{6} + \frac{3r^2 (2\pi - 3\sqrt{3})}{6}
\]

\[
P - \frac{3r^2 (2\pi - 3\sqrt{3})}{6} = n \left(\pi r^2 - \frac{2r^2 (2\pi - 3\sqrt{3})}{6}\right)
\]

\[
n = \left(\frac{6P - 3r^2 (2\pi - 3\sqrt{3})}{6}\right) \left(\frac{6}{6\pi r^2 - 2r^2 (2\pi - 3\sqrt{3})}\right)
\]

\[
n = \left(\frac{6P - 3r^2 (2\pi - 3\sqrt{3})}{6\pi r^2 - 2r^2 (2\pi - 3\sqrt{3})}\right)
\]

\[
n = \left(\frac{6P - 3.26109}{16.67548}\right)
\]

In this case, it is also possible to simplify the equation by using rounding: \(\pi = 3.14159; \sqrt{3} = 1.73205\).

\[
n = \left(\frac{6P - 3.26109}{16.67548}\right)
\]

The last stage of this research involved comparing the coverage of triangular and square networks consisting of \(n\) number of parcel lockers. Table 6 presents two variants where, respectively, 75% and 90% of the surveyed inhabitants of the Lubuskie Voivodship would be within walking or cycling distance of the nearest parcel locker.

Table 6. Coverage comparisons between square and triangular parcel locker networks.

<table>
<thead>
<tr>
<th>(n)</th>
<th>(r = 300) m, 75% of Users in Walking/Cycling Distance</th>
<th>(r = 100) m, 90% of Users in Walking/Cycling Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n)</td>
<td>Coverage (ha)</td>
<td>Difference</td>
</tr>
<tr>
<td>Square</td>
<td>Triangular</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>28.27</td>
<td>28.27</td>
</tr>
<tr>
<td>2</td>
<td>51.41</td>
<td>54.92</td>
</tr>
<tr>
<td>3</td>
<td>74.55</td>
<td>79.93</td>
</tr>
<tr>
<td>4</td>
<td>92.55</td>
<td>104.92</td>
</tr>
<tr>
<td>5</td>
<td>115.69</td>
<td>129.96</td>
</tr>
<tr>
<td>10</td>
<td>215.96</td>
<td>255.02</td>
</tr>
<tr>
<td>20</td>
<td>421.65</td>
<td>505.16</td>
</tr>
<tr>
<td>50</td>
<td>1038.70</td>
<td>1255.55</td>
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<tr>
<td>100</td>
<td>2067.13</td>
<td>250.22</td>
</tr>
<tr>
<td>250</td>
<td>5152.42</td>
<td>6258.20</td>
</tr>
<tr>
<td>500</td>
<td>10,294.57</td>
<td>12,511.51</td>
</tr>
<tr>
<td>1000</td>
<td>20,578.86</td>
<td>25,018.13</td>
</tr>
</tbody>
</table>
A triangular network has larger coverage than a square network with the same number of parcel lockers. Even with 10 parcel lockers, the difference is over 18%. Therefore, hypothesis H5 was confirmed. However, the actual differences would depend on infrastructural, legal, and economic factors.

5. Discussion

What services and how they are provided depends on the demand as well as the supply sides of transactions. Both service providers and consumers face different kinds of constraints and various aspirations. Some solutions require obtaining a kind of compromise between both parties; otherwise, it may be impossible or unprofitable to use them. Parcel locker deliveries are one of them. It is in the interest of delivery companies to have as few delivery points as possible. For this reason, energy related to deliveries is saved, as well as the time of operations. From consumers’ perspectives, an insufficiently dense parcel locker network is unattractive compared with door-to-door delivery. In practice, this implies a lack of willingness to use parcel lockers or shifting the costs related to energy and time consumption from delivery companies to recipients. Thus, in general, the whole concept of parcel lockers could become questionable. To avoid this situation, delivery companies must provide dense enough parcel locker networks that are easily accessible to users.

The analysis provided precise data on the distance users are willing to regularly cover on foot or by bicycle. A quasi-demand curve was created, based on which network designers could decide what range of parcel lockers to choose to satisfy a specific percentage of users. However, it is important to remember that, for the results obtained to be accurate and useful, similar studies must be carried out for specific regions. This analysis concerned only the inhabitants of the Lubusz Voivodeship and its results should not be directly copied into network design in other regions of Poland, Europe, and the world. While the data obtained in this research may only be useful for designers of parcel locker networks in the Lubusz Voivodeship, it may be a reference point for others. Moreover, the method of researching and implementing consumer preferences in designing parcel locker networks is universal.

In the sample studied, characteristics such as age, gender, higher education, and type of residence did not have a statistically significant impact on the distance that respondents were willing to cover regularly on foot or by bicycle. This is particularly important for sustainable last mile deliveries from a marketing perspective. The potential of parcel lockers in this area could be used to a greater extent if service providers motivated users to cover longer distances on foot or by bicycle. This would mean a less dense network, fewer parcel lockers, and, as a consequence, lower investment and operating costs and more sustainable last mile deliveries. But effective motivation needs an appropriate selection of stimuli for a group with given needs, opportunities, and limitations. For example, service providers could reward users for collecting parcels on foot or by bicycle. Through an activity-tracking phone application, promotional points could be awarded, exchangeable for prizes or discounts. The greater the distance, the more points could be awarded. The reward system and messages should be tailored to the needs of specific groups. If research shows that older people are unable to regularly walk the same distance as younger people, it would probably be due to health limitations. In this case, a more favorable point conversion could be used. Moreover, if discounts on delivery services could be the most attractive for mature people, young people could be interested in trendy gadgets or tickets to a concert of a popular band. When it comes to education, marketing messages containing the results of scientific research and describing even complex ecological phenomena could be addressed to people with higher education levels. For others, popular science messages might be more effective.

It turns out that, in the studied region, the means of influence and marketing messages may be universal. There is no need to profile them to a specific group. However, it is worth keeping in mind that the difference measured between the gender and education groups was large. Perhaps it would prove statistically significant in many other regions.
In the first step of the network-designing process, data on consumer preferences should be used to determine the appropriate range of parcel lockers. In the second step, it is important to optimize the arrangement of parcel lockers with a range defined earlier. For this purpose, one can use not only complex optimization methods, but also simple geometric principles, which are often overlooked. A triangular parcel locker network allows increasing coverage by even more than 20% compared with a square one. Looking at this from the other side, to construct a triangular network of a given density and coverage, fewer parcel lockers are needed than in the case of a square network. In practice, this means that, when using a triangular network, delivery cars stop less often, which saves energy and time. What is most important is that these savings occur without any loss to consumers when it comes to the distance they need to walk, cycle, or drive to collect the parcel.

The concept of a triangular network should be a baseline for advanced designing methods. It should be remembered that, regardless of the design method, consumer preferences are a key factor in the whole process. The ability to cover a certain distance to a parcel locker may vary significantly geographically. Therefore, it is desirable to carry out appropriate research among the inhabitants of a given region to find out what distances to take as a reference point. This study, in opposition to some theoretical considerations presented in some scientific articles, shows that it is not a good approach to arbitrarily assume the range of a parcel locker. This is an individual value for all users. Only by knowing the distribution of preferences can one decide to meet the needs of a given part of society. In this research, the range of the parcel lockers that satisfied 75% of users was 300 m and for 90%, it was 100 m, when, in other studies, values adopted arbitrarily were 250 m [17] and 250 × 500 m [19], and the value determined by an experiment was 150 m [20].

It should also be noted that the triangular network could be used for other applications, e.g., to support advanced methods of designing bike-[30] or car-sharing systems.

The presented geometric network design concept represents a demand point of view. First of all, consumer preferences were taken into account. At a later stage of the research, the radius of parcel lockers should be corrected by data on fuel consumption by delivery cars, the time of parking at the parcel locker, the intensity of their use, and operating costs.

6. Conclusions

This article proposes a method for designing parcel locker networks that increases their potential in the light of sustainable last mile deliveries. First of all, users’ preferences should be recognized and the range of parcel lockers should be determined based on them. Secondly, the location of parcel lockers with a given range should be planned so that their given number covers the largest possible area.

The inhabitants of Lubusz Voivodeship who took part in the research usually collected parcels by walking or cycling if they lived within 500 m from parcel lockers. This value coincides with the median of the declared maximum distance to pick up parcels on foot or by bicycle. However, it should be taken into account that the designed network should be denser to limit the use of motor vehicles in the collection of parcels.

In the sample studied, factors such as gender, age, education, and type of residence did not have a significant impact on the differentiation of the distance that users were willing to travel to the parcel locker on foot or by bicycle. This means that the impact on parcel locker users, e.g., by promoting the collection of parcels on foot, may be universal, without demographic profiling.

The triangular network of parcel lockers proposed in this study allows covering over 20% more area than the square network. This means that using a triangular network leads to using more potential of parcel lockers in terms of sustainability than a square network. Patterns to be used in the design of a parcel locker network were also presented. However, their actual shape will depend on infrastructural factors. It should be noted that the results of this research may also be helpful in completely different applications than deliveries using parcel lockers.
This research did not take into account the problem of capacity and overflow of parcel lockers. Also, the conditions of sustainable deliveries through parcel locker networks from the demand side were not sufficiently researched. This is the main direction of future research. Attempts should be made to outline a general function of energy consumption depending on the adopted range of parcel lockers, which could be applied to the analyzed regions. Such a function, combined with the demand data obtained in this study, could indicate the exact balance point of parcel locker range/network density in terms of sustainability.

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