

Clustering Honeybees by Its Daily Activity

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Abstract: In this work, we analyze the activity of bees starting at 6 days old. The data was collected at the INRA (France) during 2014 and 2016. The activity is counted according to whether the bees enter or leave the hive. After data wrangling, we decided to analyze data corresponding to a period of 10 days. We use clustering method to determine bees with similar activity and to estimate the time during the day when the bees are most active. To achieve our objective, the data was analyzed in three different time periods in a day. One considering the daily activity during in two periods: morning and afternoon, then looking at activities in periods of 3 hours from 8:00am to 8:00pm and, finally looking at the activities hourly from 8:00am to 8:00pm. Our study found two clusters of bees and in one of them clearly the bees activity increased at the day 5. The smaller cluster included the most active bees representing about 24 percent of the total bees under study. Also, the highest activity of the bees was registered between 2:00pm until 3:00pm. A Chi-square test shows that there is a combined effect Treatment \times Colony on the clusters formation.

1 INTRODUCTION

This work is part of a larger effort to characterize and provide tools for the analysis of individual behavior patterns of honeybees in their natural environment, i.e. the hives in the field. The goal is to be able to observe the variations in behavior of individuals instead of reasoning on aggregates and averages at the population level. In this paper, the bee activity is represented by the events entering (E) and exiting (S) the hive. Bees were marked with individual tags and recognized when passing an optical detector located at the only entrance of the hive, which can associate each event with an individual bee based on its tag. Our hypothesis is that the individual patterns of behavior will form clusters of bees with similar activity, which can inform us on the latent parameters associated to the individual bees. The categorical features “Treatment” and “Colony” have not been taken into account in the clustering task avoiding the use of a similarity distance involving mixed attributes like the

Gower distance. However, the effect of both features on the clusters formation is discussed in detail in section 3.2. The main goal of this work is to find out clusters of bees with similar activity.

This paper is organized as follows: In section 2 the datasets used and wrangling of the times series data are detailed. In section 3, the clustering process is discussed. In section 4, an explanation of the finding of the time interval with the peak activity is given. Finally, in the last section, we mention the conclusions of this work.

2 DATA PREPARATION

2.1 Datasets

In this study, we have considered seven datasets from experiments with bees carried out at the INRA (France). The first three datasets are coming from an

experiment carried out in 2014 by C. Bordier (Bordier et al., 2017). In there, newly emerged bees were infested with *Nosema* spores. The behavioral recording started at age 1. The experiment was replicated 3 times using 3 bee counters (colonies) each time. All the data are pooled in the same file. In this work, we have separated it into three datasets. The recordings started on the following dates : 02-04-2014(dataset 2014-I) , 14-05-2014 (dataset 2014-II) and 18-06-2014 (dataset 2014- III). In this experiment, one tag was used more than once. Thus, there are some tags that appear in dataset 2014-I and dataset 2014-II and even in dataset 2014-III. The remaining datasets were collected by A. Prado in 2016 (Prado et al., 2019). Prado used 6 Treatments (5 pesticides mixture and one control) started at 6 days old. The experiment was replicated 6 times using 2 bee counters (colony L and colony M) each time. Recordings for experiment April 2016 started on April 12 ,2016 and ended on May 1, 2016. In here, this dataset is named 2016A. The first experiment from June 2016, included cohort1, started on 31-05-2016 , and cohort2 , started on 13-06-2016. The bees are from colony L and theirs activity recordings end on July 4, 2016. We have named as 2016J to the dataset including results from this experiment. The second experiment from June 2016 included cohort1, started on 31-05-2016, and cohort2 , started on 13-06-2016. The bees are from colony M and recordings end on July 4, 2016. We have called 2016JB to the dataset containing results from this experiment. In both experiments 2016J and 2016JB, the cohort2 has only 21 days of measurements. However, we have found that bee with tag B4359 from the 2016JB has records in days 8th,10th and 12th of June. Bee’s activity recordings for the experiment from September, 2016 started at 13-09-2016 and emded on 17-10-2016. However, there are two bees with recordings as earlier as 08-09-2016. This dataset is named 2016S. The first rows of a typical dataset (2016JB) are shown in table 1.

Table 1: First rows of the 2016JB dataset.

| Id | Date | Time | BeelD | Dir. | Trt. | Colony |
|----|------------|----------|-------|------|---------|--------|
| 1 | 31-05-2016 | 09:42:17 | B4826 | S | mix C | M |
| 2 | 31-05-2016 | 09:42:27 | B4823 | S | mix C | M |
| 3 | 31-05-2016 | 09:42:27 | B4823 | E | mix C | M |
| 4 | 31-05-2016 | 09:42:45 | B4826 | E | mix C | M |
| 5 | 31-05-2016 | 10:49:16 | B5113 | S | Control | M |
| 6 | 31-05-2016 | 10:54:19 | B5113 | E | Control | M |
| 7 | 31-05-2016 | 10:54:53 | B5113 | S | Control | M |
| 8 | 31-05-2016 | 10:56:11 | B5113 | E | Control | M |

An exhaustive report of the data recollection can be found in (Prado et al., 2019).

In this work, we are only interested in the bee activity with respect to either entering (E) or exiting (S) the hive. The features “Treatment” and “Colony” have not been taken into account in the clustering task

avoiding the use of a similarity distance involving mixed attributes like the Gower distance. However, after the clustering task, we have used both attributes to explain the clusters formed. Our goal is to find out clusters of bees with similar activity. This paper is organized as follows: In section 2 the wrangling of the times series data is detailed, in section 3, the clustering process is discussed, in section 4 an explanation of the finding of the time interval with the highest activity is given, finally in the last section we mention the conclusions of our work.

2.2 Data Wrangling

In order to have a more accurate clustering process, we have cleanup the data by considering only bees with more than 10 activities, somehow equivalent to having more than 5 trips (see Table 2, column 4). All the datasets have miss detections for direction values, since several SS (S=Exit) or EE (E=Enter) sequences for a given bee appear recorded. These can be fixed but up to certain amount. It is not recommended to fix more than 30 percent of missed detection since bias will be generated (see Table 2,column 5). However, in this paper we have not cleanup miss detection in the collected data, since we are interestred in the bee activity regardless if it is an entering or an exiting.

Table 2: The number of bees per experiment, number of recording days per experiment, number of bees to be considered for the clustering processing and the number of bees for which miss detected data can be fixed.

| Exp | Total number | Days of Recording | More than 5 trips | less than 30 percent of missdetection |
|----------|--------------|-------------------|-------------------|---------------------------------------|
| 2014-I | 300 | 34 | 219 | 186 |
| 2014-II | 300 | 29 | 185 | 115 |
| 2014-III | 300 | 28 | 220 | 174 |
| 2016J | 740 | 35/21 | 544 | 513 |
| 2016JB | 691 | 35/21 | 490 | 423 |
| 2016A | 251 | 20 | 144 | 125 |
| 2016S | 239 | 34 | 203 | 159 |

We have merged datasets 2016J and 2016JB since bees’ activities included in these two datasets were recorded by the same time calendar. In total, there are 1431 bees, the activity recording of 786 of them started on May 31, 2016 (first cohort) and the recording of the remaining 645 started on June 13, 2016 (second cohort) . After removing the bees with less than 5 trips (10 activities) the number of bees is reduced to 1034. The Bee B4359 was discarded for inconsistency in its recordings as mentioned in section 2.1. Thus, only 1033 bees are considered in this work. From these, 572 bees belong to the first cohort and 461 bees belong to the second cohort.

Table 3: Numbers of bees with similar time duration (given in days) for each dataset.

| Exp | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|----------|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 2014-I | 7 | 4 | 9 | 9 | 6 | 6 | 10 | 5 | 6 | 11 | 10 | 8 | 6 | 3 | 8 | 12 | 8 | 12 | 9 | 5 | 11 | 11 | 6 | 9 | 3 | 4 |
| 2014-II | 2 | 2 | 5 | 7 | 7 | 15 | 14 | 15 | 14 | 17 | 11 | 13 | 8 | 14 | 7 | 6 | 7 | 3 | 5 | 4 | 1 | 2 | 0 | 1 | 0 | 2 |
| 2014-III | 2 | 6 | 7 | 21 | 15 | 13 | 7 | 13 | 13 | 18 | 16 | 13 | 13 | 17 | 12 | 6 | 8 | 2 | 5 | 3 | 0 | 3 | 1 | 2 | 2 | 1 |
| 2016A | 1 | 14 | 10 | 11 | 13 | 8 | 5 | 3 | 12 | 7 | 7 | 5 | 5 | 7 | 10 | 6 | 11 | 8 | 0 | 1 | | | | | | |
| 2016J | 2 | 8 | 11 | 23 | 31 | 42 | 32 | 42 | 34 | 31 | 42 | 46 | 22 | 24 | 19 | 17 | 30 | 14 | 10 | 11 | 13 | 16 | 3 | 6 | 5 | 0 |
| 2016Jb | 2 | 9 | 14 | 22 | 28 | 16 | 21 | 33 | 32 | 31 | 21 | 32 | 23 | 27 | 23 | 19 | 16 | 17 | 24 | 10 | 3 | 10 | 5 | 11 | 5 | 8 |
| 2016S | 0 | 7 | 16 | 4 | 12 | 13 | 15 | 19 | 7 | 11 | 14 | 10 | 10 | 11 | 9 | 6 | 2 | 1 | 6 | 8 | 2 | 3 | 2 | 3 | 3 | 2 |

2.3 Preparing the Data for Clustering

Our goal is to group bees according to similar activity. Since clustering must be performed on data tables with rows of equal length, first, we have to find out bees with similar time duration of recording. We cannot cluster bees with different time duration of recording, say a bee with three days of recording cannot be clustered along a bee with 20 days of recording. We wrote an R script using the R package *lubridate* to find out bees with equal length time of recordings, using days as measure of time (Grolemund and Wickham, 2011). This does not mean that we are looking for bees with activity recorded in the same days. In fact, one day (24 hours) of recording can involve two days-calendar. In our program, basically we found the time duration (in hours) for the recordings of a bee and then this time is converted into days. Finally, we group the bees for their time duration in days. Table 3 shows the number of bees with similar number of days recorded for each of the datasets. Day=0 means that less than 24 hours of bee activity was recorded, day=1 means that between 24 hours and 47.99 hours of bee activity was recorded, and so on. From Table 3, we can notice that there are few activity recordings after day 25.

In this paper, due to space limitations, for clustering tasks we have only considered datasets from June 2016. Furthermore, these datasets are the ones with less inconsistencies. In order to have a large sample for clustering, after merging the 2016J and 2016JB datasets, we considered all the bees with 10 or more days of activities but considering only a time period of length ten days. For instance, if a bee has a recording of 13 days, we will only took in account its first 10 days of activities. Using this criterion, we ended up with 382 bees in the first cohort and 188 bees in cohort 2 as is showed below.

Cohort 1:

Days: Bees 0:2, 1:7 2:9 3:19 4:12 5:18 6:32 7:33 8:32 9:27 10:34 11:42 12:26 13:26 14:25 15:27 16:37 17:23 18:21 19:11 20:21 21:18 22:8 23:17 24:10 25:8 26:8 27:3 28:3 29:2 30:3 31:1 32:5 33:2

Cohort2:

Days: Bees 0:2 1:10 2:16 3:26 4:47 5:40 6:21 7:42 8:34 9:35 10:29 11:36 12:19 13:25 14:17 15:9 16:9 17:8 18:13 19:10 20:5 21 :8

3 PERFORMING THE CLUSTERING TASK

We have carried out clustering in each June's cohort separately. For that, we performed subsetting of the data file into the two cohorts and count the number of bee's activities per hour in each of them. The output was saved in two csv files one for each cohort. In the counting of the activity, we have not distinguished the type of activity, so E and S counts as one activity each of them. The first six rows of the output file for cohort1 looks like in Table 4.

Table 4: First six rows of the dataset showing counts of bee activity per hour.

| | beesID | hour | Count |
|---|--------|----------------|-------|
| 1 | B4002 | 6/1/2016 17:00 | 2 |
| 2 | B4002 | 6/3/2016 15:00 | 1 |
| 3 | B4002 | 6/3/2016 16:00 | 1 |
| 4 | B4002 | 6/5/2016 16:00 | 2 |
| 5 | B4002 | 6/6/2016 15:00 | 1 |
| 6 | B4002 | 6/7/2016 9:00 | 2 |

Then, we built a dataframe showing the 382 bees along the number of their activities per day-calendar but taking into account if the activity was either in the morning (before 12.00) or in the afternoon (12.00 or later) from May 31 until June 9. Thus, the dataframe has 382 rows and 22 columns. The first six rows of the dataframe are shown in Table 5.

Using outlier detection techniques (Mahalanobis distance, Local Outlier Factor(LOF) and even clustering itself), we have detected that bees with tags B4387 and B5134 are clearly outliers (Tan et al., 2005). Both bees are from colony M. In Figure 1, we compare the activity of a typical bee (B4013) with the activity of the two outliers bees. Notice that the outliers bees began an unusual activity during the mornings starting at day 5. This highly active bees may represent highly especalized such as water foragers (Robinson et al.,

Table 5: Numbers of bees with similar time duration (given in days-calendar).

| | BeelD | Total | 31m | 31a | 1m | 1a | 2m | 2a | 3m | 3a | 4m | 4a | 5m | 5a | 6m | 6a | 7m | 7a | 8m | 8a | 9m | 9a |
|---|-------|-------|-----|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1 | B4002 | 32 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 1 | 2 | 2 | 1 | 2 | 0 | 1 |
| 2 | B4005 | 226 | 0 | 2 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 7 |
| 3 | B4006 | 161 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 2 | 2 | 2 | 0 | 0 |
| 4 | B4010 | 77 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 4 | 0 | 2 | 1 | 1 | 0 | 32 | 0 | 6 |
| 5 | B4011 | 97 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 3 | 0 | 2 | 0 | 4 | 0 | 4 | 0 | 26 |
| 6 | B4012 | 50 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 2 | 2 | 4 | 0 | 5 | 1 | 6 |

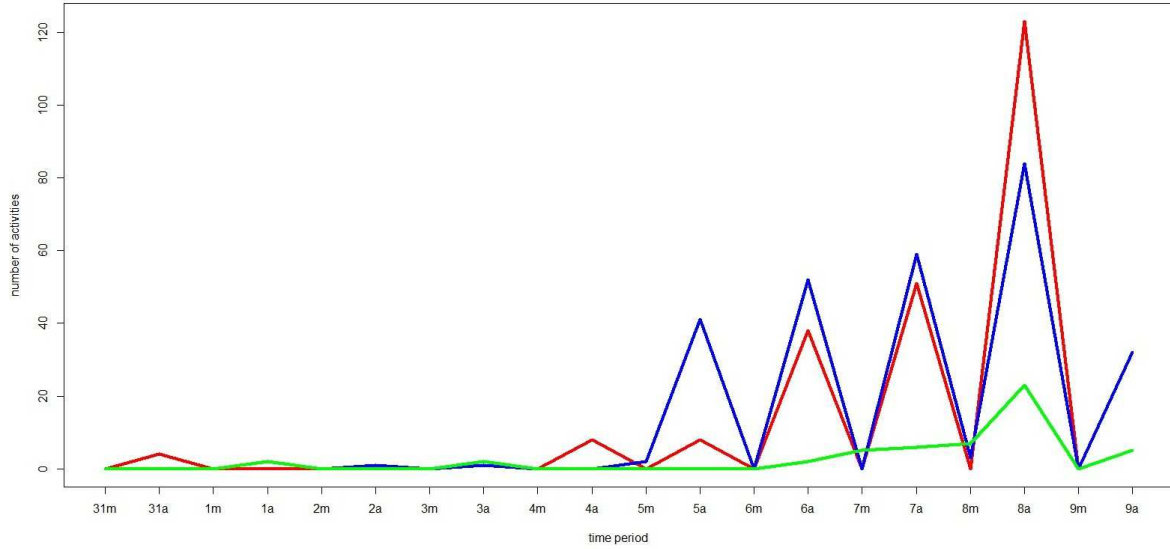


Figure 1: Plot to compare the activity of a normal bee (green) with the two outliers bees (B4387 and B5134) in cohort 1.

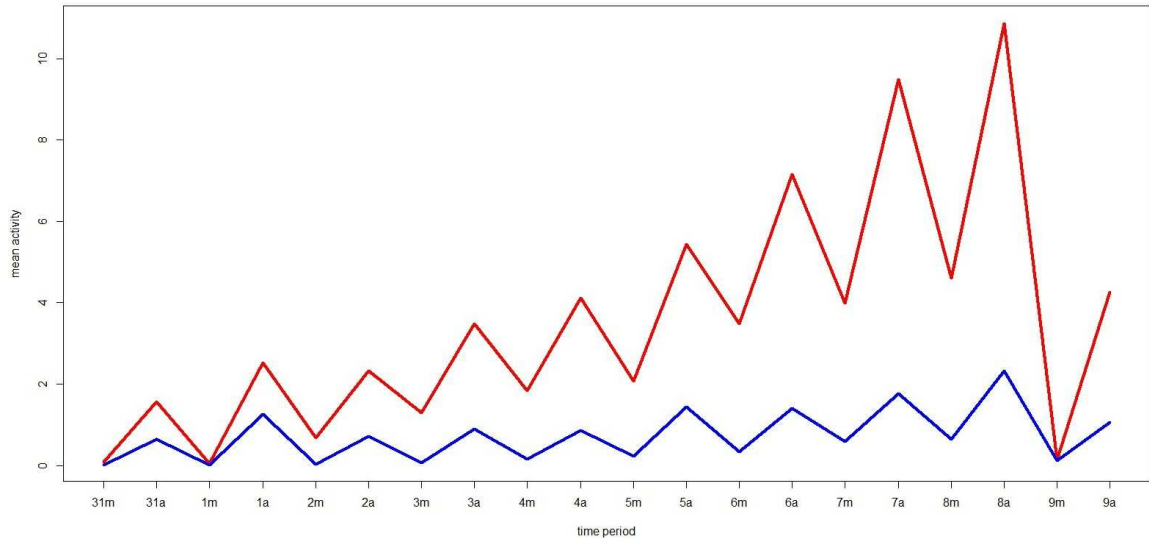


Figure 2: Plot of bees' activity means at each time period of the two clusters formed using kmeans.

1984). Therefore, we have excluded this two bees because it can harm the clustering process, in particular kmeans, which requires means computation.

To find the groups with similar activity formed from the 380 bees in cohort 1, we apply two clustering algorithms: Kmeans, Partitioning around medoids (PAM) and Agglomerative hierarchical (AGNES) to

the data partly shown in table 5 (Jain and Dubes, 1988). We have evaluated from two up to six clusters. In Table 6, we show the sizes of each cluster, grouping the data from 2 up to 6 clusters, without taking into consideration the two outliers

Notice that when two clusters are formed using kmeans, the smaller cluster contains the most active

Table 6: Cluster sizes using three algorithms, excluding the two outliers.

| Algorithm | K=2 | K=3 | K=4 | K=5 | K=6 |
|-----------|---------|------------|--------------|-------------------|-----------------------|
| Kmeans | 288,92 | 264,8,108 | 7,91,238,44 | 27,34,234,5, 80 | 240, 26 ,41, 3, 5, 65 |
| PAM | 246,134 | 240,50,90 | 186,71,43,80 | 186,69,39,6,80 | 186,69,36,6,68,15 |
| Agnes | 227,143 | 237,13,130 | 227,5,8,130 | 237, 5,8, 100, 30 | 237, 4, 8,100, 30, 1 |

bees is about 24 percent of the total number of bees. Similar porcentaje (20 percent) was found in (Tenczar et al., 2014). Also, when three clusters are considered, both Kmeans and AGNES show a third cluster of very small size compared with the other two. This suggests the existence of more outliers.

3.1 Clustering Validation

Now, in order to determine the optimal number of clusters, we have computed 4 internal cluster validation measures: The Silhouette, Dunn Index, Davies-Bouldin Index, and the Calinski and Harabasz index (Halkidi et al., 2001). A Silhouette value close to 1 indicates a good clustering. The number of clusters with the highest Dunn index is the best one. According to the Davies-Bouldin index the best number of clusters is the one with the minimum value. The optimal number of clusters according to the Calinski and Harabasz index is the one with the highest value.

Table 7 shows the results of the measures for the kmeans algorithm. The Davies-Bouldin index was computed using R package's *clusterSim* and the remaining ones using the R package's *fpc*.

Table 7: Internal measures for clustering validation using kmeans, (*) indicates the best result for a clustering validation measure.

| Measure | K=2 | K=3 | K=4 | K=5 | K=6 |
|--------------------|---------|---------|--------|--------|--------|
| Silhouette | 0.4557* | 0.4483 | 0.3813 | 0.3773 | 0.3865 |
| Dunn | 0.0571 | 0.0780* | 0.0607 | 0.0607 | 0.0685 |
| Davies-Bouldin | 1.6793 | 1.3964* | 1.8070 | 1.6652 | 1.6955 |
| Calinski- Harabasz | 133.97* | 125.74 | 108.74 | 98.22 | 88.64 |

From Table 7, we can see that the optimal cluster number can be either two or three. By visualization (see Figure 4) three clusters are suggested, but according to co-authors of this paper with high domain knowledge on bees behavior is better to consider only two clusters.

In Table 8, we show the cluster validation measures for the clusters obtained using the PAM algorithm.

Table 8: Internal measures for clustering validation using PAM, (*) indicates the best result for a measure.

| Measure | K=2 | K=3 | K=4 | K=5 | K=6 |
|--------------------|---------|---------|--------|--------|--------|
| Silhouette | 0.4019* | 0.3882 | 0.1971 | 0.1961 | 0.2110 |
| Dunn | 0.0395 | 0.0464* | 0.0242 | 0.0255 | 0.0255 |
| Davies-Bouldin | 1.6773* | 2.1711 | 2.1964 | 1.9573 | 1.8428 |
| Calinski- Harabasz | 126.69* | 97.18 | 74.17 | 83.34 | 80.26 |

Using voting it seems that two clusters could be the optimum number of clusters. In this case, there is a concordance with the opinion of our co-authors with domain knowledge on bees behavior.

3.2 Clusters Visualization

In this section, we will show plots for both two and three clusters given by the kmeans algorithm and the two clusters given by PAM.

From Figure 2, it can be seen very clearly bees from the smaller cluster (red) have always more activity than bees in cluster 1 (blue). Also, we can notice that the bees's activity start to increase at day 5. This is very clear in the red cluster. On the other hand, bees's activity is noticeable greater in the afternoons. The majority of the members of clusters 1 are coming from colony M (168 bees out of 288, 58.33%), whereas most of the bees in cluster 2 are from colony L (55 bees out of 92, a 59.78%). Performing a Chi-Square test yields a p-value of .014, hence there is statistical significance of dependency between clusters and colonies. On the other hand, the other categorical attribute: "Treatment" behaves in similar way for both clusters, giving a p-value of .499. However, most of the members of cluster 1 (23.96 percent of bees) are coming from treatment "Mix D", whereas a 21.74 percent of bees in cluster 2 are coming from treatment "Mix E". Finally, we analyzed the combined effect of both "Treatment" and "Colony" on the cluster formation, and in fact, there is an effect. In the small cluster that includes 92 bees, the p-value for the Chi-square test is .017, which is highly significant. In the large cluster including 288 bees, the p-value for the Chi-square test is .016. A 27.27 percent of members of cluster 1 belongs to colony L and treatment "Mix E". Also, in the second cluster a 25.95 percent of bees belong to colony M and Treatment "Mix D".

Figure 3 shows the bees grouped into two clusters according to their daily activity. From Figure 4, clearly we can notice that bees in Cluster 2(in Blue) have more activity than bees in cluster 1 (red) and cluster 3 (cyan), But bees in cluster 3 start to increase their activity at day 7 and become the leading group. The majority of the members of clusters 1 and 3 are coming from colony M, but most of the bees in cluster 2 are from colony L. Finally in Figure 5, we visualize the two clusters obtained by PAM. Figure 5 suggests

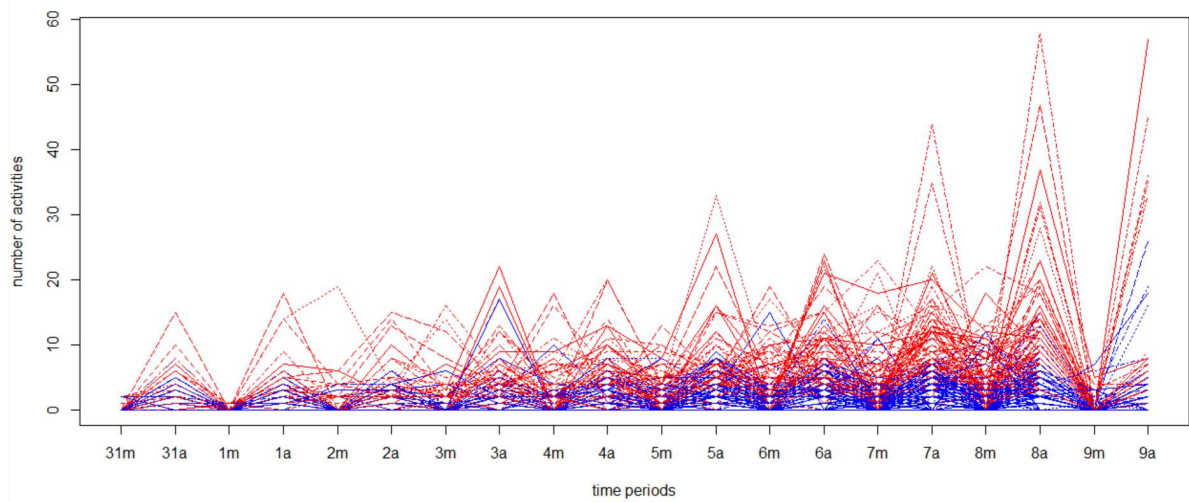


Figure 3: Plot showing activity of bees in two clusters given by kmeans.

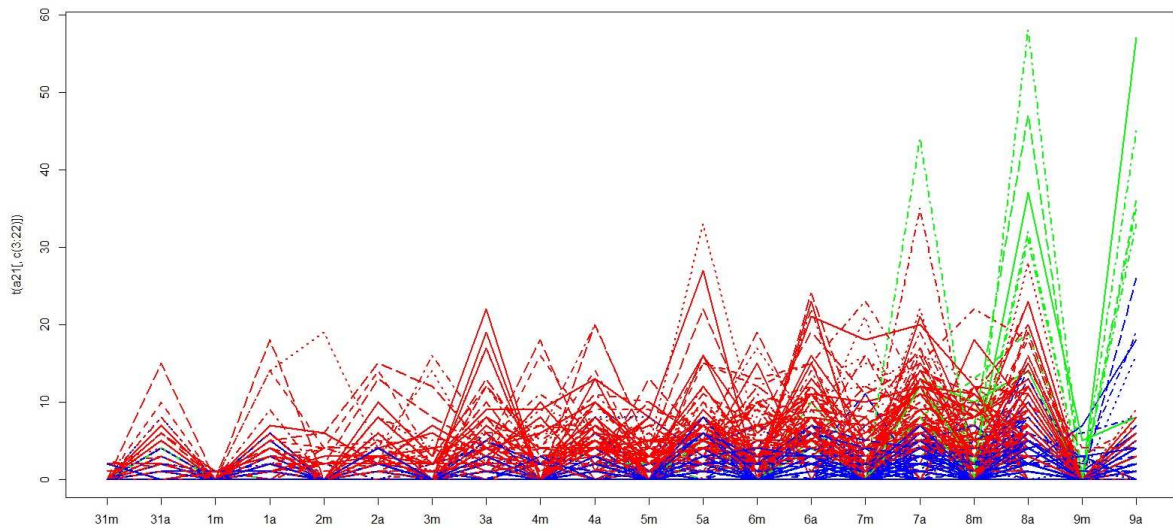


Figure 4: Plot showing activity of bees in three clusters given by kmeans.

same result as Figure 3.

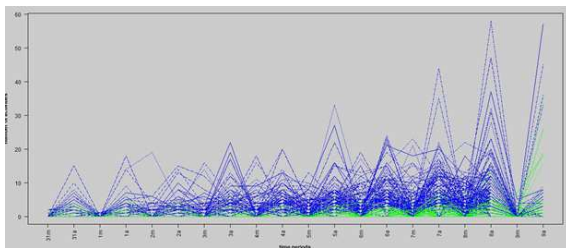


Figure 5: Plot showing activity of bees in two clusters given by PAM.

Plotting the clusters means per hour of the two clusters formed (see Figure 6), we can notice that one cluster (red) shows an increasing mean activity respect to days. Also, the highest activity is recorded between

the time interval from 2:00pm to 5:00pm. For the second cluster (blue) the same trend is showed but bees are less active.

4 FINDING THE TIME INTERVAL WITH THE PEAK ACTIVITY

During the data wrangling process as well in the clustering task, we noticed that most of bees' activity was between 8am and 8pm. Therefore, first we did an analysis for four periods of time: 8:00am-11:00am, 11:00am-2:00pm, 2:00pm-5:00pm and 5:00pm-8:00pm. We identified that the time-period 2:00pm-5:00pm had the largest count of activ-

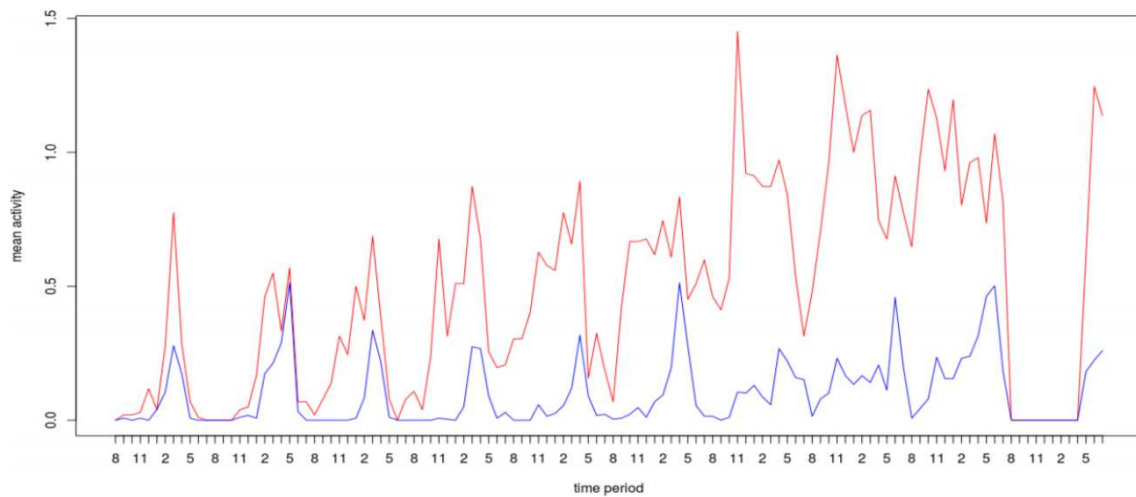


Figure 6: Plot showing means activity per hour of bees in the two clusters given by kmeans.

ity (1796) during the last four days, followed by the time period 5:00pm-8:00pm. Finally, we carried out an analysis by hour of the 380 bees during 8:00am-8:00pm, and we found out that most of counting of activity (809 counts) was from 2:00pm-3:00pm, followed by the time period 1:00pm-2:00pm(582 counts) and in third place the time period 3:00pm-4:00pm with 568 counts.

5 CONCLUSIONS

In this work, we have perform clustering on data about bees' daily activity during a time period of 10 days. According to the cluster validation measures we decided to use two clusters as the optimum number. Two categorical attributes "Treatment" and "Colony" although were no used in the clustering process, they are used in a posterior step to justify cluster formation. Using a Chi-square test we conclude that "treatment has no effect on the cluster formation, but "Colony" and "Treatment \times Colony" affect indeed the cluster formation.

Using data wrangling and visualization, we conclude that in one of the clusters the activity increases with the time and remarkably starting at the day 5. Furthermore, the highest bees' activity occurs between 2:00pm to 3:00pm.

The R scripts and a R shiny program used in this paper are available upon request from the first author.

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REFERENCES

- Bordier, C., Suchail, S., Pioz, M., Devaud, J., Colleta, C., Charreton, M., Conte, Y. L., and Alaux, C. (2017). Stress response in honeybees is associated with changes in task-related physiology and energetic metabolism. 98:47–54.
- Grolemund, G. and Wickham, H. (2011). Dates and times made easy with lubridate. 40(3):1–25.
- Halkidi, M., Batistakis, Y., and Vazirgiannis, M. (2001). On clustering validation techniques. 17:107–145.
- Jain, A. and Dubes, R. (1988). *Algorithms for clustering data*. Prentice-Hall, Inc., Upper Saddle River, NJ, USA.
- Prado, A., Pioz, M., Vidau, C., Requier, F., Jury, M., Crauser, D., Brunet, J.-L., Conte, Y. L., and Alaux, C. (2019). Exposure to pollen-bound pesticide mixtures induces longer-lived but less efficient honey bees. 650:1250–1260.
- Robinson, G., Underwood, B., and Henderson, C. E. (1984). A highly specialized water-collecting honey bee. 15(3):355–358.
- Tan, P., Steinbach, M., and Kumar, V. (2005). *Introduction to data mining*. Addison-Wesley Longman Publishing Co., Inc, Boston, MA, USA.
- Tenczar, P., Lutz, C. C., Rao, V. D., Goldenfeld, N., and Robinson, G. E. (2014). Automated monitoring reveals extreme interindividual variation and plasticity in honeybee foraging activity levels. 95:41–48.