Enterprise for Society

Digitalization & sustainable logistics

Semester project

May 2023

"Optimal WiFi placement within buildings."

Charlotte Ahrens
Sofia Estero
Ana Cristina Vides Gomez
Claas Klatte
Siméon Migeotte

1 Executive Summary

This report introduces an optimization solution for the placement of WiFi routers in big apartment complexes. The underlying problem we identified is the overuse of WiFi routers within apartment complexes. The excessive amount of routers is caused due to individual purchases of routers for every apartment, while the reach of the routers goes beyond the individual apartments. The report covers several steps in order to have a 360° approach to this topic. First, it explains the building of a mathematical model using various assumptions and parameters. Then it proceeds to describe how these insights and assumptions were implemented in Python code. The model created and used in this project is a simplified model, which is applicable to specific situations. However, it is flexible in terms of adapting to many parameters to fulfill the need of specifications. Furthermore, the report sheds light on various fields in our society, including sustainability aspects, energy, and health challenges, which are impacted by WiFi routers. Lastly, the report discusses the opportunities and limitations of the model.

While social aspects and more practical considerations need to be examined in more detail, the results focus on the environmental implications of the optimization. The model with the given test parameters showed the potential to reduce the number of WiFi routers in one complex from 180 to 4 or 13 routers, depending on the router (2.4GHz or 5.0GHz) chosen. These numbers might be overly optimistic but show a strong indication of the impact this model can have on sustainability. From an energy-saving point of view, this could lead to a saving of a total of 8317.8 kg CO_2e due to lower production of routers and 18499.6 kWh from the use of the devices per year. While this is the first key takeaway of the optimization model, the results and potential opportunities are promising to have an enormous impact on the building sector in the future.

Contents

2 Introduction

In today's world, technology holds immense significance in various facets of human existence, ranging from communication to leisure. The internet, alongside WiFi, spearheads this transformative era of technology, witnessing a remarkable surge in usage across different dimensions of time and space. Indeed, digital connectivity has become an essential tool for many human activities, both at work and in personal life. One key example of its increasing importance was its role during various lockdowns due to the Covid-19 pandemic. WiFi is a wireless networking technology and, as the word says, it allows users to connect to the internet without wires. In fact, its functioning is based on radio waves that grant internet access in local and relatively small areas. More specifically, the term WiFi is a trademark owned by the WiFi alliance to certify those technologies based on the IEEE 802.111 family standards (Jian, il 2), which refers to a set of standards that define communication for wireless local area networks (WLANs) (Jeffery, 2023). Despite WiFi being initially developed for industrial and corporate applications, it spread to homes and public spaces at a fast pace. (Swalih, 2023) In fact, in a few years, WiFi has become an indispensable tool in houses, allowing young and old to digitally connect with the external world from the comfort of their homes.

This report explains the creation and usage of an optimization model developed to address the issues arising from the placement of many WiFi routers in apartment complexes. While the first chapter is devoted to the explanation of the problems which are caused by an intensive WiFi supply, the following chapter describes the parameters, assumptions, and mathematical formulations that are the result of our research, providing the foundations for the development of the model. Moreover, the third chapter explains the different results obtained by focusing on different frequencies, which highly impact the strengths of the WiFi signal and the latter maximum reach. Finally, the fourth chapter deals with sustainability considerations mainly focusing on carbon emission and energy consumption, as well as some possible effects of WiFi usage on human health. Furthermore, this last chapter provides insights regarding future usages of the created model, explaining its possible extensions, as well as limitations.

3 Problem statement

The accelerated spread of the need for internet connection in everyday life activities, together with the rise of smart home and IoT devices, has triggered the demand for a throughout internet coverage both in professional and residential settings. As far as apartments are concerned, it usually occurs that entering an apartment unit, our devices detect numerous WiFi connections that are locked by passwords and therefore are accessible only by the owners of the router. The problem is that each household owns a personal network, therefore causing an overlap of WiFi connections. This creates superfluous costs for each apartment owner, as they have to buy a router for personal use and to subscribe to an internet plan, not to mention the energy and maintenance costs that are associated with the functioning of the device. On a broader scale, this has a large impact on society. If we look at the idea of having a common router shared among different apartments and compare it to the current state of redundant routers employed in buildings, the latter contributes to higher energy consumption (which also fuels the current energy crisis) and enhanced material usage (in particular metals and other electronic components). Moreover, the ongoing debate on the impact of increased WiFi networks on human health will be discussed in more detail in chapter five.

In order to understand the reach of this problem, we developed a logistic model to optimize the number of routers deployed in a four-building apartment complex, while ensuring safe internet access and full coverage in all apartments. In our opinion, the proposed solution could be further developed into a new business model used by internet providers. Providers, motivated by sustainability and financial aspects could propose internet plans for entire buildings, targeting the landlord instead of single households. In this regard, similar business models are already applied in comparable contexts, such as student housing, corporate buildings, and universities.

4 Methodology

In order to work on the stated problem, this section takes a mathematical approach to solve the open question. We will take a closer look at Assumptions, the mathematical model, as well as the model implementation.

4.1 Assumptions

Let us start by explaining the problem in a mathematical context. We have met several assumptions, which are based on research and simplification purposes.

We build a Facility Location Problem (FLP), meaning we are looking at the optimized location within a building complex to place WiFi routers in specific apartments, with the goal of covering other surrounding apartments, while assuming: that one apartment is made up of four rooms, separated by different types of walls, which we distinguished based on material:

- Within the apartment, we have thin walls made out of lumber.
- Between the apartments we assume the walls are made out of masonry blocks.
- The outside of each building is made of an 15 cm thick concrete wall.
- The ceilings between each floor are made of a 30 cm thick concrete layer.

We make two more assumptions concerning the router placement. Each room within each apartment is a possible location to set up the WiFi router and the WiFi router is placed centrally within the room.

We chose several deterministic parameters including the WiFi wavelength in open areas, as well as the deduction of wavelength due to walls and ceilings.

Based on the material and the thickness of the wall, we determined the impact it has on the WiFi wavelength. Throughout our research, we have discovered that walls and obstacles exert an influence on the wavelengths of WiFi signals. However, this influence is directly proportional to the remaining wavelength. In simpler terms, when a WiFi wavelength passes through a wall, the distance it covers is reduced by a percentage rather than a specific meter measurement. To incorporate these assumptions into our code, and in order to simplify the model, we did not use percentage reduction at each wall, instead, we performed calculations to determine the average impact of walls on the WiFi signal, this impact is in meters. In performing these calculations, we utilized the following percentage reductions for the effects of different types of walls: 10% for small walls, 20% for medium walls, 33% for big walls, and 50% for the ceiling. We were quite generous with these estimations, they should be taken with a grain of salt as we were inspired by a few articles: (ekahau, 2021) and (Newth, 2021). The favorable outcomes anticipated in the subsequent section are undoubtedly attributed to our generous consideration of the obstacles' impact. We consider these numbers to be of limited significance as they are contingent upon the composition of buildings/apartments and can be customized for each specific case. This brings us to the signal reduction table 1 which was calculated considering 5x5 meter rooms. We will use this table for our different models independently of the room dimensions.

Table 1: WiFi Signal Reduction by Different Walls

Wall type	Reduction 5GHz in (m)	Reduction 2.4GHz in (m)	Composition
Small wall	1.8	4.2	Lumber
Medium wall	2.6	7.5	Masonry block
Big wall	5	11.7	Concrete, ∼15 cm
Ceiling	6.6	18.8	Concrete, ∼30 cm

For instance, let's consider a medium wall that is set every 10 meters (if we consider a room size of 5x5 meters), and a router with a range of 30 meters operating at a frequency of 5 GHz, with a -20% reduction in wavelength due to the wall. In this scenario, we found that on average, each wall that the signal passes through reduces the latter effective range by approximately 2.6 meters. To shed more light on this process, the following paragraph gives an example of the computational process for the medium wall.

Starting with a total reach of the WiFi router of 30 meters, we advance 10 meters away from the position of the device, encounter a wall, and apply a 20% reduction on the remaining 20 meters, resulting in a reduction of 4 meters. This leaves us with 16 meters. We proceed another 10 meters. Then, applying a 20% reduction on the remaining 6 meters, we subtract approximately 1.2 meters. Thus, the average impact of the wall is estimated to be (-)2.6 meters on the router's reach.

We would like to clarify that our current analysis does not take into consideration other types of walls apart from the ones mentioned above. While our calculations focus on the specific type of walls, we acknowledge that there may be additional variations that could impact the overall results. For a more accurate and comprehensive analysis, further investigation of the effects of various wall types and other obstacles would be necessary.

In the scenario involving big walls and a 5 GHz signal, we made an adjustment to the distance between the big walls. Instead of assuming a distance of 30 meters between the big walls, we adjusted it to 15 meters, in order to have the signal pass-through for the 5.0GHz wavelengths. This adjustment was made to ensure that the router's reach would not be exhausted before reaching the first big wall.

By employing this approach, we have simplified the complexity of our model. However, we recognize that the results obtained are less precise, yet they serve as a good approximation. In a more realistic scenario, further research should be conducted to investigate the impact of walls on the router's reach. Implementing a percentage-based wall reduction would be a valuable enhancement to improve the precision of our model's results.

4.2 Mathematical Model

After having a common understanding of the assumptions that were made for the facility location model, we take a closer look at the variables including mathematical expressions of those. As seen above, the reduction in wavelength is set at fixed values. They vary based on the router (2.4GHz versus 5.0GHz) which were used in our models. In our scenario, we distinguish between these models, as the reach of the wavelength is differently impacted by each wall. Moreover, due to different apartment buildings, the variables for the size of the apartment, the number of floors, the number of apartments within each complex, as well as the distance between different apartment complexes are set to be user-based inputs, in order to adapt the model to each practical case. The parameters in our model are as follows:

A) Mathematical Problem Definition:

- A set of (m) rooms on the x,y, and z-axis that need to be covered by WiFi wavelength
- A set of (n) WiFi routers
- The # of floors (f)
- WiFi router (i)
- The reach of the router type (D)
- Room (j)
- The # of rooms on the x or y axis (R)
- We have a set of (n) routers that need to cover the entire set of (m) rooms.
- The distance between the WiFi router (i) and (k) is $d_{ij}, (i, j) \epsilon \ (R * R * f)$
- Parameters $i \ \epsilon \ \{1, ...n\}; \ a_{ij}, \ j \ \epsilon \ \{1, ...m\}$

B) Mathematical Formulation:

- Decision Variables:

- 1. Does the room have a WiFi router placed?

$$x_i \; \epsilon \; \{0, 1\}, \; i = \{1, ..., n\}$$

$$(x_i = 1, \; if \; WiFi \; router \; (i) \; is \; placed, \; otherwise \; x_i = 0)$$

- 2. Do two WiFi routers cover the whole line between them?

$$y_{ij} \epsilon \{0, 1\}, (i, j) \epsilon \{1, ...n\} \{y_{ij} = 1 \; if \; d_{ij} \leq 2 * D\}$$

- Objective Function: The goal is to minimize the total number of routers used:

$$z = \sum_{i=1}^{n} x_i$$

- Constraints: Each room must be covered by at least one WiFi router.

- 1: Binary variables (a_{ij}) indicating if the room (j) would be covered by WiFi router (i):

$$\sum_{i=1}^{n} (a_{ij}) x_i \geq 1 \; j \; \epsilon \; \{1, ...m\}$$

- 2: Total area covered by two routers next to one another:

$$\textstyle\sum_{j \in R*R*f, \; j \neq i} y_{i,j} \geq 1 \quad \forall i \in R * R * f$$

4.3 Implementation

After defining our model mathematically we implemented it into a coded optimization problem, using the programming language Python. The complete code can be found on the GitHub repository Logistic Optimization: WiFi (Ahrens, 2023). To better understand how we transferred our model into code, one can refer to Figure 1, which shows the underlying idea of our model. It describes a symmetric square model in which each integer in every direction (x, y, and z) represents the allocation of one room (blue squares). Starting in one corner with coordinates (0,0,0), all of our code is based on simple calculations and integer comparisons. This gives us the possibility to easily change the sizing parameters of our rooms without making any changes to the model outcome itself. As one can see in the top view, our model consists of 4 buildings (orange squares), which have 5 floors (side view). On each floor, there are 9 apartments (yellow boxes around each square of 4 rooms) with 4 rooms (blue boxes) each. Each room can allocate a WiFi router or not, which is the baseline for

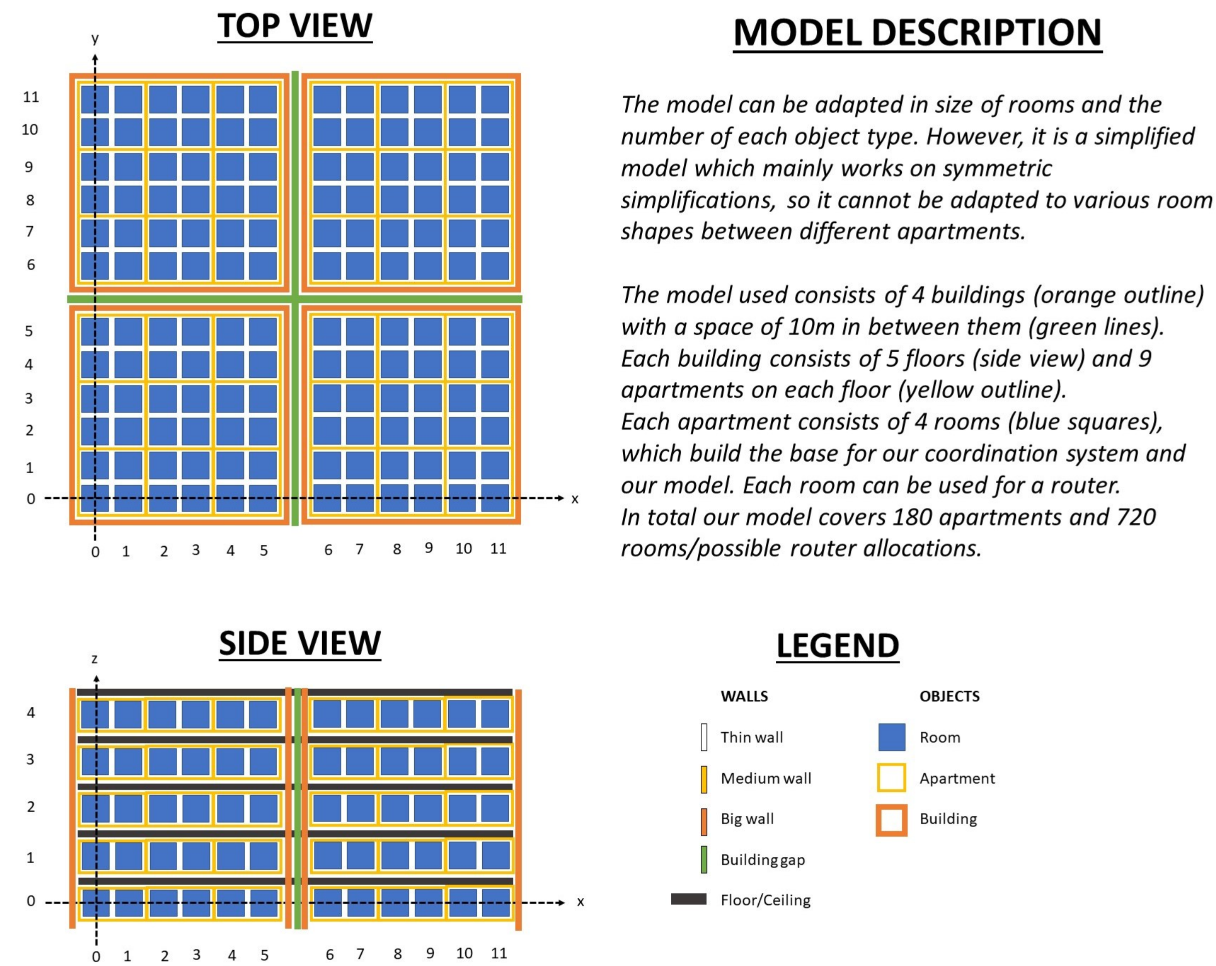


Figure 1: Model Visualisation

our optimization code. The full code can be found in Figure 13 to Figure 17 in the appendix and is implemented as follows.

Firstly, we install several libraries, which are required for the optimization model (Figure 13 in the appendix). These include Google OR tools, which help us to create an optimization model, as well as the mathematical and visualization libraries to do calculations in our code and to visualize the results of our model for further data analysis.

In the next step, we define our model parameters (Figures 14 and 15 in the appendix). We realized that we needed to make several assumptions and simplifications to our model. Therefore we decided to create many parameters that can be easily changed in this section to make our model more flexible and adaptable to different buildings and environments. On top of defining the underlying model with Google OR tools, we explain the following parameters:

1) `min_distance`: This parameter describes the reach of our router signal in an outside environment since different router types have different reach. Also, there are different es-

timations of reach within buildings however we decided on the outside reach as our model calculates the inside reach including on our specific parameter definition.

2) s, f, ac and `num_blocks`: These parameters describe the room allocation and the general coordinate system for our model. s is the number of apartments per building in one horizontal direction (in this case 3, which corresponds to 6 rooms among the line of 1 building. f is the number of floors (set to 5 in our model), ac is the number of buildings next to each other, while `num_blocks` simply calculates the total number of rooms, which is also the number of possible router allocations.

3) l, w, h: These parameters describe the individual rooms by stating their length, width, and height. Every room will have the same design in our model, which was a necessary simplification. However, with these parameters, we are able to adapt our model to roughly fit the actual sizes of rooms, by adjusting especially the length and width.

4) sw, mw, bw, c, hd: These parameters are needed for our constraints. We estimated the barriers of the WiFi signal through walls by adding additional distances that the signal would need to travel corresponding to this barrier. We defined different types of walls, based on their composition and thickness, so that we can add these to our model. We will explain the constraints in more detail in the next paragraphs.

Our constraints are implemented in the way we calculate our distance matrix, which uses a `euclidean_distance` function that we defined in Figure 16 in the appendix. The general distance between two points in three dimensions can be calculated by the same formula, which takes x, y, and z coordinates into account. This is the first line in our function definition in Figure 16. The next three lines in Figure 16 help us analyze what happens in each direction by calculating the directional distance differences for each coordinate: diffz, diffx and diffy.

The following blocks of code implement the constraints that each obstacle forces onto our WiFi signal. We do data pre-processing here. We implement the distance constraints already in the way we define our distance matrix so that later on we can simply work with this distance matrix in our model and do not have to add additional constraints to the model.

Starting with the ceilings (Figure 2), which block the WiFi signal the most in the vertical direction. If there is a vertical distance between two points, then we add the distance the signal has to travel plus the distance effect of the ceiling c defined by the parameters. The formula (diffz/h) calculates how many ceilings are between the two points.

```
  #ceiling effect
if diffz > 0:
  distance += (diffz/h)*c      #add distance for every ceiling/floor that we pass through
```

Figure 2: Code for ceiling constraint

The small wall effect (Figure 3) refers to every wall between rooms. We have to add this effect to every room that the signal travels through (once in the x direction and once in the y direction). The calculation works in the same way as for the ceiling effect.

```
#small wall effect
if diffx > 0:
  distance += (diffx/l)*sw    #add distance for every small wall that we pass through
```

Figure 3: Code for small wall constraint

When it comes to the medium wall effect (Figure 4), there are various possibilities we need to check for. Every apartment is surrounded by a medium wall, which means that every two rooms there is a medium wall. Hence, firstly in our code, we check if the two points in the x-direction are an exact multiple of two apart from each other. If that is the case one can see in Figure 1, that there is always the number of medium walls between the two points as the number of rooms, which is calculated by the (diffx/l)//2 line. This is then multiplied by the thickness of the medium wall (mw) and subtracted from the thickness of the thin wall (sw). The subtraction is due to the fact that with our thin wall constraint, we add a thin wall between every point. To avoid adding a distance for a thin wall and a medium wall, which would not exist next to each other and, hence, duplicate it in our model, we have to subtract this thin wall. When the distance between two points is an odd number we arrive at a problem because an odd number means there are two possibilities of a number of medium walls between the two points. Taking in 1 and looking just at the bottom line of rooms in the x-direction, we can take the example of points x1 and x8, which are seven (uneven) rooms apart. They have four medium walls in between (simplified in this code: the gap between the building blocks is seen as one medium wall, which will further be taken into account in the big wall calculation). However, points x2 and x9 are also seven (uneven) rooms apart but have only 3 medium walls in between them. Our code takes this into account by an additional if statement, which checks if the left room of the two (according to our x coordinate in 1) has an even number. If that is the case it means there is a medium wall right to the left of it and it has a lower number of medium walls between itself and the other room. If it is an odd number it has one more medium wall in between the two rooms, hence we add and subtract the additional (mw-sw) in the else-statement. The same code structure is then applied in the y direction.

```
#medium wall effect
if (diffx/l) % 2 == 0:
  distance += ((diffx/l)//2) * mw
else:
  if (a[1]<b[1] and (a[1]/l)%2==0) or (b[1]<a[1] and (b[1]/l)%2==0):
      distance += ((diffx/l)//2) * (mw-sw)
  else:
      distance += ((diffx/l)//2) * (mw-sw) + (mw-sw)
```

Figure 4: Code for medium wall constraint

For the big wall effect (Figure 5) the code checks whether both rooms are in different buildings (e.g.: whether they are located more than the number of rooms in one building apart from each other). If that is the case in one of the two horizontal directions we analyze the situation similarly to the medium wall effect. More concretely we check for the two different possible conditions of the location of the room within the building which influence whether it is one more or less big walls between both rooms. Based on this analysis, we multiply the number of these building gaps by two times the big side walls of the building and the distance between the buildings, subtracting the medium wall and small wall. These walls have been added according to the previous lines of codes but can be replaced here by the big wall effect. One should note here that we started with a code that simply checks the big wall effect for a model of 2x2 buildings. The code presented here in Figure 5 is more complex and works with any squared arrangement of buildings, so one could even check for 5x5 buildings with this code. However, when running the code we discovered that this calculation needs a lot of time. Already for the 2x2 buildings this new more complex code takes significantly longer than our simpler code before. This complex code works correctly, but for bigger housing complex projects one needs a lot of computing power and time to get to results.

```
    #big wall effect
  if (diffx/l) // (s*2) > 0:
    if (a[1]<b[1] and (a[1] % (s*2)) < ((s*2)-((diffx/l) % (s*2)))) or (b[1]<a[1] and (b[1] % (s*2)) < ((s*2)-((diffx/l) % (s*2)))):
        distance += ((diffx/l) // (s*2)) * (2*bw + hd - sw - mw)
    else:
        distance += ((diffx/l) // (s*2)) * (2*bw + hd - sw - mw) + (2*bw + hd - sw - mw)
```

Figure 5: Code for big wall constraint

The distance returned by our code is the final distance between two points, which already includes the theoretical additional distance the signal has to travel due to all the wall constraints. Hence, it is a theoretical distance that represents the distance the WiFi signal would travel outside without any obstacles. It is a pre-processed distance that already includes some of our constraints, which makes the rest of our model code easier to run.

After this pre-processing of our distances, we can run our optimization model.

The variable "points" in Figure 6 are initialized as a list comprehension that generates a set of points representing the possible locations of routers. The range function is used to specify the boundaries of the space in three dimensions (length, width, and height). The variable "selected_points" is an adapted point matrix according to real distances, since we multiply the coordinates with real distances h,l, and w.

The variable "distance" is initialized as a nested list comprehension. It calculates the Euclidean distance between each pair of selected points using the `euclidean_distance` function, which was defined above. It takes into account the different obstacles that we added to our model.

```
#create model of room location
points = [(i, j, k) for i in range(f) for j in range(s) for k in range(s)]     #simple point matrix with distance 1 between points
selected_points = [(i*h, j*l, k*w) for i, j, k in points if i in list(range(f)) and j in list(range(s)) and k in list(range(s))]   #adapted point matrix according to real distances

#create distance matrix between all rooms
distance = [
    [euclidean_distance(a, b) for b in selected_points] for a in selected_points
]
```

Figure 6: Code: creating the points

The variable "x" in Figure 7 is created as a list of decision variables using `model.NewIntVar`. Each decision variable represents the installation of a router in a specific room. It takes binary values, 1 if a router is placed in room j and 0 if not. The list comprehension `model.NewIntVar`$(0, 1, ``x[\%i]"\%i)$ for i in range(num_blocks) creates "num_blocks" decision variables named x[0], x[1], and so on. The variable "z" is created as an integer decision variable using `model.NewIntVar`. It represents the total number of routers used and is the objective to be minimized. It has a lower bound of 0 and an upper bound of num_blocks.

The line `model.Add`(z == sum(x)) adds a constraint to the model that ensures that the variable "z" is equal to the sum of all the decision variables "x". This constraint indicates that the objective is to minimize the total number of routers used.

A loop is used to iterate over each room or point (num_blocks), and a constraint is added to the model for each room. The constraint ensures that there is at least one router placed within a minimum distance (min_distance) from the room and thus, it ensures that each room is covered by at least one WiFi router. This is achieved by checking the distances in the distance matrix. The constraint is expressed using the sum function and a conditional expression [x[j] for j in range(num_blocks) if distance[i][j] = min_distance] that sums the decision variables for the rooms that satisfy the distance condition. The sum is constrained to be greater than or equal to 1, indicating that at least one router must cover the room. The line `model.Minimize`(z) indicates that the objective of the model is to minimize the variable "z", which represents the total number of routers used. We are then able to solve the model. If the status is optimal (cp.OPTIMAL), the code proceeds to print the minimum number of routers used (solver.Value(z)) and the values of the decision variables (solver.Value(x[i]) for each i).

```
# define decision variables - coverage of router x=1 if covered
x = [model.NewIntVar(0, 1, "x[%i]" % i) for i in range(num_blocks)] #decision, where we put routers (1 if we use router in room, 0 if not)
z = model.NewIntVar(0, num_blocks, "z") #total number of routers used (want to minimize)

#objective to minimize:
model.Add(z == sum(x))

#constraints
for i in range(num_blocks):
        model.Add(sum([x[j] for j in range(num_blocks) if distance[i][j] <= min_distance]) >= 1)


model.Minimize(z)
solver = cp.CpSolver()
status = solver.Solve(model)
if status == cp.OPTIMAL:
  print("z:", solver.Value(z))
  print("x:", [solver.Value(x[i]) for i in range(num_blocks)])
  print("NumConflicts:", solver.NumConflicts())
  print("NumBranches:", solver.NumBranches())
print (len(x))
```

Figure 7: Code: Solving the model

The code in Figures 8 and 9 displays the results of a room coverage visually. It starts by extracting the coordinates of the selected points (representing rooms) and the router placements obtained from the solver. The router placements are then separated into their individual coordinates. Next, the code rotates the router coordinates and the overall coordinates to adjust their positions for plotting purposes. Finally, a 3D visualization is created using matplotlib. The room coordinates are plotted as blue squares, and the router coordinates are plotted as red triangles. The resulting plot provides a visual representation of the room coverage optimization results, showing the locations of the rooms and the placement of routers.

This visualization gives insights into how the routers are distributed within the rooms, helping to understand the effectiveness of the optimization algorithm in achieving the desired coverage.

```
# Extract the coordinates of selected points and router placements
coordinates = np.array([list(point) for point in selected_points])
router_placements = np.array([solver.Value(x[i]) for i in range(num_blocks)])

# Separate the router placements into individual coordinates
router_coordinates = coordinates[router_placements == 1]
display(router_coordinates)
rotated_router_coordinates = np.copy(router_coordinates)
rotated_router_coordinates[:,0] = router_coordinates[:,2]
rotated_router_coordinates[:,1] = router_coordinates[:, 1]
rotated_router_coordinates[:,2] = router_coordinates[:, 0]
display(rotated_router_coordinates)
# Rotate the coordinates and adjust the position
rotated_coordinates = np.copy(coordinates)
rotated_coordinates[:, 0], rotated_coordinates[:, 1], rotated_coordinates[:, 2] = coordinates[:, 2], coordinates[:, 1], coordinates[:, 0]

# Plotting the 3D visualization
fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')


# Plot all room coordinates
ax.scatter(rotated_coordinates[:, 0],rotated_coordinates[:, 1],rotated_coordinates[:, 2], c='blue', marker='s', label='Room')

# Plot router coordinates
ax.scatter(rotated_router_coordinates[:, 0], rotated_router_coordinates[:, 1], rotated_router_coordinates[:, 2], c='red', marker='^', s=110, alpha=0.8, edgecolors='black', label='Routers')
```

Figure 8: Code: Visualization

```
# Set labels and legend
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
ax.set_title("Wifi Router Placement")
ax.legend()

plt.show()
```

Figure 9: Code: Visualization

In conclusion, while our current code serves as a solid foundation, there are several ways in which we can further improve our model. These possibilities will be explored and discussed in the discussion part.

5 Results

The optimization model that we created allows the user to input different values in the parameters, according to the various apartment sizes and the WiFi router selections. In this section, we compare the outputs of different models resulting from considering different values for those parameters, that are listed in Table 2, as well as for the frequency signal of the router which can take values 2.4GHz or 5.0GHz.

In order to amplify our range of applications, we decided to apply the models to two situations: first, to a single building made of 5 floors, each floor containing 9 apartments, therefore summing up to 45 apartments in total. Since each apartment has 4 rooms, we consider a total of 180 rooms. Extending the model, we considered 4 different buildings, with the same structure as the one described above. In total, we conducted three tests with different parameters, which are summarized in the table below. The three tests vary based on the number of buildings as well as the input parameters. Test_1 was conducted on the default parameters that we chose for a building, however, only considering one apartment building. Test_2 has the same parameters, for comparison purposes, but now the model is extended to 4 apartment buildings (2*2 in the x, y-axis). In test_3 we keep the number of buildings equal to four, as before, however, now changing the parameters, creating a bigger and higher apartment building.

Input data (characteristics)	test_1	test_2 (default_values)	test_3
length	4	4	3
width	4	4	6
height	3	3	4
# of floors	5	5	8
# of apartments in x,y	3	3	3
distance between houses	10	10	20
# of apartment complexes in x,y	1	2	2

Table 2: Input Parameters for 3 different test runs

In addition, it must be considered that we start counting the apartments at (0,0,0), moving along the x-axis for each room count, then moving over by 1-y and moving again along the x-axis from (0,1,0), and so on. When the ground floor is covered, from the next floor, the model continues counting. Knowing the apartment number will be interesting for the landlord, so he or she can approach the tenants who require the placement of the WiFi router within their apartments. As soon as the apartment number is given, the specific room within the apartment can be fine-tuned.

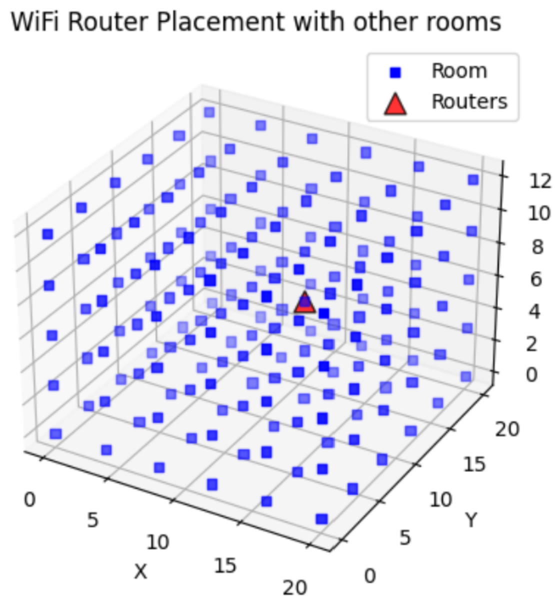
5.1 One apartment building

First, we tested our model on one building. This apartment complex has 9 apartments on each floor. Assuming we have 5 floors and each apartment with a total size of $8*8 = 64m^2$ is evenly divided into 4 rooms.

- 2.4GHz WiFi frequency. Considering the case of a single building discussed before, together with the 2.4 WiFi frequency, we find that we would only require one router for the whole building. This WiFi router would be required to be placed in room #94, on the third level. The level can be determined since we know that there are 9 apartments*4 rooms per apartment = 36 rooms/floor. Therefore, room #94, is between (room numbers 73 - 108), which indicates the rooms for the third floor. This would correspond to apartment #23, which can be easily found by dividing the number of rooms by 4, as each apartment is composed of 4 rooms. The results are shown by the (Figure 10 (test_1))

- 5.0GHz WiFi frequency. Considering the same model, and varying the WiFi wavelengths by switching to a 5GHz router, we clearly see an increase in the number of

```
The following apartments need to be equipped with a WiFi router:
Apartment 94
```




```
Here is a visualization of only the router placements:
```

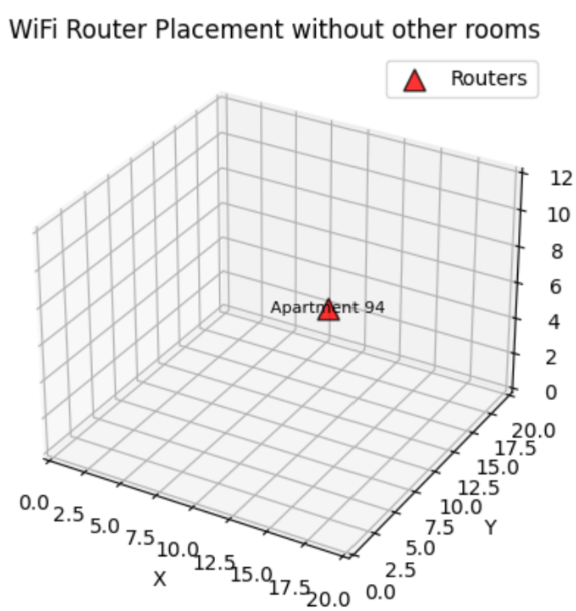


Figure 10: Result for 2.4GHz WiFi router, 1 apartment building

necessary devices (Figure 18 (test_1) in the Appendix). For the same apartment building, we now require four routers in order to cover each room within each apartment. These routers are placed within rooms 3 and 34 on the first level (ground floor), and 128 and 131 on the fourth level.

Until now we covered the case of a single building. In order to make the model more complex and applicable to real-life scenarios, we study how the WiFi router placement changes when considering a shared WiFi router network among neighboring buildings. Real-life examples for this scenario are represented by student housing, or apartment complexes that are leased by agencies. This makes the model more interesting due to its parallelism to real-life case studies.

5.2 Four apartment buildings

- 2.4GHz WiFi frequency. Due to the long reach of the 2.4 GHz frequency in open spaces, compared to the 5.0GHz, this router would be useful when it is necessary to cover apartments across different buildings that are separated by a substantial open space. However, our (test_2 default values) results in the Appendix (Figure 19) show that in this specific case and for the input parameters that we chose, sharing the WiFi routers across apartments does not provide any additional benefit. Indeed, we have a total of 4 routers for the four building complexes, which would still entail one router per building complex, which corresponds to the result we found in the previous study of a single building. For the third test parameter (test_3, Figure20, we chose bigger room sizes, a higher ceiling, an increasing number of floors (8 floors, instead of 5 previously), as well as twice the distance between the complexes (which before was 10m and now increased to 20m) to consider the case in which these buildings are far from each other. This change impacts the number of routers needed. Table 3 shows that for the 2.4GHz scenario, the number of routers doubles. Possible explanations are the increasing number of ceilings, which have a big impact on blocking wavelengths, as well as the bigger apartment size which increased from 64^2 to 72^2.

- 5.0GHz WiFi frequency. Taking a closer look at the data resulting from the 5GHz scenarios (Figure 21), it is possible to notice that sharing WiFi routers among apartments is valuable since the optimization allows to place fewer routers than the current state. Even though in the 2.4 scenario we were not able to find additional benefits from considering a whole block of buildings, in this scenario we reduced the amount of routers. Table 3 shows that by supplying only an individual apartment building, with 5.0 GHz WiFi frequency, four routers are required. Extending this example to four apartment complexes, we would require 16 routers (4 routers * 4 apartment complex buildings). Instead, by sharing routers among buildings the optimization model reduces the # of routers to 13. Therefore, by spreading routers across buildings, we can "save" 3 routers. Moreover, just as before, we varied the parameters within our model for Test 3 (Figure22). The required number of routers increases to 22 due to the increased amount of ceilings, as well as, additional space between apartment buildings. Especially due to the low reach of 5GHz routers, increasing the distance between the buildings has a greater negative impact than for 2.4GHz routers.

5.3 Comparison

Test set	2.4GHz	5GHz
test_1	1	4
test_2 (default_values)	4	13
test_3	8	22

Table 3: Output for each scenario: # of WiFi routers required

Overall Table 3 shows the WiFi devices which are required for each model, varying among the input parameters. In general, the table shows, that 5GHz requires more routers. However, when comparing it to the current situation in which each apartment requires one individual router, this result is still highly positive. For example, taking the one-building model:

- There are 45 apartments, which are likely to be 45 WiFi routers
- Having one 2.4GHz router instead of 45: 97.8% reduction rate in the number of routers.
- Having four 5.0GHz router instead of 45: 91.1% reduction rate in the number of routers.

Furthermore, we can take away that 5GHz routers are more useful in smaller, dense apartment complexes, while 2.4GHz should be used when complexes are further apart from one another. Due to the different reaches, as well as the impacts that different blockages like walls and ceilings have on the model different environments favor different WiFi routers.

Lastly, we realize the impact that this model and business idea can have on our society. This idea can span over various life aspects including health, sustainability, energy, and so on. In order to have a broader understanding of the effect, we will discuss various aspects within the next sections.

6 Discussion

6.1 Sustainability considerations

As presented in the results chapter, for test 2, which looks at 4 apartment buildings in close proximity, the optimization model allows the number of WiFi routers to be decreased from 180 (one per apartment) to 4 using the 2.4 GHz frequency and to 13 using the 5 GHz frequency in the test_2 scenario. The latter is preferable as it provides a better connection to the internet. Hence, the implications of the decrease in the number of routers will be covered in terms of sustainability considerations such as carbon emissions, energy consumption, and human health concerns. The first two elements will be reviewed from a Life Cycle Assessment perspective based on the data and results obtained in a Master Thesis that evaluates the carbon footprint of an internet service provider (Kübler, 2022).

6.1.1 Life Cycle Assessment of Routers

According to Kübler, a Life Cycle Assessment (LCA) is a systematic analysis tool and a process model used to estimate a variety of potential environmental impacts (Kübler, 2022). Therefore, it can be used to measure the effect that materials and processes have on several environmental indicators. In this report, our focus will be on carbon emissions equivalent (CO_2e) as they are deemed to have the most significant impact during the router's lifetime according to the results obtained by an Italian LCA team (Giacomello et al., 2013) when compared against impacts such as ozone depletion, particulate matter (photo smog), acidification, and eutrophication.

One of the first steps when performing an LCA is to define the functional unit, which describes a quantity of a product on the basis of the performance it delivers in its end-use application (Office, date). The functional unit that will be useful for this report is the router called "Fritz!Box 7530" from a telecommunications service provider in Germany, which is a 310-grams router that provides data routing at both 2.4 and 5.0 GHz. The next step for the LCA is to select the system boundaries in order to determine the scope of the analysis. The LCA of the router conducted by Kübler (Kübler, 2022) had a cradle-to-grave approach. This means that the LCA covers all life cycle stages of the product form the raw material acquisition of all its components to its end of life, including a use time of 9 years (working 24 hours, 7 days a week) in its 2.4 GHz frequency. The results of this LCA show that the total carbon emitted by this WiFi router is 425.3 kg CO_2e equivalent. The emissions by stage are split as follows:

- 45.2 kg CO_2e in production
- 0.04 kg CO_2e in transport
- 379.4 kg CO_2e in the use phase
- 0.7 kg CO_2e in its end of life

Annualizing the total emissions, we observe that the carbon emitted in a year by this product is 47.3 kg CO_2e. On the other hand, if we simulate the calculations to obtain the emissions coming from this same router working on its 5 GHz frequency, we observe that in 9 years it would have emitted 466.5 kg CO_2e and 51.8 kg CO_2e per year. Consequently, we can compute the savings in carbon emitted by taking this router as a proxy of the routers that are used in our model of residential buildings. As an example, we will state the calculations of the savings for the simulation that uses 2.4 GHz frequency. First, we compute the original carbon footprint per year by multiplying the carbon footprint by the original number of routers, which in this case is 180 under the assumption that each apartment owns its own WiFi router.

$$Original\ carbon\ footprint = 47.3\ kg\ CO_2e * 180\ routers = 8507\ kg\ CO_2e$$

Then, we calculate the minimized carbon footprint per year by multiplying the carbon footprint by the optimized number of routers.

$$Minimized\ carbon\ footprint = 47.3\ kgCO_2e * 4\ routers = 189\ kg\ CO_2e$$

Lastly, we compute the difference between these two quantities to obtain the savings per year of carbon emissions due to the optimization.

$$Savings = 8507\ kg\ CO_2e - 189\ kg\ CO_2e = 8317.8\ kg\ CO_2e$$

As we can observe, we can avoid a large amount of carbon emissions by minimizing the number of WiFi routers. A summary of the emissions savings for routers working at both frequencies can be found in Figure 11.

Router frequency	Carbon footprint (kg CO2e/year)	Original number of routers	Original carbon footprint (kg CO2e/year)	Optimized number of routers	Minimized carbon footprint (kg CO2e/year)	Savings (kg CO2e/year)
2.4 GHz	47.3	180	8507	4	189.0	8317.8
5 GHz	51.8	180	9330	13	673.8	8655.7

Figure 11: Carbon footprint scenarios and emissions savings by optimization

6.1.2 Energy consumption

According to the Information and Communications Technology Sector Guidance (GeSI and Trust, 2017), between 85 % to 95 % of emissions in this sector come from the use phase of its products. In the results obtained by Kübler (Kübler, 2022), this estimation is confirmed as the use phase represents 89 % of the emissions from the router. Such emissions can be traced back to the energy consumption of the router during its lifetime as it is estimated that this router consumes 946 kWh if it is working in its 2.4 GHz frequency, 24 hours, 7 days a week for 9 years, while in its 5 GHz frequency, it would consume 1049 kWh. This energy consumption represents 105 kWh for 2.4 GHz and 117 kWh for 5 GHz per year and per router. Therefore, each router that is not in use can be regarded as a benefit for the environment and for the people who will be able to decrease their energy bills.

The energy savings are computed similarly to the calculations of the emissions savings. With the routers working at their 2.4 GHz frequency as an example, first, we obtain the original energy consumption per year by multiplying the energy consumption by the original number of routers, which in this case is 180 under the assumption that each apartment owns its own WiFi router.

$$Original\ energy\ consumption = 105.1\ kWh * 180\ routers = 18920\ kWh$$

Then, we calculate the minimized energy consumption per year by multiplying the energy consumption by the optimized number of routers.

$$Minimized\ energy\ consumption = 105.1\ kWh * 4\ routers = 420.4\ kWh$$

Lastly, we compute the difference between these two quantities to obtain the savings per year in energy consumption due to the optimization.

$$Savings = 18920\ kWh - 420.4\ kWh = 18499.6\ kWh$$

This amount is equivalent to around 4 times the average yearly consumption of a Swiss household (Axpo, 2023) and the amount represents almost 5,000 CHF (SWI, 2022). As we can observe, we save large amounts of energy from a household perspective by minimizing the number of WiFi routers. A summary of the energy savings for routers working at both frequencies can be found in Figure 12.Nevertheless, we recognize that the impacts of decreasing the number of routers in a residential building would lead to a relatively small decrease in terms of overall energy consumption and material usage across all countries and industries. However, it would provide a more sustainable solution to a problem that today involves the majority of the population. Furthermore, our model implies that there is a common agreement on the use of shared WiFi routers and hence, on the shared payment of the corresponding energy bill among the residents of our model residential building, which is not always an easy agreement to reach.

Router frequency	Energy consumption (kWh/year)	Original number of routers	Original energy consumption (kWh/year)	Optimized number of routers	Minimized energy consumption (kWh/year)	Savings (kWh/year)
2.4 GHz	105.1	180	18920	4	420.4	18499.6
5 GHz	116.5	180	20971	13	1514.6	19456.8

Figure 12: Energy consumption scenarios and energy savings by optimization

6.1.3 Health concerns

Another potential conflict that would have to be discussed in the common agreement of sharing WiFi routers among the residents are the health concerns around WiFi signal and whether it represents a threat to human health or not, since our optimized model implies that only certain residents and their families would be exposed to the strongest radiation coming from the WiFi router; although in the usual practice, every family is exposed to its own WiFi signal. To decrease the distress around this topic, we consulted a review paper (Dongus et al., 2022) that analyzes more than a thousand articles related to the topic.

The methodology that the authors applied in this research was to assess the studies that explored the biological and health effects of WiFi exposure according to established quality criteria. The types of studies assessed include epidemiological, human experimental, *in vivo* and *in vitro* studies using realistic WiFi exposure settings. The first remark that this review paper makes is that WiFi's contribution to total radiofrequency electromagnetic field (RF-EMF) is low. Then, regarding the human experimental studies, the exposure levels applied were below the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines on limiting exposure to electromagnetic fields (on Non-Ionizing Raditation Protection, 2020) for the general public (0.08 W/kg), which is comparable to the levels we are exposed to during our day-to-day activities. Lastly, this paper concluded that there are no detrimental health effects from WiFi exposure below regulatory limits.

6.2 Extension

The possible applications of the model mainly depend on the assumptions and parameters on which the function was built. In the following, we classified the potential application opportunities, considering those concrete situations in which the model can be used changing only the values of the current parameters. On the other side, we described also potential limitations, which are perceived as such as they represent those situations for which new parameters need to be included in the model, or for which the function needs to be changed.

6.2.1 Opportunities

Despite the model being built on many simplistic assumptions, as described in the second chapter, it still allows to change and combine different parameters, therefore increasing the range of possible applications. In particular, the model already provides the commands and functions that are necessary to modify the dimensions and composition of the apartment. Indeed, while the size of the house is directly proportional to the number of routers, the material used in the construction of the buildings may affect in disparate ways the reach of the routers.

In our model, we considered walls of different dimensions mainly made of concrete or drywall. However, current advancements in the architectonic and construction industry are contributing to the development of new materials such as Cross Laminated Timber and Hollow Clay Bricks (Sadana, 2022) which have different effects on the maximum reach of the WiFi. In this regard, recent studies (Limited, 2022) (Wavlink, 2022)show that the attenuation of the signal highly depends on the material used, varying greatly from wood to concrete with a ratio of 1 to 15. We would also like to emphasize that in order to gain a comprehensive understanding of the impact of obstacles on the wavelength, conducting field experiments would be beneficial to further investigate our assumptions. We acknowledge that our assumptions may have been overly optimistic regarding the reduction effect of walls on the signal, and it is likely that their impact is stronger than initially presumed.

Our model can further be extended regarding other constraints that we did not take into account for simplicity and time reasons. For example, as we discussed there can be different needs of people, some people need faster WiFi while others can handle slower connections. So, in the future, we can adapt our model to have the possibility of installing different types of routers depending on the needs of each apartment, which can be defined as a number indicating the type of WiFi user in that apartment. Also, there might be a limit to the number of people who can use one router, which we can include in future versions of this model. We also know that interference of WiFi router signals with each other and signals from other appliances can have an effect on the reach and signal strength, which can be added as another constraint in our model. Internet providers should be able to offer a router and an internet connection capable of simultaneously supporting more than 45 people (if we count one person per apartment) avoiding network overload; not to mention the necessity to provide immediate assistance in case of a malfunction in the WiFi system. All of these things are possible constraints that make our model more complex, but also more precise and would be feasible regarding the coding, given enough time to do this.

Lastly, right now we only have router placements in the apartments. More practical would be a placement in the hallways or outside, where also the tenants have access to it in case of malfunction or other problems. These special design parts are not included in our model, so we would need to adapt the fundamental model design to add the possibility of router placements in these "special" spots.

6.2.2 Limitations

As stated previously, our model uses multiple simplifications, which limit its use and accuracy in the real world. Firstly, we simplified the model to be symmetric. With symmetry, we mean that all rooms and, hence, all apartments have the exact same shape, which is a simple cuboid. However, in reality, different apartments have usually different room sizes and also more complex shapes than simple squares. Our model can adapt to this thus far that we can make x and y distance adjustments to each room size to approximate the effects of differently shaped apartments. This is not 100% accurate but sufficient enough for the basic estimations of our model. Furthermore, in building complexes that we aim for the apartment structure is usually always the same on every floor, as big building companies use also symmetry in their structures to make planning and building of the houses more efficient, so in this regard, our simplification also matches the real world application.

Secondly, our model is limited to the router allocation. In our model, we assume a router allocation in the exact center of the room, which would not be the case in reality. The router is more likely placed right at a wall in the corner of a room, where it is less visible. This is a small difference to reality, but given the small size of rooms and the bigger effect of walls, we neglect this in our model, as we assume that a placement right at the wall or 2 meters away from the wall will not have big consequences on the overall reach of the router across multiple rooms. Also, our model does not take router allocations outside of rooms into account. There could be the possibility of placing routers in hallways or even outside of the building. This would be an interesting extension in the future, but our simplified model does not include hallways or the outside area as a possible placement for the routers. Given the reality of a project like this and the accessibility need of the routers for everyone in the building, this is a serious limitation to our model that needs to be carefully considered when using it.

Thirdly, our wall constraints are also simplifications we used. In reality, the reduction of router signals through obstacles is defined in percentage on a logarithmic scale. This would make our model a lot more complex, which is why we decided to estimate average distance reductions of one wall based on the logarithmic reduction described in the chapters before. Furthermore, the walls in a building can be built very differently with different materials and thicknesses. To make our model adaptable to this, we set many parameters at the beginning of the code, so the constraints can be adapted to real cases in which one would need to individually assess the effect of the different types of walls in a building. Hence, whilst limited and simplified in this regard, our model can still be used by different stakeholders with different building designs.

By continuously striving to refine and expand our code, we can create a robust and versatile tool for assessing WiFi signal propagation in different architectural settings.

7 Conclusion

This report extensively explains the functioning and purpose of our model, together with all the assumptions, parameters, and mathematical formulations that are concealed behind the Python code. Indeed, we can state that we created a simple model, which due to the many assumptions may be only applicable to those specific cases that meet the model criteria. Nevertheless, it gives accurate results, which show that the model may provide promising extensions for further applications. In fact, as described in the last chapter, there are some aspects that may be further implemented when using the model for concrete applications, such as the actual location of the router, which could be placed close to walls or also in the hallway or outside the building, or the presence of furniture and household appliances that may interfere, together with the walls, with the signal of the router.

Moreover, it is necessary to make practical considerations about the feasibility of the project regarding social behavior and the resources of stakeholders. However, we decided to focus on our main concern: sustainability. Since the beginning, our goal has been to find a solution to minimize the impact of WiFi usage in a world that is continuously evolving and increasing its internet demand. Indeed, not only we were able to minimize the number of routers from 180 (assuming one router per apartment) to 4 or 13 (according to the frequency chosen), but we dedicated a whole chapter of the report to meticulously describing the consequences of the use of our model in terms of environmental and human's well-being. Discovering that using this model in four buildings composed of 180 apartments, we would save a total of 8317.8 kg CO2e due to lower production of routers and 18499.6 kWh from the use of the devices per year. In particular, the latter value corresponds to the yearly energy consumption of 1.8 households in the USA (EIA, 2021) or to around 4 times the average yearly consumption of a Swiss household (Axpo, 2023). This goes in line with what circular economy implies as there is a reduction in the number of devices used and an increase in the number of people sharing single products. However, we did not cover the behavioral change that our project conveys and this can be further explored in future reports on the topic.

This is a simplified solution to a more complex problem. We see our model firstly as a proof of concept, meaning that we can clearly show that there is a big potential for a reduction in WiFi router usage. Whether our model shows the perfect solution or not, it definitely shows that there can be improvements from the current approach to WiFi router distribution. Secondly, our model is an additional point of data for house planning. While social aspects and needs have to be considered alongside our model's suggestion it definitely helps in a first draft of how to design a house and its WiFi distribution. Our model would be used but then critically assessed with potential problems like WiFi malfunction and the social behavior of tenants.

In light of the potential impact of router minimization, we are confident that in the near future, similar solutions will be proposed and implemented by internet providers and accepted by householders. Indeed, despite the challenges that may arise beyond the optimal positioning, concerning customer acceptance and the technical feasibility of the project, we believe that the current innovation rate would allow us to develop and implement solutions that pose an end to this unnecessary use of resources.

References

Ahrens, C. (2023). GitHub repository: Logistics_Optimization_Wifi. https://github.com/Clahrens/Logistic_Optimization_WiFi.

Axpo (2023). The swiss electricity market. https://www.axpo.com/ch/en/about-us/media-and-politics/power-market-switzerland.html#:~:text=Electricity%20consumption%20per%20household%3A%20An,including%20electric%20hot%20water%20preparation).

Dongus, S., Jalilian, H., Schürman, D., and Röösli, M. (2022). Health effects of wifi radiation: a review based on systematic quality evaluation. *Critical Reviews in Environmental Science and Technology*, 52(19):3547–3566.

EIA (2021). How much electricity does an american home use? https://www.eia.gov/tools/faqs/faq.php?id=97&t=3%23:~:text=In%202021%2C%20the%20average%20annual,about%20886%20kWh%20per%20month.

ekahau (December 15, 2021). How to measure wall attenuation for spotless wi-fi network designs. *ekahau*. https://www.ekahau.com/blog/how-to-measure-wall-attenuation-for-spotless-wi-fi-network-designs/.

GeSI and Trust, C. (2017). Ict sector guidance built on the ghg protocol product life cycle accounting and reporting standard. *GHG Protocol Product Standard*. https://ghgprotocol.org/sites/default/files/GHGP-ICTSG%20-%20ALL%20Chapters.pdf.

Giacomello, L., de Benedetti, B., Tecchio, P., and Rollino, S. (2013). Life cycle assessment of sustainable home gateways and product category rules definition for environmental labeling. *INTELEC Journal*, 13(17):376–380.

Jeffery, I. (2023). Wi-fi history. *Purple*. https://purple.ai/blogs/history-wifi/.

Jian, H. (2022, April 2). What is wifi? wifi vs. wlan. *Huawei*. https://info.support.huawei.com/info-finder/encyclopedia/en/WiFi.html.

Kübler, M. T. (2022). Carbon footprint of an internet service provider. Master's thesis, SE-100 44 STOCKHOLM, SWEDEN.

Limited, K. (04/04/2022). Wi-fi signal attenuation coefficients when passing through different materials. https://help.keenetic.com/hc/en-us/articles/213968869-Wi-Fi-signal-attenuation-coefficients-when-passing-through-different-mater

Newth, J. D. (14.10.2021). Which building materials can block wi-fi signals? *eyenetworks*. https://eyenetworks.no/en/wifi-signal-loss-by-material/.

Office, D. A. M. (no date). Defining functional units for lca and tea.

on Non-Ionizing Raditation Protection, I. C. (2020). Icnirp guidelines for limiting exposure to electromagnetic fields (100 khz to 300 ghz). *Health Physics Journal*, 118(5):483–524.

Sadana, N. (2022). Innovative construction materials used around the world. *RTF — Rethinking the Future*. https://www.re-thinkingthefuture.com/2020/06/18/a1072-10-innovative-construction-materials-used-around-the-world/.

Swalih (2023). Who invented wi-fi? names and details. *Tech Quintal*. https://www.techquintal.com/who-invented-wifi/.

SWI (2022). Swiss retail power prices to soar next year. https://www.swissinfo.ch/eng/politics/swiss-retail-power-prices-to-soar-next-year-/47881306.

Wavlink (08/12/2022). Wi-fi signal attenuation- king of connection, by wavlink. https://blog.wavlink.com/en-us/article/TechnicalNews/92442c2444eaa02541dd27fe90bed782.html.

8 Appendix

```
!pip install ortools
from __future__ import print_function
from ortools.sat.python import cp_model as cp
import math

#for visualization
import numpy as np
import matplotlib.pyplot as plt
import sys
from PyQt5.QtWidgets import QApplication, QMainWindow, QLabel, QPushButton
from mpl_toolkits.mplot3d import Axes3D
from ipywidgets import interact, Dropdown
```

Figure 13: Code: Import

```python
# ensure that all inputs are of a type that can be used as a parameter
def get_valid_integer_input(prompt):
    while True:
        try:
            value = int(input(prompt))
            return value
        except ValueError:
            print("Invalid input. Please enter an integer and try again.")

# definition of the two router types and their respective specifications in terms of reach
def wifi_router_selection(frequency):
    global min_distance, sw, mw, bw, c, h
    if  frequency == "5GHz":
        min_distance = 91
        # Set other parameters based on the chosen option
        sw = 4.2
        mw = 7.5
        bw = 11.7
        c = 18.8
    elif frequency == "2.4GHz":
        min_distance = 30
        # Set other parameters based on the chosen option
        sw = 1.8
        mw = 2.6
        bw = 5
        c = 6.6
```

Figure 14: Code: Parameter Definition

```python
# Dropdown options for frequency selection
frequency_options = ["2.4GHz", "5GHz"]

# Using interact to create the dropdown menu
@interact(frequency=Dropdown(options=frequency_options, value="2.4GHz", description="WiFi Router:"))
def select_frequency(frequency):
    wifi_router_selection(frequency)

# Get user input for other parameters
l_input = input("Enter an integer for the length of a room (default: 4): ")
l = int(l_input) if l_input else 4
w_input = input("Enter an integer for the width of a room (default: 4): ")
w = int(w_input) if w_input else 4
h_input = input("Enter an integer for the heights of a room (default: 3): ")
h = int(h_input) if h_input else 3
f_input = input("Enter an integer number of floors (default: 5): ")
f = int(f_input) if f_input else 5
s_input = input("Enter an integer number of apartments in x, y in the building (default: 3): ")
s = int(s_input) if s_input else 3
hd_input = input("Enter an integer for the distance between house blocks (default: 10): ")
hd = int(hd_input) if hd_input else 10
ac_input = input("Enter an integer for the # of apartment complexes next to another (default: 2): ")
ac = int(ac_input) if hd_input else 2

#number of apartment complexes
s= 2*s*ac

# Calculate num_blocks based on user input
num_blocks = s*s*f #number of sections on one length (x or y axis) -> we have three apartments, but each apartment is divided into 4 se
```

Figure 15: Code: Parameter Definition continued

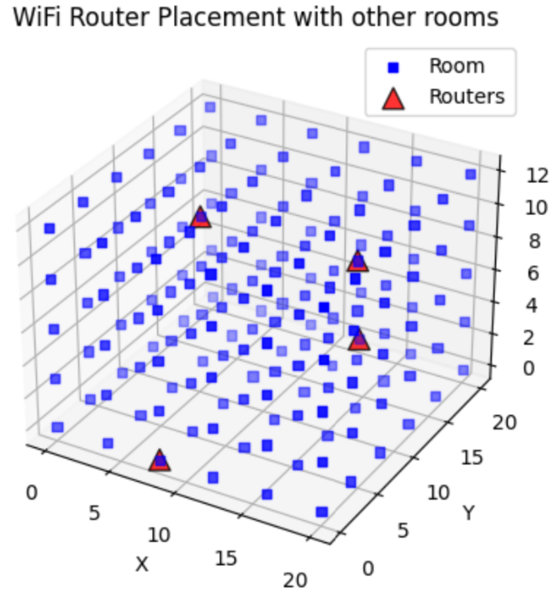
```
#Defining the model
model = cp.CpModel()

#calculating the distance between all rooms
def euclidean_distance(a, b):
  distance = math.sqrt(sum([(a[i] - b[i])**2 for i in range(len(a))]))   #general equation to calculate distance between two points in 3
  diffz = abs(a[0] - b[0])   #distance in z direction
  diffx = abs(a[1] - b[1])   #distance in x direction
  diffy = abs(a[2] - b[2])   #distance in y direction

    #ceiling effect
  if diffz > 0:
    distance += (diffz/h)*c     #add distance for every ceiling/floor that we pass through

    #small wall effect
  if diffx > 0:
    distance += (diffx/l)*sw    #add distance for every small wall that we pass through
  if diffy > 0:
    distance += (diffy/w)*sw    #add distance for every small wall that we pass through
```

Figure 16: Code: Constraint Definition

```
    #medium wall effect
  if (diffx/l) % 2 == 0:
    distance += ((diffx/l)//2) * mw
  else:
    if (a[1]<b[1] and (a[1]/l)%2==0) or (b[1]<a[1] and (b[1]/l)%2==0):
        distance += ((diffx/l)//2) * (mw-sw)
    else:
        distance += ((diffx/l)//2) * (mw-sw) + (mw-sw)

  if (diffy/w) % 2 == 0:
    distance += ((diffy/w)//2) * mw
  else:
    if (a[2]<b[2] and (a[2]/w)%2==0) or (b[2]<a[2] and (b[2]/w)%2==0):
        distance += ((diffy/w)//2) * (mw-sw)
    else:
        distance += ((diffy/w)//2) * (mw-sw) + (mw-sw)

    #big wall effect
  if (diffx/l) // (s*2) > 0:
    if (a[1]<b[1] and (a[1] % (s*2)) < ((s*2)-((diffx/l) % (s*2)))) or (b[1]<a[1] and (b[1] % (s*2)) < ((s*2)-((diffx/l) % (s*2)))):
        distance += ((diffx/l) // (s*2)) * (2*bw + hd - sw - mw)
    else:
        distance += ((diffx/l) // (s*2)) * (2*bw + hd - sw - mw) + (2*bw + hd - sw - mw)

  if (diffy/w) // (s*2) > 0:
    if (a[2]<b[2] and (a[2] % (s*2)) < ((s*2)-((diffy/w) % (s*2)))) or (b[2]<a[2] and (b[2] % (s*2)) < ((s*2)-((diffy/w) % (s*2)))):
        distance += ((diffy/w) // (s*2)) * (2*bw + hd - sw - mw)
    else:
        distance += ((diffy/w) // (s*2)) * (2*bw + hd - sw - mw) + (2*bw + hd - sw - mw)
  return distance
```

Figure 17: Code: Constraint Definition continued

```
The following apartments need to be equipped with a WiFi router:
Apartment 3
Apartment 34
Apartment 128
Apartment 131
```




```
Here is a visualization of only the router placements:
```

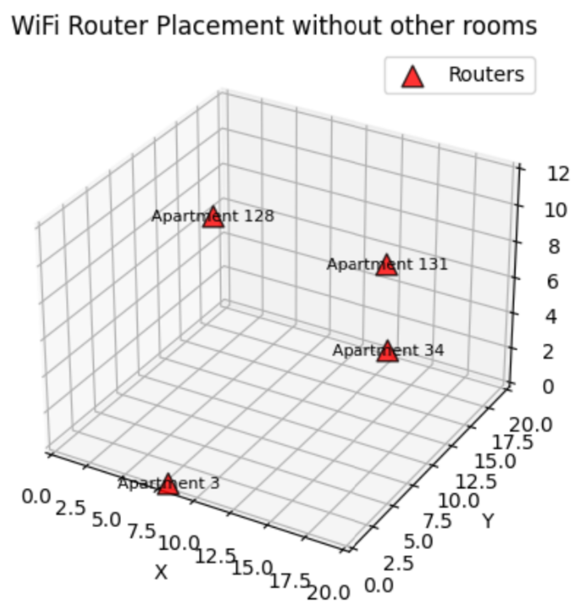
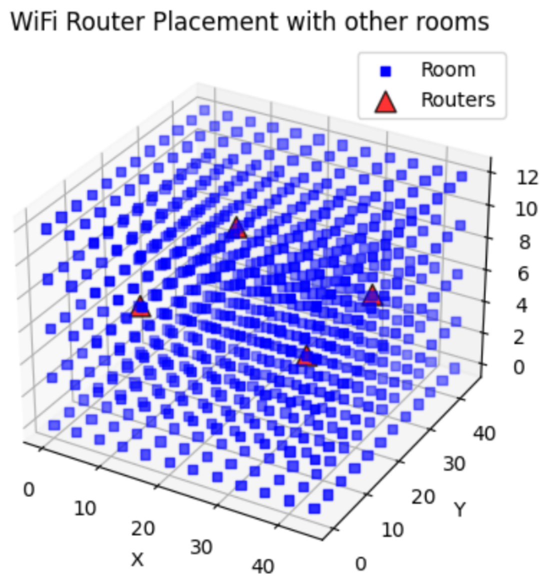


Figure 18: Result for 5.0GHz WiFi router, 1 apartment building

```
The following apartments need to be equipped with a WiFi router:
Apartment 327
Apartment 334
Apartment 394
Apartment 411
```




```
Here is a visualization of only the router placements:
```

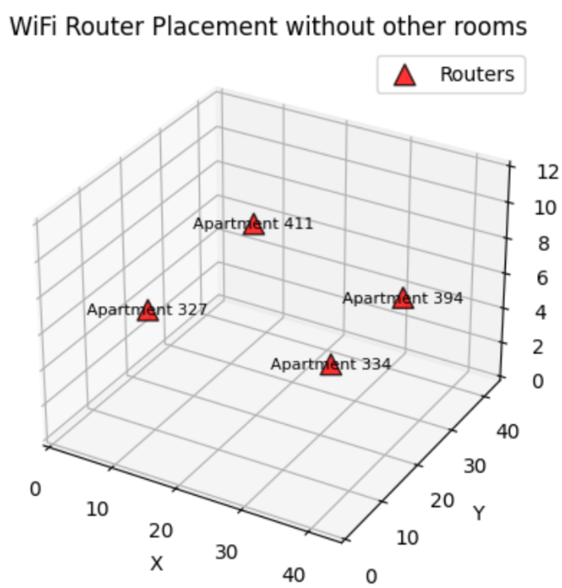


Figure 19: Result for 2.4GHz WiFi router, 4 apartment buildings, default

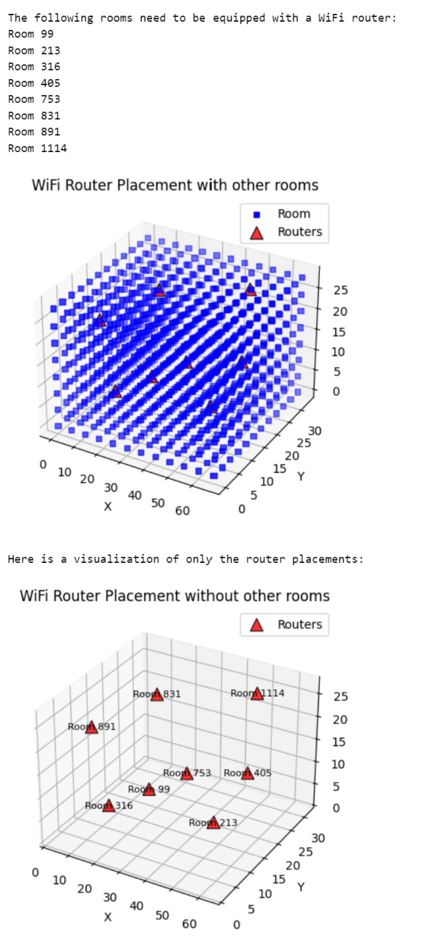
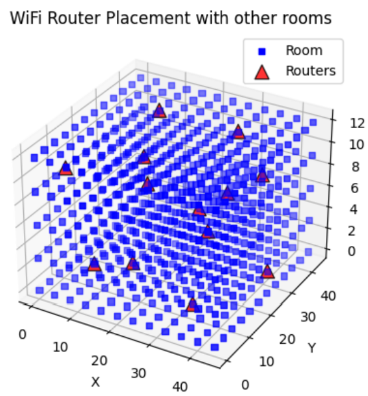


Figure 20: Result for 2.4.0GHz WiFi router, 4 apartment buildings, test_3

```
The following apartments need to be equipped with a WiFi router:
Apartment 45
Apartment 64
Apartment 107
Apartment 160
Apartment 258
Apartment 266
Apartment 429
Apartment 455
Apartment 469
Apartment 502
Apartment 618
Apartment 676
Apartment 681
```




```
Here is a visualization of only the router placements:
```

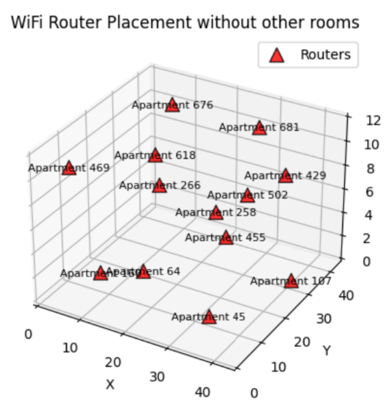
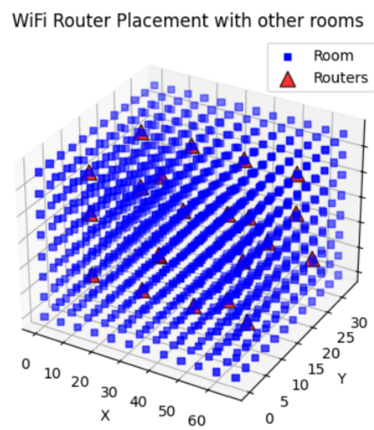


Figure 21: Result for 5.0GHz WiFi router, 4 apartment buildings, default

The following rooms need to be equipped with a WiFi router:
Room 99
Room 182
Room 185
Room 188
Room 191
Room 248
Room 275
Room 414
Room 455
Room 474
Room 554
Room 562
Room 614
Room 647
Room 896
Room 902
Room 905
Room 911
Room 962
Room 965
Room 968
Room 971



Here is a visualization of only the router placements:

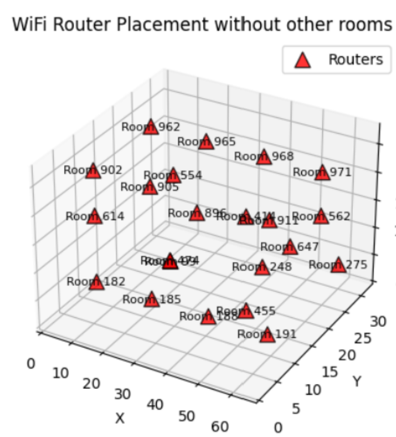


Figure 22: Result for 5.0GHz WiFi router, 4 apartment buildings, test_3