

Article

Improving Room Carrying Capacity within Built Environments in the Context of COVID-19

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Abstract: The COVID-19 pandemic that has struck the world since March 2019 has established an unusual *modus operandi* for all of us. During this transient situation, some of the activities have been severely altered, especially those which are performed in indoor spaces such as classrooms, restaurants, or libraries. As physical distance is mandatory in most countries, the capacity of these places has been severely reduced, causing unsustainable economic and logistical issues. This work aims to analyze the possible ways of distributing seats in symmetrical spaces for different uses and room sizes. For that purpose, the classical seat arrangement in rows and columns is compared with an equilateral triangle-based seat pattern, which is proposed as a better solution in most cases. Results show that a greater number of seats is achieved in most situations using the proposed patterns, with mean increases of 13% and peaks from 25% to 50% in some specific circumstances. A discussion about an optimized layout, shape and size of the furniture used in multiple seat tables is included. The outcome shall generate a positive impact on schools, colleges, restaurants, libraries, and similar built environments where seating capacity is crucial.

Keywords: COVID-19; carrying capacity; built environment; numerical analysis; geometric optimization

1. Introduction

The COVID-19 outbreak declared in Wuhan (China) in late 2019 has brought major changes to personal and social behavior worldwide. This pandemic's effects have been different in each country, depending on the date that the pandemic arrived in, and the strategy followed by them. Up to 25 August 2020, the pandemic has affected 213 countries and territories around the world and two international conveyances (Figure 1). The number of reported cases worldwide exceeds 23,000,000—more than 6,000,000 currently active—the death toll is beyond 800,000 [1,2].

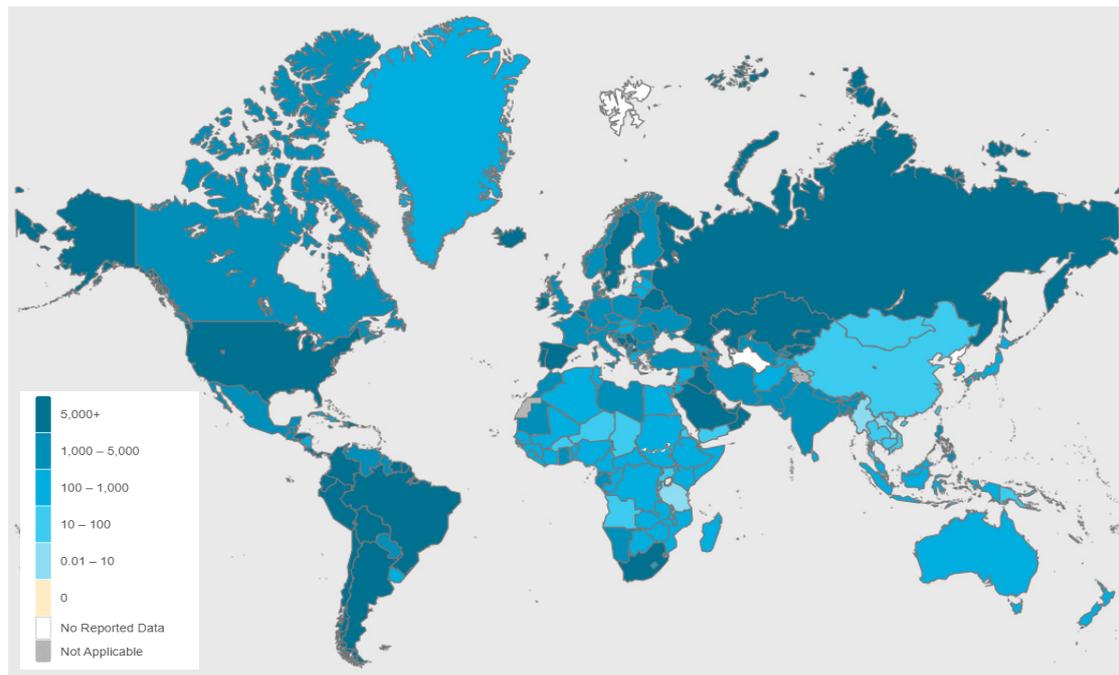


Figure 1. Total COVID-19 cases per 1 million population worldwide as of August 25, 2020 [3].

SARS-CoV-2 coronavirus has demonstrated to have a high infection capacity in comparison with other infectious diseases. Several studies determine a basic reproduction number (R_0) between 1.4 and 6.5, with mean values around 3.5 [4–7]. This number indicates the transmissibility of a virus, representing the average number of new infections generated by an infectious person. If this value is equal or greater than 1.0, the disease will continue to spread over time following a geometric progression with a common ratio R_0 . When R_0 values keep under 1.0, the disease is contained, and the number of cases decrease progressively until no new infections are produced.

According to the World Health Organization (WHO), disease transmission can be classified into three different groups:

- Sporadic cases: with one or more cases, imported or locally detected;
- Clusters of cases: experiencing cases, clustered in time, geographic location and/or by common exposures;
- Community transmission: experiencing larger outbreaks of local transmission defined through an assessment of factors including, but not limited to large numbers of cases not linkable to transmission chains, large numbers of cases from sentinel laboratory surveillance, and/or multiple unrelated clusters in several areas of the country/territory/area.

Figure 2 shows the predominant COVID-19 transmission type in each country. As can easily be seen, most countries currently have community transmission or clusters of cases, sporadic cases being relatively uncommon. Both kinds of transmission are more suitable to be developed into crowded indoor spaces where people gather and spend a considerable amount of time together.

Additionally, several outbreak investigation reports revealed that COVID-19 transmission could be especially effective in crowded indoor spaces, such as classrooms, theaters, restaurants or auditoriums [8–10]. Mechanical ventilation systems with air recirculation in confined indoor spaces are also associated with increased transmission of respiratory infections and COVID-19 specifically [10–12].

As a vaccine is not already available, governments around the world have adopted different measures to prevent the transmission of the disease, aiming to reduce R_0 values. There are several universal strategies that could reduce transmission, especially at workplaces, schools and other crowded

indoor spaces: hand hygiene, wearing proper facemasks, physical distancing, mobility reduction, regular environmental cleaning and disinfection, risk awareness and communication, and contact management [13].

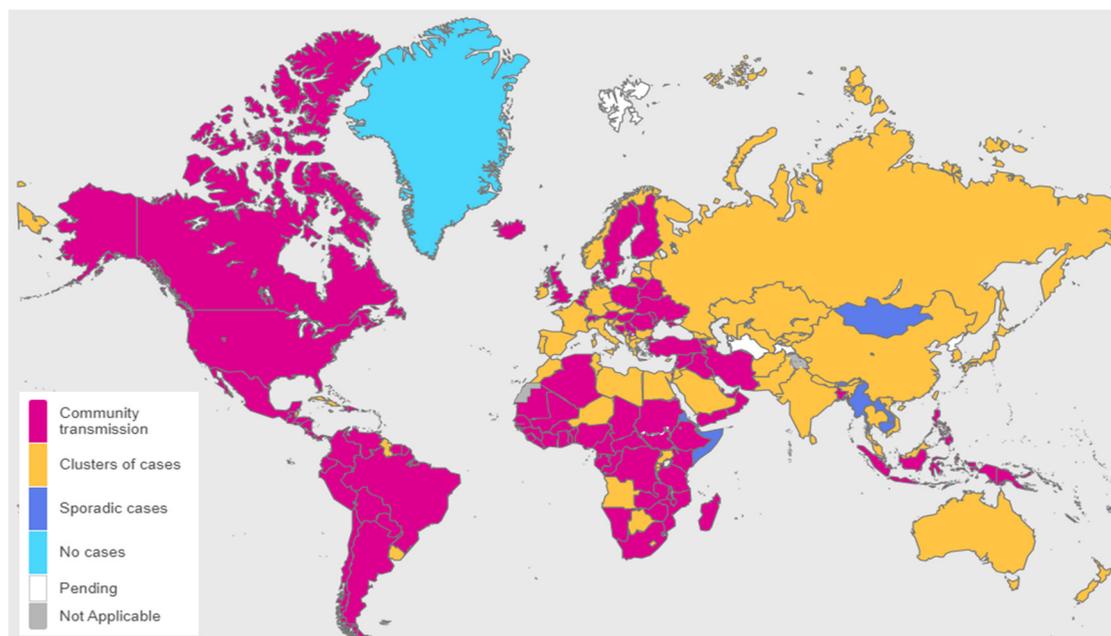


Figure 2. Predominant transmission type in the COVID-19 infected countries, August 2020 [3].

Physical distancing is one of the factors that can be easily achieved, especially in confined places with a seat setting such as classrooms, theaters, restaurants, auditoriums, or in buses and trains. The droplets generated in common respiratory activities (i.e., speaking, coughing and sneezing) can reach from 0.16 to 2.76 m without wearing facemasks, according to Cheng et al. [14]. WHO recommends at least a physical separation of one meter within desks at schools and workplaces [13,15], while most governments usually raise it between 1.5 to 2 m (see Table 1), and take additional measures such as wearing mandatory facemasks [16–23]. The imposition of these geometric restraints severely affects the capacity of these places by reducing it dramatically. This capacity decrease makes it difficult for them to be economically viable, as in restaurants or theaters, or to perform adequately specific in-person activities such as teaching [18,22,24].

Table 1. Minimum mandatory physical distance between individuals in different countries [19–23].

Country	Minimum Physical Distance (m)
Canada, United Kingdom	2.0
United States of America	1.8 ¹
Australia, Germany, Greece, The Netherlands, Spain	1.5
China, Denmark, France, Italy, Hong Kong, New Zealand, Singapore	1.0

¹ The imposed restriction is 6 feet, approximately 1.8 m.

Several authors have studied this issue and raised engineering solutions driven by the need to keep a minimum separation in built environments [25]. Some solutions are oriented to improve the air quality through room ventilation, reducing the concentration of virus-laden microdroplets in the air exhaled by the occupants [26]. This can be achieved by using natural ventilation, opening windows and doors during school hours in countries with a warm climate [27], or by means of mechanical ventilation systems with no air recirculation, instead of using particulate filters and disinfection in recirculated airflows. Other studies have proposed desk rearrangement strategy in offices and

classrooms to guarantee the minimum distance [28,29]. Hospitals usually solve this problem by creating restricted isolated areas for infectious diseases [30] or by establishing safety protocols to minimize contact to infected patients, including physical distancing guidelines [31–34]. Many educational institutions (e.g., universities or schools) have developed COVID-19 safety guidelines that include seating distributions for their indoor spaces using specific values of physical distance between desks, but comprehensive studies for maximizing room carrying capacity under these circumstances were not found in the scientific literature.

In that context, this work provides a simple and inexpensive solution to evaluate the maximum seating capacity in this kind of symmetrical covered space keeping the minimum physical distance. The rest of the paper is organized as follows: Section 2 sets the initial conditions and develops the equations to solve the seat distribution optimization problem. Section 3 presents and analyzes the obtained results. Section 4 makes some concluding remarks and sets future research lines.

2. Materials and Methods

2.1. Problem Definition

With the aim to confront the problem, the room has been divided into three different areas of activity (Figure 3): (i) the performing area (which could not exist in some cases), where the lead performer(s)—teacher(s), lecturer(s), actor(s), singer(s), musician(s), etc.—carry out the main activity; (ii) the circulation area, used for general internal circulation of individuals along with space; and (iii) the seating area, where the audience takes a seat to watch or participate in the main activity.

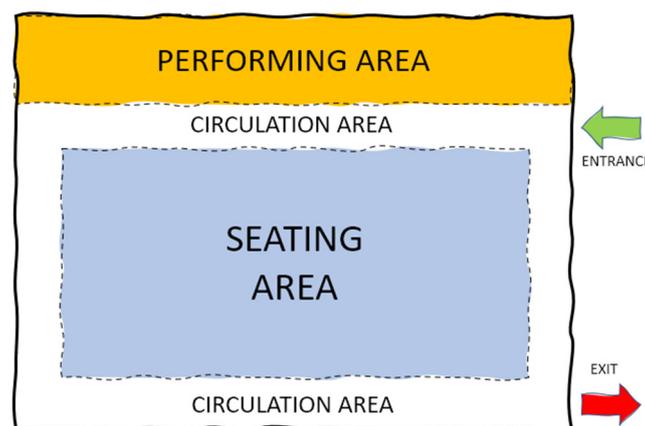


Figure 3. Areas of activity considered in this study for a generic indoor space.

In this study, we assume that:

- The space is open plan—that is, without any architectural element placed within its perimeter.
- The shape of the seating area could be assimilated into a rectangle. This is a common setting for most of the indoor activities requiring seats (e.g., classrooms, sports courts), as the walls usually follow orthogonal directions.
- The seating area cannot be modified, and therefore it is the same before and after the seat redistribution.
- There is no possibility of placing any surface that blocks the airflow between two or more seats, such as transparent protective screens or partitions.

According to the Euclidean geometry of the plane, there are three possible distribution patterns that we can consider for distributing the maximum quantity of people in a determined area:

- (a) Square pattern (Figure 4a): this is the most common distribution adopted for rectangular surfaces in pre-COVID spaces, as it is simple to plan and easy to deploy.

- (b) Equilateral triangle pattern (Figure 4b,c): this is the most compact distribution per se, as it guarantees a constant distance between its vertexes with the minimum surface area, but under certain boundary conditions may not be the optimal solution. It has two possible optimal orientations, which are obtained by making one side of the triangle parallel to each side of the rectangular area.

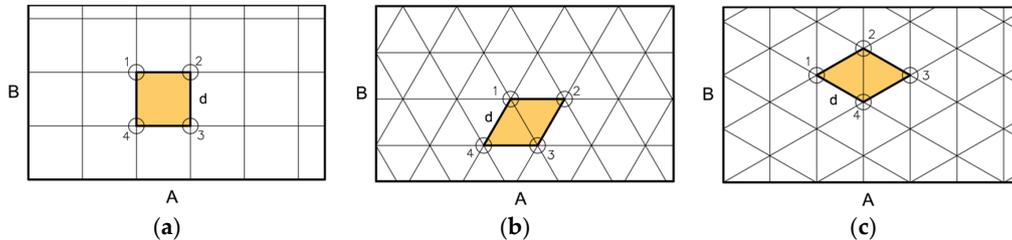


Figure 4. Possible seat distribution patterns on a rectangular area: (a) Square pattern; (b) Equilateral triangle pattern, aligned to side A; and (c) Equilateral triangle pattern, aligned to side B. The shaded areas have the same number of vertexes (seats).

Consequently, the optimization problem to solve is which of these three distributions provides the maximum quantity of people with a minimum separation d between them, in a rectangular surface with dimensions $A \times B$.

2.2. Model Development

In the first place, we have to take into account that it is necessary to detract from the initial gross seating area an unused perimetral fringe as it is necessary for placing the furniture (i.e., desks, chairs) of those seating places located at the boundaries, as it can be seen in Figure 5. Thus, the effective net area for the model, S_{eff} , will be

$$S_{eff} = (W - 2a)(L - 2b) = A \times B \tag{1}$$

where W and L are, respectively, the width and length of the seating area, and a, b are the horizontal and vertical distance from the center of any individual place to its edge, including the desk if present.

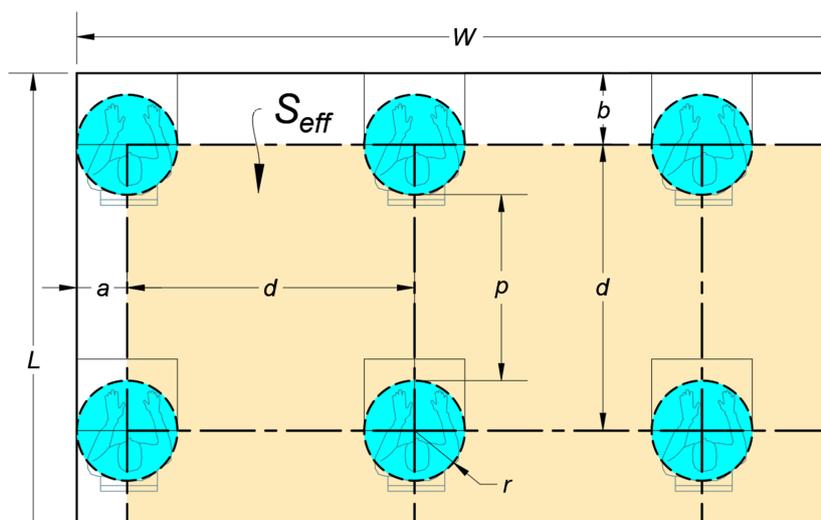


Figure 5. Definition of the seating area parameters.

The parameter d previously shown in Figure 4 refers to the length of the side of each cell, as a result of the addition of two sub-parameters: the intimate distance radius, r —typically 0.3–0.4 m

according to [35]—and the minimum physical distance between subjects, p , as defined in Table 1, which frequently adopts values from 1 to 2 m. Hence, it can be expressed as follows:

$$d = 2r + p \quad (2)$$

A trivial solution could be first presented for the case of an infinite or semi-infinite surface area, which could be applied for a seating area with A and B values significantly greater than d . In that particular circumstance, any of the triangular distributions will always lead to a greater number of individuals, according to the ratio K defined in the following equation:

$$K = \frac{S_{\square}}{S_{\Delta}} = \frac{2}{\sqrt{3}} = 1.1547 \quad (3)$$

where S_{\square} is the surface area of a square and S_{Δ} is the surface area of two contiguous equilateral triangles with the same side length as the squares. Therefore, in this case there will be 15.47% more seats by using the triangular pattern instead of the square one.

However, when the covered surface area is much smaller, as is the case with most actual indoor spaces, we need to determine which of the three configurations will give us a greater number of seats (N_{max}): square pattern (N_{sq}), horizontal triangle pattern (N_{th}), and vertical triangle pattern (N_{tv}):

$$N_{sq} = (1 + \alpha)(1 + \beta) \quad (4)$$

$$N_{tv} = (1 + \alpha)(1 + \beta') - \left\lfloor \frac{1 + \beta'}{2} \right\rfloor \delta_{\alpha} \quad (5)$$

$$N_{th} = (1 + \alpha')(1 + \beta) - \left\lfloor \frac{1 + \alpha'}{2} \right\rfloor \delta_{\beta} \quad (6)$$

$$N_{max} = \max(N_{sq}, N_{th}, N_{tv}) \quad (7)$$

where $\alpha = \lfloor A/d \rfloor$, $\alpha' = \lfloor 2A/\sqrt{3}d \rfloor$, $\beta = \lfloor B/d \rfloor$, $\beta' = \lfloor 2B/\sqrt{3}d \rfloor$, $\delta_{\alpha} = \lfloor A/d + 0.5 \rfloor - (1 + \alpha)$, and $\delta_{\beta} = \lfloor B/d + 0.5 \rfloor - (1 + \beta)$. The parameters α and β stand for the number of spaces between rows and a column for a square pattern layout. The parameters α' and β' are used instead of α and β in horizontal and vertical triangle patterns, respectively, in order to consider the height of the triangle ($d\sqrt{3}/2$). Eventually, the parameters δ_{α} and δ_{β} are applied in certain cases to correct the overall number of seats.

Figure 6 shows a detailed flowchart of the methodological process followed for algorithm definition and results production.

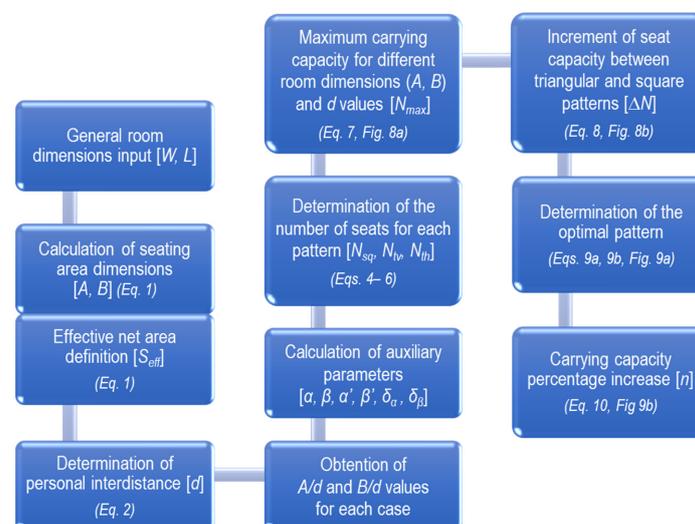


Figure 6. Workflow of the methodological process followed in this study.

3. Results and Discussion

3.1. Analysis of Environment Uses and Sizes

There are three main parameters to determine the maximum amount of seats and their pattern distribution: the net seating area dimensions (A , B) and the distance d adopted (see Table 2). These parameters can be easily converted into two dimensionless values: A/d and B/d , which will be used for displaying the results.

Table 2. Common values adopted for d .

p (m)	$r = 0.30$ m	$r = 0.35$ m	$r = 0.40$ m
2.0	2.6	2.7	2.8
1.8	2.4	2.5	2.6
1.5	2.1	2.2	2.3
1.0	1.6	1.7	1.8

Table 3 shows the range of values that are commonly adopted for A/d and B/d for the five building typologies and uses studied in this work. The upper and lower limits for each typology were calculated by dividing the typical room dimensions according to [36] by the maximum and minimum value of d shown in Table 2. The covered ranges for each typology are represented in Figure 7. In the same figure there are defined three kinds of zones which will be analyzed subsequently: (a) The area of study (zone 1), which comprehends all the possible values ranging from 1 to 20; (b) the area of usual values (zone 2), which is defined by merging the areas defined for each typology; and (c) the area of shared values (zone 3), obtained as the intersection of the five typological zones. The blank parts of that graph show rare or infrequent combinations of A/d and B/d values for length and width. Values over 20 (i.e., an open-plan seating area over 40 m long or wide) are very rare.

Table 3. Values adopted for A/d and B/d attending to the type of space and its dimensions [36].

Typology	Small	Medium	Large
Classroom	1.7–3.7	2.5–5.6	3.6–9.4
Lecture hall	2.1–6.3	4.3–9.4	5.7–12.5
Restaurant / Dining court	3.2–7.5	4.3–8.9	6.1–14.4
Library	4.3–11.3	6.3–18.0	7.1–25.0
Sports court / venue	5.4–15.6	14.3–37.5	32.1–75.0

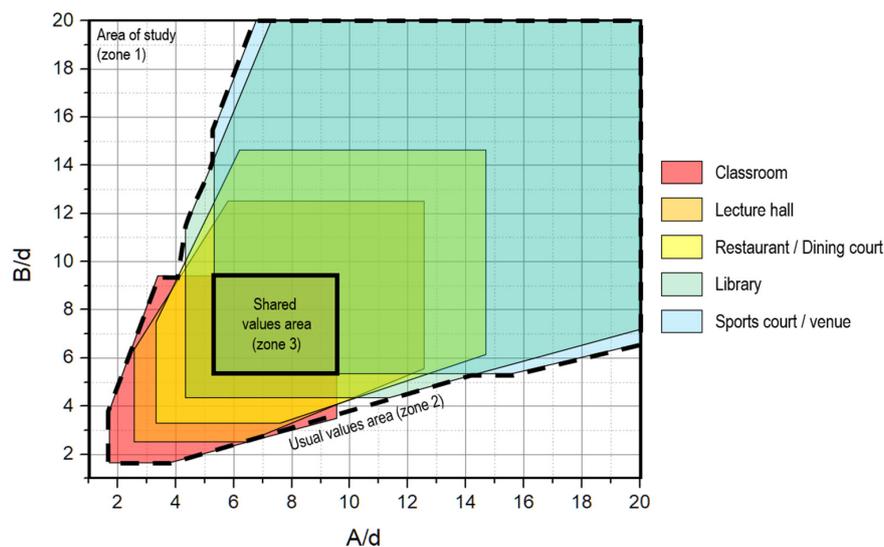


Figure 7. The usual range of dimensions of the seating area for the studied building typologies and uses. Graphical definition of usual values area and shared values area within the area of study.

Figure 8a shows the maximum capacity that can be obtained in the seating area, using the best of the three patterns defined in Figure 4, according to (7). Figure 8b displays the increment of seat capacity (ΔN) obtained by (8), when it exists, respect to the square pattern, if a triangular distribution is used. The blank spaces indicate no gain in seating capacity, or even a decrease.

$$\Delta N = N_{max} - N_{sq} \geq 0 \tag{8}$$

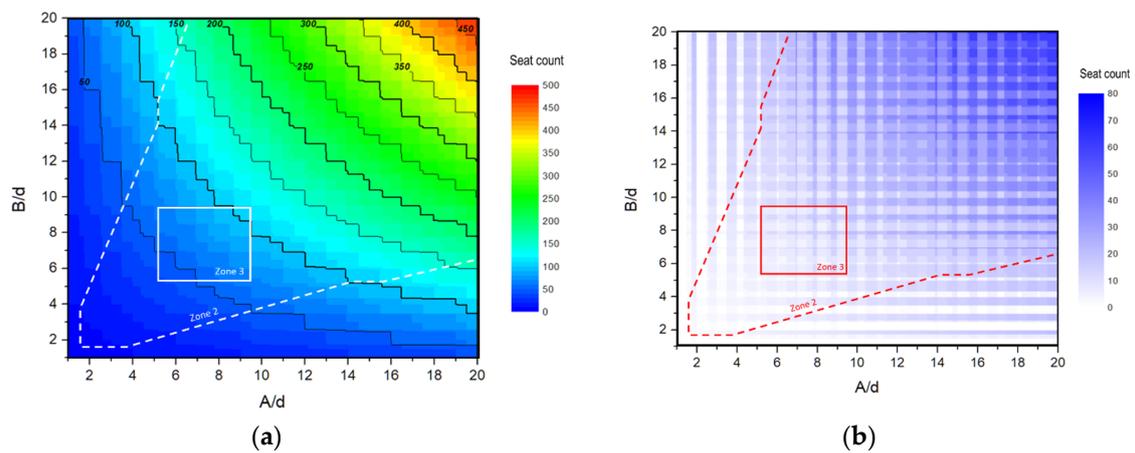


Figure 8. (a) Maximum seat capacity achieved by using the most suitable seat pattern; (b) Increment of seat capacity (ΔN) using a triangular seat distribution pattern, compared to a square pattern.

The pattern that maximizes the number of seats can be determined by (9a) and (9b). Depending on the value of these two dimensionless parameters, A/d and B/d , it can be observed that triangular patterns permit to obtain a greater number of seats, especially when A/d or B/d is greater than 4.5. In fact, if we look at Figure 9a, it is only for lower usual values of A/d and B/d that the square pattern has an advantage over the triangular seat distribution. For the values of these two parameters located in zone 3, the triangular distribution is preferred in almost 100% of the situations.

$$\begin{cases} \max(N_{th}, N_{tv}) > N_{sq}, & \text{triangle pattern} \\ \max(N_{th}, N_{tv}) = N_{sq}, & \text{indistinct} \\ \max(N_{th}, N_{tv}) < N_{sq}, & \text{square pattern} \end{cases} \tag{9a}$$

$$\begin{cases} N_{th} > N_{tv} > N_{sq}, & \text{horizontal triangle pattern} \\ N_{tv} > N_{th} > N_{sq}, & \text{vertical triangle pattern} \end{cases} \tag{9b}$$

$$n = \frac{\Delta N}{N_{sq}} 100 \tag{10}$$

Attending to the percentual increment in the number of seats (n) caused by using the triangular pattern instead of the square one (10), Figure 9b shows that when the number of seats is low (e.g., small classrooms), certain combinations of A/d and B/d values can add up to 50% more seats in the room. However, in this zone, there are isolated windows of values where the square pattern is more convenient. For mid-sized spaces, the increments usually are between 20% to 30%, whereas for larger areas, the values oscillate from 4% in a few points up to 25%. As previously stated in (3), as the surface area grows, the trend is to stabilize on 15.5%. Focusing on the rectangular region where there are the most frequent values, which go from 4.5 to 9.5, the maximum increase obtained is 28%, and the average value reaches 13%.

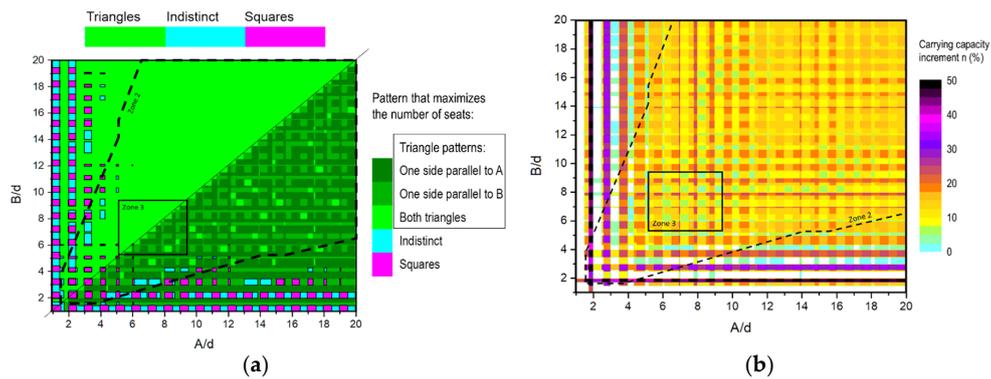


Figure 9. (a) Seat pattern for obtaining the highest carrying capacity, by general pattern type (upper left zone) and by specific pattern type (lower right zone); (b) Percentage increase of seating capacity using a triangular pattern, compared to a square pattern.

Table 4 shows the percentual distribution of carrying capacity increase attending to the three areas defined in Figure 7. Results show that there is no capacity increase in the 2.7% of the usual cases, whereas in almost 80% of the cases located in this area the carrying capacity increases from 10% to 25%; in almost half of these, the increment ranges from 15% up to 25%. If we observe what happens in the shared values area, the results are similar: only 0.4% of the cases do not add up any seat, while roughly 75% of the cases guarantee from 10% to 25% of seat capacity growth. Figure 10 shows the individual and accumulated distribution of these increments of seating capacity in the three delimited areas.

Table 4. Increments in room’s seat capacity attending to the analyzed cases.

Carrying Capacity Increase Range (%)	% of Total Cases (Zone 1)	% of Usual Cases (Zone 2)	% of the Shared Cases (Zone 3)
0	12.9	2.7	0.4
(0–10)	15.2	15.6	24.3
[10–15)	28.7	38.7	40.2
[15–25)	33.6	39.0	30.3
[25–35)	7.1	3.7	4.8
[35–45)	0.4	0.1	0.0
[45–50]	2.1	0.2	0.0

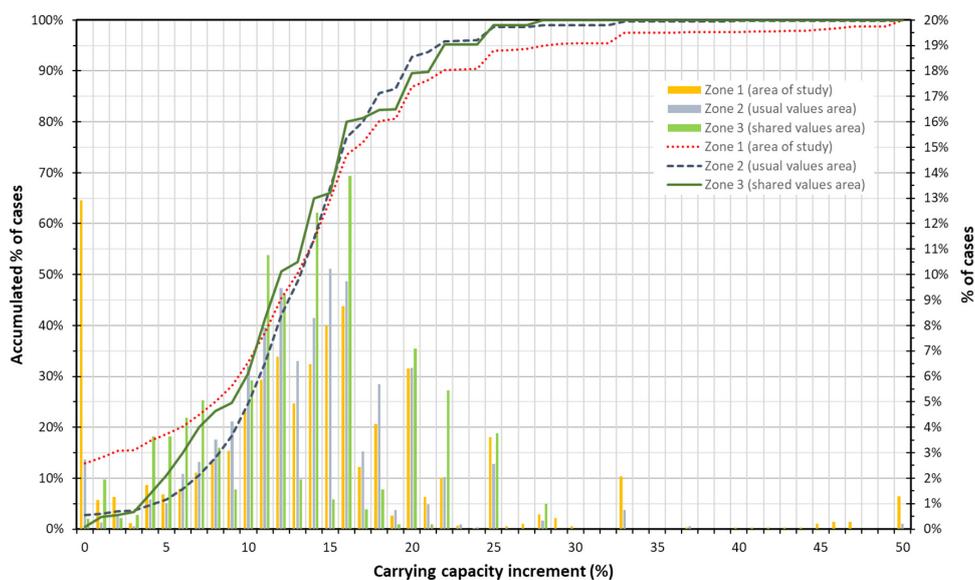


Figure 10. Carrying capacity increment distribution for the three zones defined.

3.2. Remarks on Furniture Types and Dimensions

The previous results can be accurate for individual distribution of the seats, but in some places like certain classrooms [37], libraries, or dining spaces, the subjects usually share a table. For those situations, it could be very useful to study the possible table allocations and the very geometry of the table—that is, its shape and size.

Figure 11 illustrates four of the most common distributions for the different seat patterns studied in this work. It can be observed in Figure 11b that some of the table layouts could lead to a decrease in the number of seats, which can alter the results shown in the previous subsection.

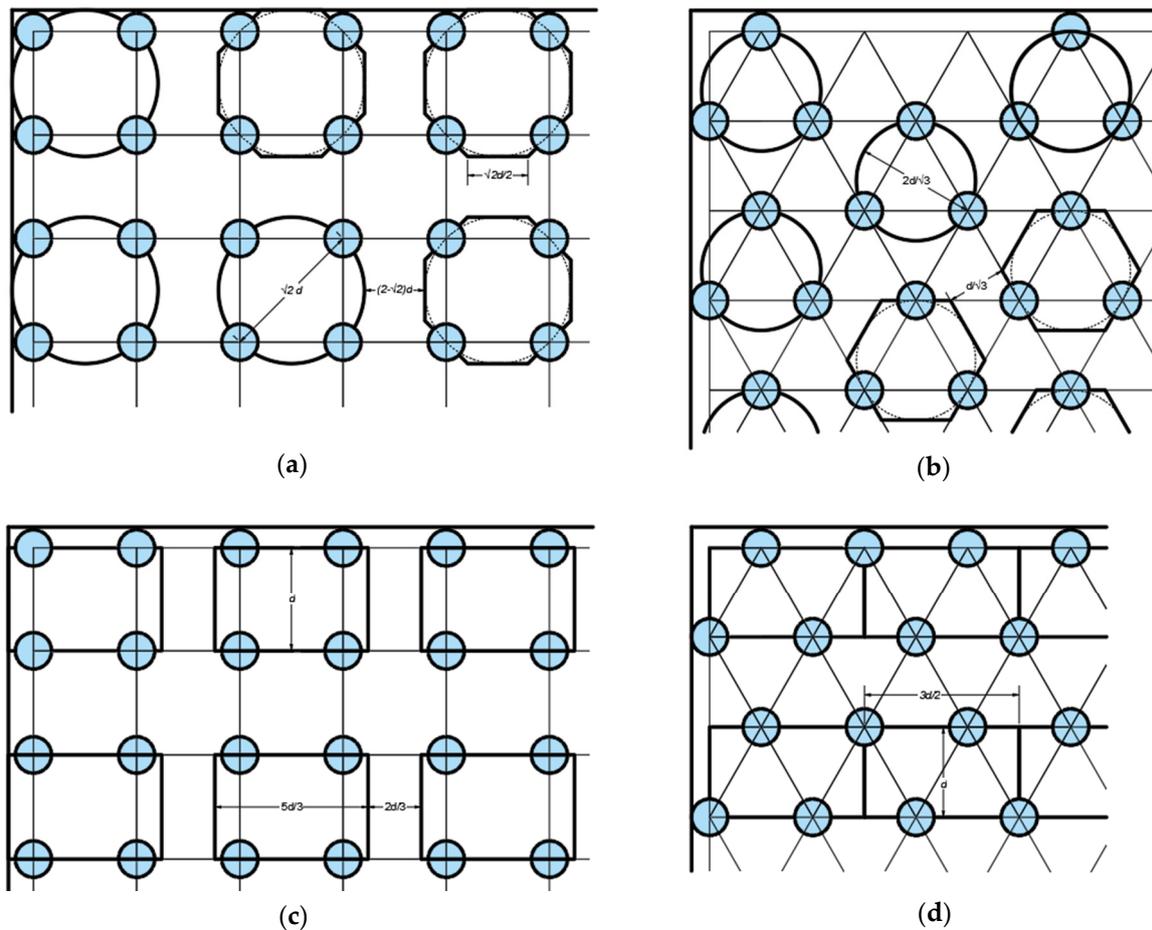


Figure 11. Possible table layouts: (a) Round or octagonal tables for four people in a square seat pattern; (b) Round or hexagonal tables for three people in a triangular seat pattern; (c) Rectangular tables for four people in a square seat pattern; (d) Rectangular tables forming continuous rows in a triangular seat pattern.

That figure also reveals that the dimensions of the tables are conditioned by the physical distance d . For that reason, as shown in Table 5, it is possible to determine the range of valid table sizes for each value of d , previously defined in Table 2.

In case of the tables that have a lesser diameter or length, they can be easily adapted by placing a new board with the correct dimensions above the existing table surface. However, as it can be noted, some of the values can be excessive for a regular table. It is not common to find tables with a diameter greater than 2.5 m, or rectangular tables more than 3.5 m wide, for example.

Table 5. Dimensions of the tables for the adopted values of d .

d (m)	Diameter for Round/Octagonal/Hexagonal Tables (m)		Length for Rectangular Tables (m)	
	Square Seat Pattern	Triangle Seat Pattern	Square Seat Pattern	Triangle Seat Pattern
1.6	2.26	1.85	2.67	2.40
1.7	2.40	1.96	2.83	2.55
1.8	2.55	2.08	3.00	2.70
2.1	2.97	2.42	3.50	3.15
2.2	3.11	2.54	3.67	3.30
2.3	3.25	2.66	3.83	3.45
2.4	3.39	2.77	4.00	3.60
2.5	3.54	2.89	4.17	3.75
2.6	3.68	3.00	4.33	3.90
2.7	3.82	3.12	4.50	4.05
2.8	3.96	3.23	4.67	4.20

4. Conclusions

In this paper, a comprehensive model for optimizing the number of seats on orthogonal closed spaces is presented. The study compares the traditional seat layout in square pattern with the most effective seat distribution using equilateral triangles. The effectivity of this uncommon distribution has been analyzed for several kinds and sizes of indoor spaces, concluding that in most cases the alternative pattern is preferable to the classic one. When the number of seats is low, this pattern can add up to 50% more seats in the room. For intermediate-sized spaces, the capacity increments range between 20% to 30%, while for larger areas the values oscillate from 4% to 25%. Results also show that triangular patterns add no carrying capacity only in the 2.7% of the usual cases analyzed, whereas in almost 80% of the cases located in this zone the carrying capacity increases by 10% to 25%. The implications of the size and shape of the existing furniture for shared table layouts have also been discussed.

As a further line of research, this methodology could be extended to other geometric shapes, not as common as the rectangular, or rooms with irregular contours. More complex numerical models will be needed for solving this problem.

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