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Social distancing in airplane seat assignments

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ABSTRACT

This paper addresses the airplane passengers' seat assignment problem while practicing social distancing among passengers. We proposed a mixed integer programming model to assign passengers to seats on an airplane in a manner that will respect two types of social distancing. One type of social distancing refers to passengers being seated far enough away from each other. The metric for this type of social distancing is how many passengers are seated so close to each other as to increase the risk of infection. The other type of social distancing refers to the distance between seat assignments and the aisle. That distance influences the health risk involved in passengers and crew members walking down the aisle. Corresponding metrics for both health risks are included in the objective function. To conduct simulation experiments, we define different scenarios distinguishing between the relative level of significance of each type of social distancing. The results suggest the seating assignments that best serve the intention of the scenarios. We also reformulate the initial model to determine seat assignments that maximize the number of passengers boarding an airplane while practicing social distancing among passengers. In the last part of this study, we compare the proposed scenarios with the recommended middle-seat blocking policy presently used by some airlines to keep social distancing among passengers. The results show that the proposed scenarios can provide social distancing among seated passengers similar to the middle-seat blocking policy, while reducing the number of passengers seated close to the aisle of an airplane.

1. Introduction

The spread of the novel coronavirus (SARS-CoV-2) has resulted in unprecedented measures in terms of travel and socio-economic activities worldwide, while the estimated negative economic effects can be seen in many areas. As a result, the global economy is projected to have a gross domestic product contraction of −3%, worse than the one generated by the 2008–2009 financial crisis, a reduction of the global merchandise trade volume by 13%–32% compared to 2019 and a decline in international tourism monetized with a reduction between USD 330 billion – USD 590 billion compared to 2019, mostly due to the travel restrictions applied in almost 96% of travel destinations (ICAO, 2020).

Airplane transportation is one of the main sectors affected by the coronavirus outbreak due to the both the limitations imposed on international flights in different countries and to the reluctance of passengers to engage in air travel (Taylor, 2020). In a recent study entitled "COVID-19 Air Transport Near Term Impacts and Scenarios" by Fast Future and Future Travel Experience, based on a 16-question survey, completed by 269 industry professionals from 47 countries, supplemented by a series of research and expert interviews, it has been reported that the passengers' reluctance to fly would be heightened in the COVID-19 period by the confusing protocols used by different countries, airlines and airports (Taylor, 2020). As airline transport is made through enclosed spaces in which a large number of people are fit in, this type of transport has been closely associated with the potential risk of spreading the virus (Vandycke, 2020), producing both social and economic effects because the consumers might be tempted to change their behavior and to seek private means of transport to the detriment of airline transportation. As Iacus et al. (2020) have shown, the air traffic industry has been closely related to the past pandemic outbreaks such as SARS in 2003 and MERS in 2015 (Iacus et al., 2020), while the effects of these pandemic periods have been visible at both regional and global scale. As a result, the airline companies have the duty of ensuring the safety and health of their passengers in these hard times by increasing their trust in this industry which is already significantly affected by the COVID-19 situation. As Vandycke (2020) recently stated, a short-term chaos

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could bring long-term transformation in the transportation industry (Vandycke, 2020). In this context, the author envisions the end of the "giant planes" and "first class" as airlines need more flexibility in order to provide a higher level of safety for their passengers (Vandycke, 2020). The IATA Medical Advisory Group (IATA, 2020) suggests that airlines take the following measures to ensure passenger safety: social distancing, proper management of the boarding process, limit carry-on luggage, and sequential boarding starting from passengers with seats in the rear of the airplane and window seats.

Social distancing, i.e., reducing interactions between individuals in order to slow down the spread of the virus (De Vos, 2020), has been one of the most discussed measures proposed by the World Health Organization (WHO) to mitigate the horrendous impact of the COVID-19 pandemic (WHO, 2020). The measures included in the term of "social distancing" feature keeping a sufficient distance among the people, avoiding mass gathering and closing public places (Nguyen et al., 2020), all of them representing an effective non-pharmaceutical approach for limiting the disease transmission (Ferguson et al., 2006). Imposing a social distance measure for airplane passengers is mentioned in a recent report of the European Union Aviation Safety Agency (EASA), which states that "airplane operators should ensure, to the extent possible, physical distancing among passengers" (EASA, 2020). As social distancing in airplane boarding requires both passengers' self-willingness to respect the suggested social distance and a well-designed seat assignment strategy, in this work, we focus on proposing a proper passenger seat assignment to practice social distancing, rather than offering some general safety guidelines to the passengers, as these guidelines are considered known by passengers and passengers' compliance can be only partially supervised by the airline companies. To be more specific, we formulate a mixed integer programming (MIP) model to assign passengers to seats on an airplane to respect two types of social distancing: keeping the passengers seated far enough away from each other and providing a safe distance between seat assignments and the aisle. The primary goal of this paper is to show how the proposed model can be used to properly assign the passengers to their seats while effectively preserving the social distancing among them.

The rest of this paper is organized as follows: the next section provides a short literature review on both airplane boarding methods research and optimization techniques used in airplane boarding. Section 3 features the proposed method and underlines the assumptions for passenger assignment and the MIP model formulation. Section 4 provides the numerical simulation on different cases, while accounting for one or two levels of social distancing among seated passengers. An additional discussion is made in Section 4 in relationship to the airlines' current policy for social distancing. Section 5 concludes the paper and provides some guidelines for further research directions.

2. Literature review

2.1. Airplane boarding and mixed integer programming

Airplane boarding techniques are the main focus concerning the research papers in the area of minimizing the airplane turn time and reducing the airline costs incurred by passenger boarding time (Delcea et al., 2018c). An extensive literature is dedicated to proposing new boarding methods under different conditions, such as the presence of jet bridges (Bachmat et al., 2009; Jaehn and Neumann, 2015; Milne and Kelly, 2014; Soolaki et al., 2012; Steffen, 2008a; van den Briel et al., 2005) or the use of the apron buses (Delcea et al., 2018a, 2019; Milne et al., 2019b). As a result, a series of methods have been recommended and analyzed under various considerations such as airplane occupancy (Kierzkowski and Kisiel, 2017; Milne and Kelly, 2014; Notomista et al., 2016; Qiang et al., 2014; Steffen and Hotchkiss, 2012; van den Briel et al., 2005; Van Landeghem and Beuselinck, 2002), passengers boarding using one or both doors of the airplane (Bachmat et al., 2009; Bidanda et al., 2017; Delcea et al., 2018a, 2019; Kuo, 2015; Milne et al., 2018; Milne and Kelly, 2014; Milne and Salari, 2016; Nyquist and McFadden, 2008; Qiang et al., 2014; Soolaki et al., 2012; Steffen, 2008a; Steiner, and Philipp, 2009; Tang et al., 2018a; van den Briel et al., 2005), passengers' physical characteristics (Hutter et al., 2018; Kierzkowski and Kisiel, 2017; Qiang et al., 2014), the rules for passenger movement (Steffen, 2008a, 2008b), seat selection (Ferrari and Nagel, 2005; Steffen, 2008b), the presence of carry-on hand luggage (Milne et al., 2018; Milne and Kelly, 2014; Qiang et al., 2014; Steffen, 2008a; Tang et al., 2018a), seat and aisle interferences (Delcea et al., 2018b; Qiang et al., 2017; Ren and Xu, 2018), and group behavior (Milne et al., 2020; Tang et al., 2018b, 2018a; Zeineddine, 2017). In most of the approaches, the passengers boarding rules apply in the same manner for both sides of the aisle, preserving a symmetry with respect to the aisle (Cotfas et al., 2020; Milne et al., 2019a).

The literature provides a variety of techniques for evaluating boarding methods, featuring: linear programming (Bazargan, 2007; Milne et al., 2018; Milne and Salari, 2016; Soolaki et al., 2012), computer simulation (Steffen, 2008a; Steiner, and Philipp, 2009; Tang et al., 2012; van den Briel et al., 2005; Van Landeghem and Beuselinck, 2002), grid-based simulation and cellular automata (Qiang et al., 2014; Schultz, 2017), agent-based and stochastic modelling (Delcea et al., 2018c, 2018d; Milne et al., 2019b; Schultz, 2018a, 2018b), simulated annealing (Wittmann, 2019), empirical tests (Steffen and Hotchkiss, 2012), etc.

MIP modelling has been a popular choice for addressing the airplane boarding problem. Milne and Salari (2016) propose a MIP model that determines the seats to assign to each passenger based on the passenger's carry-on bags. Numerical results show that the proposed approach reduces the boarding time with higher reductions in boarding time when the total number of luggage carried on board increases (Milne and Salari, 2016). In another study, by considering both the passengers' carry-on hand luggage and the earlier reserved seats by the high priority passengers, Salari et al. (2019) proposed another MIP for passengers' seat assignment. The obtained results indicate an average boarding time reduction ranging between 5% and 20% when compared to a baseline situation (Salari et al., 2019). In the case of airplane two-door boarding using apron buses, Milne et al. (2020) uses a MIP to assign the passengers to one of the two apron buses used for passengers' transport from the airport terminal to the airplane while accounting for the passengers traveling in groups. As a result, they observe up to 27.31% boarding time improvement versus a baseline approach. In a proposed MIP model by Bazargan (2007), the model minimizes the total interferences among passengers boarding into an airplane. The author considers one of the classical boarding methods, the reverse pyramid, and the passengers' velocity when proposing the approach. Starting from the results obtained by Bazargan (2007), Soolaki et al. (2012) model the problem as a MIP (minimizing interferences) which they solve with a genetic algorithm with results similar to previous methods but obtained more quickly.

2.2. Social distancing in times of COVID-19

Social distancing has been one of the most discussed measures taken during the COVID-19 outbreak due to the beneficial effects on reducing the coronavirus spread among humans (Sen-Crowe et al., 2020) and also due to the fact that is was one of the most controversial measures as it might affect people's mental health and emotional wellbeing (Donovan, 2020).

A broad range of subjects related to social distancing have been addressed in the scientific literature such as: political, economic, social and religious challenges (Yezli and Khan, 2020), adolescents' motivations to engage in social distancing (Oosterhoff et al., 2020), sexual activity (Jacob et al., 2020), the relation with telework implementation (Kawashima et al., 2020), the impact on crime (Mohler et al., 2020), personal wellbeing (Nyenhuis et al., 2020), social and ethical basis for social distancing (Lewnard and Lo, 2020), etc., while in the area of travel and human mobility the primary research areas focused on: travel behavior (De Vos, 2020), uncontrolled travelers effect on the spread of the coronavirus (Gómez-Ríos et al., 2020), airline employment evolution (Sobieralski, 2020), estimating and projecting air passenger traffic (Iacus et al., 2020), and comparing classical airplane boarding methods while considering social distancing rules (Cotfas et al., 2020).

Public authorities have used different approaches to support social distancing, such as: drawing circles in public parks for delimiting personal space (Harrouk, 2020), marking the metro seats (METROREX, 2020) and train seats (Trenitalia, 2020) that may be occupied, and creating a passenger-powered app feature to inform others of on-board passenger volumes (Intelligent Transport, 2020).

In passenger air transport management, the following measures have been taken: passengers assigned to the rear seats board first (implemented by Delta Air Lines (Writers, 2020)); boarding based on passengers' seat numbers (trialed by EasyJet and Gatwick Airport (Future Travel Experience, 2020)); passengers assigned to the seats in front rows board first while entering an airplane from the rear door (implemented by GoAir (Ash, 2020)); airplane passengers de-boarding will be made starting with front rows (implemented by "Henri Coandă" Airport (Romanian Transport Ministry, 2020)).

A few researchers have developed optimization and heuristic based methods to facilitate decisions on the social distance positioning of people in several contexts. Fishetti et al. (2020b) leverage one of their author's earlier work (Fischetti et al., 2020a) on where to place offshore windfarm turbines to the contexts of where to position restaurant tables and beach umbrellas to support social distancing (Fischetti et al., 2020b). The wake effects from wind turbines interfering with other turbines is analogous to the expiration of COVID-19 droplets from an infected diner at a restaurant table infecting nearby diners. Lustig (2020) summarizes a prototype for determining seat assignments at a sports venue (Lusting, 2020).

3. Proposed method

In this section, we focus on the details of the proposed method including the main assumptions and the proposed MIP formulation for the passengers' assignment to seats on an airplane.

3.1. Assumptions and objectives for passenger assignment

As our primary focus in this work is on the passenger assignment to seats in an airplane, we don't concentrate on the boarding sequence of passengers. This includes ignoring the time it takes a passenger to sit down and/or to store his/her luggage in an overhead bin compartment. Similar to many related studies (Milne et al., 2019b; Milne and Salari, 2016; Salari et al., 2019), we use the Airbus A320 having one aisle, 20 rows and three seats on each side of the aisle to conduct our experiments. To find the distance between seats, we define the seats' width, aisle width, and the distance between seats in consecutive rows (known as seat pitch) as 17.5, 22, and 32 inches (equivalent to 44.45, 55.88 and 81.28 cm), respectively[1] (Fig. 1). In formal definitions, seat pitch refers to the distance from any point on one seat to the same point on the seat in front or behind it. While it is not the exact equivalent of "legroom", it does give a good indication of how much leg room exists. To practice social distancing in the passenger seat assignment advised by the WHO, we calculate the distance between a certain seat and all other seats in the airplane (WHO, 2020). We use the Euclidian approach to calculate the distance between the center of a seat and the center of another seat. Fig. 2 presents a simple algorithm to calculate the Euclidian distance between seats in an airplane. The algorithm also establishes the value of a binary parameter β(described below) that indicates whether the distance between seats is within a specified range of interest.

After finding the distance between a target seat and all other seats in the airplane, we define a parameter that exhibits the seats which are between a lower and upper bound distance from the target seat. The parameter l indicates seat position ($l = 1$ means window seat; $l = 2$ means middle seat, and $l = 3$ means aisle seat). For the seat l on the side s of row r, the binary parameter $\beta^{r,s,l}_{r',s',l',k}$ indicates whether seat l', on side s' and row r' is within a particular range of distance from the seat represented with the superscripts (r, s, l). For this parameter, we use the subscript k with tighter lower and upper bounds in shorter distances to greater respect the importance of social distancing in closer distances.

For instance, we defined the lower and upper bounds distance where $k = 1$ as $Lb_1 = 0$ and $Ub_1 = 3.3$, so $\beta^{r,s,l}_{r',s',l',1} = 1$ indicates seats that are in less than or equal to 3.3 feet distance from the seat l on the side s of row r of an airplane. We selected the 3.3 feet distance for the upper bound of $k = 1$ as the World Health Organization (WHO) advises people to keep at least 3.3 feet (equivalent to 100 cm) distance from each other while practicing social distancing (WHO, 2020). So, the passengers who are sitting less than 3.3 feet distance from each other are not following the guidelines advised by WHO. For the second category ($k = 2$), its lower bound is equal to 3.3 feet and its upper bound is equal to 6.6 feet. This second category is for passengers that are seated more than 3.3 feet from other passenger(s) and yet are seated within 6.6 feet of at least one passenger. Passengers within this second category are penalized but with a lower penalty value than those in the first category who are seated closer to other passenger(s). We defined the second category based on the operational guidelines for the management of air passengers and aviation personnel in relation to the COVID-19 pandemic published by European Union Aviation Safety Agency (EASA, 2020), in which it is specified that the current scientific studies and articles confirm that in general, the distance that large respiratory droplets travel is up to 2 m (equivalent to 6.6 feet) when coughing. Therefore, we employed this distance (i.e., 6.6 feet) to construct the second category of passengers distancing.

As a way of illustration, Fig. 3 shows the 6, 9, and 8 seats which are less than or equal to 3.3 feet distance from the window seat of row 17 on the left side of the aisle, the aisle seat of row 5 and the middle seat of row 14 on the right side of the airplane respectively.

In addition to the seating location distance among passengers, we are interested in the seating location's distance from the aisle of the airplane. The aisle is used by passengers for walking to the washroom or opening the overhead compartments, and by flight attendants for serving the passengers. The passengers' distance from aisle can play a crucial role in practicing social distancing. There are three levels of distance between seats and the aisle of the airplane because the aisle seats are closest to the aisle and window seats are safest in terms of the highest distance from the aisle and middle seats in between. Concerning maximizing the distance from the aisle, we aim to minimize the number of passengers sitting in the aisle seats and middle seats. In this regard, the aisle seats, as they are closer to the aisle, are prioritized with higher penalties than the middle seats. We introduced the parameter α_l to indicate the importance of penalizing the passengers' assignment to aisle seats more than for their assignment to middle seats. In other words, α_l emphasize the importance of avoiding assigning aisle seats because of their close distance to the aisle compared to middle and window seats. Moreover, α_l is zero for all window seats as the window seat location is the best practice concerning the distance from the aisle of an airplane.

The seats located in the first rows and last rows of the airplane are more penalized for violating social distancing in the airplane as these rows are closer to the flight attendants' cabin and the airplane washrooms. To address this effect, we introduce λ_r as weights to stress the importance of minimizing the number of passengers assignments on seats close to the front and rear of the airplane. To extract the value of λ_r

[1] We employ these values averaging the seat pitch and seat width for several airlines worldwide. Readers can refer to:https://www.airlinequality.com/info/seat-pitch-guide/, https://modernairliners.com/airbus-a320-introduction/airbus-a320-interior/.

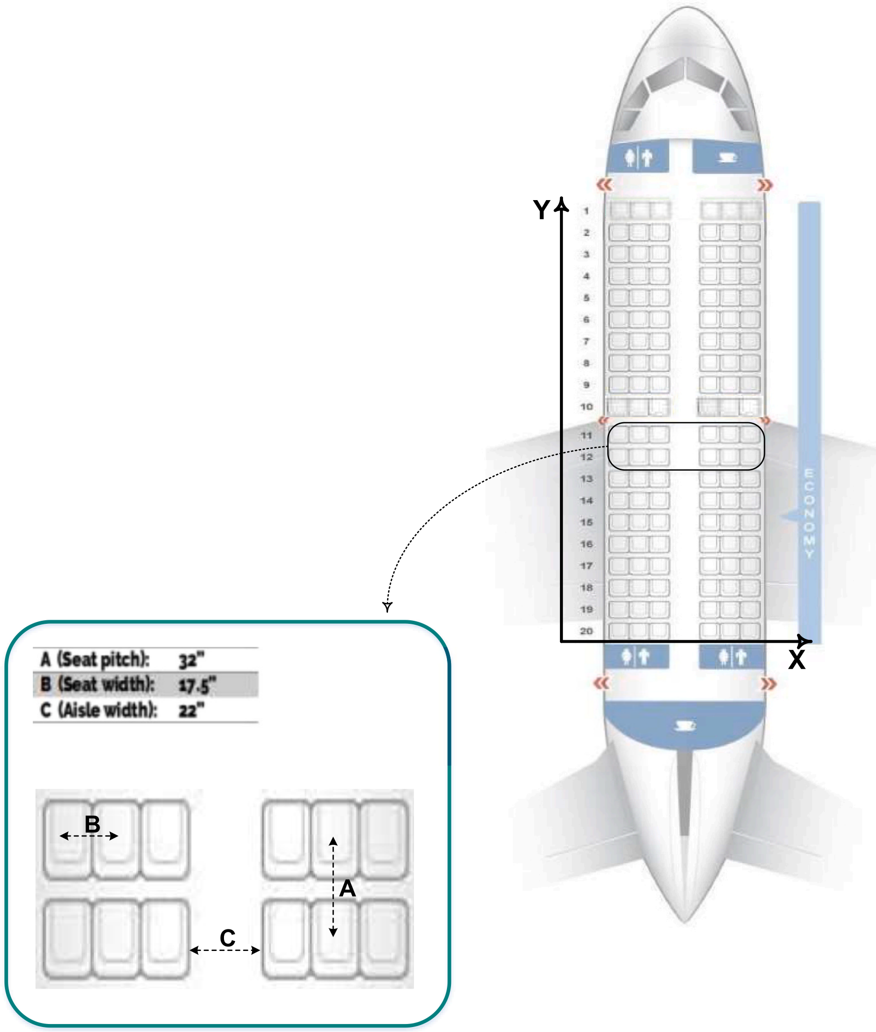

Fig. 1. The layout and dimensions of an Airbus A320.

for each row, we suggest the following approach:

$$\lambda_r = \left(\frac{1}{r}\right)^{\frac{1}{\gamma}} \forall r \in R \backslash r \leq 10 \tag{1}$$

$$\lambda_r = \left(\frac{1}{21-r}\right)^{\frac{1}{\gamma}} \forall r \in R \backslash r > 10 \tag{2}$$

where in Eqs. (1&2), γ controls the weights assigned to each row. The higher the value of γ, the more the importance of not assigning passengers to seats closer to the front/rear of the airplane.

Table 1 weights emphasize the importance of keeping the passenger's assigned seat away from the very first and last rows using different values of γ. For instance, we see that λ_r for rows 10 and 11 are only 10% of the row 1 penalty when γ is 1 and 77.4% of the row 1 penalty when γ is 9.

3.2. Mixed integer programming model formulation

We introduce $X_{r,s,l}$ as the main binary decision variable that shows the occupancy of the seat l at row r and side s of the airplane. we defined two separate models for passenger seat assignment. In the first model introduced in section 3.2.1, the primary goal is to assign passengers to seats in a way to better practice social distancing between them. This involves minimizing the number of passengers seated very close to each other (within 3.3 feet) and close to each other (within 6.6 feet but not within 3.3 feet) as well as the number of passengers seated close or very close to the aisle of the airplane. In the second model, we employed the objective function variables of the first model in the set of constraints aiming to maximize the load of passengers while, to a certain degree, practicing the social distancing among passengers. In what follows, we first introduce subscripts, superscripts, sets, parameters and variables of the models 1 and 2. This will be followed by introducing the objective function and the constraints of each model.

Subscript & superscript

$r\&r'$	row of the airplane
$s\&s'$	side of the airplane. $s, s' = 1$ represents the left side and $s, s' = 2$ indicates the right side of the aisle
$l\&l'$	seat of the airplane. $l, l' = 1$, $l, l' = 2$ and $l, l' = 3$ respectively indicates the window, middle and aisle seat

```
Find the Euclidian distance D between each pair of seats and establish the binary parameter β :
Define X and Y coordinates according to Fig. 1
Define the upper bound (Ub_k) and lower bound (Lb_k) distance for each k . For k > 1 , Lb_k = Ub_{k-1} (e.g.
k = 1  ⇒  Ub_k = 3.3 feet, Lb_k = 0 feet )
Do for r = 1 to 20
   Do for l = 1 to 3
      Do for s = 1 to 2
            Find the center of the seat (l, s, r) and set it as (x, y)
           Do for r' = 1 to 20
              Do for l' = 1 to 3
                 Do for s' = 1 to 2
                      Find the center of the seat (l', s', r') and set it as (x', y')
                      Calculate D = sqrt((x − x')^2 + (y − y')^2)
                      Do for k = 1 to |k|
                           If D > Lb_k and D ≤ Ub_k :
                                β^{r,s,l}_{r',s',l',k} = 1
                           Else:
                                β^{r,s,l}_{r',s',l',k} = 0
                     End do for k loop
                 End do for s'
              End do for l'
           End do for r'
      End do for s
   End do for l
End do for r
```

Fig. 2. Algorithm to find the value of the binary β that indicates the distance between seats.

k — category of distance between seats. In this work, we define two levels of k

Sets

R — Sets of rows: $R = \{1, 2, 3, \ldots, 20\}$
S — Sets of sides: $S = \{1, 2\}$
L — Sets of seats: $L = \{1, 2, 3\}$
K — Sets of category of seat distances: $K = \{1, 2\}$

Parameters

$\beta^{r,s,l}_{r',s',l',k}$ — Binary parameter to indicate whether the seat (r', s', l') is within the range of distance defined in category k distance from the seat (r, s, l)
λ_r — Weight corresponding to row r
γ — Value to be used for finding the value of λ_r
δ_k — Weights pertaining to each category of seat distance from other seated passengers
w_1, w_2 — Weights of the first and the second objective function variables
$\eta_{Z_1}\eta_{Z_2}$ — Upper bounds of the first and the second objective function variables
α_l — Weights pertaining to the seating locations with respect to their distance from the aisle. α_l should inherit higher values for aisle seats than for middle seats
ϑ — Number of passengers boarding the airplane

Variables

Z_1 — Variable of the objective function that represents the number of passengers seated within certain distances of each other
Z_2 — Variable of the objective function that represents the number of passengers who are close and very close to the aisle
Z_3 — Variable of the objective function that shows the number of passengers who board the airplane
$X_{r,s,l}$ — Binary variable that determines if the seat location represented by (r, s, l) is occupied by a passenger (value of 1) or not (value of zero)
$Y^{r,s,l}_{r',s',l'}$ — Binary variable that determines if the seat locations represented by (r, s, l) and (r', s', l') are both occupied by passengers (value of 1) or at least one of them is not occupied (value of zero)

3.2.1. Model 1: Minimizing the social distancing interferences

The primary focus of the first model is to best practice the social distancing among passengers according to the introduced metrics with a pre-specified load of passengers. The objective function variables in this model are combined in a singular function having weights to emphasize the importance of each element:

3.3. Objective function

$$Z = \min(w_1 Z_1 + w_2 Z_2) \tag{3}$$

The first component of the objective function is to minimize the number of passengers who are about a certain distance from each other.

$$Z_1 = \sum\nolimits_{l,l' \in L} \sum\nolimits_{s,s' \in S} \sum\nolimits_{r,r' \in R} \sum\nolimits_{k \in K} \delta_k Y^{r,s,l}_{r',s',l'} \beta^{r,s,l}_{r',s',l',k} \tag{4}$$

where in Eq. (4), the value of δ_k, i.e., $0 < \delta_k < 1 \ \forall k \in K$ is a weight that decreases as k increases. This parameter implies that it is more important to minimize the number of passengers who are sitting close to a certain passenger than minimizing the distance between passengers who are sitting farther away from each other.

$$Z_2 = \sum_{l \in L} \sum_{s \in S} \sum_{r \in R} \alpha_l \lambda_r X_{r,s,l} \tag{5}$$

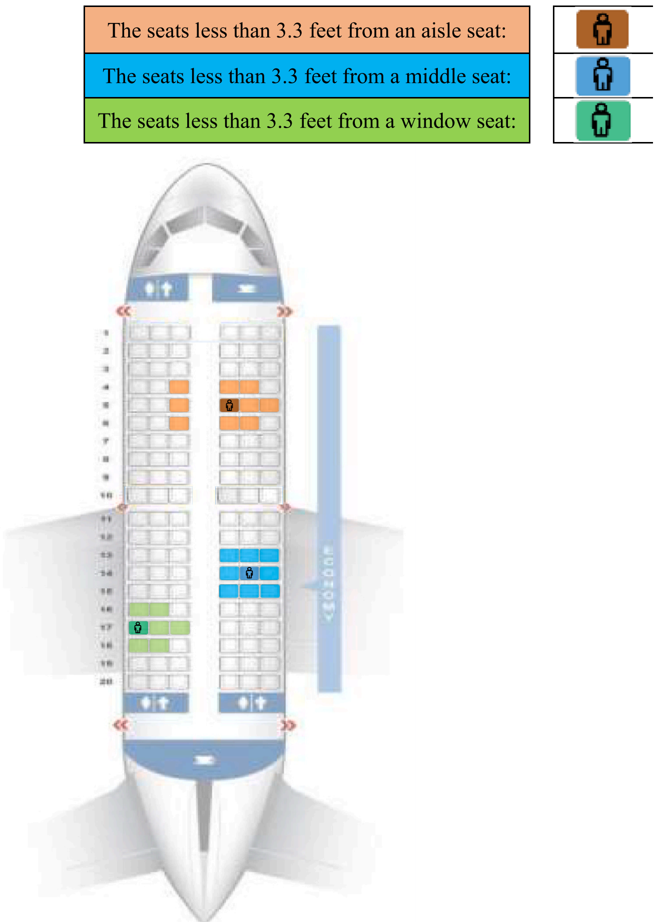

Fig. 3. Seats located less than 3.3 feet in distance from the three occupied seats.

Table 1
Example of the value of λ for each row with respect to two values of γ

Row (r)	$\gamma = 1$	$\gamma = 9$
1	1.000	1.000
2	0.500	0.926
3	0.333	0.885
4	0.250	0.857
5	0.200	0.836
6	0.167	0.819
7	0.143	0.806
8	0.125	0.794
9	0.111	0.783
10	0.100	0.774
11	0.100	0.774
12	0.111	0.783
13	0.125	0.794
14	0.143	0.806
15	0.167	0.819
16	0.200	0.836
17	0.250	0.857
18	0.333	0.885
19	0.500	0.926
20	1.000	1.000

with Eq. (5), we minimize passenger assignments to seats that are closer to the airplane aisle. In this equation, we also take into account the weight λ_r, i.e., $0 < \lambda_r < 1 \ \forall r \in R$, corresponding to each row of the airplane. With a higher value of λ_r for the first several rows and the last rows of the airplane, the distance from the aisle will not be penalized in the middle rows of the airplane as much as for the first and last rows.

$$\sum_{l\in L}\sum_{s\in S}\sum_{r\in R} X_{r,s,l} = \vartheta \tag{6}$$

Eq. (6) is the occupancy constraint that deals with a load of passengers boarding an airplane. For the Airbus A320, the capacity is 120. A load of passengers, i.e., ϑ, which should be less than capacity, can be obtained by enforcing Eq. (6). In other words, $\vartheta = 20$ would only assign 20 passengers to seats in the Airbus A320.

$$X_{r,s,l} + X_{r',s',l'} - 1 \le Y^{r,s,l}_{r',s',l'} \quad \forall r, r' \in R, s, s' \in S, l, l' \in L, (r,s,l) \neq (r',s',l') \tag{7}$$

Eq. (7) ensures that $Y^{r,s,l}_{r',s',l'}$ equals 1 if both binary variables $X_{r,s,l}$ and $X_{r',s',l'}$ are equal to 1.

3.3.1. *Model 2: Maximizing the (safe) load of passengers*

Practicing social distancing in the seat assignment problem can be viewed from a different perspective where the goal is to maximize the load of passengers while limiting the number of passengers assigned to seats within a pre-specified minimum distance among passengers and/or sitting close to the aisle of airplane. To address this objective, the predefined objectives in Eqs. (4) and (5) should be included in the list of constraints for Model 2 with specified upper bounds, i.e., η_{Z_1}, η_{Z_2}.

3.4. *Objective function*

$$Z_3 = \max\left(\sum_{l\in L}\sum_{s\in S}\sum_{r\in R} X_{r,s,l}\right) \tag{8}$$

The objective function introduced for model 2 in Eq. (8), replaces model 1's Eq. (3), and maximizes the number of passengers assigned to seats in the airplane. This function was introduced as a constraint, i.e., Eq. (6), in the formulation proposed in section 3.2, where the aim was not to maximize the load of passengers but rather to accommodate a pre-specified number of passengers. Equation (6) is omitted from model 2.

$$\sum_{l,l'\in L}\sum_{s,s'\in S}\sum_{r,r'\in R}\sum_{k\in K}\delta_k Y^{r,s,l}_{r',s',l'}\beta^{r,s,l}_{r',s',l',k} \le \eta_{Z_1} \tag{9}$$

$$\Sigma_{l\in L}\Sigma_{s\in S}\Sigma_{r\in R}\alpha_l\lambda_r X_{r,s,l} \le \eta_{Z_2} \tag{10}$$

The constraints of the formulation proposed in this section should include Eq. (7). The objective function variables Z_1 and Z_2 are included in Eq. (9) and Eq. (10) as constraining upperbounds to limit the number of passengers who are seated to close to another passenger and to limit the number of passengers seated close to the aisle.

4. Numerical results

We implemented the MIP formulation proposed in Section 4 using GUROBI 9.0 as the MIP solver on a personal computer with a 3.4 GHz Intel® Core™ i7-6700 U-type processor and 16 GB of memory. We used GUROBI solver keeping the default parameter settings except that we used a zero optimization tolerance gap.

4.1. *Results from proposed MIP in model 1*

We defined different scenarios introduced in Table 2 concerning the values of the parameters in the MIP formulation in Model 1. On one hand, scenario I provides the most emphasis on keeping the desired passengers' distance from each other. On the other hand, scenario II emphasizes the desirability of not assigning the passengers to seats close to the aisle of the airplane. Scenario III, while giving similar nominal importance to each objective, attempts to simultaneously emphasize the importance of seat assignments to keep the safe distance between passengers and the distance from the aisle of the airplane.

Fig. 4 represents the passengers' seat assignment for 30 passengers, i. e., $\vartheta = 30$, under scenarios I, II described in Table2.[2]

In Fig. 4, for each target passenger assigned to a seat, we define three classes based on the number of passengers assigned to seats which are in less than 3.3 feet distance from the target passenger. The classes include one, two, and three or more passengers sitting close to the target passenger and the corresponding cells to these classes are highlighted as yellow, orange and red, respectively. Using scenario I, we expect the seat assignments to be more focused on keeping passengers socially distant from each other. As illustrated in Fig. 4, this is the case with the seat assignment under this scenario where no seat assignment violates the 3.3 feet social distancing policy. Scenario II, however, minimizes the number of passengers assigned to aisle seats to emphasize the passengers distance from the aisle of an airplane. Under this scenario, the number of passengers assigned to aisle seats reduces to no passengers compared to 10 passengers assigned to aisle seats in scenario I.

We also evaluate the number of passengers in the first and second social distancing categories when γchanges from 1 to 9 for the same load of passengers, i.e., $\vartheta = 30$ (Fig. 5). For both values of γ, scenario I results in the fewest possible passengers sitting very close to each other (category $k = 1$). Because scenario II emphasizes passengers sitting further from the aisle, the downside consequence is that more passengers are sitting too close to each other than for scenario I. The disparity increases while gamma $\gamma = 9$, because the higher the value of gamma, the more severe the penalty for the assignment of passengers to seats close to the front and rear of the airplane.

Tables 3 and 4 evaluate the seat assignments under different scenarios concerning the passengers' distance from each other and their distance from the aisle for a load of passengers. Note that $\gamma = 1$ the recommended seat assignments results are presented in Table 3, while $\gamma = 9$ the results are presented in Table 4. We also report the computer runtime corresponding to each load of passengers and each scenario in the last column of these tables. In Tables 3 and 4, passengers distance from other occupied seats is divided into the three classes previously introduced for Fig. 4. The different values of γ in Tables 3 and 4 address the importance of not assigning passengers to the first and last rows of the airplane as these rows are close to the washroom or flight attendant cabin. According to the results presented in these two tables, scenario II keeps passengers away from the aisle seats, especially in the very first/last rows. However, scenario II does not do as well as scenario I in keeping passengers seated further from each other. With heavier loads of passengers, i.e., $\vartheta = 60, \vartheta = 90$, the number of passengers in class 3 (more than 3 persons sitting within 3.3 feet of a target passenger) increases when seat assignments are based on scenario II instead of scenario I. For instance, for the seat assignment according to scenario II and the load of 60 passengers in Table 3, the number of passengers in class 3 is 52, while there is no passenger in this class using the first scenario for the seat assignment. Moreover, comparing the other two classes for the

Table 2
Different scenarios defined for seat assignment.

Scenario	w_1, w_2	δ_k	α_l
I	$w_1 = 0.9, w_2 = 0.1$	$\delta_1 = 0.9, \delta_2 = 0.1$	$\alpha_3 = 0.6, \alpha_2 = 0.4, \alpha_1 = 0$
II	$w_1 = 0.1, w_2 = 0.9$	$\delta_1 = 0.6, \delta_2 = 0.4$	$\alpha_3 = 0.9, \alpha_2 = 0.1, \alpha_1 = 0$
III	$w_1 = 0.5, w_2 = 0.5$	$\delta_1 = 0.9, \delta_2 = 0.1$	$\alpha_3 = 0.9, \alpha_2 = 0.1, \alpha_1 = 0$

same load of passengers in this table, it is clear that scenario I emphasizes seat assignments that minimizes the average number of passengers in classes 2 and 3.

Seat assignments based on scenario III in all loads of passengers presented in Tables 3 and 4 is more reminiscent of scenario I than scenario II. This happens because compared to the second objective, the first objective related to the passengers distancing from each other contributes more to the optimized value of the combined objective function (Eq. (3)). For instance, the seat assignment based on scenario III for the load of 60 passengers in Table 4 offers 20, 40, and 0 passengers in classes 1,2 and 3 which are very close to the values offered for these classes based on the scenario I compared to scenario II. To find a better balance between scenarios I and II, we adjusted weights of objective function variables to 0.3 and 0.7 for the first and second objectives and the weights of each category of seat distance is updated to 0.7, 0.3 for the first and the second category, respectively, while keeping the remaining parameters' values according to the scenario III in Table 2. Table 5 presents the effect of the updated weights on the seat assignment for a load of 60 passengers and different values of γ.

According to Table 5, the modified scenario recommends a seating layout that is generally between what scenarios I and II offer in terms of the passengers in different classes and the passengers assigned to aisle seats. For instance, when $\gamma = 9$, passengers seat assignments based on scenarios I and II include 36 and 8 passengers in class 2 where two passengers sit close to each other. However, this value for the seat assignment recommended by the modified scenario is 19 which is a value between 8 and 36 ($8 < 19 < 36$). Moreover, in terms of the passengers in class 3, the modified scenario suggests 35 passengers sit close to three or more passengers while this value for the recommended seating assignment in scenarios I and II are 0 and 52, respectively. The number of passengers assigned to aisle seats based on the modified scenario is 6 which is also a value between the number of passengers dedicated to the aisle seats in scenarios I and II.

To study the effect of γ value on passengers' seat assignment, in Fig. 6, we evaluated the seat assignments when $\gamma = 1$, $\gamma = 9$ and for a load of 60 passengers based on scenario II.

According to Fig. 6, when $\gamma = 9$, the proposed seat assignment puts more emphasis on keeping the aisle seats (especially the aisle seats in the very first/last rows) free of passengers. As a result, there is no passenger assigned to aisle seats when$\gamma = 9$. However, when $\gamma = 1$, there are passengers assigned to aisle seats but still, the proposed seat assignment distributes most of the passengers of aisle seats to the middle rows, i.e., rows 9 and 12. Avoiding the passenger assignment to aisle seats is a trade-off that requires assigning more passengers sitting close to each other. Therefore, comparing the seat assignments when $\gamma = 1$ and $\gamma = 9$, we observe that the number of passengers in class 2 increases from 5 when $\gamma = 1$ to 8 when $\gamma = 9$.

4.2. Results from proposed MIP in model 2

In model 2, with the aim of maximizing the number of passengers, we specify the maximum number of passengers that are seated too close to another passenger and too close to the aisle, as defined in the right hand side values of Eqs. (9) and (10). Fig. 7 shows a resulting seating layout of passengers where both Eqs. (9) and (10) are active (with righthand side values of zero) allowing no passenger to sit closer than 3.3 feet distance from another passenger and for no passenger to occupy an aisle seat (left side of the seating assignment in Fig. 7). With this set of constraints, the maximum load of passengers is 20 which is one-sixth of the maximum possible load of passengers to board the airplane in the absence of social distancing. We also evaluate the maximum possible load of passengers only restricting the passengers seating assignment to have no passengers seated closer than 3.3 feet distance from another passenger while permitting passengers to sit in aisle seats (right side of the seating assignment in Fig. 7). This results in 10 additional passengers being assigned to seats on the airplane while violating the social distancing

[2] Please note that $\gamma = 1$ for the seat assignment in Fig. 4.
[3] W,M,A refers to as window, middle and aisle seats, respectively.

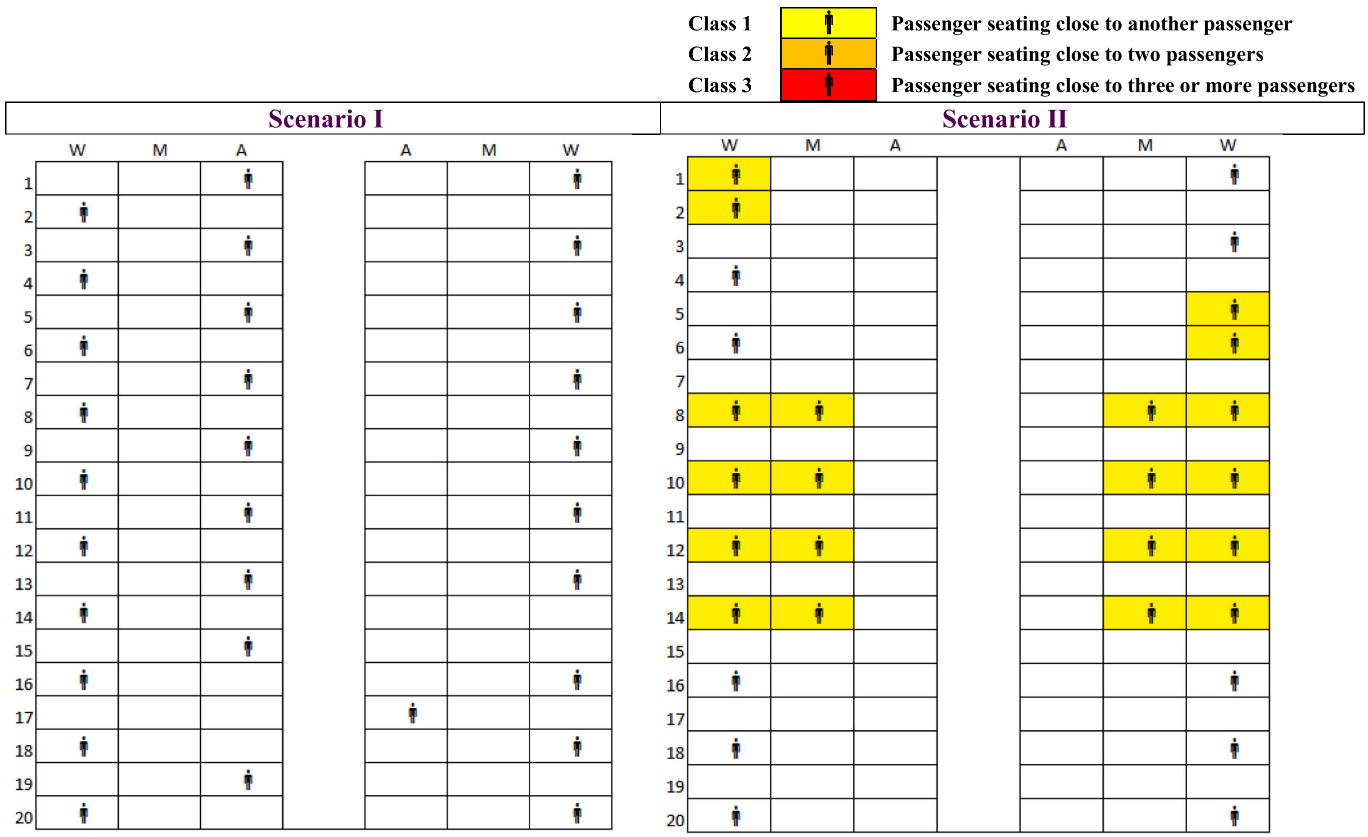

Fig. 4. Seat assignment for 30 passengers using scenarios I and II[3]

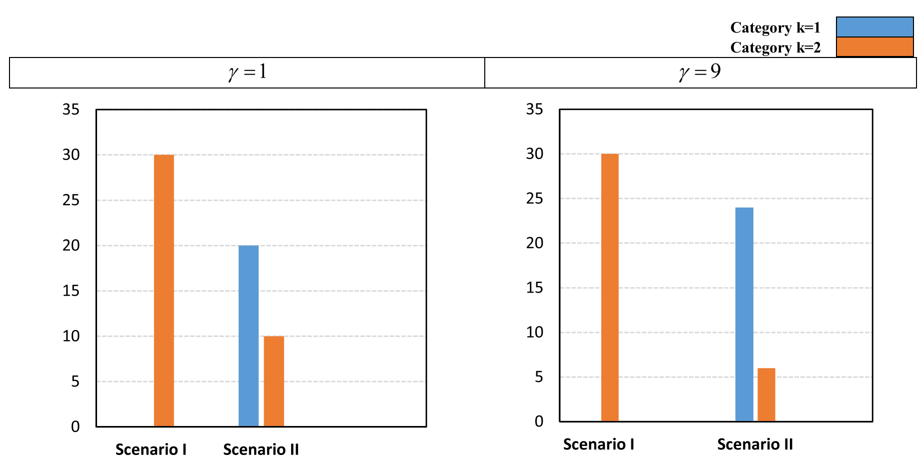

Fig. 5. Passengers in categories $k = 1$ and $k = 2$ for 30 passengers using scenarios I and II.

from the aisle by assigning 10 passengers to aisle seats. Assigning passengers to aisle seats to maximize the load of passengers may be a reasonable strategy for airlines as long as they take preliminary actions to minimize activity in the aisle or if they are not particularly concerned about the risk of infection from aisle activity.

To create Table 6, we specify a very big value for the upper bound of Eq. (10) to allow the model to assign passengers to the aisle seats. We also specify different upper bounds for Eq. (9) to evaluate the effect of practicing social distancing among seated passengers on the maximum load of passengers. To obtain Table 6, we focused on the first category, i.e., $k = 1$, of social distancing while δ_1, δ_2 are set to 1 and 0, respectively. Expectedly, as the number of passengers in category $k = 1$, increases, more passengers can be assigned to seats. In the last column of Table 6, we evaluate the percentage of increase in the number of passengers compared with the previous row of the table. As we observe in Table 6, when the specified maximum number of passengers in category 1 is low, there are few class 2 and class 3 passengers. However, once the maximum number of passengers in category 1 rises to 51 and 63, the number of class 2 and class 3 passengers dramatically rises respectively.

In Table 6, we introduced the upper bound only for Eq. (9). However, to compare the effect of employing both Eqs. (9) and (10) on the maximum load of passengers, we also present an upper bound greater than zero for Eq. (10) and present the result of a specific case in Fig. 8. Fig. 8 shows a resulting seating assignment layout where in the left-sided

Table 3
Passengers seat assignment results for different loads of passengers while $\gamma = 1$.

Passengers' Load	Scenario	# Passengers seated within 3.3 feet			#Passengers in the aisle seat	Passengers in the aisle seats first/last three rows	Runtime (seconds)
		1 person Class 1	2 persons Class 2	≥3 persons Class 3			
30	I	0	0	0	10	3	51
	II	20	0	0	0	0	66
	III	0	0	0	10	3	67
60	I	26	34	0	20	6	68
	II	2	5	52	2	0	56
	III	22	38	0	18	4	94
90	I	0	4	86	28	8	51
	II	0	0	90	10	0	44
	III	0	0	90	26	8	46

Table 4
Passengers seat assignment results for different loads of passengers while $\gamma = 9$.

Passengers' Load	Scenario	# Passengers seated within 3.3 feet			#Passengers in the aisle seat	Passengers in the aisle seats first/last three rows	Runtime (seconds)
		1 person Class 1	2 persons Class 2	≥3 persons Class 3			
30	I	0	0	0	10	3	18
	II	12	12	0	0	0	22
	III	0	0	0	10	3	41
60	I	24	36	0	20	6	48
	II	0	8	52	0	0	57
	III	20	40	0	20	4	52
90	I	0	0	90	26	8	25
	II	0	0	90	10	0	69
	III	0	0	70	26	8	45

Table 5
Seating assignment comparison between scenarios I and II and the modified scenario.

γ	Scenario	# Passengers seated within 3.3 feet			#Passengers in aisle seat	Passengers in the aisle seats first/last three rows
		1 person Class 1	2 persons Class 2	≥3 persons Class 3		
$\gamma = 1$	I	26	34	0	20	8
	II	2	5	52	2	0
	Modified	19	38	3	17	3
$\gamma = 9$	I	24	36	0	20	8
	II	0	8	52	0	0
	Modified	0	19	35	6	0

seating assignment, Eqs. (9) and (10) allow 36 passengers to be allocated on seats less than 3.3 feet distance from each other and 5 passengers to be assigned to aisle seats. The right-sided seating assignment resulted from employing the same upper bound for Eq. (9), while defining a very large value for the upper bound of Eq. (10) to not restrict the passengers' assignment to the aisle seats. With the activation of only Eq. (9), the maximum load of passengers is 48, while with the active presence of both Eqs. (9) and (10) the maximum load decreases to 46. This is expected as the extra set of constraints reduces the feasible region for seating assignments. Interestingly, the combined use of Eq. (10) along with Eq. (9) in the left-sided seating assignment places no passenger in class 3 while there are three passengers in this class in the other seating assignment. This reduction comes with the cost of increasing the number of passengers in classes 1 and 2. In the left sided seating assignment, the number of passengers in classes 1 and 2 increases to 29 and 14, respectively compared to the 27 and 8 for classes 1 and 2 in the right sided seating layout.

4.3. Comparison with airlines' current policy for social distancing

During the SARS-CoV-2 outbreak, airlines try to adjust their boarding and seat assignment policies to better follow the requirements for passengers' safety. For instance, Delta Airlines implemented back-to-front boarding so that passengers do not have to pass seated passengers while boarding (Delta Airlines, 2020). American Airlines announced that it is practicing a "new relaxed seating policy" and reducing food and beverage services. United Airlines as another major airline in the United States, has dedicated a full page on its website to the SARS-CoV-2 response, indicating new policies for aircraft disinfection, access to hand-sanitizer, and new protocols for boarding and checking-in to limit individual contacts (Fowler, 2020).

In a similar practice to keep social distancing among seated passengers, some airlines including Delta Airlines and American Airlines announced that they block 50 percent or all of the middle seats in an airplane to keep effective distancing among passengers. In this subsection, we evaluate this middle seat-blocking policy comparing it with the proposed seat assignment. Fig. 9 demonstrates the middle seat-blocking policy versus our proposed seat assignment based on scenarios II and I for forty passengers. Concerning the middle-seat blocking policy, we assume that the passengers are seated in every other row so there is enough social distancing among passengers sitting the same distance from the aisle (i.e., either window or aisle seat).

According to Fig. 9, there are 20 passengers assigned to aisle seats in the middle-seat blocking policy while it reduces to 10 and even 0 passengers using our proposed formulation in Model 1 with scenarios I and II, respectively. Concerning the passengers of aisle seats in the first/last three rows of the airplane, scenarios I and II provide improvement over the middle-seat blocking policy as well. According to the middle-seat blocking policy, 6 passengers are assigned to the aisle seats of the first/last three rows while it reduces to 3 and 0 passengers employing scenarios I and II. We also consider the social distancing among passengers in terms of the three classes defined in Fig. 9. There are 20 passengers (a group of two passengers) who are sitting close to another passenger (class 1) following the middle-seat blocking for seat

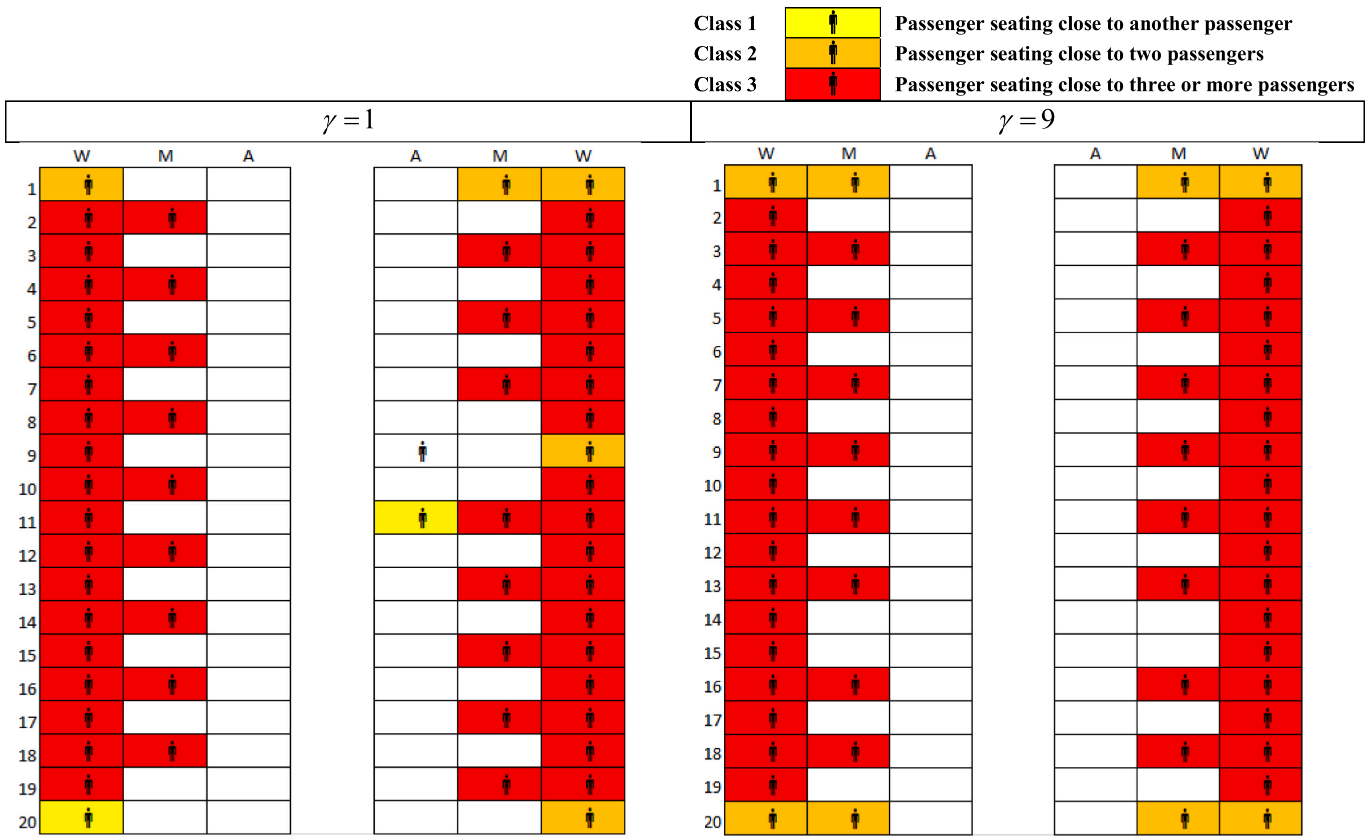

Fig. 6. Seat assignment for 60 passengers using different value of γ.

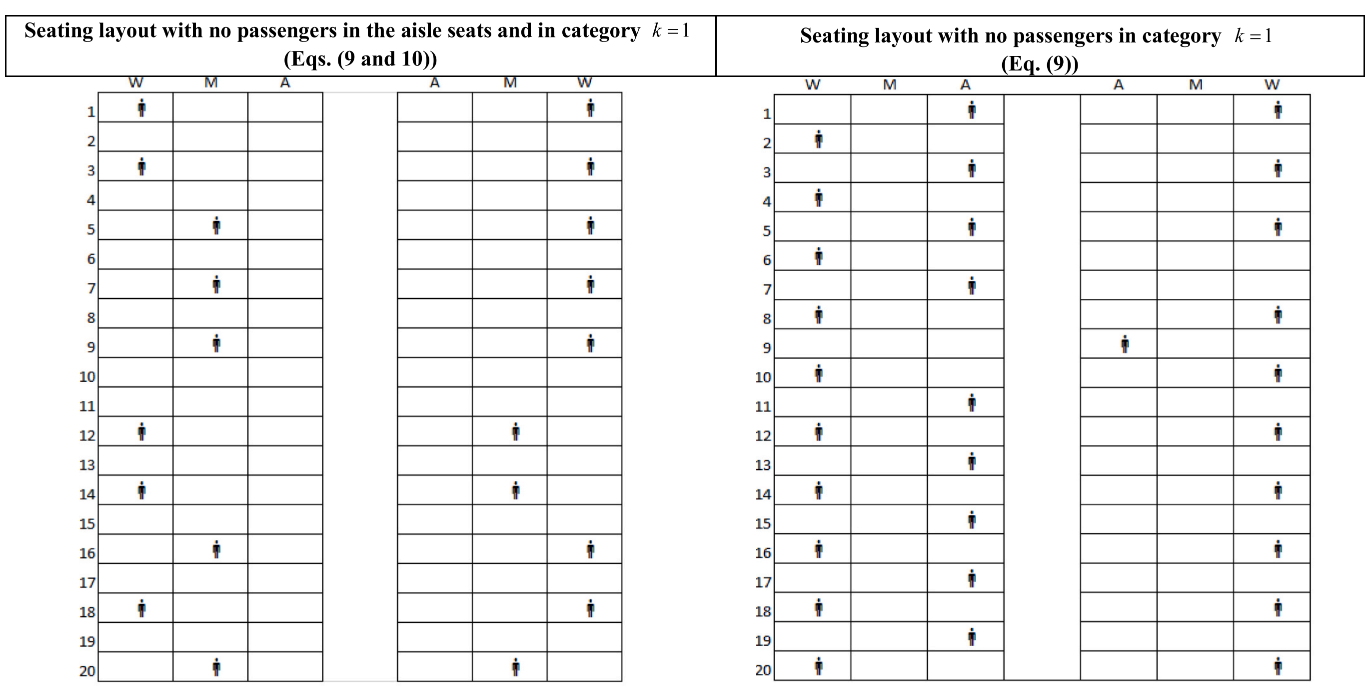

Fig. 7. Seat assignment using different upper bounds in Eqs. (9) and (10).

assignment. Adopting the seat assignment recommended by scenario II, we observe that while minimizing the number of passengers assigned to aisle seats, this scenario unavoidably violates the social distancing policy as the number of passengers in class 1 increases to 34 passengers while 4 and 2 passengers are included in classes 2 and 3. Scenario I, while offering the same number of passengers in class 1 as the middle-seat blocking policy does, reduces the number of passengers in the aisle seats and the first/last three rows of the airplane.

Table 6
Seating assignment comparison for different level of social distancing among passengers.

Number of passengers in Category 1 (k = 1)	# Passengers seated within 3.3 feet			Max load	Increase in the load of passengers
	1 person Class 1	2 persons Class 2	≥3 persons Class 3		
0	0	0	0	30	–
10	10	0	0	35	0.17
20	20	0	0	40	0.14
36	27	8	3	48	0.20
51	23	24	5	54	0.13
63	16	8	39	63	0.17

Compared to scenario II, the middle-seat blocking policy seems to work better when all passengers are traveling individually rather than in groups (e.g. families). Although we do not consider groups of passengers traveling together explicitly within this paper, scenario II provides a better theoretical foundation for future research involving groups of passengers boarding together in which the middle seat may be occupied. In such future research, the approach of scenario II can mitigate the risk of assigning passengers to aisle seats when passengers are traveling in groups who can sit next to their fellow group members. Moreover, scenario I can perform (moderately) better than the middle-seat blocking policy when passengers are not traveling in groups and social distancing among seated passengers is the priority for their seating assignment.

5. Conclusion

Practicing social distancing among passengers seated in an airplane will better assure their health safety in a flight during a SARS-CoV-2 or similar outbreak. We viewed social distancing in a flight by introducing two metrics: the passengers' distance from each other and the passengers' distance from the aisle of an airplane. The proposed MIP model addresses social distancing in an airbus A320 with twenty rows, single aisle and three seats on each side of the aisle.

In the SARS-CoV-2 context, when social distancing is important, the proposed MIP provides a more intelligent approach for determining passenger seating assignments than simple rules of thumb such as blocking all middle seats. We illustrate how the MIP can provide the same social distancing between seated passengers as blocking all middle seats, but with a reduced number of passengers seated close to the airplane's aisle where they may be exposed to passengers and crew members emitting COVID-19 droplets as they traverse the aisle. We illustrate how the model parameters may be varied to generate efficient tradeoffs between an airline's relative preferences for the two metrics of social distancing.

In particular, we defined two formulations introduced as models 1 and 2 where in model 1 we addressed aim to minimize the possible interferences in social distancing for a specified load of passengers based on the two metrics including the distance of passengers from each other and their distance from the aisle of an airplane. In the latter model, we focus on maximizing the load of passengers while providing a certain level of social distancing among the passengers.

In model I, we define three scenarios I, II, and III where the first two scenarios emphasize preserving social distancing among seated passengers and the distance of passengers from the aisle of an airplane, respectively. The third scenario tries to address a middle ground between two scenarios where both social distancing viewpoints equally matter. We present the results based on the number of passengers seated close to each other dividing them in three classes, while classes 1,2 and 3 include one, two, and three or more passengers, respectively, who are sitting too close to each other, i.e., belonging to the category $k = 1$.

Fig. 8. Seat assignment to maximize the load of passengers using Eqs. (9 and 10).

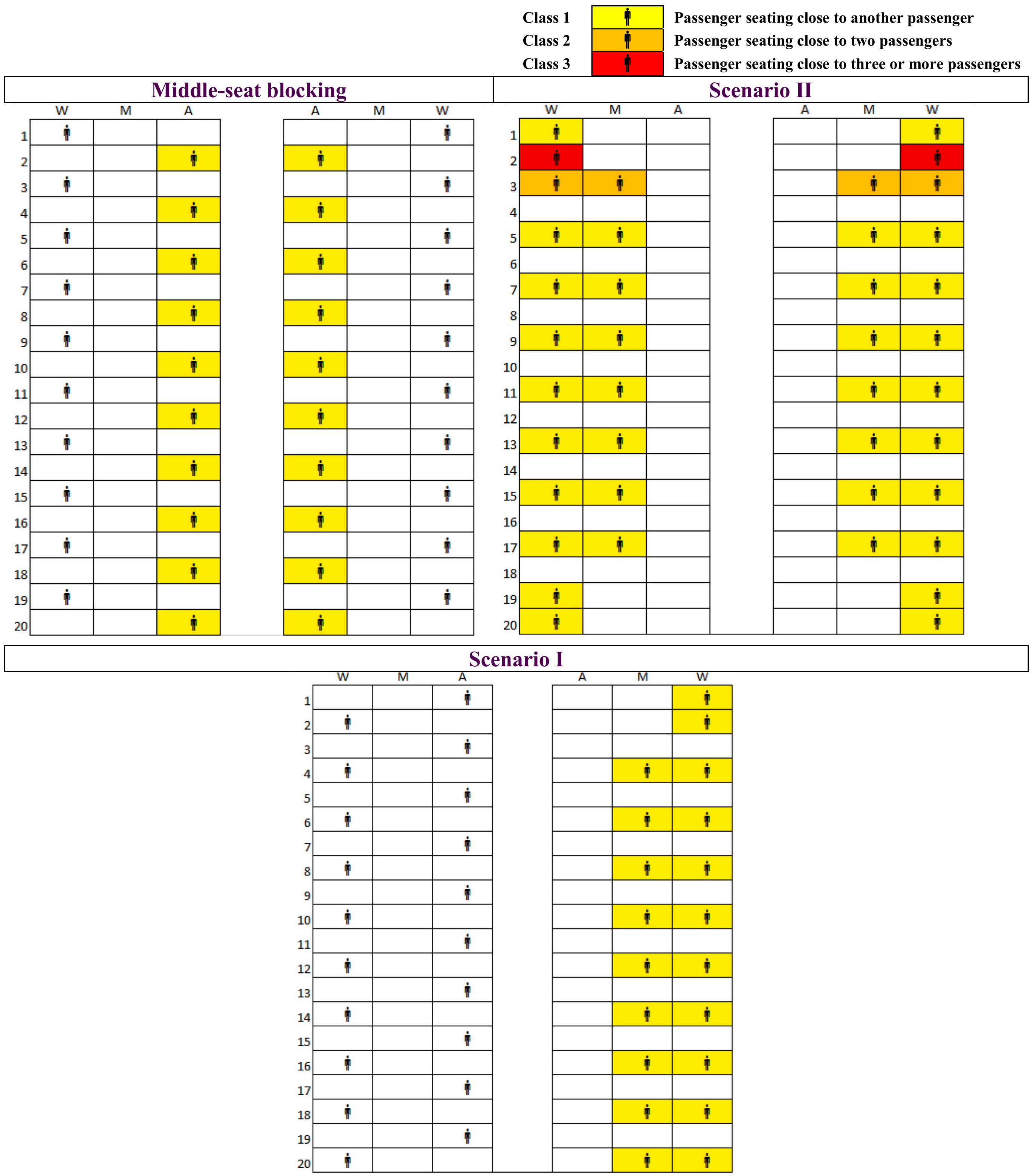

Fig. 9. Seat assignments for 40 passengers using middle-seat blocking, scenarios I and II.

Using scenario I, we observe that the number of passengers in class 1 is significantly less than the same number using scenario II for different loads of passengers. However, scenario II can significantly decrease the number of passengers' assignments to the aisle seats while not considerably worsening the number of passengers whom are seated close to each other. Specifically, for heavier loads of passengers, 60 or 90 passengers, the number of passengers belonging to class 2, i.e., two passengers sitting within 3.3 feet distance from a passenger, and class 3, i.e., three or more passengers are seated close to a passenger, don't increase using scenario II, as much as this scenario contributes to reducing the number of passengers assigned to aisle seats. We also realize scenario III, which uses equal weights for the abovementioned viewpoints in social distancing, might not lead to the results that equally satisfy both the passengers distancing from each other and their distancing from the aisle. Therefore, we updated the weights corresponding to this scenario to obtain a seating assignment that similarly please both objectives in terms of social distancing.

Model 2 includes the set of constraints related to the social distancing metrics introduced in Model 1. These right-hand side values of the social distancing metrics present the acceptable level of social distancing while maximizing the load of passengers. We set the upper bounds of the social distancing metrics to zero allowing no passenger in the aisle seats and no passenger to be seated closer than 3.3 feet from another passenger. The results indicate that the maximum load of passengers to completely practice social distancing with respect to the two introduced metrics is 20 passengers. Alternatively, we show that the maximum load of passengers could be increased to 30 if passengers are permitted to sit in the aisle seats. However, the passengers' assignment to aisle seats should be accompanied by guidelines to minimize the aisle activities by passengers and the flight crew. We also compare the seating layout where the set of constraints includes one or both of the social distancing metrics. Results indicate that employing both metrics can effectively improve the level of social distancing among passengers while adversely affecting the maximum load of passengers.

Eventually, we analyzed the proposed middle-seat blocking policy by some airlines for a load of forty passengers. Comparing scenario I and the middle-seat blocking policy, we observed equal number of passengers belonging to class 1 while scenario I reduced the number of passengers assigned to the aisle seats. Scenario II, however, could not beat the middle-seat blocking policy in terms of the number of passengers in class 1, but it significantly reduced the number of passengers seated close to the aisle of the airplane. Using an integrated model that jointly provides the ideal seating assignment and the sequence of boarding for passengers to reduce the risks both during the boarding process and during the flight may be a promising future research direction. Moreover, we recommend extending the current approach for seating assignment considering family boarding while it is appropriate to assign family members to seats close to each other.

CRediT authorship contribution statement

Mostafa Salari: Conceptualization, Methodology, Software, Writing - original draft. **R. John Milne:** Conceptualization, Methodology, Validation, Writing - review & editing. **Camelia Delcea:** Writing - original draft, Investigation, Writing - review & editing. **Lina Kattan:** Supervision, Writing - review & editing. **Liviu-Adrian Cotfas:** Validation, Writing - review & editing.

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