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Social distancing in airplane seat assignments for passenger groups

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ABSTRACT

We provide a mixed-integer programming model (MIP) to assign airplane passengers to seats while preserving two types of social distancing: the distance from the passengers' seats to the aisle and the distance among groups of passengers who are not travelling together. The method assigns passengers travelling within a family group to seats near others of the same group. We present a heuristic algorithm to solve the proposed MIP. This algorithm is warm started with an initial seat assignment. Stochastic simulation experiments using the new method confirm that more passengers can be assigned safely to the seats when family groups are considered. For a certain load of passengers, as the percentage of family groups compared to singleton passengers increases, the model can practice social distancing among more passengers from different groups. The proposed model provides a superior seating assignment compared to an airline policy of blocking all middle-seats.

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Airplane seat assignment; airplane group boarding; COVID-19; SARS-CoV-2; social distancing; mixed-integer programming

1. Introduction

The novel coronavirus (SARS-CoV-2) outbreak severely hit worldwide economic sectors. As air flights involve a large number of travellers crowded into the airplane's cabin, this mode of transportation is strongly connected with potential infections, especially in the symptomatic phase of illness (Olsen et al. 2003). This high chance of infection along with the notorious history of the air traffic industry in the previous pandemic, i.e. MERS-CoV, adversely affects the willingness of passengers to trust air transportation (Iacus et al. 2020; Regan et al. 2016; Forsyth, Guiomard, and Niemeier 2020), even when personal protective equipment is used (Forouzandeh, O'Dowd, and Pillai 2021). This deepened the crisis the air transport industry was facing due to COVID-19. To mitigate the devastating effect of the coronavirus crisis, airlines need to take rapid actions to adjust to the current situation and ensure passengers' health safety (Serrano and Kazda 2020). The international air transport association (IATA) medical advisory group recommends airlines practice social distancing, also named physical distancing, among passengers to secure passengers' health safety before and during a flight. This includes social distancing among passengers while seated, during airport check-in, immigration, security, departure, and during the boarding process (IATA 2020). Following the conclusion of the present pandemic, the work we present in this paper should be helpful in addressing future pandemics and

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other concerns about passenger health. Furthermore, in addition to the health advantages, social distancing may provide passengers with increased enjoyment of their flights.

Social distancing is one of the unprecedented measures that became a new norm in travel and other activities (De Vos 2020). It reduces interactions between individuals to restrict the spread of the coronavirus. The World Health Organization (WHO) stressed the importance of social distancing measures to reduce the rate of infection among people who share the same activities (WHO 2020). The preventive measures associated with social distancing include keeping sufficient distance among people, closing public places, and avoiding crowded gatherings (Nguyen et al. 2020). The above-mentioned preventive measures offer effective non-pharmaceutical attempts to reduce the disease spread (Ferguson et al. 2006). Enforcing social distancing measures for airplane passengers has been recently advised by the European Union Aviation Safety Agency (EASA). As its report instructs, 'airplane operators should ensure, to the extent possible, physical distancing among passengers' (EASA 2020). The best practice of social distancing among passengers in an airplane requires both the passengers' willingness to respect social distancing guidelines as well as a well-structured seat assignment methodology. Salari et al. (2020) and Pavlik et al. (2021) address the social distancing in airplane seat assignment to minimize the transmission risk on airplane (Pavlik et al. 2021; Salari et al. 2020), while Haghani and Bliemer (2020) underlines the need for methods and solutions for crowd management and safety needed in confined spaces such as airplanes.

Preserving social distance among seated passengers reduces the spread of infectious disease such as COVID-19 (as mentioned above), but it cannot eliminate the possibility of disease spread. Designing an effective seat assignment is a more challenging task for passengers who travel in groups and would like to sit close to their other family (group) members. As Schultz and Soolaki (2021) state in a recent paper, in the research literature, there are two possible meanings for the term 'group' (Schultz and Soolaki 2021). The first one refers to a cluster of passengers who are called to board the airplane together, e.g. all passengers having seats near the windows, and it is mainly used for describing the rules accompanying the classical boarding methods (e.g. WilMA, back-to-front, reverse pyramid, etc.). The second meaning refers to passengers travelling together for leisure or business purposes and who prefer not to be separated during an airplane boarding process (Wittmann 2019). Concerning the latter meaning, previous studies emphasize the importance of considering groups in the passenger boarding problem (Tang et al. 2018a, 2018b; van den Briel, Villalobos, and Hogg 2003). In this paper, we also refer to the family group as in the second situation, including in this notion the groups made by families, friends, co-workers, etc., which are travelling together, and which prefer not to be separated during boarding or their seat assignments. We refer to these groups as 'family groups' to distinguish them from singleton groups.[1] There may be other co-workers or friends who prefer to remain socially distant from each other; a collection of these people would not be referred to as a family group in this paper. As a result, if a group of passengers does not want to sit together, they are treated in the model as individual passengers travelling alone. This preference could be mentioned to the airline when buying tickets for the group or by buying each ticket in an individual manner. In recent work, Schultz and Soolaki (2021) address the group boarding and seating assignment trying to minimize the effect of the virus spread between groups (Schultz and Soolaki 2021). Our proposed model, however, keeps members of a family group nearby using a reward point system whereas their work keeps passengers from the same group near each other only when required to reduce contagion. This reward point system is especially useful for low loads of passengers where passengers from a family group don't need to be assigned seats close to each other to practice social distancing with passengers outside the group. Moreover, the proposed model recognizes the advantage of keeping passengers away from the aisle. This could reduce infection from later boarding passengers and the flight crew walking down the aisle.

2. Literature review

The literature review is structured in three subsections: first, a brief review of the research focusing on boarding methods in the presence/absence of jet bridges/apron buses, various levels of occupancy, passengers' characteristics, and methods used to model/validate proposed approaches; second, a review of the papers written in the area of group boarding; and third, a summary of the works written in the field of air transportation in times of the COVID-19 pandemic.

2.1. Airplane boarding

The airplane boarding problem is a well-known research direction that focuses on minimizing the boarding time of passengers in an attempt to decrease airline operation cost incurred by airplane turn time (Delcea, Cotfas, Salari, et al. 2018). The research works that study this problem can be placed into different categories concerning the boarding assumptions and modelling techniques. Regarding the boarding assumptions, extensive literature proposes new boarding methods in the presence of jet bridges (Bachmat et al. 2009; Jaehn and Neumann 2015; Milne, Salari, and Kattan 2018; Milne and Kelly 2014; Milne and Salari 2016; Salari, Milne, and Kattan 2019; Soolaki et al. 2012; Steffen 2008a; van den Briel et al. 2005) and apron buses (Delcea et al. 2019; Delcea, Cotfas, Chiriţă, et al. 2018; Milne, Delcea, et al. 2019). To model different boarding conditions, there are also studies that model the boarding methods under different levels of occupancy (Kierzkowski and Kisiel 2017; Steffen and Hotchkiss 2012; Qiang et al. 2014; Notomista et al. 2016), with the assumption of boarding through one door or through both front and rear doors of an airplane (Delcea, Cotfas, Chiriţă, et al. 2018; Kuo 2015; Milne, Cotfas, et al. 2019; Steiner and Philipp 2009), considering passengers' distinctive characteristics such as walking time and number of carry-on bags (Hutter, Jaehn, and Neumann 2018; Kierzkowski and Kisiel 2017; Milne, Salari, and Kattan 2018; Milne and Salari 2016) and seat assignment selection (Ferrari and Nagel 2005; Salari, Milne, and Kattan 2019; Steffen 2008a). A summary of the pre-pandemic research topics in the air transport domain has been highlighted in (Tanrıverdi, Bakır, and Merkert 2020).

Concerning the modelling methods, studies addressing the airplane boarding problem provide a
3 variety of techniques to mathematically construct and evaluate boarding methods, featuring linear and mixed-integer programming (MIP) (Bazargan 2007; Milne, Salari, and Kattan 2018; Milne and Salari 2016; Salari, Milne, and Kattan 2019), meta-heuristic algorithms (Soolaki et al. 2012; Wittmann 2019), computer simulation (Milne and Kelly 2014; Steffen 2008b; Steiner and Philipp 2009; Tang et al. 2012; van den Briel et al. 2005), grid-based simulation (Qiang et al. 2014; Schultz 2017; Zeineddine 2021), agent-based and stochastic modelling (Delcea, Cotfas, and Paun 2018a, 2018b; Milne, Delcea, and Cotfas 2021; Milne, Delcea, et al. 2019; Schultz 2018a, 2018b) and empirical experiments (Steffen and Hotchkiss 2012), etc.

Among the modelling techniques, linear programming and MIP modelling have been a favourite choice in many studies. As one of the first studies in this field, Bazargan (2007) developed a MIP formulation to minimize the interferences among passengers while boarding an airplane (Bazargan 2007). Soolaki et al., (2012) took the same direction to minimize the passengers' interferences and use a genetic algorithm to solve the model (Soolaki et al. 2012). Based on the sequence of boarding introduced by Steffen (2008a), Milne and Salari (2016) propose a MIP formulation that determines the optimal seat assignment to passengers based on the number of their carry-on bags (Milne and Salari 2016; Steffen 2008a). Their work shows improvement in boarding time over the heuristic method developed by (Milne and Kelly 2014). Concerning passengers' carry-on bags and reserved seats by so-called 'high priority passengers', Salari et al. (2019) introduced a MIP formulation that reduces boarding time, on average, between 5% and 20% compared to a baseline scenario (Salari, Milne, and Kattan 2019).

2.2. Group boarding/seat assignment

Airplane boarding in family groups is a sub-problem of airplane boarding that recently received attention from researchers. According to Schultz and Soolaki (2021), up to 70% of tourists travel in groups and up to 30% of business passengers (Schultz and Soolaki 2021). This underscores the need to properly address groups of passengers travelling together when considering airplane passengers' boarding.

The number of works considering group boarding is limited in the research literature, compared to other aspects. One of the works in this area is conducted by Tang et al. (2018a) who developed a boarding model to study the impacts of group behaviour on each passenger's motion, seating conflict, time of handling luggage, and total boarding time (Tang et al. 2018a). As an extension, the authors consider group boarding behaviour while accounting for the number of passengers' carry-on luggage (Tang, Yang, and Chen 2019; Tang et al. 2018b). It has been observed that when considering the group behaviour, the boarding time could be shorter than expected since internally, the group succeeds in minimizing conflicts – e.g. reducing/eliminating the occurrence of the seat interferences (Tang et al. 2018a). Another observation related to the group boarding process has been made by Kierzkowski and Kisiel (2017) which advise a boarding strategy by rows, given the fact that a group's passengers prefer sitting in the same row (Kierzkowski and Kisiel 2017). The desire of passengers towards seating or boarding in groups has been considered by (Wittmann 2019). In the research, the author accounted for the passengers' speed distribution, amount of luggage, and the occupancy of the overhead bin or the neighbouring bins. Two boarding patterns have been proposed, which allow a subset of the passengers to board in groups of two or three. The author concludes that using the proper method, an improvement in boarding time can be achieved, even in the case in which the customers' wishes regarding boarding together are considered.

The group boarding behaviour is also studied in a recent publication by Milne, Delcea, et al. (2020) in which they consider a rewarding mechanism to encourage seating assignments that put passengers of the same group as close as possible to each other (Milne, Delcea, et al. 2020). The authors have considered groups ranging between two and six passengers and the presence of the apron buses, which are used for transporting the passengers between the airport and the airplane. They observe that the use of their proposed MIP-based method reduces the boarding time by up to 27.31% when compared with the baseline approach.

During the novel coronavirus outbreak context, the passenger group problem during airplane boarding has been addressed by (Schultz and Soolaki 2021). In this work, the authors consider a social distance of 1.6 m and have determined the value for the transmission risk. According to the authors, the consideration of the boarding groups will contribute to a faster boarding process when compared to a standard random boarding procedure.

2.3. Social distancing COVID-19 related research

Social distancing shows a great potential to reduce the coronavirus spread among people (Sen-Crowe, McKenney, and Elkbuli 2020) while also being a controversial measure as it might affect people's mental health and well-being (Donovan 2020). Because of the benefits of social distancing, public authorities introduced different ways to practice social distancing such as blocking metro seats and train seats (Metrorex 2020; Trenitalia 2020), personal space determination by drawing circles in public parks (Harrouk 2020), and personal apps to inform people about the volume of passengers on-board (Intelligent Transport 2020). On the other hand, social distance has been determined to have a significant impact on reducing the performance of both security control lanes (Kierzkowski and Kisiel 2020) and airplane boarding methods (Cotfas et al. 2020). While being the most discussed measure, social distancing has been addressed in a broad range of scientific studies including, but not limited to, political, economic, and social challenges (Yezli and Khan 2020), the relationship between telework activities and social distancing (Kawashima et al. 2020), and the social and ethical basis for social distancing (Lewnard and Lo 2020). Concerning travel and human mobility, some studies address the impact of social distancing on travel behaviour (De Vos 2020), airlines' employment programmes during and after the pandemic (Sobieralski 2020), the airplane deplaning process by considering the existence of the patients with acute airborne disease (Xie et al. 2021), projecting future air passengers traffic evolution (Iacus et al. 2020), the future of airports operations post COVID-19 (Serrano and Kazda 2020), post-pandemic requirements for aircraft turnaround operations (Schultz et al. 2020), COVID-19 impact on passenger demand and airports (Forsyth, Guiomard, and Niemeier 2020), and the effect of COVID-19 on the global airline industry (Maneenop and Kotcharin 2020). As a result, social distance is one of the measures considered in the proposed approach of this paper.

3. Modelling assumptions and performance metrics

In this section, we describe our primary assumptions and the details of the proposed passenger seat assignment model formulation, and our method for solving it.

3.1. Assumptions and objectives for passenger assignment

We focus on the assignment of passengers to seats on an airplane. We do not investigate alternative methods of boarding passengers (as this action requires additional research, some of which has been published as discussed in Section 2), nor do we consider the time to board the airplane.

In line with many other studies, we implement the proposed seating assignment on an Airbus A320 as shown in Figure 1, having one aisle, twenty rows, and three seats on each side of the row (Milne, Delcea, et al. 2019; Milne and Salari 2016; Salari, Milne, and Kattan 2019). We use the average seat width, aisle width, and seat pitch (the distance between seats in consecutive rows) reported by airlines to configure seating placement in an Airbus A320. These values are defined as 17.5, 22, and 32 inches (equivalent to 44.5, 55.8, and 81.28 centimeters) for seat width, aisle width, and seat pitch, respectively. We are interested in determining the seat locations that keep the social distancing advised by WHO among passengers on a flight. We employ the Euclidian method to calculate the distance between the centre of every two seats.[2] Following the calculation of the distance between seats, we introduce a binary parameter that indicates whether the distance between two seats is less than or equal to 3.3 feet (equivalent to 1m). For instance, if the seat location (r, s, l) where $r, s\&l$ represents the row r, side s ($s = 1$ means left side and $s = 2$ means right side) and seat l ($l = 1$ means window seat; $l = 2$ means middle seat, and $l = 3$ means aisle seat) is in less than 3.3 feet from seat location (r', s', l'), then the binary parameter $\beta^{r,s,l}_{r',s',l'}$ is equal to 1 and zero otherwise. We select 3.3 feet to preserve safe distancing among passengers as advised by WHO, according to which people are required to keep at least 3.3 feet distance from each other to practice social distancing (WHO 2020). For instance, Figure 2 highlights seating locations for a one-member group, i.e. singleton passenger, and a family group of two passengers travelling together. The one-member group is seated in the aisle seat of row 4 on the right side of the airplane. The other group of passengers is sitting in the window and middle seats of row 15 on the left side of the airplane. The seating locations of passengers in those two groups are red-highlighted in Figure 2. The other seats less than 3.3 feet from these two groups are yellow-highlighted in the figure.

Along with the seating location distance among passengers of different groups, the seating location distance from the aisle is also a relevant factor to practice social distancing. The aisle of an airplane is repeatedly used by passengers walking to the washroom and by flight attendants to serve passengers. For the layout of an Airbus A320, there are three levels of distance between the seat locations and the aisle with the windows seats as the farthest seats from the aisle and the aisle seats as the closest ones. To maximize the distance of passengers from the aisle, we minimize the aisle seat and middle seat allocations. To address this, the aisle seats are assigned a higher penalty than the middle seats during the seat assignment. We proposed the parameter α_l as a penalizing factor to specify the relative importance of passengers' assignment to window seats over middle seats, and the passengers' allocation to middle seats over the aisle seats. Note that, α_l is set to zero for all window seats as the window seat location provides the ideal practice concerning the distance from the aisle of an airplane.

The seats in the first and last rows of an airplane are more susceptible to interrupted social distancing as these rows are located closer to the washroom and flight attendants' cabins. We introduce the parameter λ_r to stress the significance of minimizing the allocations of seats in the rows close to

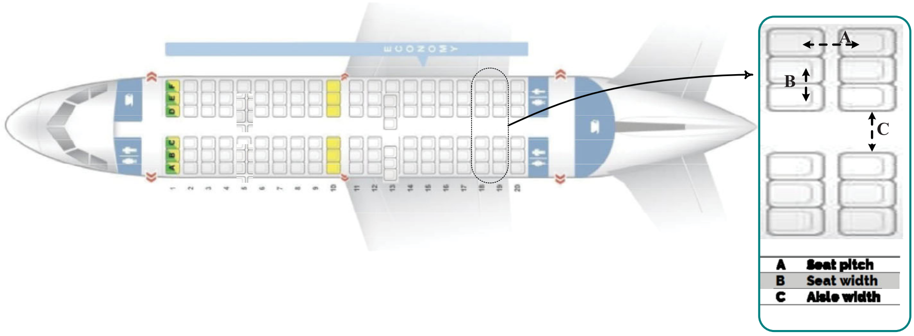


Figure 1. Seat layout of Airbus A320.

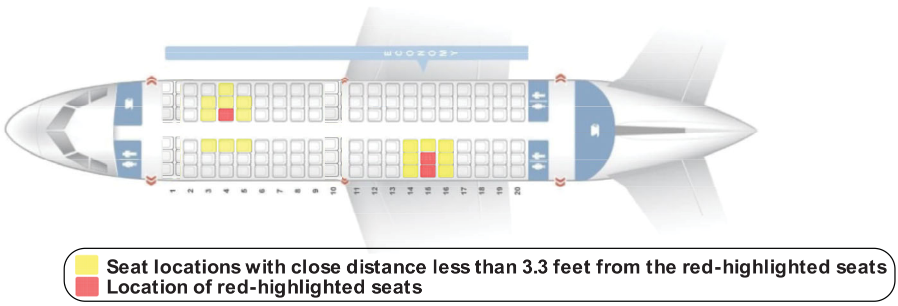


Figure 2. Seating location of passengers and surrounding seats with less than 3.3 feet.

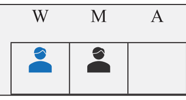
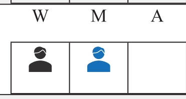
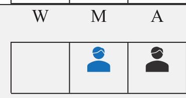
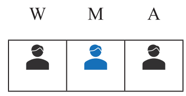
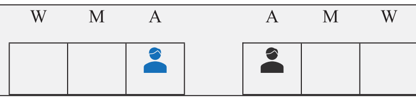
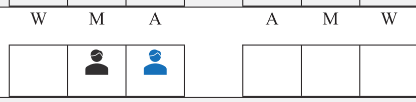
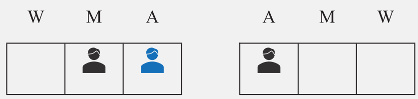
the rear and the front of an airplane. We suggest two equations to determine the value of λ_r where $\lambda_r = \left(\frac{1}{r}\right)^{(1/\gamma)}$ applies to the first ten rows, i.e. $r \leq 10$, and $\lambda_r = \left(\frac{1}{21-r}\right)^{(1/\gamma)}$ calculates this parameter for the remaining rows, i.e. $10 < r \leq 20$, of an airplane. In these two equations, γ is a scaling parameter inheriting a value between 1 and 9 while the lower the value of γ, the higher the significance of avoiding passenger assignments to rows located close to the front/rear of the airplane.

3.2. Assumptions for group boarding

Contrary to the individual seating assignment problem where it's assumed passengers travel individually without any preference for seating close to any specific passenger, the group seating assignment problem addresses the situation where passengers are travelling in groups, i.e. family groups, that do not require social distancing among members of a group. We assume that passengers of a family group prefer to sit close to each other on a flight. Seating close to other members of a group can positively affect the satisfaction of a passenger. For instance, a married couple with two small children would prefer that each child sits close to a parent. Milne, Delcea, et al. (2020) address the seating preference of passengers who travel in groups (Milne, Delcea, et al. 2020). They define a point scoring system that incentivizes the seating assignments that place the passengers in a group as close as possible to each other. We employ the same scoring system and in Table 1, we demonstrate how the proposed system works.

The seven possible cases introduced in Table 1 explain how seating preference points are assigned for any possibility in terms of group seating assignments. For instance, Table 2 demonstrates two possible seating assignments for a family group of four passengers and a family group of seven passengers. In this table, for a family group of four passengers, the first possibility is a combination of C_1 and C_2 on both sides of the airplane for a total seating preference score of 4 points (determined by aggregating 1

Table 1. Assignment of seating preference points based on the seats occupied by passengers in the same group.

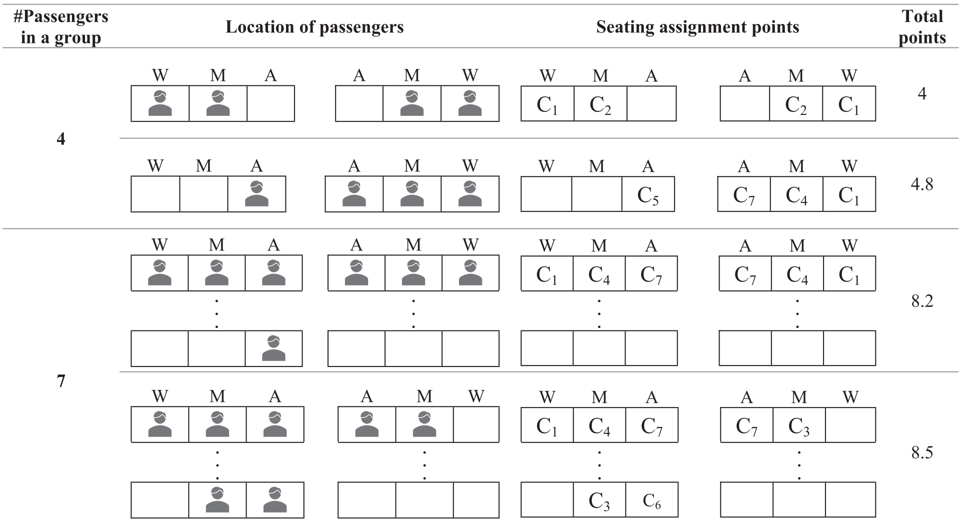
Seat of blue-highlighted passenger	Case	Description	Location of passengers	Point(s) assigned to blue-highlighted passenger
Window seat	C_1	A passenger is assigned to the middle seat next to the window seat passenger		1
Middle seat	C_2	A passenger is assigned to window seat next to the middle seat passenger		1
	C_3	A passenger is assigned to the aisle seat next to the middle seat passenger		1
	C_4	Two passengers are assigned to the window and aisle seats next to the middle seat passenger		1.7
Aisle seat	C_5	A passenger is allocated to the other aisle seat in the same row of an airplane		0.7
	C_6	A passenger is assigned to the middle seat next to the aisle seat passenger		1
	C_7	A passenger is assigned to the middle seat on the same side and row and the other passenger is assigned to the aisle seat on the opposite side of the airplane		1.4

point each from C_1, C_2, C_2 and C_1 of the four seats where the 1 point for C_1 and 1 point for C_2 is shown in Table 1). In the second possibility for this group of passengers in Table 2, the seating assignment combines C_5 on one side of the other side of the aisle and C_1, C_4, and C_7 on one side for a total seating preference score of 4.8 points (determined by aggregating 0.7, 1.4, 1.7, and 1 points respectively for C_5, C_7, C_4 and C_1 of the four seats using the Table 1 data). Comparing these two possibilities employing the rewarding system proposed by Milne, Delcea, et al. (2020), the second seating assignment results in a higher score (4.8 seating preference points) as it assigns passengers from the same group to the left and right side of any passenger from this group except for the passenger assigned to the aisle seat on the left side where the middle seat next to that aisle seat is available for other passengers (Milne, Cotfas, et al. 2020).

In the first seating assignment proposed for a family group of four passengers in Table 2, the passengers assigned to the middle seats on both sides of the airplane are only accompanied by the passengers of the same group who are assigned to window seats in the same row. However, the aisle seats are available for other passengers. According to the Milne, Cotfas, et al. (2020), a passenger's assignment to a middle seat accompanied by only a window seat passenger from the same group (C_2) earns a lower score (fewer seating preference points) than the situation where the middle seat passenger is sitting together with the window and aisle seat passengers from the same group (Milne, Cotfas, et al. 2020).

For the family group of seven passengers, it's not possible to accommodate all passengers within the group in one row of the airplane; therefore, they need to be assigned to different rows. The first

Table 2. Total seating preference points for example seating assignments.



possible seating assignment for this group of passengers, shown in Table 2, fills a row of the airplane with the passengers of this group and assigns the remaining passenger to another row. This last passenger who is allocated to the aisle seat of a different row is not seated near any other passenger of the same group, meaning that he/she is treated as a singleton passenger for purposes of seating preferences. In the second seating assignment for this group, each passenger of this group may enjoy the companionship of another passenger from the same group. Therefore, as we observe, the second seating assignment receives a higher score (8.5 points) than the other possible seating assignment presented in Table 2 (8.2 points).

3.3. Proposed formulation

We define two mutually sets G' and G'' respectively represent the set of groups with more than one passenger, i.e. family groups, and singleton passengers, i.e. one-member groups, respectively. The union of sets G' and G'' constitutes the set of all groups, i.e. $G' \cup G'' = G$. The subscript g where $g \in G''$ represents a singleton passenger and where $g \in G'$ represents a family group. In the proposed formulation, $X_{g,r,s,l}$ is the main binary decision variable that shows the occupancy of the seat l at row r and side s of the airplane for a passenger belonging to the group g while that group could be a singleton passenger or a passenger belonging to a family group.

The primary goal is to provide a seating assignment that best practices social distancing. The proposed objective function components involve minimizing the number of passengers from different *groups* seated too close to each other as well as the number of *passengers* sitting close to the aisle of the airplane. The proposed seating assignment also considers the desire of passengers within a group to be seated close to each other. In the following, we first introduce the subscripts, sets, parameters, and decision variables of the model. Those will be followed by an introduction of the objective function and the constraints.

Subscripts and superscripts:

$r\&r'$: 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
$g\&g'$: Group of passengers. A passenger travelling alone would be the only member of its group
i: Index of seating preference point(s) assigned to a passenger in a group

Sets:

R: Set of rows : $R = \{1, 2, 3, \ldots, 20\}$
S: Set of sides: $S = \{1, 2\}$
L: Set of seats: $L = \{1, 2, 3\}$
G: Set of all passengers, $G = G' \cup G''$
G': Set of family groups that have more than one member (i.e. passengers travelling together)
G'': Set of one-member groups (i.e. passengers travelling alone)
I: Set of cases introduced in Table 1 where $I = \{1, 2, 3, \ldots, 7\}$

Parameters:

$\beta^{r,s,l}_{r',s',l'}$: Binary parameter that has a value of 1 if the seat (r', s', l') is within the 3.3 feet from the seat (r, s, l) and a value of zero otherwise
N_g: Number of passengers in the group $g, g \in G$
λ_r: weight corresponding to row r
w_1, w_2, w_3: weights of the first, the second, and the third objective function components
α_l: weights of the seating locations concerning their distance from the aisle. α_l should have higher values for aisle seats compared to middle seats
η_i: seating preference points related to the seat assignment involving the C_i case
ϑ: Number of passengers boarding on the airplane

Variables:

$X_{g,r,s,l}$:Binary variable that determines if the seat location represented by (r, s, l) is occupied by a passenger of group g or not
$Y^{g,r,s,l}_{g',r',s',l'}$: Binary variable that determines if the seat locations represented by (r, s, l) and (r', s', l') are both occupied by passengers from different groups (including singleton passengers as groups). $Y^{g,r,s,l}_{g',r',s',l'} = 1$ if $X_{g,r,s,l} = 1 \,\&\, X_{g',r',s',l'} = 1 \; \forall g, g' \in G \backslash g \neq g'$; $Y^{g,r,s,l}_{g',r',s',l'} = 0$ otherwise
Z_1: First objective function component that addresses the social distancing among passengers
Z_2: Second objective function component that addresses the distance of passengers from the aisle
Z_3: Third objective function component that reflects the desire of passengers travelling together to sit near other passengers of the same family group
$P_{i,g,r,s,l}$: Binary variable that is one if the seating preference point(s) from the case i will be assigned to the passenger of the group $g, g \in G'$ that is assigned to the seat location (r, s, l) – and zero otherwise. This variable is not defined for $g \in G''$.

Objective Function:

$$Z = \min(w_1 Z_1 + w_2 Z_2 - w_3 Z_3) \tag{1}$$

The first component of the objective function is to minimize the number of passengers who are seated too close to each other.

$$Z_1 = \sum_{l' \in L} \sum_{s' \in S} \sum_{r' \in R} \sum_{\substack{g, g' \in G \\ g \neq g'}} Y^{g,r,s,l}_{g',r',s',l'} \beta^{r,s,l}_{r',s',l'} \tag{2}$$

Equation (2) addresses the social distancing among passengers from different groups. The social distancing between a singleton passenger and the passengers of another group is addressed in the first set of summations.

$$Z_2 = \sum_{l \in L} \sum_{s \in S} \sum_{r \in R} \sum_{g \in G} \alpha_l \lambda_r X_{g,r,s,l} \tag{3}$$

With Equation (3), we intend to minimize passenger assignment 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 λ_r for the first couple of rows and the last rows of the airplane, the distance from the aisle will not be rewarded in the middle rows of the airplane as much as for the first and last rows.

$$Z_3 = \sum_{g \in G'} \left(\sum_{r \in R} \sum_{s \in S} \sum_{l \in L} \sum_{i \in I} \eta_i P_{i,g,r,s,l} \right) \tag{4}$$

Equation (4) determines the third objective function component where the convenience of passengers in a group is taken into account. The third objective attempts to maximize the seating preference points based on the rewarding system proposed by Milne, Cotfas, et al. (2020) that incentivizes the accommodations of a group of passengers to seats as close as possible to each other.

$$\sum_{r \in R} \sum_{s \in S} \sum_{l \in L} X_{g,r,s,l} = N_g \ \forall g \in G \tag{5}$$

$$\sum_{g \in G} X_{g,r,s,l} \leq 1 \ \forall r \in R, s \in S, l \in L \tag{6}$$

$$\sum_{g \in G} \sum_{r \in R} \sum_{s \in S} \sum_{l \in L} X_{g,r,s,l} = \vartheta \tag{7}$$

Equation (5) ensures the number of passengers assigned to seats from a group is equal to the number of passengers in that group. Equation (6) guarantees that not more than one passenger is assigned to a seat. Equation (7) is the occupancy constraint that ensures each passenger boarding the airplane is assigned a seat. For the Airbus A320, the capacity is 120.

$$X_{g,r,s,l} + X_{g',r',s',l'} - 1 \leq Y^{g,r,s,l}_{g',r',s',l'} \quad r, r' \in R, s, s' \in S, l, l' \in L, g \in G, g \neq g' \tag{8}$$

Equation (8) determines 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.

$$2 \times P_{1,g,r,s,1} \leq X_{g,r,s,1} + X_{g,r,s,2} \quad \forall g \in G', r \in R, s \in S \tag{9-I}$$

$$2 \times P_{2,g,r,s,2} \leq X_{g,r,s,1} + X_{g,r,s,2} \quad \forall g \in G', r \in R, s \in S \tag{9-II}$$

$$2 \times P_{3,g,r,s,2} \leq X_{g,r,s,2} + X_{g,r,s,3} \quad \forall g \in G', r \in R, s \in S \tag{9-III}$$

$$3 \times P_{4,g,r,s,2} \leq X_{g,r,s,1} + X_{g,r,s,2} + X_{g,r,s,3} \quad \forall g \in G', r \in R, s \in S \tag{9-IV}$$

$$2 \times P_{5,g,r,s,3} \leq X_{g,r,s,3} + X_{g,r,s',3} \quad \forall g \in G', r \in R, s \in S \backslash s \neq s' \tag{9-V}$$

$$2 \times P_{6,g,r,s,3} \leq X_{g,r,s,3} + X_{g,r,s,2} \quad \forall g \in G', r \in R, s \in S \tag{9-VI}$$

$$3 \times P_{7,g,r,s,3} \leq X_{g,r,s,3} + X_{g,r,s',3} + X_{g,r,s,2} \quad \forall g \in G', r \in R, s \in S \backslash s \neq s' \tag{9-VII}$$

$$P_{i,g,r,s,l} \leq X_{g,r,s,l} \quad \forall i \in I, g \in G', r \in R, s \in S, l \in L \tag{9-IIX}$$

Equations (9-I) to (9-IIX) address the relationship between the $P_{i,g,r,s,l}$ and the $X_{g,r,s,1}$ variables and how the seating preference points scoring mechanism is activated for each seating location. For instance, Equation (9-IV) corresponds to C_4 where the passenger of a group is assigned to the middle seat on a side and row of the airplane and two adjacent seats (window and aisle seats) on the same side are also assigned to the passengers from the same group.

$$\sum_{i \in I} P_{i,g,r,s,l} \leq 1 \; \forall g \in G', r \in R, s \in S, l \in L \tag{10}$$

Equation (10) implies that for each passenger, at most, one of the scoring cases introduced in Table 1 can be assigned. For instance, for a middle-seat passenger, it is possible to assign, at most, one of the passenger seating preference scores corresponding to the cases C_2–C_4.

$$X_{g,r,s,l}\,,\; P_{i,g,r,s,l}\,,\; Y^{g,r,s,l}_{g',r',s',l'} \in \{0,1\} \tag{11}$$

$$Z_1, Z_2, Z_3 \geq 0 \tag{12}$$

3.4. Normalization of objective function components

Among the three objective function components proposed in Section 3.3, the results presented by the first two objective function components are in distance units while the result of the third objective function component is in rewarding units proposed in Section 3.2. Therefore, it's essential to normalize these components to combine them in an integrated function. We employ a common normalization procedure in the weighted sums method (WSM) in which Utopia and Nadir points are used to normalize objective function components. In what follows, we provide a short introduction of these points (Grodzevich and Romanko 2006):

Utopia point: A point where all objective function components reach their optimum values simultaneously. If we show this point as f^U, then the following vector demonstrates the Utopia points for the three objective function components presented in the previous section:

$$f^U = \left[\min_{x \in \Omega} Z_1(x), \min_{x \in \Omega} Z_2(x), \max_{x \in \Omega} Z_3(x)\right] = [f_1^U, f_2^U, f_3^U] \tag{13}$$

where x represents all decision variables and Ω is the feasible space for the decision variables. In Equation (13), we need to minimize the first two objective function components to reach the Utopia point but require to maximize the third objective function component to reach the Utopia point for this component.

Nadir point and Pseudo-Nadir points: This is a point in the solution space denoted by f^N where all objective function components accomplish their worst values. The following vector shows the Nadir points for the three objective function components proposed in this work:

$$f^N = \left[\max_{x \in \Omega} Z_1(x), \max_{x \in \Omega} Z_2(x), \min_{x \in \Omega} Z_3(x)\right] = [f_1^N, f_2^N, f_3^N] \tag{14}$$

The normalized integrated objective function can be formulated as below:

$$Z = \min(w_1 Z_1 + w_2 Z_2 - w_3 Z_3)$$

$$Z_{wsm} = \min\left(w_1\left(\frac{Z_1 - f_1^U}{f_1^{SN} - f_1^U}\right) + w_2\left(\frac{Z_2 - f_2^U}{f_1^{SN} - f_2^U}\right) - w_3\left(\frac{Z_3 - f_3^{SN}}{f_3^U - f_3^{SN}}\right)\right) \tag{15}$$

In Equation (15), the weights multiplied by the normalized objective function components stress the relative importance of each component and can be determined based on expert judgment. We use the normalized objective function, Equation (15), in place of Equation (2) throughout the remainder of the paper. And to do so, we first calculate the Nadir and Utopia points of each of the three objective function components for each set of input parameters for which we use the MIP. Thus, for each set of input parameters, we conduct seven MIP runs – six to calculate the Nadir and Utopia points for each of the three objective function components and the seventh run with Equation (15) as the objective function.

Table 3. The runtime and gap of implementation of the proposed MIP for the different load of passengers.

Load of passengers	Number of groups		Results
	One-member	Family	
30	11	5	0% gap in 51.5 seconds
40	14	7	0% gap in 127.9 seconds
50	13	10	55.3% gap in 9810 seconds
60	18	12	64.3% gap in 10,560 seconds
70	16	15	70.2% gap in 10,300 seconds

4. Solution algorithm

We programmed the proposed MIP in the Python 3.7 platform and employ Gurobi 9.1 as one of the well-known solvers to extract the exact solutions of the problem. We installed this version of GUROBI on a personal computer with a 3.4 GHz Intel® Core™ i7-6700 U-type processor and 16 GB of memory. We used the GUROBI solver keeping the default parameter settings except for the tolerance gap. We implemented the proposed MIP for five instances, setting a maximum run time of 10,800 seconds, i.e. three days. The five instances are different in terms of the load of passengers and the number of family groups in each load.

The last column of Table 3 presents the optimality gap achieved in the 10,800 seconds time interval for each instance.[3] Note that in the last column of Table 3, the time that the minimum gap achieved within the 10,800 seconds window is reported. In this table, passengers board either as one-member groups or family groups. Each family group consists of six, five, four, three, or two members. For instance, the five family groups for a load of 30 passengers presented in Table 3 consist of two groups with five members, and one group each of four, three, and two members. The combination of family groups and one-member groups is arbitrarily selected.

According to the results presented in Table 3, the runtime of the proposed MIP increases as the load of passengers increases. For instance, comparing the fourth and fifth rows of this table, we observe that there is almost 6% difference in gap, i.e. 70.2% to 64.3%, between the achieved results in a relatively similar runtime. Concerning the considerable gap to the optimal solution for the relatively higher load of passengers, we devised a heuristic method to achieve local optimal solutions for the proposed MIP in a short period. The proposed heuristic is an iterative procedure in which we employ an initial seat assignment as a warm start for the main decision variable, i.e. $X_{g,r,s,l}$. This initial seat assignment method proceeds in a greedy algorithm manner, assigning one group at a time beginning with the largest groups first. The largest groups are assigned first because these are the most difficult to assign safely within the unassigned seats remaining on the airplane. For each group, the primary criterion is minimizing the number of additional passengers that are seated too close to each other. The secondary criterion is for members of a family group to sit near each other. The third and final criterion is to favour seat assignments as close to the rear of the airplane as possible while respecting the first two criteria. That third criterion tends to lead to more contiguous rows of passengers available after each group's assignment than otherwise, except that favouring seat assignments close to the front of the airplane would perform equally well in this respect.

Figure 3 presents the stepwise approach to implement the initial seat assignment that is used to warm start the proposed heuristic method.

The warm start solution containing the initial assignment of passengers to seats becomes the incumbent solution for the proposed heuristic algorithm to improve upon. The proposed algorithm proceeds through a set of 13 iterations. At each iteration, most of the main decision variables are fixed to their values in the incumbent solution ($X_{g,r,s,l}$). A proper subset of those decision variables are unfixed and thus free to be changed by the proposed MIP optimizing on those unfixed variables. The decision variables to unfix during an iteration correspond to the four set of rows in Table 4 associated with the iteration number. For example, for the third iteration, the 24 seats in rows 9-12 are

Method to Determine Initial Seat Assignment

Inputs:

Size of groups N_g in G

Set of rows, R, sides S, and seats L

Define h as the acceptable range for social distancing (in our case, $h = 3.3$ feet)

Sort all groups of passengers in descending sequence of N_g

For the list of groups in descending sequence of N_g **do**:

If $N_g = 1$:

Assign the passenger in group g to a seat that results in the fewest number of additional passengers assigned to seats that are in less than h distance from another assigned passenger group.

If ties occur:

Assign the passenger in group g to a seat as close to the rear of the airplane as possible

End-if

Else:

Determine $Nrows$ as the minimum number of rows on the airplane in which there would be only K additional pair of groups sitting closer than h distance from each other, where K is as small a non-negative integer as possible. Ideally, K will be zero.

If $K = 0$ is not possible:

$K = 1$ would be better than $K = 2$, and $K = 2$ would be better than $K = 3$, etc.

End-if

Assign group g's passengers to available seats in $Nrows$ in descending preference of the below priorities:

- Minimizes the value of K
- Maximizes the group g seating preference score so that passengers within group g sit as near each other as possible and
- As close to the rear of the airplane as possible

End-if

End-for

Figure 3. The initial assignment of passengers.

Table 4. Subset of rows optimized in each iteration of the optimization.

Iteration#	Rows to select	Side to select	Seat to select
1	1–4	Left and right	W,M,A
2	5–8		
3	9–12		
4	13–16		
5	17–20		
6	3–6		
7	7–10		
8	11–14		
9	15–18		
10	1,2,19,20		
11	3,4,17,18		
12	5,6,15,16		
13	7,8,13,14		

Table 5. Utopia and Pseudo-Nadir points for different loads of passengers.

Load of passengers	Number of groups		Utopia point			Nadir point			Runtime (in seconds)
	One-member	Family	f_1^U	f_2^U	f_3^U	f_1^N	f_2^N	f_3^N	
30	11	5	0	0	50.4	213120	4.6	0	56.1
40	14	7	0	0	44.2	372960	5.8	0	124.1
50	13	10	80	3.1	61.7	449328	5.6	0	148.2
60	13	13	150	3.7	78.4	577200	8.9	0	160.4
70	14	16	228	4.1	93.7	772560	9.5	0	240.1

re-optimized so that the values of $X_{g,r,s,l}$ may change in rows 9-12. At each iteration, the new solution becomes the incumbent solution which may be better and could be the same as the previous incumbent solution.

Figure 4 provides a step-wise graphical illustration to presents the input and the procedure toward reaching the *local optimal seating assignment*. According to this figure, the initial assignment, subsets of R, and the parameters introduced in Section 3.3 are the input of the model. After the implementation of the proposed MIP for a subset R, the seating assignment should be updated for this subset of rows. In the following step, the visited subset R should be updated. The 'visited subsets of R' refers to subsets R that are already used for the passengers seating optimization. If the visited subsets of R equals all the subsets of R defined in Table 4, then the most recently updated seating assignment should be reported as the optimum seating location of passengers, otherwise, the MIP should be implemented for the most updated subset R.

5. Numerical results

We implemented the proposed model (and proposed heuristic) using the objective function components individually to obtain the Utopia and Pseudo-Nadir points related to each objective function. Table 5 shows an instance of the Utopia and Pseudo-Nadir points obtained for each objective function component for a load of passengers ranging between 30 to 70 passengers. The average runtime for determining the three Utopia points and the three Pseudo-Nadir points is reported in Table 5 for each load of passengers.

Salari et al., (2020) suggest that the maximum load of passengers to board an A320 airplane with 20 rows and three seats on each side of a singular aisle without violating the 3.3 feet social distancing requirement is 30 passengers. Using their proposed model, the seating location of 30 passengers consists of five family groups and 11 one-member groups without violating social distancing is presented in Seating location A of Figure 5. Their model is based on the assumption that passengers travel individually; therefore, their model doesn't allow any two passengers to sit less than 3.3 feet from each

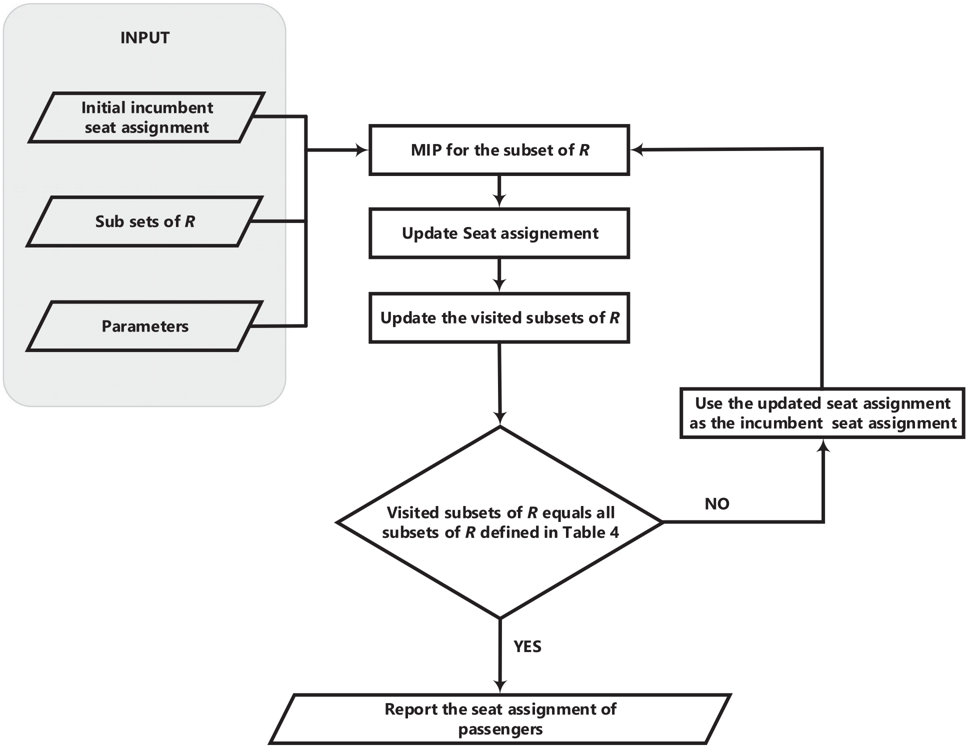


Figure 4. Steps of the proposed heuristic algorithm.

other. In the present work, however, we assume passengers can also travel in family groups of more than one passenger, and allow the passengers of the same family group to sit close to each other (i.e. less than 3.3 feet). Seating location B of Figure 5 demonstrates the seating location of 30 passengers for the same combination of family groups and one-member groups used in Seating location A. Without compromising the social distancing between the passengers from different groups by using the first objective function component as a constraint, Seating location B shows that there exist a lot of available seating areas and more passengers can be accommodated to the airplane compared to Seating location A. Seating location C is provided to illustrate such a situation where more passengers can be accommodated in the airplane considering passenger family groups. In this scenario, 40 passengers are assigned to seats while still practicing social distancing between groups.

In Figure 5, in the seating locations B and C, we use social distancing as a constraint to assure there is no violation in social distancing among groups. However, we are also interested in the evaluation of the social distancing practice where social distancing is introduced as one of the objective function components and not as a firm constraint. Table 6 examines the percentage of social distancing practice through 60 trials per row with the average number of occurrences of family groups and one-member groups presented in this table. The average number of occurrences of each family group size and one-member groups are obtained based on the cumulative summation of the existence of a specific size group through all trials divided by the number of trials. For instance, for the load of 40 passengers, the value of 1.1 for the two-member family group means that, through 60 trials, 66 two-member family groups were generated. This results in 1.1 two-member groups on average for each trial.[4]

In this table, 'social distancing practice' refers to the criteria where no passenger from different groups, i.e. family groups and one-member groups, are sitting less than 3.3 feet from each other. For instance, 85% of 'social distancing practice' for the load of 40 passengers means that out of 60 trials, in 51 trials, there was no violation in practicing social distancing among groups. With no enforcement to

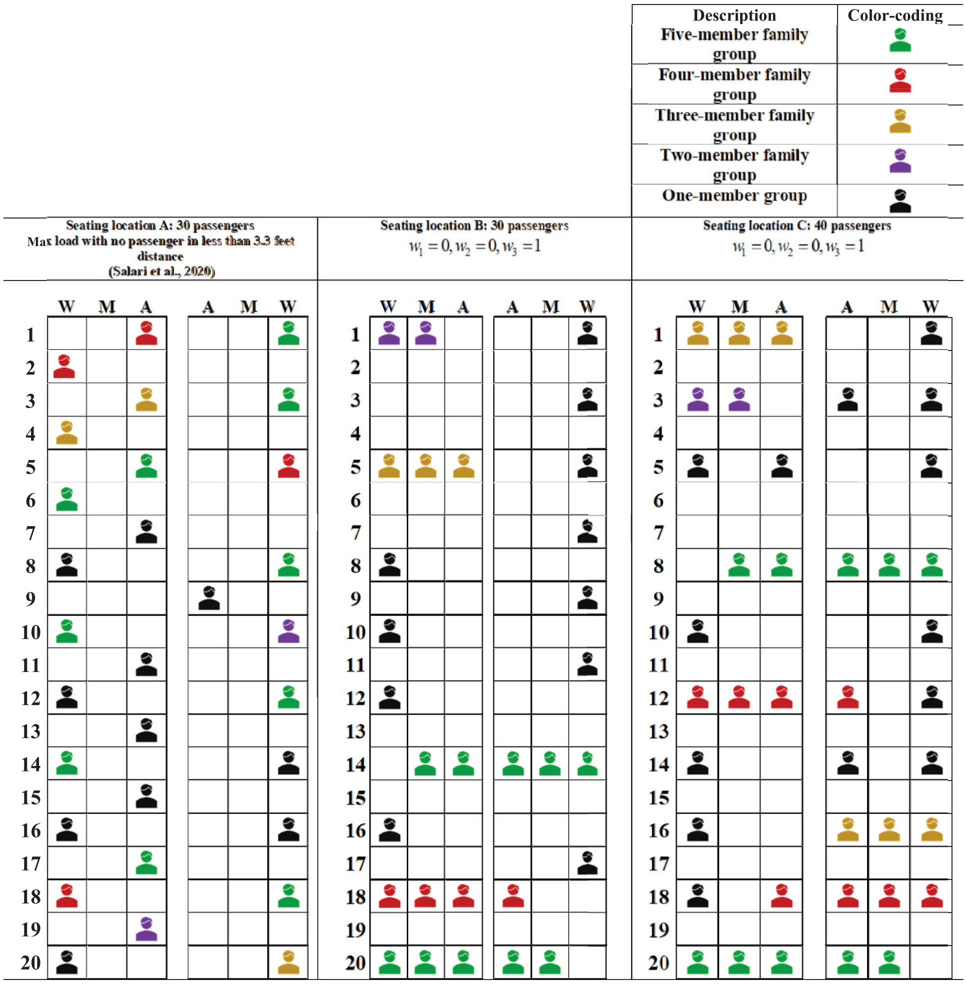


Figure 5. Seating location of passengers using the proposed model and Salari et al. (2020)'s model.

Table 6. The percentage of trials in which all passengers practice social distancing where $w_1 = 0.5, w_2 = 0, w_3 = 0.5$.

Load of passengers	Average occurrences of one-member groups	Average occurrences of people in family groups					Social distancing practiced by all passengers (percentage)
		2	3	4	5	6	
40	18.4	1.1	1.3	0.6	1	1.2	85.0
50	20.3	2.1	2	1.2	1.6		21.7
60	22.4	4	3.1				0.0
70	25.1	3.8		1.9	2	1.7	

reduce the number of passengers assigned too close to the aisle of airplane ($w_2 = 0$) and equal level of significance on the practicing social distancing and the assignment of passengers within a group to sit as close as possible to each other, the percentage of practicing social distancing considerably drops as the load of passengers increases. This is expected as with the higher load passengers there are fewer unassigned seats to provide distance between passengers.

To better evaluate in which situation the social distancing occurs for a certain load of passengers through 60 trials, we provide Figure 6, as an example, in which blue-highlighted bars show the trials in

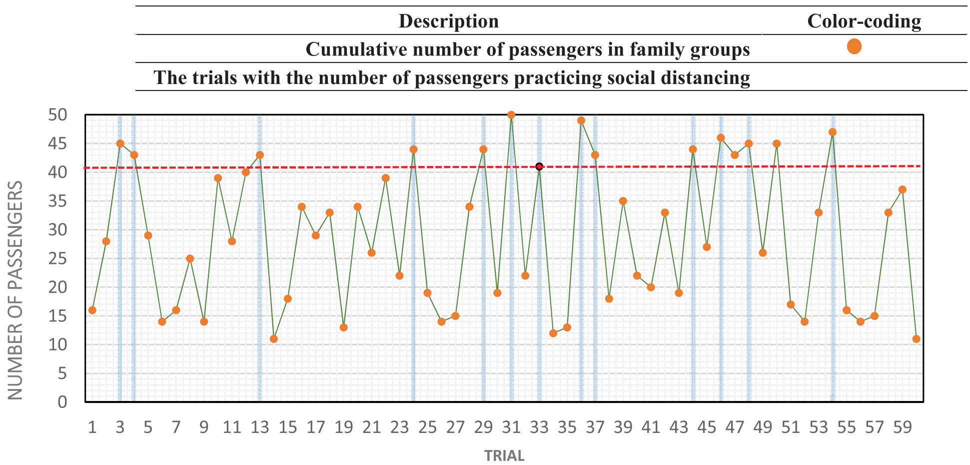


Figure 6. Social distancing practice through 60 trials for 50 passengers.

which all passengers from different groups practice social distancing in Table 6 for a load of 50 passengers. For example, trial 3 is one of the instances where none of the passengers from different groups sit in less than 3.3 feet from each other while the cumulative number of passengers in family groups, i.e. more than a one-member group, is 45 passengers and only 5 passengers belong to one-member groups. The dashed red line determines the boundary for the empirical minimum value of the *cumulative* number of passengers in family groups that results in universal practicing of social distancing. This line for the load of 50 passengers shows that social distancing occurs for these 60 trials when at least 41 out of 50 passengers belong to family groups and at most 9 passengers belong to one-member groups. This figure shows that more likely, social distancing is possible where the cumulative number of passengers in family groups increases. It is due to the reason that with more family groups, more passengers can sit close to each other, opening up more seating spaces between different groups.

In Figure 7, for 60 trials, we compare the practice of social distancing for all passengers presented in the last column of Table 6 (presented as Scenario A in Figure 7) to where the average number of one-member groups *decreases* between 20% and 30% and also the average number of passengers in family groups, i.e. four-member, five-member, and six-member family groups, increases between 15% and 30% (as presented as Scenario B in Figure 7). The results show that as the percentage of one-member groups decreases and the percentage of more populated family groups increases, i.e. Scenario B, then the percentage of times all passengers practice social distancing, i.e. when no passengers from different groups sit in less than 3.3 feet from each other, increases. For instance, for a load of 40 passengers, Scenario A shows that the rate of practicing social distancing is 85% (51 times out of 60 trials) while in Scenario B, where the rate of more populated family groups increases, the percentage of all passengers practicing social distancing increases to 91.67 (55 times out of 60 trials). According to Scenario B, in 1.67% of the time (1 out of 60 trials) the load of 60 passengers were able to practice social distancing. This is a special case where ten six-member family groups could be assigned to seats without violating social distancing.

In Table 7, we evaluate the level of meeting the goal of each objective function component expressed using a percentage scale through 60 trials using three criteria introduced as 'Social distancing' (related to the first objective function component), 'Passenger distance from aisle' (related to the second objective function component) and 'Family group seating' (pertaining to the third objective function component). In this table, a 100% level of social distancing occurs when there is at least 3.3 feet among all passengers from different groups (including distance among singleton passengers, among one-member and family groups, and passengers from different family groups). The 100% level of distance from the aisle is defined as the number of passengers not assigned to aisle seats divided

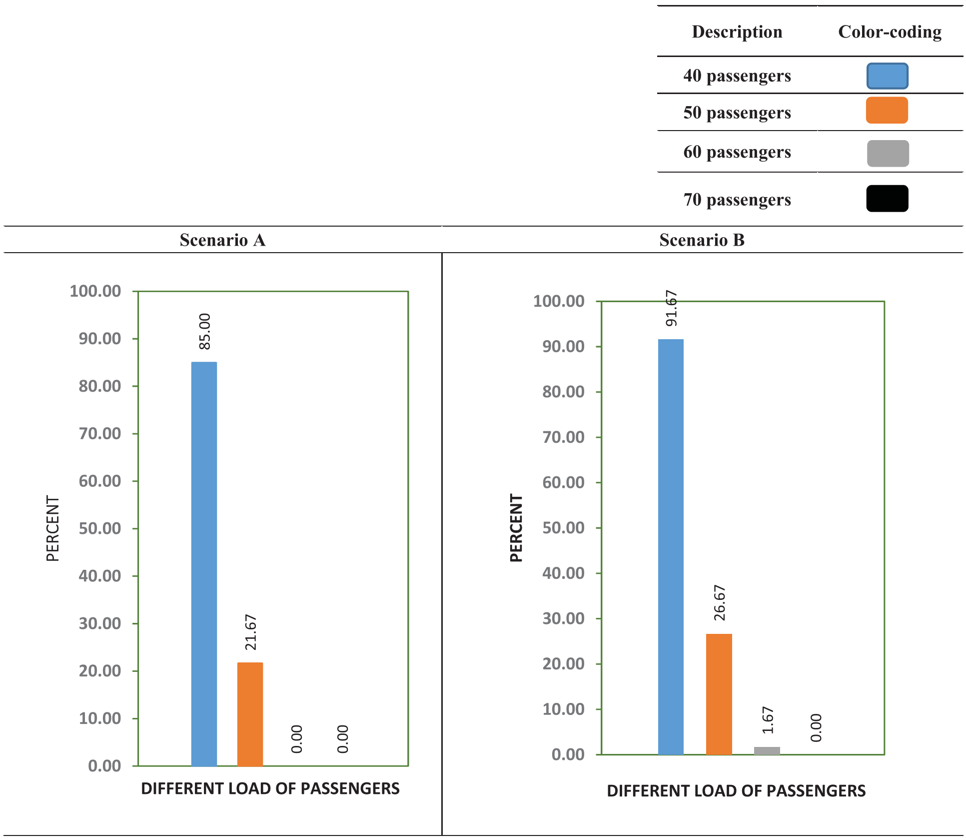


Figure 7. Evaluation of no violation in social distancing for the different load of passengers.

by the number of aisle seats. Finally, the ideal situation for family group seating is where no passengers of a family group is assigned to a seat that is not close to any other member of the same family group. While the weights of the objective function components can be adjusted based on their relative importance, the results indicate that, regardless of the weights of the objective function components, the increase in the load of passengers adversely affects all three objective function components while this effect is most considerable in the first objective function that concerns 'social distancing' among groups. For instance, where higher importance is assigned to the social distancing among groups, i.e. $w_1 = 0.8, w_2 = 0.1, w_3 = 0.1$, as the load of passengers increases from 30 to 90, the 100% social distancing drops to zero. The feasibility of practicing social distancing is considerably impacted by the load of passengers.

Another finding from Table 7, which is also reflected in Figure 8, is the alignment of three criteria listed in Table 7 based on the different combinations of weights. The first criterion, i.e. social distancing, is less affected by the third weight combination compared to the second weight combination. The third criterion also shows the same behaviour where the biggest adverse impact on this criterion is when the weights are according to the second weight combination. For instance, in Figure 8, for the load of 30 passengers, the first criterion is 100% in the first combination. It drops to 91.7% while using the third combination of weights for the objective function. The biggest reduction for this criterion, however, is when using the second weight combination which puts more emphasis on passengers' distance from the aisle is employed for the objective functions. A similar pattern can be identified for this criterion and the third criterion in the other load of passengers.

Table 7. The percentage of passengers practicing social distancing, passengers distance from the aisle, and family groups seated close to each other through a different load of passengers for distinctive weight combinations of the objective function components.

Weight combination		Load of passengers[a]	Social distancing (Percentage)	Passengers distance from the aisle (Percentage)	Family groups seating (Percentage)
1	$w_1 = 0.8, w_2 = 0.1, w_3 = 0.1$	30	100	69.5	99.4
		40	88.3	43.5	87.1
		50	23.3	19.5	81.9
		60	0	0	76.2
		70			71.3
		80			70.6
		90			64.8
2	$w_1 = 0.1, w_2 = 0.8, w_3 = 0.1$	30	89.4	74	95.7
		40	66.7	62	89.7
		50	15	30.5	81.4
		60	0	8.5	76.8
		70		0	74.1
		80			68.2
		90			63.1
3	$w_1 = 0.1, w_2 = 0.1, w_3 = 0.8$	30	91.7	68	100
		40	76.7	50.5	95.4
		50	18.3	14.5	86.4
		60	0	0	88
		70			79.4
		80			75.3
		90			70.4

[a]Average cumulative number of passengers in family groups are 22.04, 34.8, 39.8, 48.3, 56.4, 66.8, 76.9 for the loads of 30, 40, 50, 60, 70, 80 and 90 passengers.

6. Social distancing for groups with middle seat blocking policy

As a response to SARS-CoV-2 outbreak, many airlines adjusted their boarding and seating assignment policies to satisfy the requirements for passengers' safety. As one of the preliminary measures, Delta Airlines operated a back-to-front boarding policy so that passengers do not have to pass each other while boarding (Delta Airlines 2020). United Airlines published a full page on its website to explain the response measures to SARS-CoV-2 including new protocols for boarding and checking-in to minimize individual impacts (besides rules which are not strictly related to airplane boarding such as aircrafts disinfection, access to hand-sanitizer). In an attempt to keep social distancing among passengers, Delta Airlines and American Airlines announced that they would block all or 50% of the middle seats to keep distance among seated passengers. We evaluate these policies by introducing them as the constraint of the proposed model. Table 8 shows the result of implementing 50% or full middle-seat blocking policies as well as the proposed model where equal weights are assigned to each objective function component ($w_1 = 0.33, w_2 = 0.33, w_3 = 0.33$) for a relatively low load of passengers. We select a relatively low load of passengers as with a higher load of passengers, models are forced to sacrifice among the three objective function criteria. In Table 8, five seating location scenarios provided by the proposed model, i.e. proposed model without middle seat blocking, with 30% middle seat blocking, with 50% middle seat blocking, with 80% middle seat blocking, and with full middle-seat blocking, are implemented for 60 trials and the results of the trials for the three criteria are reported.

The results show that for the load of 30 passengers, the different percentages and full middle-seat blocking policies don't affect the first criteria, i.e. social distancing, but mostly affect the second criteria as the blocked middle seats force the model to assign passengers to aisle seats. We observe the same trend for the load of 40 passengers while in this case, the first criteria is also affected by middle-seat blocking policies. The results, especially for the load of 40 passengers, illustrate the better performance of the proposed model concerning the distance between different groups, i.e. social distancing, the

Table 8. Results of the proposed model, 30%, 50%, and 80%, and full middle-seat blocking policies for the different passenger loads.

	Seating location scenarios								
Load of passengers	Without middle seat blocking	30% middle-seat blocking	50% middle-seat blocking	80% middle-seat blocking	Full middle-seat blocking	Social distancing (Percentage)	Passengers in aisle seats (Percentage)	Groups seating (Percentage)	Satisfaction of Passengers
30	☑	–	–	–	–	100	70.1	99.1	92.075
	–	☑	–	–	–		50.6	96.3	85.8
	–	–	☑	–	–		33.4	92.6	79.65
	–	–	–	☑	–		16.1	86.2	72.125
	–	–	–	–	☑		14.3	83.5	70.325
40	☑	–	–	–	–	85.4	46.2	87.4	76.6
	–	☑	–	–	–	81.3	26.8	75.2	64.625
	–	–	☑	–	–	80.8	8.9	70.4	57.625
	–	–	–	☑	–		0	63.1	51.75
	–	–	–	–	☑			62.8	51.6

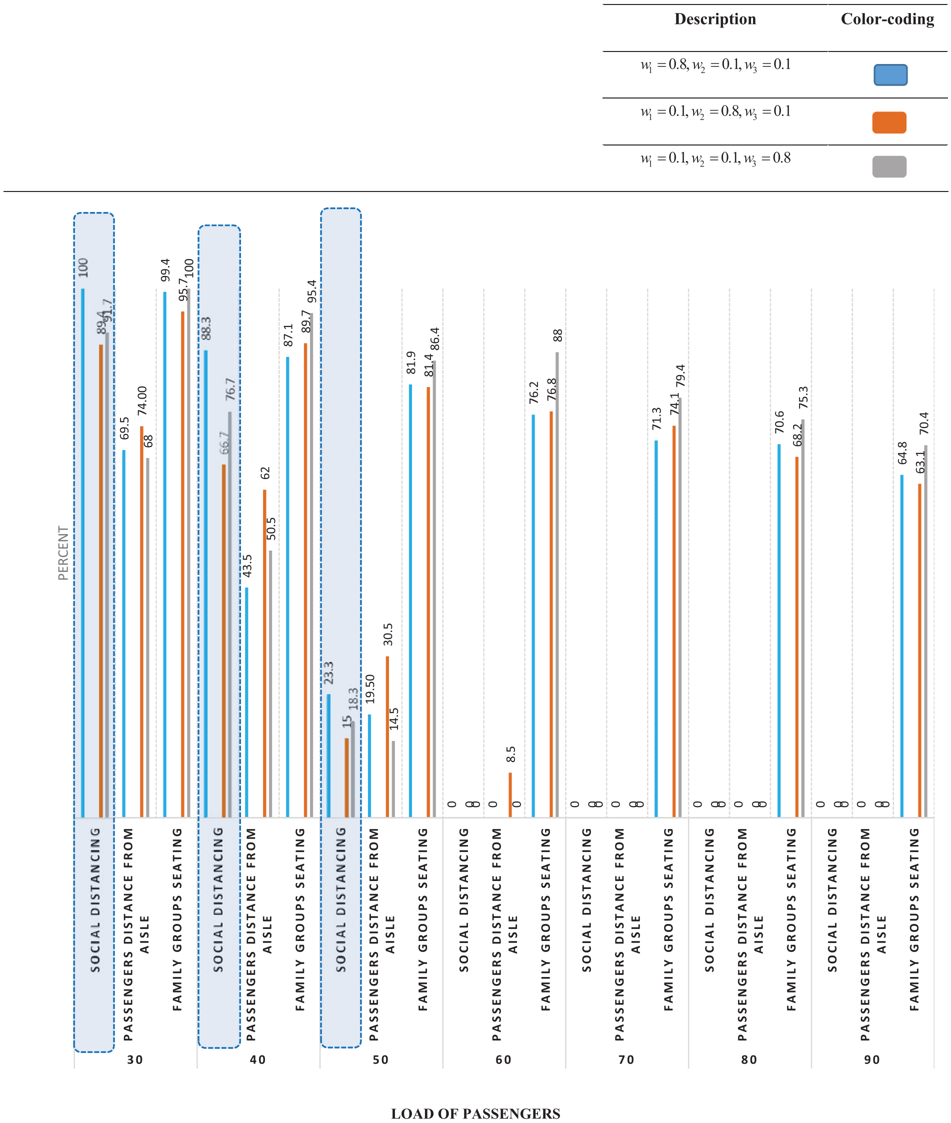


Figure 8. Comparison of the criteria introduced in Table 7 for the different load of passengers.

distance from the aisle, i.e. passengers in aisle seats, and seating closeness of passengers from the same group, i.e. group seating.

To evaluate the satisfaction of passengers, we used the three objective function criteria introduced in Table 8. We divided these three criteria into two categories including the satisfaction of passengers concerning practicing social distancing (include the social distancing and distance from the aisle criteria) and satisfaction of passengers concerning their seating location distance from their family groups (third objective function components). For the first category of satisfaction, we assign equal weights to the first and second criteria components. Moreover, we considered similar significance between the first and the second category of satisfaction. The following equation shows how the satisfaction of passengers is calculated using three criteria:

$$0.5 \times \frac{(f_1 + f_2)}{2} + 0.5 \times (f_3) \tag{16}$$

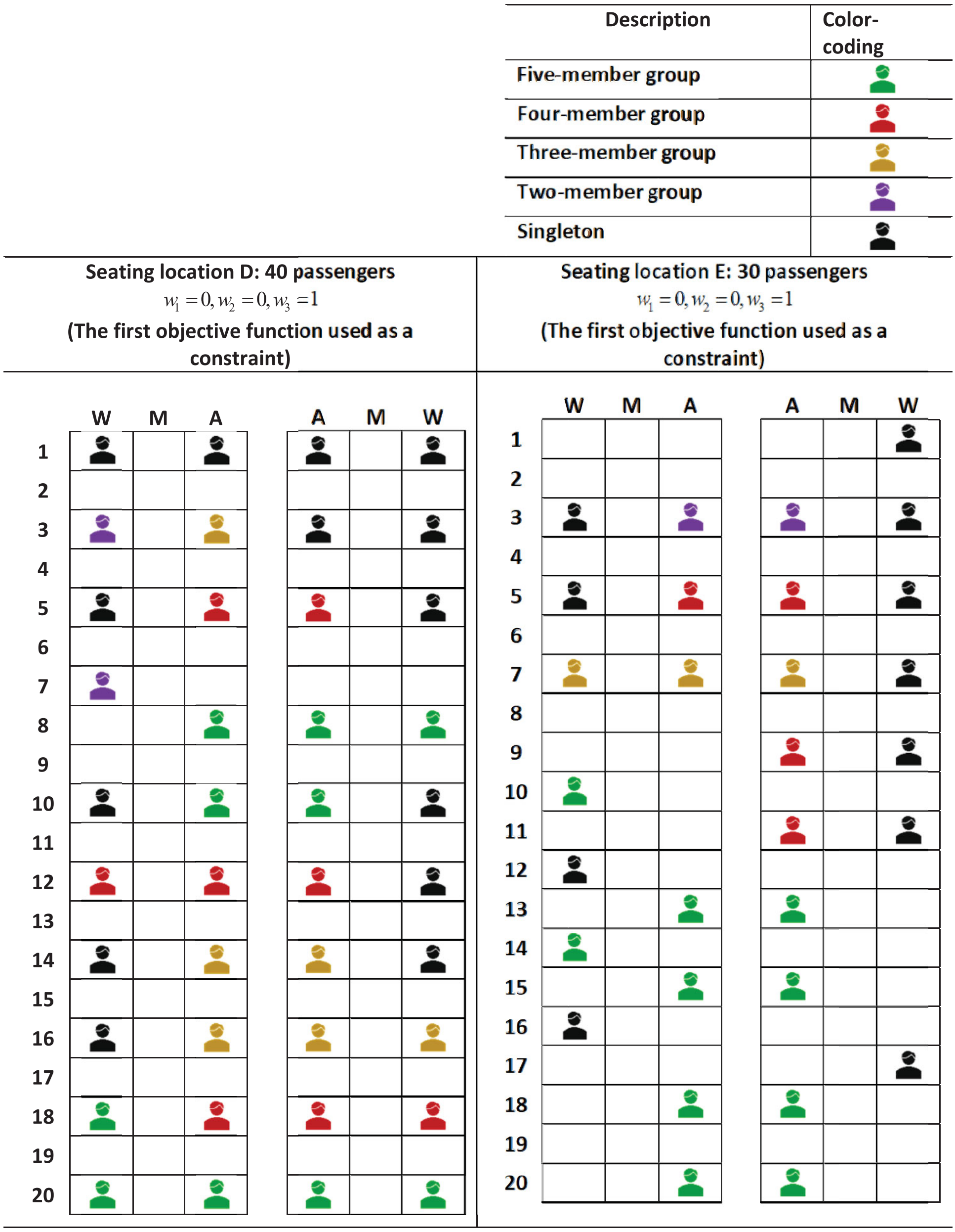


Figure 9. Seating assignments of passengers with full middle-seat blocking policy.

f_1: Social distancing criteria (Percentage), f_2: Passengers in aisle seats (Percentage), f_3: Groups seating (Percentage)

We put the result of the passenger satisfaction evaluation in the last column of Table 8. This result shows that the proposed model can better satisfy passengers compared to the variations of the middle-seat blocking policy while for all seating strategies including the proposed model, the satisfaction of passengers is adversely affected by the increase in the load of passengers.

We provide Figure 9 as an example to show the passengers' seating assignment with full middle seat blocking for 30 and 40 passengers where the highest weight is given to the passengers from the same group to sit as close as possible to each other (i.e. $w_1 = 0, w_2 = 0, w_3 = 1$).

The number of family groups is equal to the same values already employed for Figure 5. Moreover, similar to Figure 5, we constrained the model to force 100% social distancing among all groups of passengers. For the load of 40 passengers, forcing 100% social distancing causes infeasibility of the model for some combinations of family groups, particularly those with a relatively high number of one-member groups. The results show a considerable dispersion in the seating location of the passengers from the same group for both 30 and 40 passengers compared to the seating location provided in Figure 5 for these loads of passengers. Furthermore, inevitably, the number of passengers in the aisle seats increases for both loads of passengers compared to where no middle-seat blocking was enforced.

7. Conclusion

Keeping social distancing among passengers in an airplane can effectively reduce the health safety risk of a flight during the SARS-CoV-2 outbreak or other pandemic conditions. We study social distancing among passengers assuming some passengers are travelling in groups that do not require social distancing (e.g. family living in the same household).

Compared to the consideration of passengers travelling individually, allowing passengers of the same group to sit close to each other shows that it is possible to accommodate more passengers to be assigned to airplane seats without compromising the social distancing between passengers from distinctive groups. In other words, the proposed model suggests that airlines can sell more tickets to passengers during an outbreak while not violating health safety protocols. From a financial standpoint, this is a seminal finding as ticket-selling constitutes a considerable portion of airline revenues. Moreover, group seating assignments are also beneficial for a relatively low load of passengers as their seating assignments can provide more distance among different groups. Furthermore, our method provides seating that will be preferred by passengers who enjoy sitting near other family members.

We studied the social distancing practice through simulation experiments for different loads of passengers and ranges of the cumulative number of passengers in family groups. The results indicate that as the average cumulative number of family groups compared to the cumulative number of one-member groups increases, the model has more success in practicing social distancing. Moreover, the presence of higher populated family groups (family groups with six, five, and four members) positively impacts the practice of social distancing among groups. We evaluate the level of reaching the ideal situation for each of the proposed objective function components for the different loads of passengers. According to the results, the normalized objective function components do not necessarily reflect the same intention. For instance, where the weight of the second objective function component that signifies the distance of passengers from the aisle increases, it adversely affects the third objective function component that encourages group seating. We observe a similar behaviour between the first objective function component which addresses social distancing between different groups and the second objective function component.

We analyze the middle-seat blocking policies including 50% blocking and full blocking of middle seats proposed by some airlines. The results indicate that these policies adversely impact all of the objective function components (when compared with the proposed model) especially the second objective function component which promotes the distance of passengers from the aisle of the airplane. We provide two instances for the load of 30 and 40 passengers where seating assignments could thoroughly follow social distancing between groups and assign passengers of the same groups as close as possible to each other using the proposed model while it was not possible to keep that level of distancing between different groups as well as closeness for passengers within a group by imposing the middle seat blocking policy.

In summary, among the important contributions of the work are a proposed mixed-integer programming model (MIP) for determining seat assignments, a heuristic method for determining an initial solution to the MIP, and a proposed heuristic method for improving the solution to the MIPs that provides the following advantages in the resulting seat assignments:

- Safe social distancing among more passengers – safer than when family groups are not considered
- Safer than the 'middle seat empty' policy
- Seating assignments preferred by passengers who enjoy sitting near other family members
- Social distancing away from the aisle of the airplane
- Favours aisle seat assignments towards the middle of the airplane (away from the bathrooms)

Implementing the method directly would involve the airline determining the seat assignments using the MIP. Billions of people and millions of businesses have adjusted their behaviour as a result of the present pandemic. Implementing the method directly would be another adjustment. Given the health and economic impacts, airlines and their customers may be willing to accommodate the direct use of the method. Pavlik et al. (2021) show with regard to the COVID-19 airplane boarding problem, that the importance of the health benefits often exceeds the hardship of applying social distancing measures.

Alternatively, future research could be conducted to determine how to blend the concepts of our paper into a new practice in which customers have a role in selecting their seats. For example, rather than having customers select the seats they prefer, maybe the airline could record the relative preferences of particular customers for the types of seating assignments they prefer (e.g. all family members in the same row, seats near the front of the airplane), and the airline assigns seats that respect those passenger seat preferences, including perhaps an opportunity for some passengers to pay an additional fee to guarantee their preference is met.

Other future research possibilities include: the consideration of the passengers' carry-on bags on the virus transmission risk in an airplane, the development of risk models and seat assignments tailored for each type of airplane, introducing new indicators for passengers' satisfaction with the airplane boarding process, blocking the middle seat adjacent to passengers travelling alone, placing vulnerable passenger groups (e.g. groups having person(s) with weak disease immunity) in particular parts of the airplane to reduce transmission risk, and integrating seat assignment methods with boarding methods optimized on efficiency and health.

Notes

1. We also refer to a singleton passenger as a one-member group. Moreover, the general term 'group' refers to as both 'family group' and 'one-member' groups.
2. Please refer to Salari et al. (2020) for more details on the seat distance calculation.
3. For the results presented in Table 3, we set the weights of objective function as 0.5, 0, 0.5 for w_1, w_2&w_3, respectively.
4. The details of the group generation for each trial are explained in the Appendix.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix: Generation and selection of family group combinations

The following algorithm generates each possible combination of one-member groups and family groups that results in the specified total number (load) of passengers. After the generation of all feasible combinations, one of the combinations is randomly selected for each trial.

Method to Determine Initial Seat Assignment

Inputs:

Size of groups N_g in G

Set of rows, R, sides S, and seats L

Define h as the acceptable range for social distancing (in our case, h = 3.3 feet)

Sort all groups of passengers in descending sequence of N_g

For the list of groups in descending sequence of N_g **do**:

If $N_g = 1$:

Assign the passenger in group g to a seat that results in the fewest number of additional passengers assigned to seats that are in less than h distance from another assigned passenger group.

If ties occur:

Assign the passenger in group g to a seat as close to the rear of the airplane as possible

End-if

Else:

Determine $Nrows$ as the minimum number of rows on the airplane in which there would be only K additional pair of groups sitting closer than h distance from each other, where K is as small a non-negative integer as possible. Ideally, K will be zero.

If $K = 0$ is not possible:

$K = 1$ would be better than $K = 2$, and $K = 2$ would be better than $K = 3$, etc.

End-if

Assign group g's passengers to available seats in $Nrows$ in descending preference of the below priorities:

- Minimizes the value of K
- Maximizes the group g seating preference score so that passengers within group g sit as near each other as possible and
- As close to the rear of the airplane as possible

End-if

End-for

Figure A1. Method for generating all feasible combinations of family groups.

Table A1. The combination of one-member and family groups for 40 passengers.

Combination No	One-member groups	Family groups				
		Two-member	Three-member	Four-member	Five-member	Six-member
1	40	0	0	0	0	0
2	38	1	0	0	0	0
3	37	0	1	0	0	0
4	36	2	0	0	0	0
.	36	0	0	1	0	0
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
3331	0	0	0	1	0	6

Table A2. The total number of feasible combinations of one-member and family groups for each load of passengers.

Load of passengers	Total number of combinations
40	3331
50	8442
60	18,467
70	36,308

Table A1 shows some of the possible combinations of one-member and family groups for the load of 40 passengers where there are 5 categories for family groups including two-member, three-member, four-member, five-member, and six-member groups:

Table A2 shows the total number of feasible combinations of one-member and family groups where it is assumed there are five categories of family groups.