Boarding —step by step: A Cellular Automaton approach to optimising aircraft boarding time
一步一步地登机：应用元胞自动机方法优化飞机登机时间

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Abstract

For airlines it is imperative to minimise the times that their aircraft spend on the ground. One important factor in this consideration is the reduction of the boarding time of the aircraft. This submission attempts to model the presented problem by making use of a cellular automaton, to investigate possible solutions and to present recommendations as to how these solutions can be employed effectively.

The cellular automaton model is implemented in three stages:

- Initialisation of the seating layout for a chosen aircraft type and assignment of seats to passengers
- The sorting of passengers according to various proposed boarding methods
- "Propagating" the passengers through the aisle(s) of the aircraft and seating them at their assigned places.

The rules governing the automaton take into account various factors. Amongst these are the load factor (percentage filling) of the craft, different walking speeds of passengers walking through the aisle, and time delays resulting from stowing of luggage and obstructions by other passengers during the seating process. The algorithm accommodates for predefined aircraft layouts of common aircraft (we studied the Fokker 50, the Boeing 737-400 and the Boeing 777-200) and for user-defined aircraft layouts.

Various boarding strategies were modelled and tested for efficiency with regard to total boarding time and average boarding time per passenger. Thus our approach focuses not only on optimisation of the process in favour of the airlines, but also yields information regarding convenience to passengers. Random boarding (where passengers with assigned seat numbers enter the plane in a random sequence) was used as a point of reference. Amongst the other strategies tested were boarding the plane in groups from either end, boarding from seats furthest away from the aisles towards the aisles and combinations of these approaches.

It was concluded that boarding strategies starting furthest away from the entrance or furthest away from the aisles yielded shorter boarding times than random boarding. The most successful methods were identified to be combinations of these

对于航空公司来说，必须尽量减少飞机在地面上停留的时间。一个值得考虑的重要因素是减少飞机的登机时间。本文试图通过应用元胞自动机对这个问题进行建模，以研究可能的解决方案，并提出关于如何有效地使用这些解决方案的建议。

本文的元胞自动机模型分三个阶段实施：

- 初始化给定飞机类型的座位布局，并为乘客分配座位
- 根据各种提出的登机方案对乘客进行排序
- 通过飞机的过道“传送”乘客并将他们安置在指定的座位。

控制自动机的规则考虑了多种因素。其中包括飞机的座位利用率（上座百分比），乘客经过过道的不同行走速度，以及在入座过程中由于放置行李和其他乘客的阻碍而导致的时间延迟。该算法适用于常见飞机的标准座位布局（我们研究了 Fokker 50，波音 737-400 和波音 777-200）以及用户自定义的飞机座位布局。

本文对各种登机策略进行了模拟和测试，计算了与总登机时间和每个乘客的平均登机时间相关的效率。因此，我们的方案不仅关注有利于航空公司的流程优化，而且还输出了有关乘客便利性的信息。随机登机（具有指定座位号的乘客以随机顺序进入飞机）被用作参考。测试的其他策略包括分组从两端登机，从远离过道到过道的座位登机，以及这些方法的组合。

结论是，离入口最远或距离过道最远的座位先登机的策略产生的登机时间比随机登机时间短。最成功的方案被确定为这些策略的组合，其详细实施取决于所考虑的飞机的确切

strategies, the detailed implementation thereof being dependent on the exact layout/size of the aircraft under consideration. It was also found that the method yielding the shortest total boarding time was not necessarily the one producing the shortest average boarding time per passenger. By considering standard deviations of total and individual boarding times over many iterations of the simulation, conclusions were also drawn regarding the stability/consistency of the specific boarding strategies and how evenly the waiting time is distributed amongst the passengers.

布局/尺寸。此外，我们还发现产生最短总登机时间的方法不一定是产生每位乘客最短平均登机时间的方法。通过多次模拟得到的总体和个体登机时间的标准偏差，我们不仅得出关于特定登机策略的稳定性/一致性，还得到了乘客等待时间的分布。

In our estimation, by selecting appropriate strategies, time-savings of two to three minutes for small and medium aircraft could be achieved. For a custom 800-seat aircraft with two aisles, more than six minutes could be saved when compared to random boarding. After having compared these results to actual turnaround times quoted by airlines, we believe them to be realistic.

根据我们的估计，通过选择适当的策略，可以为中小型飞机节省 2 到 3 分钟的时间。对于带有两个通道的定制 800 座飞机，与随机登机相比，适当的登机策略可以节省超过六分钟。在将这些结果与航空公司引用的实际运转时间进行比较后，我们认为这些结果是切合实际的。

Contents

1 A brief description of Automata-theory and its relevance to the given problem | 自动机理论及其与给定问题的相关性的简要描述

A cellular automaton is an algorithm that determines the time development of a given system. If the algorithm is fed an initial configuration of the system, a finite set of fixed rules determines how the system develops. A time-step structure is used, such that the algorithm advances incrementally with all its rules being implemented at every time-step.

元胞自动机是一种确定给定系统的时间发展的算法。如果一个系统的初始状态作为算法的输入，则一组有限的固定规则确定系统如何发展。使用时间步长来离散时间，逐步推进算法，其所有规则在每个时间步上都要执行。

This approach was used by our team to model the various boarding strategies for airplanes. A set of rules was created to govern how passengers move in the aisle(s) of a plane and what happens when they take their seats. These rules will be discussed in detail later. Then various strategies for boarding were tested by changing the order in which passengers entered the plane. Ultimately a comparison of relative boarding times for different strategies (averaged over many iterations) was made, to select the most time-effective strategy.

我们的团队使用这种方法来模拟飞机的各种登机策略。制定了一套规则来控制乘客如何在飞机的过道中前进以及当他们坐下时会发生什么。稍后将详细讨论这些规则。然后通过改变乘客进入飞机的顺序来测试各种登机策略。最后，对不同策略（平均多次循环的结果）的登机时间进行了比较，以选择最有效的策略。

The algorithm was implemented in MATLAB and is described in detail below.

该算法由 MATLAB 中实现的，详细描述将在下文给出。

2 The algorithm | 算法

Essentially the simulation consists of three main parts:

- An input vector of the passengers
- A set of rules describing the behaviour of passengers in the plane
- A seating plan of the plane (flexible for various sizes/layouts of planes) represented as a matrix

本质上，本文的模拟包括三个主要部分：

- 乘客输入向量
- 一组描述飞机上乘客行为的规则
- 由矩阵表示的飞机座位布局图（适用于各种尺寸/布局的飞机）

The arrangement of the input vector determines in which sequence passengers enter the plane. For instance, if a selected strategy was to board window-seat passengers first, the input vector would be sorted / arranged in such a way that these passengers are at the front end of this vector which enters the aisle of the plane. The vector (which is essentially a lookup-table) also contained the following information for each passenger:

- Passenger number (to track elements moving through the matrices)
- Seat number
- Walking speed of the passenger (dependent on whether the passenger is a

输入向量的元素排列决定了乘客进入飞机的顺序。例如，如果选择的策略是靠窗座位的乘客先登机，则表示进入飞机过道次序的输入向量将被调整或排列，使得这些乘客位于该向量的前端。向量（实质上就是查表）还包含每位乘客的以下信息：

- 乘客编号（标记在矩阵中移动的元素）
- 座位号
- 乘客的行走速度（取决于乘客是健康成人，儿童还是

healthy adult, a child, or a passenger with a disability)
- Class of the passenger (first class, economy class etc.)
- The passenger's individual boarding time (determined when passenger is seated)

The set of rules governing the behaviour (or rather propagation) of the passengers in the plane takes into consideration the passengers' walking speed. The assumption was made that in the space of one seat-row, two consecutive passengers could stand in the aisle. Thus the aisle of the plane (also modelled as a vector) was created such that it has two elements for every seat row it bypasses. According to the rules a passenger could only move ahead in the aisle if the element before him/her is unoccupied. This spacing pattern was thus represented with matrices/vectors and can be shown schematically as figure 1 (using a layout of six seats per row and one aisle).

残疾人）
- 乘客类别（头等舱，经济舱等）
- 乘客的个人登机时间（当乘客坐下时即可确定）

本文控制乘客在飞机上行为（或更确切地说是传送）的规则考虑了乘客的行走速度。本文假设两个挨在一起的乘客可以站在过道中一个座位排的宽度上。因此，创建时飞机过道（也被模拟为向量）时，使得过道经过的每一排座位对应过道向量的两个元素。根据规则，如果在他前方的元素未被占用，乘客必需在过道中前进。因此，这种空间模式可以用矩阵/矢量表示，并且可以用图1示意性地表示出（每排六个座位和一个过道的布局）。

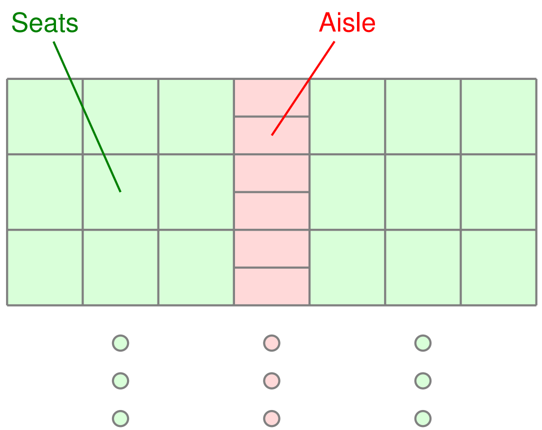

Figure 1: Structure of plane layout in terms of matrices | 基于矩阵的飞机布局结构

3 Assumptions made in the model and how they are implemented | 模型中的假设以及它们的实现方式

- Only one entrance to the aircraft was modelled. This method was chosen since most airports only have facilities for one boarding entrance to each plane.
- Not all passengers walk at the same speed. As stated, we created three categories of passengers which all move through the plane at different speeds. The notion of speed is difficult to implement in cellular automata, due to the finite time-step nature of the algorithm. Thus probabilities were used. Rules were constructed in such a way that a healthy adult definitely advances one matrix- (or rather aisle-) element per time step. Since children would move slightly slower, they only advance with a probability of 0.7. Lastly, disabled, frail or handicapped people would move the slowest, and were thus forced to advance with a probability of 0.3. In this way an idea of speed is introduced, where slow passengers hold up the faster ones in the aisle. It is also assumed that passengers do not pass each other in the aisle.
- The distribution of the three categories of passengers was decided as follows: 2% of the passengers would be disabled/frail/handicapped, 10% would be children and the remaining 88% are healthy adults. These assumptions were based on semi-educated guesses, since very little statistical data on this matter is available.
- When a passenger gets to the row of his/her allocated seat, he/she must stow his hand-luggage. Since this takes time during which he obstructs the smooth motion of other passengers through the aisle, a rule was implemented that these passengers block the aisle for 5 time steps.
- If a passenger reaches the row of his/her allocated seat, a similar time-penalty is introduced, depending on how many seated people he has to pass in this row until he reaches his seat. This is done to allow for passengers moving out of their seats and into the row to permit the given passenger to take his seat. During this time, obstruction would occur in the aisle, leading to a time-delay. This time delay was implemented using a quadratic method. A fixed time delay was multiplied by the number of seated passengers in the way squared. We considered this to be a realistic model, since several people moving into the aisle would cause a larger time delay for other passengers

- 只对从一个入口登机的情况进行了建模。选择这种方式是因为大多数机场只为每个飞机配备一个登机入口的设施。
- 并非所有乘客都以相同的速度行走。如前文所述，我们构建了三类乘客，这些乘客都以不同的速度通过飞机过道。由于元胞自动机算法具有限时间的步长，因此速度的概念难以在元胞自动机中实现。因此我们使用了概率来模拟不同行走速度。构建规则控制乘客前进，使得健康的成年人每个时间步骤都会前进一个矩阵（或者过道）元素。由于孩子的行走速度会稍微慢一点，因此他们只以 0.7 的概率前进。最后，残疾人、体弱者或残疾人的行走速度最慢，因此他们以 0.3 的概率前进。通过这种方式引入了速度的概念，使得行走速度慢的乘客在过道中阻碍行走速度快的乘客。此外，本文还假设乘客不会在过道中相互越过。
- 三类乘客的分布如下：2% 的乘客是残疾/体弱/残疾，10% 的乘客是儿童，其余 88% 的乘客是健康成人。这些假设是基于半知半解的猜测，这是因为关于这个问题的统计数据很少。
- 当乘客到达他的座位所在排时，乘客必须存放自己的手提行李后才能入座。由于存放行李需要时间，这将阻碍其他乘客在过道的继续前进，因此我们设置了一条规则：令放置行李的这些乘客阻断过道 5 个时间步。
- 如果乘客到达他的座位所在排时，则引入类似的时间延迟，这个时间延迟取决于他必须在该排座位中越过多少坐着的人直到到达他的座位。这样做是为了允许已经坐下乘客离开他们的座位进入通道，使新到达座位所在排的乘客能够通过并坐到他们自己的座位上。在此期间，过道会发生阻塞，导致时间延迟。这种时间延迟是使用二次函数模拟的：用一个固定的时间延迟乘以乘客数量的平方。我们认为这是一个较为实际的模型，因为几个人进入过道会对其他试图越过他们的

who are trying to pass them.

- Please note that the time-units quoted in the result section are arbitrary and represent individual steps of the cellular automaton. Nonetheless the time-delays are scaled in such a way that their magnitude, in the scope of motion of passengers in the aisle, is reasonable. The scale was calculated as follows
  - A healthy adult passenger advances one element in the aisle vector during each time step if he/she is not obstructed. This would be approximately 0.5 m.
  - The average walking speed in an aircraft of a healthy adult was taken to be 0.75 m/s.
  - Thus one algorithmic time-step would roughly represent 1.333 s.

  Based on these assumptions, the delays were calculated as described above.
- The general layout of most planes is such that there is more space in the first class and business class than in the economy class. Thus we implemented large time delays for luggage stowing in the economy class, smaller ones in the business class and the smallest delays in first class.
- We assumed that passengers only move in one direction in the aisle during boarding, since they all have allocated seat numbers and are able to read (hopefully!).

The model is later expanded to accommodate larger planes with two aisles, where similar assumptions were made.

乘客造成更大的时间延迟。

- 请注意，结果部分中引用的时间单位是任意的，表示元胞自动机时间步。尽管如此，在过道中乘客的移动范围内，时间延迟的缩放方式是合理的。比例计算如下
  - 如果健康的成年乘客没有受阻，则在每个时间步骤期间在过道向量中前进一个元素。这大约是 0.5 米。
  - 健康成年人在飞机中步行的平均速度为 0.75 米/秒。
  - 因此，元胞自动机算法的一个时间步长大致代表 1.333 秒。

  基于这些假设，按照上所述的方式计算时间延迟。
- 大多数飞机的总体布局是头等舱和商务舱的空间比经济舱更大。因此，我们设置了经济舱中行李存放的时间延迟大，商务舱中较小，以及头等舱中最小。
- 我们假设乘客在登机时只朝一个方向移动，因为他们都分配了座位号码并且能够识别（理想情况！）。

采用类似的假设，该模型后来被扩展到能够适用于具有两个通道的大飞机情况。

4 A step-by-step explanation of the algorithm | 该算法的逐步说明

First a seating-plan is loaded. This plan is in the form of a matrix, in which the elements represent the seats in the plane numbered sequentially. Our code was constructed such that a fixed, pre-determined seating plan could be loaded (for specified aeroplane layouts) or that a seating plan with a chosen number of rows and seats per row could be used.

The passenger vector was then initiated. A load factor was chosen, which determined which fraction of the available seats is occupied. This, of course, affects the length of the passenger vector. (Length of the passenger vector = load factor

首先输入一个座位表。该座位表采用矩阵的形式，其中元素表示飞机中顺序编号的座位。我们的代码构造成可以加载固定的、预先确定的座位表（用于指定的飞机布局），或者可以使用具有选定排数和每排座位数的座位表。

然后初始化乘客向量。选择了一个负载系数（译者：这里就是我们常说的上座率），它确定了哪一部分可用座位被占用。当然，这会影响乘客向量的长度。（乘客向量的长度 =

* total number of available seats). As stated, each element in this vector has a passenger number, and corresponding values for this passenger's seat, speed and class. This vector was then rearranged in different ways for the various boarding strategies. This was done by changing the sequence of the passengers before they enter the plane so that, for instance, passengers with window seats board first. The various boarding strategies and their efficiencies will be addressed later in this report.

负载系数 * 可用座位的总数）。如上所述，该向量中的每个元素包含一个乘客的编号，以及该乘客座位、速度和舱位等级的相应值。然后，针对各种登机策略，以不同方式重新排列该向量。这是通过在乘客进入飞机之前改变乘客的顺序来完成的，例如，具有靠窗座位的乘客首先登机。各种登机策略及其效率将在本本的后面讨论。

Next a vector representing the aisle was created. This vector has two elements per seat-row of the given plane, for reasons stated in the section 'The Algorithm'. Each of these vector elements can contain a single passenger who is then moving along the aisle (from the front of the aircraft towards the rear). As passengers moved into the aisle, their passenger numbers were stored in this vector.

接下来，创建表示过道的向量。由于在“算法”一节中所述的原因，该向量对于给定飞机的每个座位排有两个元素。向量中的每一个元素只可以包含一个乘客，该乘客然后沿着过道（从飞机的前部朝向后部）移动。当乘客进入过道时，他们的乘客号码存储在此向量中。

The propagation / motion of passengers through the aisle of the plane was implemented in finite time-steps. The aisle was checked element-by-element from the rear of the plane. When a passenger was encountered in an element, a check was carried out whether another passenger was present in the aisle element ahead of him/her. If that element was unoccupied, the passenger moved into this aisle-element with the probability (speed) associated with that individual. This check continued through the entire aisle until the entrance of the plane was reached. If the element of the aisle at the entrance to the plane was unoccupied, another passenger was extracted from the passenger vector and fed into the aisle vector. Then another time-step iteration was initiated. The process can be summarised as a sequential checking of the entire aisle (and propagation of passengers through it) during each time-step, and the feeding of new passengers from the passenger vector into the aisle vector.

乘客通过飞机过道的传送/移动是在有限的时间步骤中实现的。从飞机尾部（往飞机的入口方向）逐个检查过道向量中的元素。当在一个元素中遇到乘客时，检查在他前面的过道元素中是否存在另一个乘客。如果他前面的元素未被占用，则乘客以与该个体相关联的概率（速度）移动到该过道元素中。这个检查一直持续到整个过道，直到到达飞机的入口。如果飞机入口处的过道元素未被占用，则从乘客向量中提取一名新的乘客并将其送入过道向量。然后进入下一个时间步迭代。该过程可以概括为在每个时间步中对整个过道向量（以及乘客通过过道向量的传送）的元素顺次检查，以及将新乘客从乘客向量中送入过道向量中。

After any passenger advanced one element in the aisle, a check was carried out for whether he had reached the row of his allocated seat. If this was the case, the row containing his seat was checked for seated passengers obstructing his path, and the described time-delays were implemented. A delay for the loading of each passenger's hand-luggage was also initiated when he reached the row of his allocated seat. Qualitatively these time-delays were instituted in such a way that they resulted in this passenger spending a given number of time-steps as stationary in the aisle.

在某个乘客在过道中前进一个元素之后，检查他是否已经到达他座位所在排。如果是这种情况（已经到达），则检查其座位所在排是否有乘客阻碍其路径，并且实施所描述的时间延迟。当乘客到达他的座位所在排时，也开始一个延迟来表示乘客放置手提行李。定性地说，这些时间延迟是以这样一种方式建立的，即它们导致这名乘客在过道中停留一定数量的时间步长。

When time delays expire, the passenger is 'seated' and is removed from the aisle.

The entire algorithm was iterated until all passengers were in their allocated seats and the aisle was empty. The time taken for this entire process was recorded and stored. For a given initial setup of the passenger vector, the entire simulation was run over several iterations to obtain statistically relevant values for:

- Average time taken for the entire boarding process. This is an indication of how effective the boarding process is, since it is in the interest of the airlines to minimize the total boarding time.
- Standard deviation for this average total boarding time over all iterations. The absolute standard deviation is a quantitative measure of the consistency of the boarding procedure, i.e., how sensitive the strategy is to randomness. The relative standard deviation (absolute standard deviation divided by the average total boarding time) is a qualitative measure of the consistency of the boarding times and allows comparison between the various strategies and aircraft types.
- Average time (and standard deviation time) it takes each passenger from when he enters until he/she is seated. These values should be minimized in the interest of the passengers. The standard deviations show how uniform / consistent the boarding time per passenger is.

For larger planes and for custom layouts of the seating plan, an option for a second aisle vector was implemented. The algorithm was carried out as above, with the sequential checking procedure simply being carried out in both aisles during each time-step. Yet some modifications were required: Still only one line of passengers enters the plane. Thus this line has to split into the two aisles. This was done by checking whether the passenger at the entrance to the plane sits on the left half or the right half of the plane, and 'feeding' him/her into the relevant aisle vector. If the seating layout of the plane is such that there is an odd number of seats per row, passengers sitting on the middle seats entered that aisle which has an unoccupied first element. If the first elements of both aisles were open, the passenger entered either aisle with a 50% probability. The rest of the algorithm progressed as for the single aisle case.

当时间延迟到期时，乘客将被从过道中移除并“坐到自己的座位上”。

整个算法一直迭代，直到所有乘客都坐在他们座位上并且过道是空的。记录并存储整个过程所花费的时间。对于给定的初始乘客向量设置，整个模拟运行多次以获得相关的统计值：

- 整个登机过程所需的平均时间。这是一个表明登机过程如何效果的指标，因为航空公司为了利益最小化必需使总登机时间尽可能的短。
- 所有多次模拟的平均总登机时间的标准偏差。绝对标准差是对登机程序一致性的定量评估，即策略对随机性的敏感程度（灵稳性）。相对标准偏差（绝对标准偏差除以平均总登机时间）是对登机时间一致性的定性评估，并允许比较各种策略和飞机类型。
- 每位乘客从进入到就坐的平均时间（和标准偏差时间）。为了乘客的利益，应尽量减少这些时间。标准偏差显示了每位乘客登机时间的统一性和一致性。

对于较大的飞机和和自定义的座位表，可以定义第二个通道向量。该算法如上所述进行，每个时间步在两个通道中简单地执行顺序检查程序。然而，需要进行一些修改：仍然只有一列乘客排队进入飞机。因此，这个乘客队列必须分流进入两个通道。这是通过检查飞机入口处的乘客是否位于飞机的左半部分或右半部分，并且将他“放进”相应的过道向量中来完成的。如果飞机的座位布局使得每排有奇数个座位，则坐在中间座位上的乘客进入第一个元素未被占用的过道。如果两个过道的第一个元素都是开放的，则乘客以 50% 的概率进入其中任意一个过道。算法的其余部分与单通道情况一样推进。

5 Description, algorithmic implementation and results for various boarding strategies | 各种登机策略的描述，算法实施和结果

First the various boarding strategies will be described in detail. The results of each are discussed briefly. (Please note that complete and detailed results are tabulated in the appended Table 1 - Results for various aircraft and boarding methods). The load fractions used in the various simulations were based on statistics obtained from Transport Canada Airforecasting, Passenger Load Factors [1].

In-depth analysis of the results follows after these descriptions.

1. **Random boarding**
   Description and algorithmic implementation: Here the seat numbers in the passenger vector are arranged at random, so that the sequence of passengers entering the aisle at the front of the aircraft is random. Random boarding is common and will thus be used as a reference for comparison with other methods.
   Results: Random boarding yielded results which were, in general, only faster than those of methods which involved boarding the aeroplane from the front towards the back. This method never obtained the worst results in any of the measured categories.

2. **Dividing passengers into three groups and beginning boarding with the rear group**
   Description and algorithmic implementation: First the passenger vector is arranged randomly. By finding the highest available seat number, the seating plan is divided into three equal groups. The seat numbers in the passenger vector are arranged in these three groups. The group at the back of the plane boards first, the middle group second, and the front group boards last. Thus the three groups are internally still arranged at random.
   Results: For all aircraft sizes, this method yielded faster total average boarding times than random boarding. For larger aircraft, the average boarding time per passenger was larger than for random boarding. This may be explained due to each individual’s initial seating time. For random boarding,

首先，本文将详细描述各种登机策略。简要地讨论每种策略的结果。(请注意，完整而详细的结果列于附表 1 - 各种飞机和登机策略的结果)。各种模拟中使用的上座率是基于加拿大运输部预测的乘客负载系数的统计数据 [1]。

在这些描述之后对结果进行深入分析。

1. **随机登机**
   描述和算法实现：这种登机策略下，乘客向量中的座位号是随机排列的，因此进入飞机头部过道的乘客顺序是随机的。随机登机是一种常见的登机方式，因此将作为参考与其他登机策略进行比较。

   结果：随机登机产生的结果通常仅比将飞机从前向后登机的方法快。该方法从未在任何评价指标中获得最差结果。

2. **将乘客分成三组并从飞机尾部的组开始登机**

   描述和算法实现：首先，乘客向量是随机排列的。通过找到最大的可用座位编号，座位表被划分为三个相等的组。乘客向量中的座位号按这三组重新排列。飞机尾部的组先登机，然后是中间组，最后是飞机前部的组。因此，在这三组组内乘客仍然是随机排列的。

   结果：对于所有飞机的尺寸，这种策略给出的总平均登机时间比随机登机的更短。对于较大的飞机，每位乘客的平均登机时间大于随机登机的平均登机时间。这可以解释为每位乘客的初始就座时间。对于随机登机，

very soon after boarding commences, rapid front positioned seating occurs as people seat themselves randomly. In the case of the currently discussed boarding, people only start seating themselves after the rear passengers move to the back of the plane. Thus the aisle has to be traversed before any seating occurs. This effect is greatly pronounced if the plane is large and the aisle is longer. The relative deviation of passenger boarding times was lower than that of the random method, which implies that these individual times are more uniformly distributed.

登机开始后不久，随着人们随意就座，飞机前部的座位就会快速地被占。在当前讨论的登机策略下，只有当后排乘客移动到飞机尾部后，乘客们才开始就座。因此，在任何就座行为发生之前，乘客们必须穿过过道。如果飞机较大且过道较长，则此效果非常明显。本策略的乘客登机时间的相对偏差低于随机登机，这意味着个体的登机时间分布更均匀。

3. **Dividing passengers into three groups and beginning boarding with the front group**
Description and algorithmic implementation: As before, the available seats are divided into three equal groups. The passenger vector is arranged in such a way that boarding commences with the front group. The middle group boards second and the rear group last. As before, the three groups are internally still arranged at random.
Results: This method performs worst in almost all aspects. However, the relative standard deviations of the total boarding time are among the best. The poor performance of this particular method can be explained by the congestion of passengers near the entrance to the plane, since the front-seated passengers board first and obstruct flow through the aisle(s). This method was not tested on the largest aircraft, since it was evident that it was the most ineffective boarding strategy.

3. **将乘客分成三组，将乘客分成三组并从飞机头部的组开始登机**
描述和算法实现：和上一种策略一样，将可用座位分为三个相等的组。对乘客向量重新排列，使得从飞机头部的组开始登机。然后飞机中部的组登机，最后飞机尾部的组。和上一种策略一样，三组组内的乘客仍然是随机排列的。
结果：这种登机策略几乎在所有方面都表现最差。但是，总登机时间的相对标准偏差是最好的。这种特殊策略的不良性能可以通过飞机入口附近的乘客拥挤来解释，因为前部乘客首先登上并阻碍后续乘客穿过过道。这种方法没有在最大的飞机上进行测试，因为很明显它是最无效的登机策略。

4. **Beginning boarding by filling window seats first**
Description and algorithmic implementation: First the passenger vector is arranged randomly. By checking which seat numbers are in the first and last column of the seating matrix, passengers with window seats (arranged randomly) are extracted from the passenger vector, which is then rearranged in such a way that these passengers board first. The rest of the passengers are cued behind them at random.
Results: This method is faster than random seating, but is out-performed by seating in groups from the back of the craft to the front. The standard

4. **窗座乘客最先开始登机**
描述和算法实现：首先，乘客向量是随机排列的。通过检查哪些座位号位于座位表矩阵的第一列和最后一列中，从乘客向量中提取座位靠窗的乘客（随机排列），然后以这些乘客首先登上的方式重新对乘客向量进行排列。其余乘客在靠窗乘客的后面随机排列。

结果：这种方法比随机入座更快，但是不如从飞机后部往前部的分组登机好。所有飞机的总登机时间标

deviation in total boarding time is small for all aircraft and is the best in this category for the largest aircraft.

准偏差很小，对于最大型飞机而言，此种登机策略最佳。

5. **Beginning boarding by filling window seats first, and dividing passengers into three groups and beginning boarding with the rear group**
Description and algorithmic implementation: As above, the window seats are extracted and placed at the front of the passenger vector. Then the passenger vector is then divided into three groups (front, middle and back), and boarding commences with the group at the back of the craft.
Results: This method is a good improvement on merely commencing boarding with window seats. Thus far it yields the best results for average total boarding time, but the average time per passenger is not the best.

5. **座位靠窗的乘客先登机，然后将剩余乘客分成三组，并从飞机尾部的组开始登机**

描述和算法实现：如上所述，靠窗座位被提取并放置在乘客向量的前部。然后将乘客向量分成三组（前、中、后），并且从飞机尾部的组开始登机。
结果：这种方法是仅座位靠窗的乘客先登机策略的一个很好的改进。到目前为止，它给出了平均总登机时间的最佳结果，但每位乘客的平均登机时间并不是最好的。

6. **Beginning boarding by filling window seats first, and dividing passengers into three groups and beginning boarding with the front group**
Description and algorithmic implementation: As above, passengers with window seats are placed at the front of the passenger vector. Then the passenger vector is then divided into three groups (front, middle and back), and boarding commences with the group at the front of the craft.
Results: Especially with large aircraft, this method performed poorly. As with method 3, this can be attributed to the congestion at the entrance of the plane.

6. **座位靠窗的乘客先登机，然后将剩余乘客分成三组，并从飞机头部的组开始登机**

描述和算法实现：靠窗座位被提取并放置在乘客向量的前部。然后将乘客向量分成三组（前、中、后），并且从飞机头部的组开始登机。

结果：特别是对于大型飞机，这种登机策略表现不佳。与策略 3 一样，这可归因于飞机入口处的拥挤。

7. **Dividing passengers into three groups, beginning with the back group, and extracting window seats**
Description and algorithmic implementation: Again the passengers are grouped into front, middle and back, with the back group at the beginning of the passenger vector. The window seats are then extracted and placed at the front of the vector. Thus boarding begins with window seats (arranged back to front) and then with normal seats (grouped back to front).
Results: This method is the best of the methods mentioned thus far, with

7. **将乘客分成三组，然后从飞机尾部的组开始，并提取座位靠窗的乘客**
描述和算法实现：乘客再次分为前、中、后三组，其中后组排列在乘客向量的开头。然后提取窗座乘客并将其放置在向量的前面。因此，登机开始于靠窗的座位（从后向前），然后是普通的座位（从后向前分组）。

结果：该策略是目前为止提到的最好的登机策略，在

overall good performance in all aspects.

8. **Filling seats inwards towards the aisle(s)**
   Description and algorithmic implementation: For planes with a single aisle: Each passenger's seat is located in the seating plan matrix, and its distance (in terms of seats) from a window seat is calculated. The passenger vector is then rearranged in such a way that the passengers are arranged in terms of this distance from the window seats, beginning with the smallest distance (i.e. with the window seats themselves). Thus the plane fills up from the window seats towards the middle of the plane (which is the aisle).
   For planes with two aisles: Essentially the plane is divided into two halves, each aisle being the centre of one half. For simplicity, planes with even numbers of seats between the two aisles were considered, to simplify the location of the middle of the plane. Each half of the plane is then treated as in the previous boarding strategy (i.e. as if it were an individual plane with one aisle), and the passenger vector is arranged such that seating begins with passengers furthest from the aisles, and ends with passengers closest to the aisles.
   Results: This method is an improvement on the strategy of boarding window seats first (method 4). For all aircraft except the smallest (Fokker 50) the average total boarding time is shorter than that of method 4. However it is not among the best methods in any particular aspect, though both the average total boarding time is fairly stable (i.e. small relative standard deviation).

9. **The passengers are first sorted in groups from back to front, and these groups are further sorted towards the aisle(s)**
   Description and algorithmic implementation: As in strategy 8 the seats are arranged to fill towards the aisle(s). The seats are then further sorted into three groups, and boarding commences with the back group. The table in the left of Figure 2 shows the way in which the passenger vector is sorted before boarding for a simple aircraft layout with one aisle. The numbers in the figure show in which order seats from the various sections are sorted in the passenger vector.

所有方面都具有整体良好的性能。

8. **由窗向过道方向登机**
   描述和算法实现：对于具有单个过道的飞机：每个乘客座位都位于座位表矩阵中，并计算其与靠窗座位的距离（就座位而言）。然后重新排列乘客向量，使得乘客以离窗座的距离来排列，从最小距离开始（即从窗座本身开始）。因此，飞机登机按照从靠窗的座位朝向飞机的中间（过道）的顺序入座。

   对于有两个过道的飞机：通常飞机分为两半，每个通道都是一半的中心。为简单起见，考虑在两个通道之间具有偶数座位的飞机，以简化飞机中间的位置。然后按照之前的登机策略分别处理飞机的每一半（即，好像它是具有一个过道的单独飞机），并且乘客向量被排列成使得乘客从距离过道最远的乘客开始，并且以距离过道最近的乘客结束。

   结果：该策略是对窗座乘客先登机策略的改进（方法4）。除最小（Fokker 50）的飞机以外的其它所有飞机，平均总登机时间比方法 4 的短。然而，该策略在任何特定方面都不是最佳的，尽管平均和总的登机时间都相当稳定（即相对标准偏差小）。

9. **乘客首先从后到前分组，然后这些组进一步按照离过道由远及近排序**
   描述和算法实现：与策略 8 一样，乘客向量按照座位从窗向过道排列。然后将乘客向量中的座位号进一步分为三组，并从后组开始登机。对于只一个过道的简单飞机布局，图 2 左侧的表格显示了乘客向量在登机前进行分组排列的方式。图中的数字表示来自各个部分的座位在乘客向量中的排列顺序。

Results: This method is the one which performs best in most points (as is clear from inspection of Table 1). For small aircraft it is the fastest method. Throughout, the standard deviation of passenger boarding times is good, as is the absolute standard deviation of total boarding time.

结果：该方法是在大多数点上表现最佳的方法（从表 1 中可以清楚地看出）。对于小型飞机来说，这是最快的方法。在整个过程中，乘客登机时间的标准差和总登机时间的绝对标准差都比较小。

10. **The passengers are first sorted towards the aisle(s) and then further divided into groups from back to front**
Description and algorithmic implementation: Again the three groups are created, from the back of the craft to the front. Then the passengers are sorted within the groups such that the seats furthest from the aisles board first and those closest to the aisled board last. The table in the right of Figure 2 shows the way in which the passenger vector is sorted before boarding for a simple aircraft layout with one aisle. The numbers in the figure show in which order seats from the various sections are sorted in the passenger vector.
Results: For total boarding time of the largest aircraft, this method yielded the best result. For other aircraft it also performs well in this regard. However this strategy is not very consistent, since the standard deviations of the total boarding times were among the highest, especially for large aircraft. For all aircraft sizes this method yielded shorter average boarding time per passenger than method 9.

10. **乘客首先按照离过道由远及近排序，然后进一步从后向前分组**
描述和算法实现：同样的，从飞机的尾部往头部分成三组。然后乘客在组内排序，使得座位离过道最远的乘客最先登机，座位最靠近通道乘客最后登机。对于只有一个过道的简单飞机布局，图 2 右侧的表格显示了乘客向量在登机前进行排列的方式。图中的数字表示来自各个部分的座位在乘客向量中的排序顺序。

结果：对于最大飞机的总登机时间，这种策略给出了最好的结果。对于其他尺寸的飞机，它在总登机时间方面也表现良好。然而，这种策略并不十分一致，因为总登机时间的标准偏差是最高的，特别是对于大型飞机。对于所有飞机尺寸，当前策略给出的平均登机时间比策略 9 更短。

Method 9				
5	6	Aisle	6	5
3	4	Aisle	4	3
1	2	Aisle	2	1

Method 10				
3	6	Aisle	6	3
2	5	Aisle	5	2
1	4	Aisle	4	1

Figure 2: Illustration of seating strategies 9 and 10 (low numbers seat first) | 登机入座策略 9 和 10 的示意图（较小数先入座）

A short summary of these results (Please refer to Tables 2 and 3 in Appendix 3) | 这些结果的简短总结（请参阅附录 3 中的表 2 和 3）

In the Tables 2 and 3 the most effective boarding strategies for the four classes of aircraft are identified in order.

在表 2 和表 3 中，按顺序确定了四种飞机的最有效的登机策略。

For small aircraft (roughly 50 seats), methods 9, 5 and 7 yielded the best average total boarding times.

For slightly larger aircraft (roughly 150 seats), methods 10, 7 and 9 yielded the best average total boarding times.

For medium aircraft (roughly 300 seats), methods 7, 9 and 5 yielded the best average total boarding times.

For large aircraft (roughly 800 seats), methods 10, 9 and 7 yielded the best average total boarding times.

It is thus clear that the methods 5, 7, 9 and 10 are the most effective strategies for boarding procedures of aircraft. All these methods have in common that they begin boarding with passengers seated in the rear of the plane. Furthermore, they implement another sorting criterion (for instance boarding window seats first or filling the columns of the plane towards the aisles). It is also important to note that random boarding was amongst the three most ineffective methods for all plane classes.

对于小型飞机（大约 50 个座位），策略 9、5 和 7 给出了最佳的平均总登机时间。

对于稍大的飞机（大约 150 个座位），策略 10、7 和 9 给出了最佳的平均总登机时间。

对于中型飞机（大约 300 个座位），策略 7、9 和 5 给出了最佳的平均总登机时间。

对于大型飞机（大约 800 个座位），策略 10、9 和 7 给出了最佳的平均总登机时间。

显然，策略 5、7、9 和 10 是用于飞机登机程序的最有效策略。所有这些方法的共同之处在于，它们都是从坐在飞机尾部的乘客先登机。此外，它们还结合了另一种排序准则（例如窗座乘客先登机或由窗向过道登机）。需要注意的是：对于所有飞机类型，随机登机最无效的三种策略之一。

A discussion of Graphs 1 to 5 (Please refer to Graphs 1 to 5 in Appendix 4) | 图 1 至图 5 的讨论（请参阅附录 4 中的图 1 至图 5）

- Graph 1: Here boarding is done at random (method 1). The graph shows that passengers start taking their seats shortly after commencement of boarding and the rate of seating increases for a while. Rate of seating is then reasonably linear, and decreases again as the last passengers get to their seats.
- Graph 2: This graph shows boarding in three groups from the back (method 2). Clearly people only begin taking their seats some time after commencement of boarding, since the first passengers entering the plane (with seats at the back) have to walk the entire length of the plane before sitting down. When these passengers reach the back, a high rate of seating occurs (almost a small peak in the graph). It is clear that the gradient of this graph, even after this peak, is greater than that of Graph 1. This indicates a faster rate of seating of passengers during the main phase of boarding.
- Graph 3: Here boarding is from the windows (or from the centre of the plane

- 图 1：这里登机是按随机顺序完成的（策略 1）。图中显示乘客在登机开始后不久就开始入座，入座速率增加了一段时间。然后入座速率呈线性，并且随着最后一位乘客到达座位而再次减少。
- 图 2：该图显示了分三组并从后组开始登机（策略 2）。很明显，人们只有在登机开始后的某个时间才开始入座，因为第一批进入飞机的乘客（后排座位）在入座前必须沿着过道走过整个飞机的长度。当这些乘客到达飞机尾部时，会出很高的就座速率（图中几乎有一个小峰值）。很明显，即使在此峰值之后，该图的斜率也大于图 1 的斜率。这表明在登机的主要阶段乘客的就座速率更快。
- 图 3：这里登机是从窗户（对于两个过道的飞机，或从

in the case of two aisles) towards the aisles (method 8). Of course there is no initial lag phase, since there is no differentiation between passengers seated at the front and at the rear. The rate of seating seems to be increasing during the main phase of boarding.

- Graph 4: Here method 10 is shown. This is the graph where the rate of seating is changing most during the time of boarding. The procedures works much like a conveyor belt: the line is very ordered, so that the passengers can proceed smoothly to their seats. They are then seated in a short time-space while the next group approaches their seats in a similar manner. This explains the step-like shape of the graph.
- Graph 5: Here method 9 is shown. The graph is smoother than Graph 4, since the boarding occurs in V shapes from the back, and passengers are seated in less distinct groups.

It is useful to refer to

- the figures in the descriptions of methods 9 and 10 on page 7 and 8
- the figure in Appendix 4 which shows the seating times measured from commencement of boarding for various passenger sections after the passenger vectors were arranged according to methods 9 and 10.

飞机的中间）朝向过道（方法 8）。当然，这种登机策略没有初始滞后阶段，因为坐在前部和后部的乘客之间没有区别。在登机的主要阶段，座位速率似乎在增加（译者：斜率在增大）。

- 图 4：这里显示的是方法 10。这是在登机过程中入座速率变化最大的图。这个过程很像传送带：队列非常有序，因此乘客可以顺利地到达他们的座位。然后他们在很短的时间内就入座了，而下一组以类似的方式到达他们的座位。这解释了图形的阶梯状。
- 图 5：这里显示的是策略 9。该图比图 4 更平滑，因为登机是从飞机尾部以 V 字形进行，乘客座位的分组不太明显。

参考是有用的

- 描述策略 9 和 10 的图见第 7 页和第 8 页
- 附录 4 中的图显示了根据策略 9 和 10 排列乘客向量后各组乘客从开始登机到就座的时间。

6 Sensitivity analysis of the algorithm | 算法的灵敏度分析

Many parameters were chosen in the simulation. To see how sensitive the algorithm is to variations in these parameters, some additional simulations were carried out.

模拟中包含了许多参数。为了了解算法对这些参数的变化有多敏感，本文进行了一些额外的模拟。

1. **Changing the percentage of disabled / frail / handicapped passengers**
   Several simulations were carried out with various percentages of disabled / handicapped passengers present in the passenger vector. Some methods were affected more strongly by these changes than others. As an example, we shall provide results from a simulation with a Boeing 777-200 (medium sized aircraft), with the same load factor as used previously (0.78). In the Results section 2% of the total passengers were assumed to be handicapped, and this

1. **改变残障乘客的百分比**

   本文对乘客向量中存在的各种百分比的残障乘客进行了多次模拟。这些变化对其中某些策略的影响比对另一些策略的影响大。例如，我们将提供波音 777-200（中型飞机）模拟的结果，其乘客负载系数与之前使用的相同（0.78）。在先前的结果部分，总乘客中有 2% 被设置为残障人士，而这一比例现在变为了 6%。

was changed to 6%. Table 1 summarises the results.
Clearly method 10 is most susceptible to the change. Nonetheless the percentage change in total boarding times does not vary too greatly for the various methods. We believe that the assumptions which we made regarding statistics are fairly accurate, and a deviation from these assumptions should not affect the core results obtained too drastically.

表 1 总结了结果。
显然，策略 10 最容易受到变化的影响。尽管如此，对于各种策略，总登机时间的百分比变化并没有太大的变化。我们认为，我们对统计数据的假设是相当准确的，偏离这些假设不应影响获得的主要结果。

2. **Investigating the effect of various load factors on the total boarding time**
From the results obtained, we chose one method (method 9) and ran the simulation over a range of load factors. The result is graphically illustrated in figure 3.
A linear relation between load factor and average total boarding time is evident. The reason for the constant term in the best-fit function (see graph above), is that even with one passenger there is a delay between commencement and completion of boarding. It is evidently fairly irrelevant what load factor was used during simulations as long as the same load factor was used throughout.

2. **研究各种乘客负载系数对总登机时间的影响**

从获得的结果中，我们选择了一种策略（策略 9）并对一系列负载系数的情况进行了模拟。结果见图 3。

负载系数和平均总登机时间之间的线性关系是显而易见的。最佳拟合函数中出现常数项（见图 3）的原因是：即使只有一名乘客，登机的开始和完成之间也会有延迟。只要在整个过程中使用相同的乘客负载系数，常数项与在模拟过程中所使用的乘客负载系数显然是无关的。

Table 1: Effect of increasing number of disabled passengers to 6% | 越来越多的残障乘客导致的影响为 6%

Method | 方法	Percentage increase in average total boarding time | 平均总登机时间增加的百分比
1	16%
9	13%
10	19%

7 Advantages of our model | 我们的模型的优点

What follows is a short discussion regarding certain aspects of the model which we considered to be enlightening and useful.

The first of these advantages is that the model may be customised to accommodate any seat plan specification (an aircraft with either 1 or 2 aisles), and may

以下是关于该模型的一些我们认为具有启发性和实用性方面的简短讨论。

这些优点中的第一个是本文的模型可以修改以适应任何指定的座位表（具有 1 或 2 个通道的飞机），并且可以执行

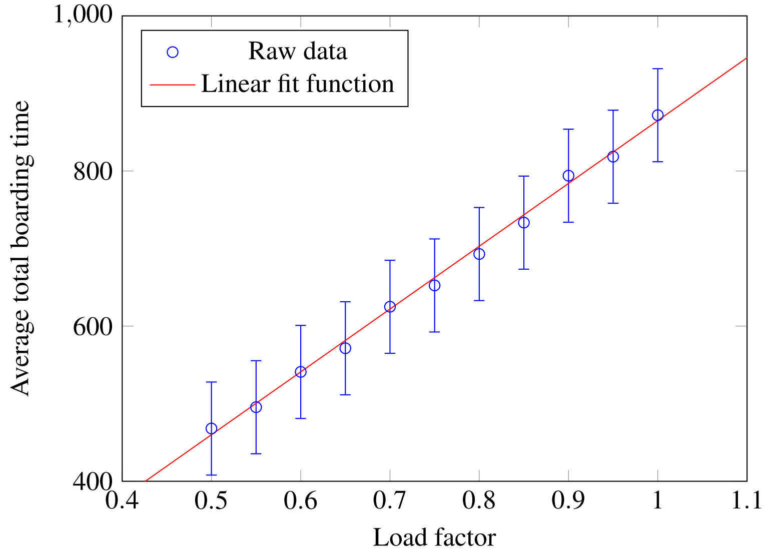

Figure 3: Average total boarding time vs. load factor (Boeing 777-200). | 平均总登机时间与乘客负载系数的关系（波音 777-200）。

be implemented to yield the required results as discussed in the Results section. Of course the number of passengers must be realistic due to computational limitations. Two decks on a plane could simply be modelled as two separate aircraft with their individual seating configurations.

以获得结果部分中讨论的所需结果。当然，由于计算限制，乘客的数量必须是实际的。双层飞机上可以简单地建模为具有各自座位配置的两个独立飞机。

As stated, averages and standard deviations for both the total boarding times and the individual boarding times are produced. Our measurements are sensible in that they provide information about 200 iterations of each boarding procedure. Thus the accuracy of the specific boarding measurements is reliable.

如上所述，产生了总登机时间和个人登机时间的平均值和标准差。我们的评价指标是合理的，因为它们给出了每种登机策略模拟的 200 次平均结果。因此，特定的登机评价指标的准确性是可靠的。

We have strived to keep all parameters constant during the simulation of each boarding strategy. This ensures that if a parameter has been allocated an unrealistic value, that the fault has a reduced effect on the outcome of the experiment and, more specifically, the comparison of the various boarding strategies.

我们尽可能的在每个登机策略的模拟过程中保持所有参数不变。这保证了如果已经为参数分配了不切实际的值，则该错误对数值实验结果的影响减小，更具体地说，是对各种登机策略的比较。

Many different boarding strategies were implemented. Some were combined with others to yield a more substantial result. In essence, any of the boarding

本文模拟了许多不同的登机策略。有些策略与其他策略给合以产生更优秀的结果。实质上，任何登机策略可以在模

strategies may be combined in the model to produce many more procedures. We did, however, select those strategies which we assumed to be realistic and which yielded a spread of data and results that are informative.

型中组合以产生更多程序。但是，我们选择了那些我们认为是实际的策略，这些策略产生了大量有用的数据和结果。

8 Possible improvements and comments on the realism of the model | 对模型的真实性进行可能的改进和评论

Several assumptions were made during the implementation of our algorithm. Some of them may affect the realism of our model. After completion of the report, the following points seemed important:

- Deboarding strategies were not addressed in this report due to a shortage of time. We are convinced, though, that it is significantly more challenging to set up effective boarding strategies, since this involves arranging passengers before they board the plane. This process involves making a fairly chaotic procedure less chaotic. In a sense, deboarding of an aircraft is inherently a more structured process. We also believe that a simple reversal of the more effective boarding procedures should save time during deboarding.
- The categories of the speed of passengers were strongly discrete. Distinction was only made between frail/handicapped passengers, children and healthy adults. This could have been done more realistically by implementing a distribution of possible walking speeds (for instance a model based on the normal distribution).
- Throughout the model the assumption was made that passengers only move in one direction in the aisle. This does not accommodate for the possibility of people moving opposite to the stream of passengers in the aisle.
- In our model, passengers could not pass each other in the aisle. This is not realistic, though in most cases passengers would probably wait for a person ahead of them to load their luggage before they pass him/her. This could have slowed the total boarding time, and would have affected the outcome of some of the boarding strategies. (some more so than others, for instance, boarding from the front would have yielded a significantly shorter boarding time). Nonetheless we believe that our model is inherently systematic and

在本文算法实现过程中，我们做了几个假设。其中一些假设可能会影响我们模型的真实性。报告完成后，以下几点似乎很重要：

- 由于时间不足，本报告未涉及下机策略。不过，我们确信，建立有效的登机策略更具挑战性，因为这涉及在登机前安排乘客。这个过程涉及使一个相当混乱的程序不那么混乱。从某种意义上说，乘客下飞机本质上是一个更有条理的过程。我们还认为，较为有效的登机程序的简单逆转应该可以节省下机时间。
- 乘客的速度类别是非常离散的。区分仅限于残障乘客、儿童和健康成年人之间。通过引入步行速度的分布（例如基于正态分布的模型），可以更真实地完成这一点。
- 在整个模型中，假设乘客仅在过道中向一个方向移动。这不适应人们在过道中与乘客流相反的可能性。
- 在我们的模型中，乘客无法在过道中相互越过。这是不现实的，尽管在大多数情况下，乘客可能会等待在他们前面的人放置完行李，再继续前进。这个假设可能会减慢总的登机过程，使总登机时间更长，并会影响一些登机策略的结果。（在某此策略中更为明显，例如，从飞机头部先登机会产生明显更短的总登机时间）。尽管如此，我们相信我们的模型具有内在的系统性，并

that the obtained results are meaningful and believable.

- It would have been sensible to allow for boarding from two doors in the plane. A consideration which led to our decision against this option was that one door at the front of the plane and one at the rear could be likened to boarding two separate planes, each from one entrance.
- In the division of passengers into groups, one could have investigated how division into more groups would have affected the simulations. Nonetheless we do believe that it is not reasonable for airport staff to have to divide passengers into so many groups, as this process itself would be time-consuming.
- Special seat allocations and boarding strategies for disabled people could have been considered, but this would not have affected the final outcome of the simulations greatly due to the small percentage of disabled passengers. Perhaps one strategy should have involved seating all disabled passengers in the front of the plane so that they do not obstruct motion through the aisles and that they do not have to walk as far in the plane.
- Many of our boarding strategies do not allow for passengers to board in groups (for instance mothers with their children), and this could cause inconveniences in its implementation in the real world.
- The assumption that two people fit into the space in the aisle next to one seat does not account for various sizes of passengers.
- The various delays in the boarding algorithm were based on guesses which we made by comparing the average walking speed of a healthy person to the average time we assumed would be needed to stow hand luggage. These delays were then implemented in the finite time-step nature of the algorithm, and could have been researched more accurately.

且所获得的结果是有意义且可信的。

- 允许从飞机上的两个入口登机是合理的。导致我们决定反对这一选择的一个考虑因素是：飞机前部和后部各有一个通道的情况可以等价为两个独立飞机的登机，每个飞机从一个入口进入。
- 在将乘客分成小组时，人们可以研究划分成更多的小组会如何影响模拟结果。尽管如此，我们确实认为机场工作人员必须将乘客划分为这么组是不合理的，因为这个过程本身会非常耗时。
- 可以考虑为残障乘客提供特殊的座位分配和登机策略，但由于残障乘客比例很小，这将不会对模拟的最终结果产生很大影响。也许一种策略是让所有残障乘客都坐在飞机前面，这样他们就不会阻碍其它乘客通过过道，也不必在飞机上移动太多距离。
- 我们的许多登机策略都不允许乘客结伴而行（例如带孩子的母亲），这可能会给策略的实际执行带来不便。
- 一个座位旁边的过道空间中可站下两个人的假设并不适用于各种尺寸的乘客。
- 登机算法的各种延迟是基于我们通过比较健康人的平均步行速度与我们假设存放手提行李所需的平均时间而做出的猜测。然后，这些延迟在算法的有限时间步长中实现，并且可以更准确地进行研究。

9 Conclusion and closing remarks | 结论和结束语

The task assigned to us was to devise and test various strategies for boarding procedures for various classes of aircraft. Using the approach of an algorithm based on a finite time-step cellular automaton, we obtained some clear results.

From our simulations it is evident that certain boarding procedures result in significant savings of time during boarding processes. As stated, the most effective

分配给我们的任务是针对不同类型飞机设计和测试各种登机策略。我们使用基于有限时间步的长元胞自动机算法进行模拟，并获得了一些明确的结果。

从我们的模拟结果可以看出，某些登机程序可以显著节省登机过程的时间。如上所述，这些策略中最有效的都有一

of these strategies have one thing in common: they all apply two filters to the passengers before the plane is boarded. One of these filters involves sorting passengers in such a way that those furthest from the entrance board first, and the second of these filters sorts passengers sensibly according to the columns of their seats. Nonetheless, as stated in the executive summary, methods that disrupt boarding of groups of adjacently seated passengers may be logistically difficult to implement or even cause irritation amongst passengers (e.g. method 10).

Time differences in total average boarding time between the most ineffective and most effective strategies were up to almost 100% for small planes and up to roughly 50% for larger aircraft. In practical terms, we estimate that up to three minutes for small planes and up to five or six minutes for larger planes can be saved in boarding time if a structured strategy is used instead of random boarding.

It is important to ask whether the implementation of these structured boarding strategies in the real world would not result in an administrative waste of time which outweighs the potential time savings. Some ways to implement the algorithms practically were suggested in our executive summary, and we believe that with relevant arrangements a significant time saving can be achieved realistically.

个共同点：它们都在飞机登机前对乘客施加两个过滤器。其中一个过滤器涉及对乘客进行分组让离入口最远的那些乘客首先登机，第二个过滤器根据乘客座位所在列的列聪明地对乘客进行排序。尽管如此，如执行摘要中所述，拆散结伴邻座乘客的登机策略在逻辑上可能难以实施，甚至可能会激怒乘客（例如，策略 10）。

对于小型飞机，最无效和最有效的策略之间的总平均登机时间的差异几乎达到 100%，而对于大型飞机而言高达约 50%。实际上，如果使用结构化策略而不是随机登机，我们的模型估计小型飞机节约的登机时间可达 3 分钟，而大型飞机最多可以节省 5 到 6 分钟。

值得深究的是，在现实中执行这些结构化的登机策略是否会因为管理而导致浪费时间，并且这种浪费超过了潜在登机节省的时间。我们的执行摘要中提出了实际实施算法的一些方法，我们相信通过适当的安排，可以显着地节省时间。

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Appendices

A Seating plans | 座位计划

1	2	-1	-1
3	4	5	6
7	8	9	10
11	12	13	14
15	16	17	18
19	20	21	22
23	24	25	26
27	28	29	30
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35	36	37	38
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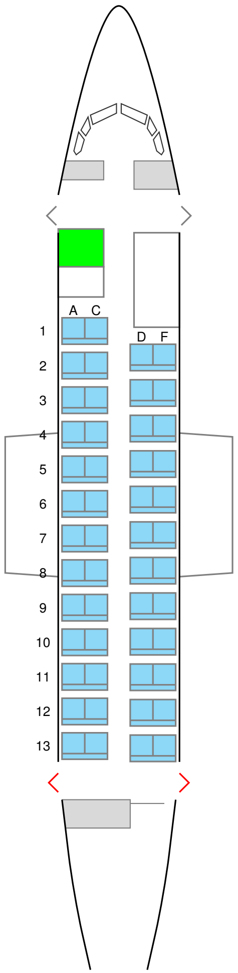
43	44	45	46
47	48	49	50
51	52	53	54



Fokker 50

-1	-1	-1	1	2	3
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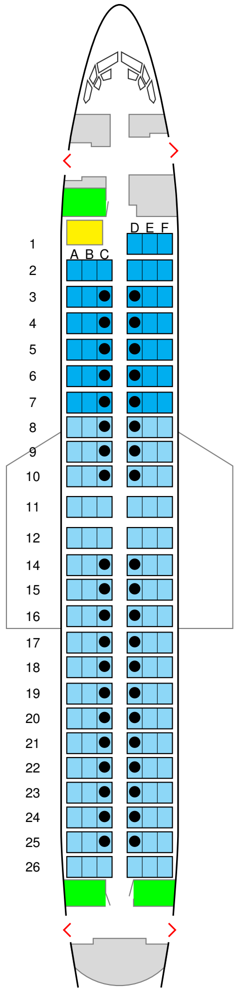

Boeing 737 400

-1	1	2	3	4	5	6	7	-1
-1	8	9	10	11	12	13	14	-1
-1	15	16	17	18	19	20	21	-1
-1	22	23	24	25	26	27	28	-1
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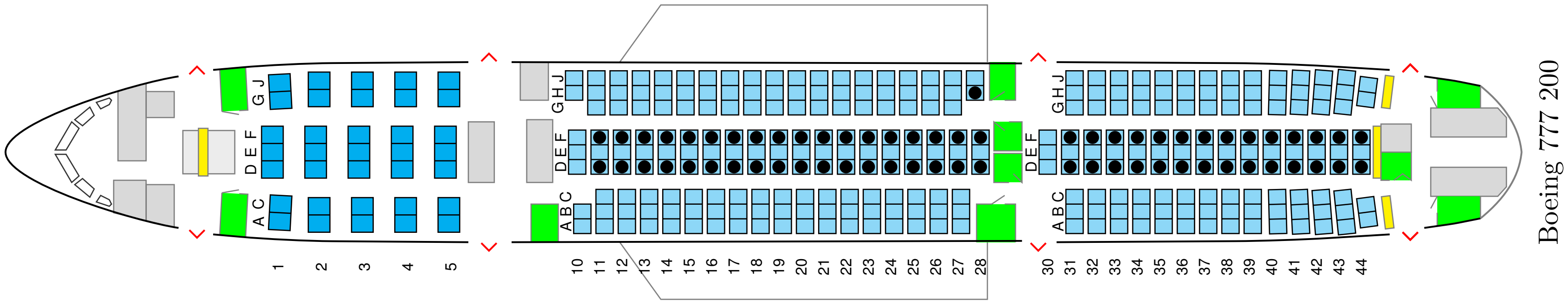
325	326	327	328	329	330	331	332	333
-1	334	335	336	337	338	339	340	-1



B Results for various aircraft and boarding methods | 各种飞机和登机方法的结果

Table 2: Results for various aircraft and boarding methods

	Method:	1	2	3	4	5	6	7	8	9	10
Fokker 50 (54 seats)	Ave total boarding time	207.4	166.5	290	196.7	151.2	269.7	155.6	197.2	149.1	157.9
	Abs. std dev total boarding time	28.7	33.5	32.4	25.5	26.1	31.8	23.4	28.3	24.2	24.4
	Rel. std dev total boarding time	0.138	0.201	0.112	0.13	0.173	0.118	0.15	0.144	0.163	0.154
	Ave individual boarding time	110.1	102.7	152.5	106.7	94.5	143.8	89.8	106.7	92.3	92.1
	Abs. std individual boarding time	51.6	32.6	83.6	48.2	29.4	78.2	37.9	48.5	29	38.3
	Rel. std individual boarding time	0.469	0.317	0.548	0.452	0.311	0.544	0.421	0.454	0.314	0.416
Boeing 737-400 (153 seats)	Ave total boarding time	485.5	431.8	671.8	454	404	616.6	377	442.5	392.9	372.1
	Abs. std dev total boarding time	51.9	63.1	59.2	46.6	54.2	50.1	53.1	39.9	50.5	41.6
	Rel. std dev total boarding time	0.107	0.146	0.088	0.103	0.134	0.081	0.141	0.09	0.129	0.112
	Ave individual boarding time	244.2	251.4	336	233.6	236.6	313.4	219.3	232.8	233.3	207.8
	Abs. std individual boarding time	119.3	90.6	193.5	111.7	82.9	177.5	97.2	109.2	81	94.9
	Rel. std individual boarding time	0.489	0.36	0.576	0.478	0.351	0.566	0.443	0.469	0.347	0.456
Boeing 777-200 (340 seats)	Ave total boarding time	828.4	741	1058.2	801.7	697.4	1000.6	684	767.4	691.1	699.1
	Abs. std dev total boarding time	60.5	70.5	64.1	62.5	63.8	61	59.5	66.1	59.3	74.1
	Rel. std dev total boarding time	0.073	0.095	0.061	0.078	0.091	0.061	0.087	0.086	0.086	0.106
	Ave individual boarding time	412.2	430.6	509.7	397.7	413.6	479.3	404.1	401.6	421.2	392.8
	Abs. std individual boarding time	191.8	144.3	292.4	184.1	135.6	275.5	150	174.4	135.4	158.6
	Rel. std individual boarding time	0.465	0.335	0.574	0.463	0.328	0.575	0.371	0.434	0.321	0.404
Custom Large Plane (792 seats)	Ave total boarding time	1956	1837.6		1902.3	1803.8	2389.8	1732	1752.3	1730.9	1661.3
	Abs. std dev total boarding time	113.7	114		105	113	107.5	115.4	115	105.5	121.5
	Rel. std dev total boarding time	0.058	0.062		0.055	0.063	0.045	0.067	0.066	0.061	0.073
	Ave individual boarding time	948.5	964.4		902.2	945.1	1124	896.5	937.2	974.5	929.6
	Abs. std individual boarding time	483	403.1		477.4	394.6	649.8	417.3	425.7	399.5	406.3
	Rel. std individual boarding time	0.509	0.418		0.529	0.418	0.578	0.465	0.454	0.410	0.437

worst performance　best performance

C Time saved using different boarding methods | 使用不同的登机方法节省了时间

Tables 2 and 3 contain the methods in order of efficiency, with the fastest average total boarding time listed first in each case. Time differences are listed with respect to the fastest time. This is done to identify the most suitable and effective methods for each type / class of aircraft.

D How the fraction of seated passengers varies with time for various methods | 乘客的比例如何随着时间的变化而变化

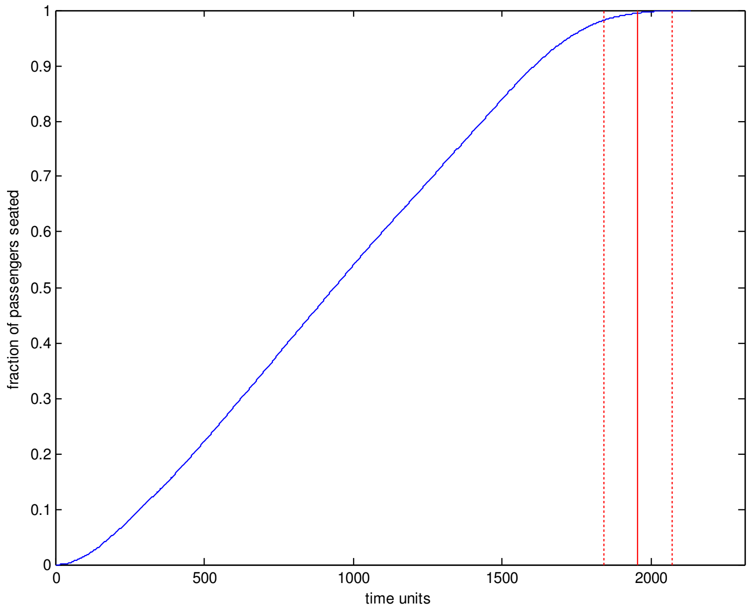


Figure 4: fraction of passengers seated vs time, method 1. Large plane ($\sim$ 800 pass.), load factor = 0.78, random boarding

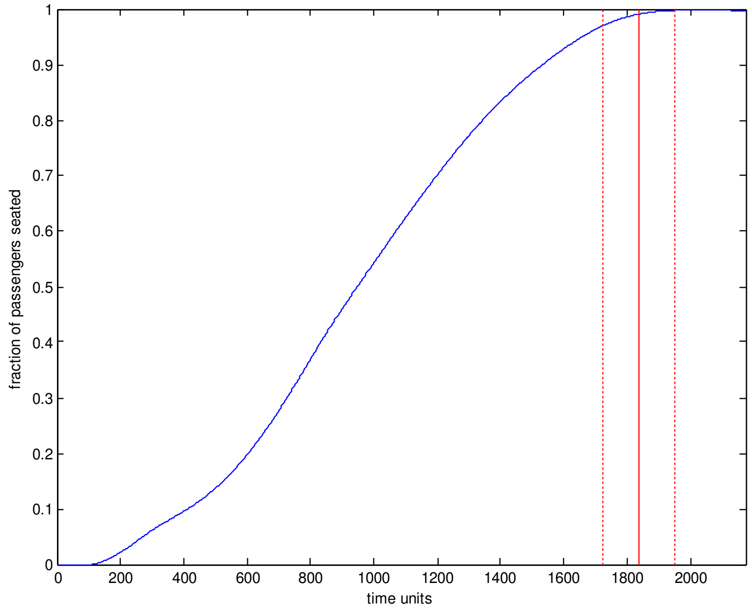


Figure 5: fraction of passengers seated vs time, method 2. Large plane ($\sim$ 800 pass.), load factor = 0.78, from back - 3 groups

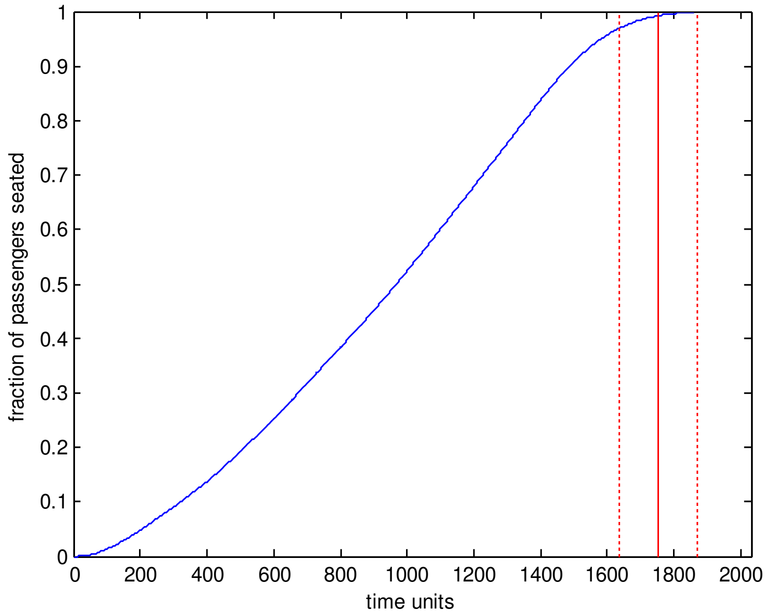


Figure 6: fraction of passengers seated vs time, method 8. Large plane (∼ 800 pass.), load factor = 0.78, from windows inwards

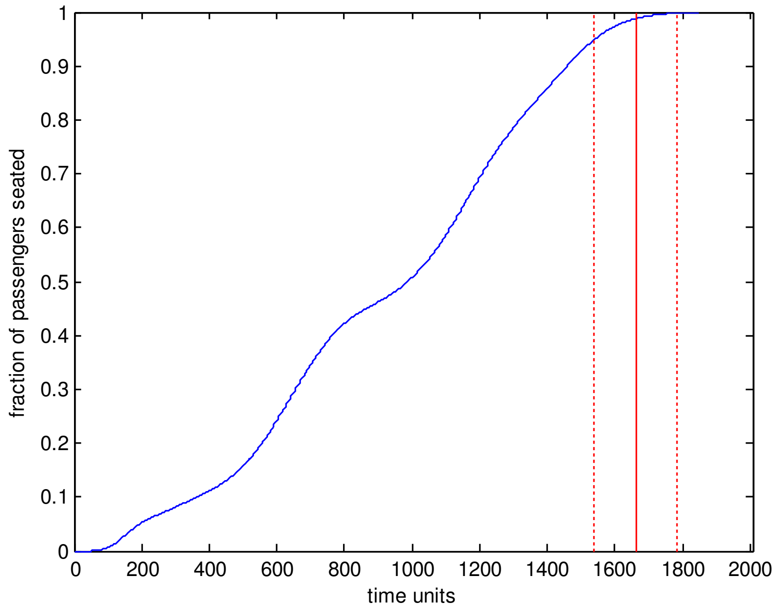


Figure 7: fraction of passengers seated vs time, method 10. Large plane (∼ 800 pass.), load factor = 0.78, from back - 3 groups, from windows inwards

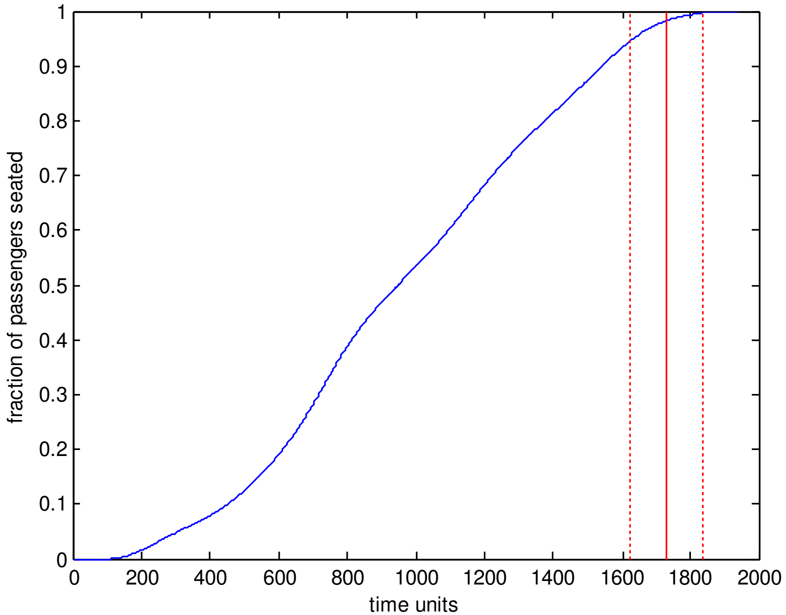


Figure 8: fraction of passengers seated vs time, method 9. Large plane ($\sim$ 800 pass.), load factor = 0.78, from windows inwards, from back - 3 groups