# APRON LAYOUT DESIGN AND FLIGHT-TO-GATE ASSIGNMENT AT LANSERIA INTERNATIONAL AIRPORT

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## ABSTRACT

Air traffic is continuously increasing and more efficient air transport systems are required to handle the air travel demand. The study investigates the expansion of Lanseria International Airport in Gauteng, South Africa. Expansion of Lanseria requires a study of the airport apron layout to ensure efficient passenger-aircraft flow as well as the efficient flow of aircraft to and from the airport. The candidate layout designs are based on the layout concept of the Hartsfield-Jackson Atlanta International Airport in Atlanta, USA. In the study, different airport apron layouts were compared, including the existing layout of Atlanta Airport, via a simulation model of each. Designs based mainly on passenger transfer distance between the terminal building and aircraft were evaluated. The cross-entropy method was used to develop a generic flight-to-gate assignment program that minimises passenger transfer distances.

## OPSOMMING

Lugverkeer groei toenemend en meer doeltreffende lugvervoerstelsels word benodig om in die lugvervoerbehoefte te voorsien. In hierdie studie word die uitbreiding van die Lanseria Internasionale Lughawe in Gauteng, Suid-Afrika ondersoek. Die uitbreiding van Lanseria vereis 'n studie van die lughawe se laaibladuitleg om doeltreffende vloei van passassiers na en van vliegtuie te verseker, asook die vloei van vliegtuie na en van die lughawe. Die moontlike uitleg-ontwerpe is gebaseer op die uitlegkonsep van die Hartsfield-Jackson Atlanta Internasionale Lughawe in Atlanta, VSA. Verskillende uitleg-ontwerpe, insluitend die bestaande uitleg van Atlanta, is in die studie met simulasie vergelyk. Die verplasingsafstand van passassiers tussen die eindpuntgebou en die vliegtuie is as hoofoorweging vir vergelyking gebruik. Die kruis-entropiemetode is gebruik om 'n generiese vlug-na-hek-toedeling te doen wat passassiers se verplasingsafstand minimeer.

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## 1. INTRODUCTION

South Africa is a developing country and a major economic role-player on the African continent. After the political change of 1994, international sanctions were lifted and world isolation ceased. The country has successfully presented at least three major international sporting events, and has become a popular tourist destination. The Gauteng province is the hub of the South African economy with its mining, manufacturing, services, and supporting industries.

O.R. Tambo International Airport, situated near the city of Johannesburg in Gauteng, processes more than 19 million passengers per annum [1]. It is predicted that this airport will be unable to handle traffic growth, and expansion into its immediate surroundings is not possible due to established developments. Forty kilometres north of Johannesburg CBD lies Lanseria International Airport (LIA), which is currently under-utilised and small compared with other South African airports. There is potential to redevelop this airport to accommodate traffic growth, as a preliminary feasibility study has proved. Virtual Consulting Engineers (VCE) started a layout design of the proposed new airport, and the authors assisted with the layout design of the airport apron. According to VCE, the LIA master plan has to satisfy three main objectives [2]:

1. High passenger processing levels of service — for example, by providing short walking distances.
2. Phasing of the development without fruitless expenditure.
3. Low capital expenditure in the short- and medium-term to reduce financial strain on the developer and enhance feasibility.

The Lanseria International Airport development is a long-term project that will only enter construction in five to 10 years' time. This will depend on a number of factors, including the economic growth of South Africa as a whole. A study of potential airport layouts was required to support the first objective above; and this article reports on the four layout designs that were considered, as well as the application of an optimisation metaheuristic, the cross-entropy method (CEM) described by De Boer et al. [3] and Rubinstein & Kroese [4]. The objective was to consider a candidate apron layout, then assign arriving aircraft to parking positions ('gates' in airport parlance) so that passenger transfer distance between aircraft and the terminal building is minimised.

We mainly applied computer simulation to assess the different candidate layout designs, and also combined the CEM with the simulation for near-optimisation. The simulation models were implemented in Simio (www.simio.com), an object-oriented simulation modelling package.

Zografos & Madas [5] state that airport design, planning, and operations are invariably associated with complex decision-making problems. These decisions are complex because they involve strategic planning, operations management and many other airport processes, a wide variety of entities that must be managed (such as passengers, cargo, aircraft, and luggage), and elements such as the runways, taxi-ways, terminals and aprons that must be operated. In many cases the numerous stakeholders involved in an airport system all have their own, often conflicting, objectives. Decision makers therefore need to find a way of evaluating all the indicators of the airport's effectiveness while considering their tradeoffs. Computer simulation is a useful technique to use to consider the needs of all stakeholders and address their conflicting objectives, because future concepts can be tested, timetable feasibility evaluated, different runway configurations compared, and bottlenecks identified at a fraction of the cost of real-world testing [6].

## 2. AIRPORT OPERATION

The layout of the airport affects the operating authority. Terminal systems can be either centralised or decentralised. Long ago, when the air transport industry was still small, the centralised concept was used in most airports. In this concept, all passenger and other processes are carried out at the main terminal building. This building is then connected to the gates by piers or transporters. Brussels airport still uses this concept. Airports such as London Heathrow and O.R. Tambo in Gauteng started off using the centralised concept, but terminals were added as traffic increased, and these airports started to operate in a decentralised manner. Other airports were decentralised from the outset, resulting in a number of terminals, each with a complete set of facilities. These include Paris Charles de Gaulle and John F. Kennedy International Airport in New York. Atlanta Airport uses decentralisation with extensive remote pier developments, as will be explained later [7]. Large centralised airports generally have long passenger transfer distances.

The three main components of an airport are the terminal(s), the apron, and the runways. The layout design of the apron is the main focus of this study. The terminals at an airport are used to process passengers, crew, and cargo, and to facilitate their movement on and off the aircraft. They serve as transfer areas, and are therefore not starting and end points for passengers and cargo [7].

Components of the apron include the aircraft stands (gates), the taxiways, the service roads, and the aircraft stand taxi lanes [8]. Passenger movement and passenger transfer distances are greatly influenced by the location and orientation of aircraft stands. In an airport flight-to-gate assignment operation, airport operators must assign aircraft to gates in a way that meets the operational requirements and that ensures the minimum delay in passenger transfer. The latter can be achieved by minimising the transfer distance from check-in to the departure gates, from the gates to the luggage claim area, and between gates for connecting flights. Using the flight schedules and booked passenger loads, airport management can develop a feasible gate assignment policy for each day [7].

The topic of gate assignment has received much attention from researchers, some of which are mentioned here. Gosling [9] developed an expert system considering constraints like facilities and the availability of personnel; Zheng et al. [10] used the tabu search and simulation to minimise variance of slack time; and Tang [11] developed a gate assignment model for the Taiwan Taoyuan Airport and considered the effect of flight delays. Gate assignment is a combinatorial problem, and quickly becomes large and complex.

## 3. THE COMPARISON STUDY

We used the concept of the Hartsfield-Jackson Atlanta International Airport in the USA to design four different airport apron layouts for Lanseria International Airport in Gauteng. Atlanta Airport consists of a terminal building and five concourses. In the first design (see Figure 1) we used the layout of Atlanta Airport. The only deviations are the number of gates and the dimensions of the apron. In the other three designs (see Figures 2, 3 and 4), we also used the concept of Atlanta Airport, but changed the orientation of the terminal building in relation to the concourses. At Atlanta Airport, an underground transportation mall connects the terminal and all the concourses. Automatic people movers (small trains) transport the passengers from the terminal to the concourses and back, and from one concourse to another. However, at the new Lanseria International Airport, passengers will not be transported by automatic people movers but by automated pedestrian walkways (similar to conveyor belts), or they will walk along the corridors. This results in the problem of long passenger transfer distances at the airport. The study is thus concerned with reducing the total passenger transfer distance at the airport.

### 3.1 The different airport apron designs

Each airport design has a main terminal building where check-in, security checks, and passport control are performed. The boarding gates (i.e. aircraft parking areas) are on opposite sides of five concourses. The concourses are narrow buildings, and one or more underground buildings/tunnels connect them to the main terminal building. These connecting tunnels between the concourses and the terminal building have been placed below the surface of the apron to avoid conflict between passengers and aircraft. Passengers thus move via a tunnel from the main terminal building to the concourse where their aircraft is parked. Once the passengers arrive at the correct concourse, they move to the aircraft gate where they board.

The gate areas at which the aircraft park are different sizes. The concourses are numbered A to E, with A at one end of the airport and E at the other end. In each design, the gates at concourses A and E are the largest, and aircraft with a wingspan of up to 80 m can park there. Nine large aircraft can park on one side of a concourse. The gates at concourses A and E (facing towards the other concourses) and the gates at concourses B and D (facing away from concourse C) are medium-sized gates. These gates are for aircraft with a wingspan of up to 65 m. The gates at concourses B and D facing towards concourse C and all the gates at concourse C are small gates. Aircraft with a wingspan of up to 40 m can park there, and 18 aircraft fit on one side of a concourse. All the concourses are of the same length. In all the apron designs, each concourse is 55 m wide. The gates on either side of each concourse are spaced evenly, and there are 144 gates in total.

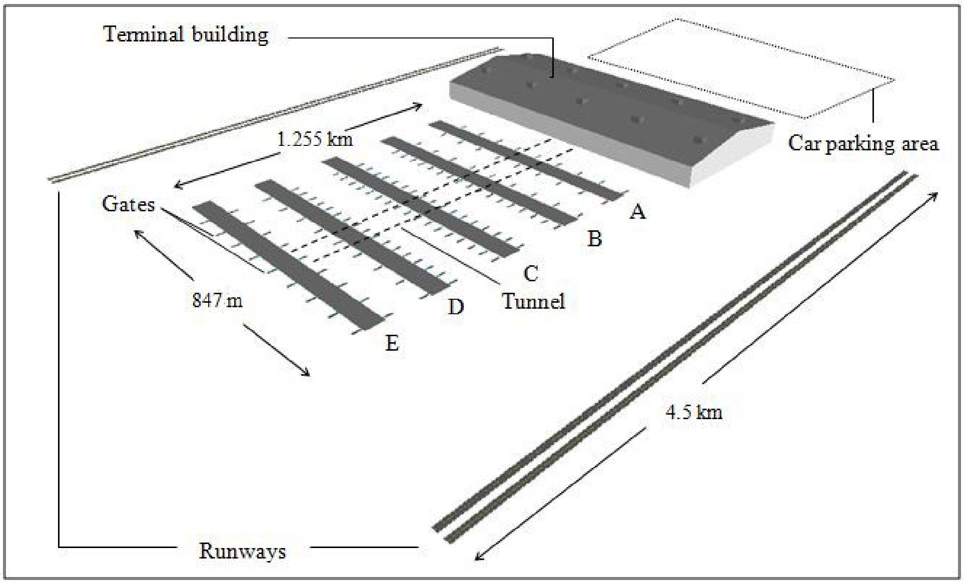


**Figure 1: Airport apron layout: Design 1**

The different airport designs we considered in this study are illustrated in Figures 1, 2, 3, and 4. *Design 1* is based on the concept of Atlanta Airport, but customised for South African requirements. This design closely resembles that of Atlanta Airport, but only a single tunnel for passenger movement connects the concourses and terminal building. At Atlanta Airport, concourses are also connected to each other to allow for transferring passengers. The five concourses are spaced parallel to the main terminal building. In this case, an underground tunnel runs from the main terminal building to the furthest concourse, connecting all the concourses. At Atlanta Airport there are many transfer passengers because it is a hub for many airlines. These transfer passengers do not need to go back to the main terminal building before boarding the next flight: they only need to move to the concourse of the next flight. It is therefore essential that the different concourses be connected to one another. Since there will be no need for transfer passengers at the new Lanseria International Airport, passenger movement from one concourse to another has been eliminated [12]. The runways are perpendicular to the main terminal. The parking area for cars is on the opposite side of the main terminal building.

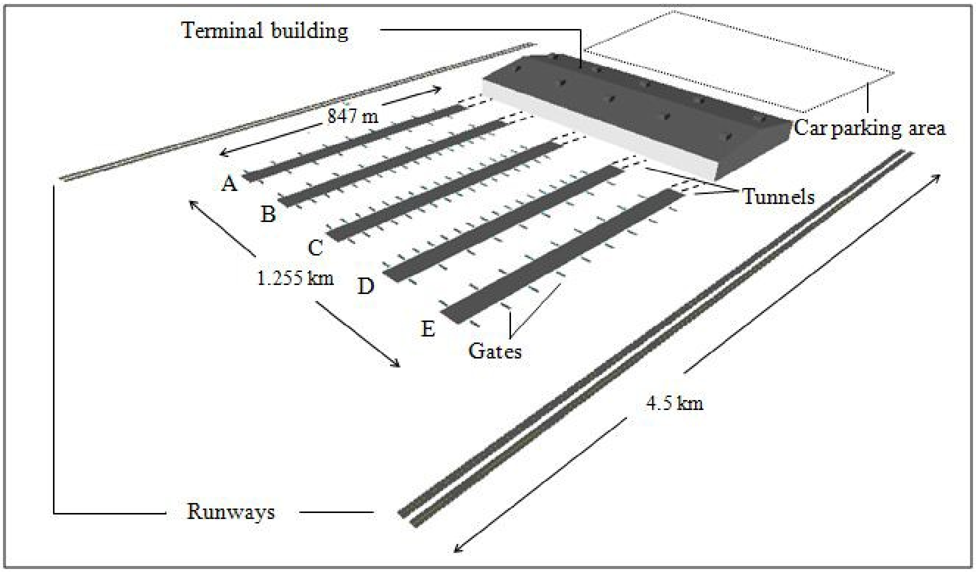


**Figure 2: Airport apron layout: Design 2**

Virtual Consulting Engineers proposed *Design 2*. The concourses are rotated to be perpendicular to the terminal building and parallel to one another, and each concourse has its own connecting tunnel to the terminal building. The space between the main terminal and the concourses will be used as aircraft taxiways. Thus, five short tunnels will be built under the taxiway, connecting the main terminal to each concourse. Again, the tunnels will have walking space as well as automated pedestrian walkways.

The runways are perpendicular to the main terminal building and parallel to the concourses. Again, the parking area for cars is on the other side of the main terminal building, opposite the concourses.

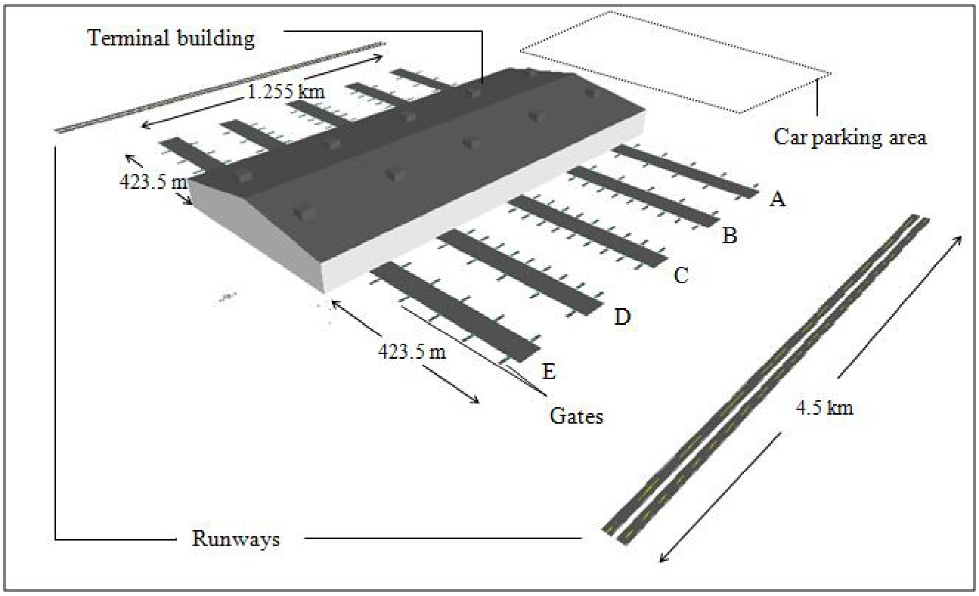


**Figure 3: Airport apron layout: Design 3**

In *Design 3*, the main terminal building will be located centrally, dividing each of the five concourses in half. The concourses are perpendicular to and on two sides of the terminal building. This design is based on Design 2, but is split to form a mirror image on either side of the terminal building. In this case, concourses are automatically connected to the main terminal building without the need for a tunnel. The runways are again parallel to the main terminal building and perpendicular to the concourses. The parking area for cars is at one end of the terminal building, and passengers will enter the terminal from that side.

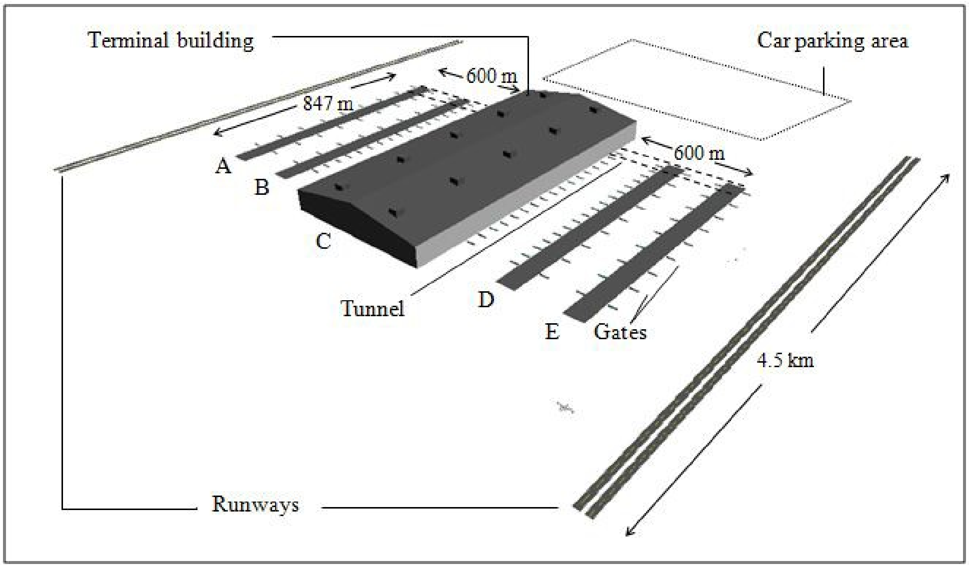


**Figure 4: Airport apron layout: Design 4**

In *Design 4*, concourse C is replaced by the main terminal building. The concourses are parallel to the terminal building and concourse C is eliminated. The parking area for cars is at one end of the terminal building. As a result, the tunnel connecting the concourses to the main terminal is located at the parking space end of the terminal. If we position the tunnel in the middle of the concourses as in Design 1, all passengers will need to walk at least half the length of the terminal, even if their boarding gates are closer to the parking space end of the terminal. This means they will need to walk all the way back in the direction of the parking area to reach their boarding gates. However, if the tunnel is placed at the side of the parking area, where all passengers will have to enter the building, they will only need to walk the distance to their boarding gates once.

### 3.2 Logic in the simulation models

We defined three types of entities [13] in the simulation models — the aircraft, the arriving passengers, and the departing passengers — and considered numerous aspects while building the models. Some are:

- The model creates arriving aircraft and their passenger counts at the same time, and assigns the aircraft to a suitable gate. If no suitable gate is available, the aircraft has to wait for one to become available.
- Once an assigned gate is available, the aircraft approaches it via the taxiways.
- After the aircraft has arrived at its gate, the passengers disembark according to a time distribution.
- The aircraft stays at its gate until the departure time of its next flight. The model creates the passengers departing on the aircraft’s next flight when the boarding time is reached. These passengers then start boarding the plane. If an aircraft has very little turnaround time on the schedule, the departing passengers for the aircraft’s next flight might arrive before the model has assigned the aircraft to a gate. The departing passengers then have to wait until the aircraft is assigned to a gate in order to know where to board. The time it takes for boarding the passengers on the

different aircraft types is summarised as follows: for aircraft of types A, B, and C: 10 minutes [14]; for aircraft of type D: 14 minutes [15]; and for aircraft of types E and F: 26 minutes [16].

- When the departing passengers have finished the boarding process and the aircraft's scheduled departure time has been reached, the aircraft starts travelling to the nearest runway.
- There are two models of each layout design because we considered two opposite wind directions for take-off and landing. Thus the wind will determine from which direction the aircraft will approach the apron. We suspected that wind direction would not have an effect on the results, but we nevertheless considered it to be sure. We assumed that the wind direction was stable for a given simulation run.

The maximum allowable taxi speed for aircraft according to Van Ravesteyn [17] and Rademan [18] is as follows: on taxiways outside the ramp area: 30 knots (55.56 km/h); on taxiways inside the ramp area: 15 knots (27.78 km/h); for a 90-degree turn: 10 knots (18.52 km/h); and for entering a gate: 4 knots (7.41 km/h). Fruin [19] stipulates the walking speeds for passengers in an airport. For passengers standing on the automated pedestrian walkways the transfer speed is 3.7 km/h, and for passengers walking freely the walking speed is 4.8 km/h. All these values were used in the simulation models.

Other inputs include the arrival and departure schedule, the size of each aircraft, and the number of passengers on each flight. For the arrival and departure schedules we obtained real data for O.R. Tambo International Airport, and scaled the data to obtain a busier schedule by reducing inter-arrival times and increasing the number of passengers per arrival. The output statistics we used to assess and compare the different designs include the average transfer distance for arriving and departing passengers, the cumulative transfer distance (taken over a simulated year), the average time that arriving and departing passengers spend in the system, the average time that aircraft spend in the system, the average aircraft travelling distance on the apron, the average delay for each aircraft, and the average number of aircraft present at the airport.

An aircraft cannot enter any taxiway at any time, as it has to avoid colliding with other aircraft. The taxiways are arranged as shown in Figure 5. The arrows indicate the allowed direction of aircraft movement. Single lines indicate that only one aircraft can travel on that section of the taxiway, while aircraft may pass one another where double lines are shown.

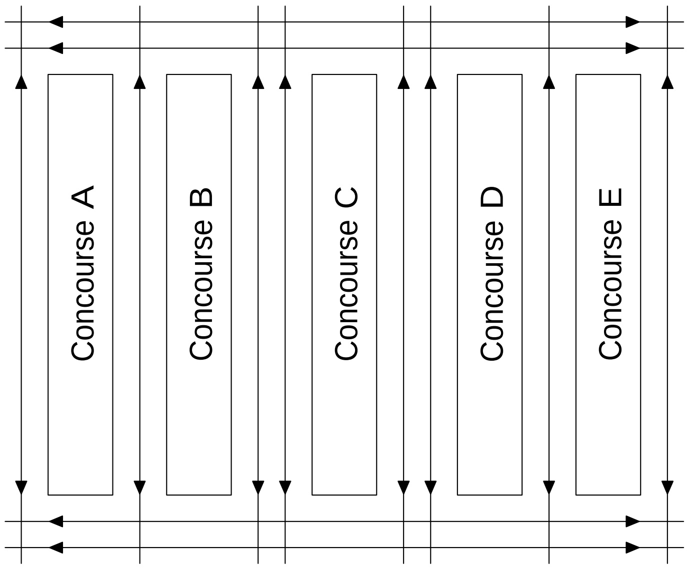


**Figure 5: The orientation and position of the taxiways for a typical design**

If another aircraft is approaching, the present aircraft can only enter that taxiway if the approaching aircraft is going to exit before they meet. If the approaching aircraft is headed for a gate or a taxiway on the other side of the present aircraft's current position — that is, if the approaching aircraft will have to pass the present aircraft — the present aircraft has to wait until the approaching aircraft has passed. This is illustrated in the two examples shown in Figure 6 and 7. In Figure 6, if aircraft B is an arriving flight (thus headed for, say, Gate 11) and aircraft A is due to depart (say from Gate 9), but the gate assigned to aircraft B (Gate 11) is on the other side of the gate at which aircraft A is waiting (Gate 9), it means aircraft B will have to pass Gate 9 on its way to Gate 11, and aircraft A is not allowed to enter the taxiway until aircraft B has passed Gate 9.

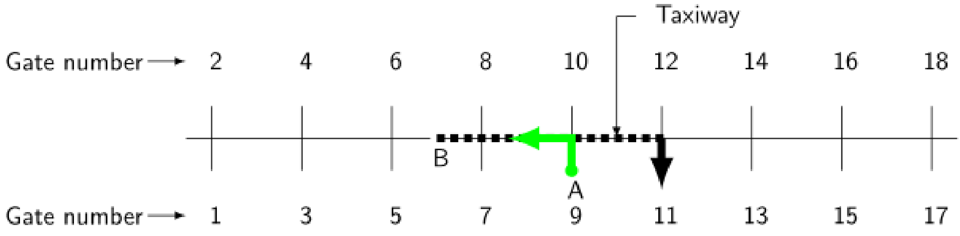


**Figure 6: Entering taxiway from a gate, scenario 1**

In Figure 7, aircraft B is assigned to Gate 3 and is on its way to park there. Aircraft A is leaving Gate 9 and travels towards aircraft B. Both aircraft may access the taxiway because of the distance separating Gate 3 and Gate 9. In this case, aircraft B will reach its gate and exit the taxiway before aircraft A reaches the vicinity of gate 3.

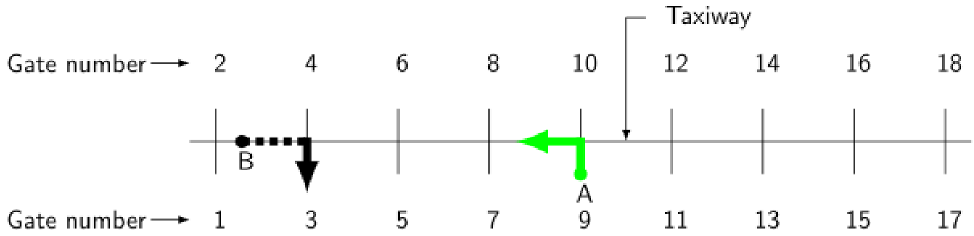


**Figure 7: Entering taxiway from a gate, scenario 2**

## 4. FLIGHT-TO-GATE ASSIGNMENT IN THE MODELS

Gate assignment during the simulation runs was done based on three different rules:

- The first model of each design was developed using a built-in rule (Rule 1) for assigning flights to gates. This rule works as follows: When a small aircraft arrives, the model assigns it to the available small gate nearest to the terminal building. If no small gates are available, the model assigns the aircraft to the available medium gate nearest to the terminal building. If no medium gates are available, the model assigns the aircraft to the available large gate closest to the terminal building. When a medium aircraft arrives, the same process is followed, except the small gates are not taken into account. When a large aircraft arrives, the model assigns it to the available large gate closest to the main terminal building. If no gates of the correct size are available for the arriving aircraft, the aircraft circles above the airport until a gate becomes available. In essence, Rule 1 is: Assign the candidate aircraft to the smallest possible gate closest to the terminal building.
- For the second model of each design, we also used a built-in rule (Rule 2) for assigning flights to gates. However, in this rule, the model can assign a small aircraft to a small, medium or large gate without first having to consider all the small gates. Thus, the model can assign a small aircraft to any available gate. The model can assign a medium aircraft to a medium or large gate without evaluating all the medium gates before considering a large gate. Large aircraft can still only

be assigned to large gates. Rule 2 thus requires that the candidate aircraft be assigned to the available gate closest to the terminal building, provided that the aircraft fits.
- We built a third model of each airport design that included the cross-entropy method (CEM) to determine the flight-to-gate assignment schedule that minimises the passenger transfer distance. This alternative is called Rule 3, which we explain in the next section.

Note that Rule 1 and Rule 2 are the same for the category of large aircraft.

## 5. APPLYING THE CEM TO MINIMISE PASSENGER TRANSFER DISTANCE (RULE 3)

A brief summary of the work on the CEM by De Boer et al. [3] and Rubinstein & Kroese [4] is given here. For an optimisation problem, let $\mathbf{X} = (X_1, \ldots, X_n)$ be a random vector from the solution space $\mathcal{X}$, and let $\Upsilon$ be some real function on this space. In the flight-to-gate assignment problem, $\mathbf{X}$ is a population of $N$ solutions. In each solution, $X_i$, all the flights in consideration are assigned to suitable gates. The real function $\Upsilon$ is the performance of that solution, i.e. the total passenger transfer distance, and is estimated with a simulation model of the airport process.

The associated optimisation statement is:

$$\Upsilon(\mathbf{x}^*) = \gamma^* = \min_{\mathbf{x}\in\mathcal{X}} \Upsilon(\mathbf{x}). \tag{1}$$

To solve the problem of (1), assume $\mathbf{u} \in \mathcal{V}$. This is a discrete problem; and, assuming a family of probability mass functions (pmfs) $\{h(\cdot;\mathbf{u}), I_{\{\Upsilon(\mathbf{x})\leq\gamma\}}\}$ on $\mathcal{X}$ and indicator functions $I_{\{\Upsilon(\mathbf{x})\leq\gamma\}}$ on $\mathcal{X}$, then the probability that $\Upsilon(\mathbf{x}) \leq \gamma$ is

$$l = \mathbb{P}_{\mathbf{u}}(\Upsilon(\mathbf{X}) \leq \gamma) = \mathbb{E}_{\mathbf{u}} I_{\{\Upsilon(\mathbf{X})\leq\gamma\}}. \tag{2}$$

$\Upsilon(\mathbf{X}) \leq \gamma$ can be estimated using importance sampling: take a random sample $\boldsymbol{X}_1, \ldots, \mathbf{X}_N$ of size $N$ from a different density $g$ on $\mathcal{X}$ and estimate $l$ using the likelihood estimator [3]:

$$\hat{l} = \frac{1}{N}\sum_{i=1}^{N} I_{\{\Upsilon(\mathbf{x})\leq\gamma\}} \frac{h(\mathbf{X}_i;\mathbf{u})}{g(\mathbf{X}_i)}.$$

Now do a change of measure with density

$$g^*(\mathbf{x}) = \frac{I_{\{\Upsilon(\mathbf{x})\leq\gamma\}} h(\mathbf{x};\mathbf{u})}{l} \tag{3}$$

which means that

$$l = \frac{I_{\{\Upsilon(\mathbf{X})\leq\gamma\}} h(\mathbf{X};\mathbf{u})}{g^*(\mathbf{X})}.$$

Both $l$ and $g^*(\mathbf{x})$ are unknown in (3), but $g^*(\mathbf{x})$ can be approximated within a family of pmfs $h(\cdot;\mathbf{v})$ where $\mathbf{v}$ is a reference parameter such that the cross-entropy between $g^*(\mathbf{x})$ and $h(\cdot;\mathbf{v})$ is minimal. This distance can be measured using the non-symmetric Kullback-Leibler distance between $g^*$ and $h$, which is defined in the discrete case as

$$\begin{aligned} D(g^*, h) &= \mathbb{E}_{g^*} \ln \frac{g^*(\mathbf{X})}{h(\mathbf{X})} \\ &= \sum_{\mathbf{x}} g^*(\mathbf{x}) \log g^*(\mathbf{x}) - \sum_{\mathbf{x}} g^*(\mathbf{x}) \log h(\mathbf{x}) \end{aligned}$$

with the expectation taken relative to $g^*$. To estimate $l$, one chooses $\mathbf{v}$ such that $\mathcal{D}(g^*, h(\cdot\,;\mathbf{v}))$ is minimal; thus

$$\sum_{\mathbf{x}} g^*(\mathbf{x}) \log h(\mathbf{x}) \tag{4}$$

must be maximised. Inserting (3) in (4) results in the following maximisation problem:

$$\max_{\mathbf{v}} \sum_{\mathbf{x}} \frac{I_{\{\Upsilon(\mathbf{x})\leq\gamma\}} h(\mathbf{x};\mathbf{u})}{l} \log h(\mathbf{x};\mathbf{v}).$$

Alon et al. [20] proved that for discrete random vectors $\mathbf{X}$, the vector $\mathbf{v}$ will always have components of the form

$$\frac{\mathbb{E}_{\mathbf{v}}\, I_{\{\Upsilon(\mathbf{x})\leq\gamma\}} I_{\{\mathbf{x}\in A\}}}{\mathbb{E}_{\mathbf{v}} I_{\{\Upsilon(\mathbf{x})\leq\gamma\}} I_{\{\mathbf{x}\in B\}}} \tag{5}$$

with $A \subset B \subset \mathcal{X}$. The random vector $\mathbf{X}$ has pmf $h(\cdot;\, \mathbf{u})$ for some $\mathbf{u} \in \mathcal{V}$, and by using the Kullback-Leibler distance, the estimation is done by making adaptive changes to the distribution. A number of probability mass functions $h(\cdot\,;\mathbf{u}), h(\cdot\,;\mathbf{v}_1), h(\cdot\,;\mathbf{v}_2), \ldots$ are created in sequence, resulting in a series of tuples $\{(\hat{\gamma}_t,\ \hat{\mathbf{v}}_t)\}$ that converge to the optimal tuple $(\gamma^*, \mathbf{v}^*)$.

For this problem, define discrete distributions $p_j$ and draw observations for random vectors $\mathbf{X}_i = (X_{i1}, \ldots, X_{in})$, for $n$ elements in the decision vector. The estimator for $p_j$ is

$$\hat{p}_j = \frac{\sum_{i=1}^{N} I_{\{\Upsilon(\mathbf{X}_i)\leq\gamma\}}\, I_{\{X_{ij}=j\}}}{\sum_{i=1}^{N} I_{\{\Upsilon(\mathbf{X}_i)\leq\gamma\}}}. \tag{6}$$

The discrete distributions $p_j$ make a vector $P_t$ where the subscript $t$ is the iteration number during optimisation. Note that $P_0 = 0.5$, and the estimated sample $1-\varrho$ quantile is an estimator for $\hat{\gamma}_t = \Upsilon_{(\lceil 1-\varrho \rceil N)}$, where typically $\varrho = 0.1$. In this problem, $i$ refers to the $i$-th candidate solution vector in $P_t$, and $j$ refers to the flight number. A scaled-down example of the solution structure consisting of five solutions and 10 flights is shown in Table 1; the solution values are fictitious. Suppose $i = 2$, $j = 5$ and $X_{ij} = X_{25} = 4$, it means that flight number 5 has been assigned to Gate 4 (indicated by 4), in solution vector 2. Flight number 10 has also been assigned to Gate 4 in this solution vector 2, but it will arrive after flight number 5 has departed. These two flights represent aircraft that can fit into the area at Gate 4. In solution vector 3, one can see that $X_{35} = 3$. In Table 1 it is also shown that the assignment $X_{25} = 4$ occurs with probability 0.2 (shown by 0.2). The actual problem structure is much greater, since $N = 100$ was used, while 125 gates were considered. The assignments of a given solution yields simulated performance values, for example the total annual transfer distance.

**Table 1: An example of a population of feasible solutions and probabilities**

| **Solution number** | **Flight number** | | | | | | | | | | **Total transfer distance (m)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | |
| **1** | 3 | 2 | 5 | 1 | 3 | 4 | 3 | 5 | 2 | 1 | 645 000 |
| **2** | 2 | 3 | 1 | 5 | 4 | 2 | 3 | 1 | 2 | 4 | 639 521 |
| **3** | 5 | 3 | 4 | 2 | 3 | 4 | 5 | 1 | 2 | 4 | 665 741 |
| **4** | 1 | 3 | 4 | 2 | 1 | 5 | 3 | 2 | 4 | 5 | 628 951 |
| **5** | 1 | 3 | 5 | 2 | 4 | 1 | 3 | 2 | 1 | 5 | 615 426 |

| **Gate number** | **Flight number** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| **1** | 0.3 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 | 0.4 | 0.1 | 0.1 | 0.0 |
| **2** | 0.1 | 0.3 | 0.2 | 0.4 | 0.2 | 0.1 | 0.3 | 0.0 | 0.5 | 0.6 |
| **3** | 0.2 | 0.0 | 0.4 | 0.1 | 0.3 | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 |
| **4** | 0.4 | 0.5 | 0.1 | 0.2 | 0.1 | 0.1 | 0.0 | 0.3 | 0.1 | 0.1 |
| **5** | 0.0 | 0.1 | 0.3 | 0.2 | 0.4 | 0.7 | 0.2 | 0.4 | 0.2 | 0.1 |

The cross-entropy method for discrete, single-objective optimisation is as follows [3]:

**Algorithm 1** CEM Algorithm for discrete optimisation

1: Set all elements in $\hat{P}_0 = 0.5$. Set $t = 0$.
2: Generate $\boldsymbol{X}_1, \ldots, \mathbf{X}_N$ using $\hat{P}_{t-1}$, and compute the sample $1-\varrho$ quantile $\hat{\gamma}_t$ of the performance function using $\hat{\gamma}_t = \Upsilon_{(\lceil 1-\varrho \rceil N)}$.
3: Use the same sample and update $\hat{P}_t$ using (6).
4: Smooth $\hat{P}_t$ as follows: $\hat{P}_t \leftarrow \alpha \hat{P}_t + (1-\alpha)\hat{P}_{t-1},\ 0 < \alpha < 1$.
5: If $t > \delta = 5$, $\hat{\gamma}_t = \hat{\gamma}_{t-1} = \cdots \hat{\gamma}_{t-\delta}$, then stop, otherwise set $t \leftarrow t + 1$ and return to Step 2.

We considered the following constraints when modelling the generation of each solution in the population:

- The optimisation process can only assign each flight to one gate.
- Each gate can only accommodate one flight at a time.
- When assigning a flight to a gate, the optimisation process must ensure that its arrival time is later than the departure time of the previous flight that was assigned to that gate.
- The process cannot assign a large aircraft to a small or a medium gate, and it cannot assign a medium aircraft to a small gate.
- If a flight arrives (in the metaheuristic process) and no suitable gates are available, the aircraft waits until a gate becomes available. The optimisation process records the waiting time.
- If no suitable gates are available for a flight, that flight waits while the next flight is assessed. This must be done because, even though no gates may be available for the current flight, there may be a gate available for the flight arriving just after it. This is because the current flight may be a large aircraft for which no large gate areas are available, while the next flight may be a small aircraft for which small or medium gates may be available.

The logic of the CEM was embedded in the Simio models using its standard library with add-on processes. A process is made up of a sequence of steps and allows for object specialisation and detailed modelling. It was necessary to embed the CEM in the models to allow for the real-time optimisation, as will be explained next.

The model performs the optimisation process using a time window: at the beginning of the simulation run, the optimisation process finds assignments for the first *m* (50 in this study) flights. Then after every *n* (25 in this study) flights, the process is performed again to find assignments for the next *m* flights. The concept is shown in Figure 4. The window size is 50 flights. After 25 flights, the window is advanced by these 25 flights, which have all arrived by that time.

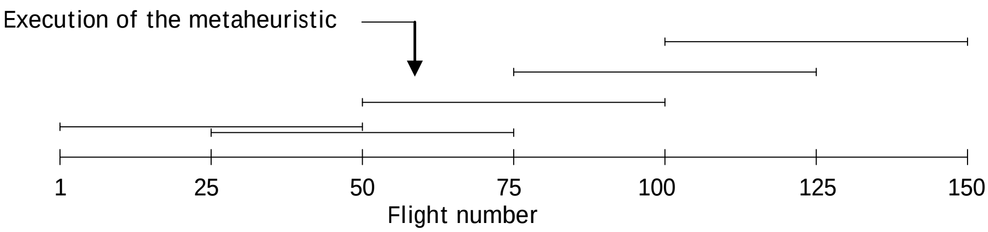


**Figure 8: Execution of the optimisation process**

When delays occur, the assignments can be repeated. In Figure 5, flight number 32 is delayed, and the assignment optimisation process is repeated with flight number 32 as starting point.

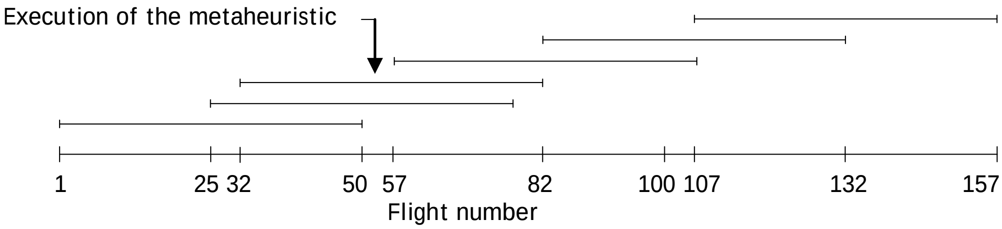


**Figure 9: Execution of the optimisation process for delayed flights**

The simulation modelling was done according to the approach of Kelton et al. [14], and will not be elaborated on here. Next, the results are presented and discussed.

## 6. RESULTS

We show the summarised results for the average transfer distances (per passenger) in Table 2 for one wind direction, and the detailed results in Table 3 to Table 6. The summarised results are of the total passenger transfer distances for the four apron layout designs and gate assignment rules that were followed. The transfer distances are the sums of the transfer distances of both arriving and departing passengers. The best combination is that of Design 2 and Rule 3, i.e. the concourses are perpendicular to the terminal building, and the flight-to-gate assignment is done over time using the CEM.

**Table 2: Summarised results of the total average passenger transfer distances**

| | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| Rule 1 | 1 751 | 1 022 | 1 364 | 1 080 |
| Rule 2 | 1 636 | 940 | 1 253 | 1 039 |
| Rule 3 | 1 502 | 870 | 1 102 | 991 |

First, we confirmed that the direction of take-off and landing does not substantially influence the results of the models. Second, we compared the different designs, based on passenger and aircraft travelling distances and the time spent in the system. It is clear from the results that Design 2 is the best when considering all the performance measures. The average time spent in the system by arriving and departing passengers, the average transfer distance of arriving and departing passengers at the airport, the average aircraft travelling distance at the airport, and the average time an aircraft is delayed (overtime) are the least in Design 2. Third, we compared the results from using the different rules for assigning flights to gates:

- Using Rule 2 results in less transfer distance than that of Rule 1.
- The passenger transfer distance for arriving and departing passengers in the models in which the generic metaheuristic optimisation process, i.e. the CEM (Rule 3), is used is smaller than in the models using Rule 1 and Rule 2 to assign flights to gates. This is the case for each of the four airport apron layout designs.
- The time spent in the system by both arriving and departing passengers is approximately the same for all three rules.

In general, the metaheuristic optimisation improves the airport layouts. Furthermore, the use of Rule 2 instead of Rule 1 for assigning flights to gates provides better results. The overall best results are produced when Design 2 of the airport apron layout is used in combination with the optimisation process we developed, using the CEM (Rule 3), for assigning flights to gates.

We recommend that *Design 2* be used for the apron layout of Lanseria International Airport, and that *Rule 3* be followed, or that a similar optimisation of flight-to-gate assignment be done once the airport is operational.

**Table 3: Detailed results for Design 1**

| Design 1 | Wind direction 1 | | | Wind direction 2 | | |
|---|---|---|---|---|---|---|
| **Statistics** | **Rule 1** | **Rule 2** | **Rule 3** | **Rule 1** | **Rule 2** | **Rule 3** |
| Average time in system of arriving passengers (min) | 25.55 | 24.82 | 24.13 | 25.20 | 24.10 | 23.34 |
| Average transfer distance of arriving passengers (m) | 877 | 816 | 752 | 876 | 810 | 754 |
| Average time in system for departing passengers (min) | 37.93 | 37.92 | 37.68 | 38.29 | 38.47 | 38.61 |
| Average transfer distance of arriving passengers (m) | 874 | 820 | 750 | 873 | 813 | 754 |
| Average travelling distance of aircraft (m) | 2 138 | 2 141 | 2 320 | 2 139 | 2 142 | 2 378 |
| Average overtime departing aircraft (min) | 2.95 | 2.78 | 3.41 | 2.95 | 2.80 | 3.40 |

**Table 4: Detailed results for Design 2**

| Design 2 | Wind direction 1 | | | Wind direction 2 | | |
|---|---|---|---|---|---|---|
| **Statistics** | **Rule 1** | **Rule 2** | **Rule 3** | **Rule 1** | **Rule 2** | **Rule 3** |
| Average time in system of arriving passengers (min) | 20.20 | 19.30 | 18.84 | 20.43 | 19.69 | 19.41 |
| Average transfer distance of arriving passengers (m) | 512 | 469 | 435 | 514 | 469 | 439 |
| Average time in system of departing passengers (min) | 37.90 | 37.76 | 37.92 | 37.70 | 37.39 | 37.37 |
| Average transfer distance of departing passengers (m) | 510 | 471 | 435 | 513 | 470 | 439 |
| Average travelling distance of aircraft (m) | 2 065 | 1 834 | 2 027 | 2 065 | 1 838 | 2 041 |
| Average overtime departing aircraft (min) | 2.51 | 2.47 | 2.63 | 2.51 | 2.46 | 2.63 |

**Table 5: Detailed results for Design 3**

| Design 3 | Wind direction 1 | | | Wind direction 2 | | |
|---|---|---|---|---|---|---|
| **Statistics** | **Rule 1** | **Rule 2** | **Rule 3** | **Rule 1** | **Rule 2** | **Rule 3** |
| Average time in system of arriving passengers (min) | 22.93 | 22.35 | 21.58 | 22.51 | 21.70 | 20.70 |
| Average transfer distance of arriving passengers (m) | 683 | 625 | 551 | 683 | 621 | 560 |
| Average time in system of departing passengers (min) | 37.85 | 37.81 | 37.60 | 38.24 | 38.38 | 38.56 |
| Average transfer distance of departing passengers (m) | 681 | 628 | 551 | 681 | 625 | 561 |
| Average travelling distance of aircraft (m) | 2 124 | 2 138 | 2 364 | 2 124 | 2 147 | 2 308 |
| Average overtime of departing aircraft (min) | 2.72 | 2.61 | 3.06 | 2.70 | 2.57 | 3.10 |

**Table 6: Detailed results for Design 4**

| Design 4 | Wind direction 1 | | | Wind direction 2 | | |
|---|---|---|---|---|---|---|
| **Statistics** | **Rule 1** | **Rule 2** | **Rule 3** | **Rule 1** | **Rule 2** | **Rule 3** |
| Average time in system of arriving passengers (min) | 20.45 | 19.96 | 19.64 | 20.56 | 20.30 | 19.92 |
| Average transfer distance of arriving passengers (m) | 539 | 518 | 495 | 539 | 519 | 488 |
| Average time in system of departing passengers (min) | 37.92 | 37.89 | 38.01 | 37.77 | 37.60 | 37.63 |
| Average transfer distance of departing passengers (m) | 541 | 521 | 496 | 541 | 5229 | 488 |
| Average travelling distance of aircraft (m) | 2 076 | 2 003 | 2 059 | 2 076 | 1 998 | 2 057 |
| Average overtime departing aircraft (min) | 2.75 | 2.72 | 3.14 | 2.73 | 2.72 | 3.17 |

## 7. CONCLUSION

This paper presented a simulation-optimisation study that was used to evaluate four different airport apron layouts and flight-to-gate assignment rules for the future Lanseria Airport in Gauteng, South Africa. The layouts were compared mainly in terms of passenger transfer distance between aircraft and the terminal building. Arrivals and departures were modelled using computer simulation and inflated real-life schedules of O.R. Tambo International Airport. A layout is suggested that can be used with real time flight-to-gate assignment metaheuristic — for example, the cross-entropy method. Also, when a schedule is disturbed by delays, a new assignment plan can be developed immediately.

The layout of Atlanta Hartsfield Airport (and other airports) requires a single underground people mover that ferries passengers between the terminal and the different concourses. The layout proposed for LIA eliminates the need for a people mover, resulting in reduced capital cost in the short and medium term, and reduced operating cost throughout the project lifecycle [2]

The results offer the airport designers additional information that can be considered when finalising the design. It is the intention of VCE to develop the model further as the proposed development approach is applicable to any two runway airport with a midfield terminal [2].

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