Methodology for Assessing and Optimizing Operation Performance in Airport systems

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Abstract

Traditionally airport systems have been studied using an approach in which the different elements of the system are studied independently. Until recently scientific community has put attention in developing models and techniques that study the system using holistic approaches in order to understand the cause and effect relationships of the integral system. This paper presents a methodology that includes different elements of the airport system such as TMA, Runway, taxi networks, and ground handling operations. It firstly aims at identifying the elements that hinder the smooth process of the air traffic and second it optimizes the system through an efficient management of the resources that play an important role in the performance of the system. In particular, in this work, a simulation model was developed using a Discrete Event simulation approach in order to evaluate the performance of the system, then an experimental design was conducted according to a multi-level factorial design to identify the main factors affecting the system. Moreover, an analysis of variance was carried out and a metamodel allowing to evaluate the performance of the system was determined. The methodology has been implemented for studying the situation of a regional airport in The Netherlands.

Keyword SIMULATION, OPTIMIZATION, PERFORMANCE ANALYSIS

1 Introduction

Air global transportation is in a continue growth, looking at the most recent statistics we see that European flights have increased by 0.7% in May 2015 compared with the same month of the last year and it was above the forecast, furthermore preliminary data for June 2015 say that there will be a 1.2% of flights increase compare to June 2014 [8]. The majority of states have seen a growth in their local flight, all these facts make evident that there will be the need of facilities able to accommodate all this traffic demand. On the other hand, statistics show that delay due tomany causes have increased by 3% in May 2015 comparing to the previous year, this can explain why facilities, in this case airports, are constantly suffering due to lack of capacity. Designing the layout and the infrastructure of an airport means allocating resources in away of matching the traffic demand without incurring in congestion situations. In this context, evaluating the performance of airports has become a crucial aspect, especially if we aim at an efficient management of the existing resources. Due to limited resources and the reduced budget to invest in new facilities, distributing resources wisely is one of the main challenge for the stakeholders. From the passenger perspective, the main factor that affect the quality of service of an airport is the delay, the less delays occur, the more passengers will evaluate positively the service provided. From the airport view, having less delays can lead to process more aircraft, that is translated in an increase of its capacity. This in turn lead to have higher revenues and the opportunity to attract airlines since more slots could be allocated. Furthermore the good level of service might keep passengers choosing that air- port as origin and destination. Airport system is made by different components, the terminal area, the airside (runway, taxiways and stands) and then the airspace (sectors, routes). Often these components are analysed separately by researchers, but in reality these components are tied each other, and they act all together as a system. Motivated by this fact, in this work it was made an analysis of the performance of an air- port system, taking into account all the components previously mentioned.

This work aims at developing a methodology that is able to identify the factors that affect the airport system the most and at a later phase we will optimize its performance in order to make an efficient use of resources. This methodology is a combination of simulation and optimization that takes into account all the components of an airport system (ground + airspace), and evaluates the airport performance in terms of capacity and in terms of delays. The simulation paradigm used in this work is a Discrete-event Simulation (DES), this approach allows modelling a wide range of systems and evaluating their performance besides making experiments comparingdifferent scenarios. With the development of this simulation model it was possible to evaluate different configurations and making analysis about the system performance, in particular in this work was carried out a design of experiment employing a multi-level factorial design with the purpose of evaluating the effect of the factors and their interactions for the system response. Moreover, with the study of the Analysis of the Variance (ANOVA), it was determined a metamodel useful to predict the performance of the system based on the value of the input factors. The last stage of this methodology includes the development of an optimization algorithm based on then main factors identified from the previous analysis, but in this work this stage is not presented.

Optimization of airport resources is a subject that was faced by many researchers in many studies, most of them treated the airport as a two separate entities, from one side airspace and from the other ground side. In this context, many techniques that tried to improve airport performance were employed, taking into account different variables. Concerning the airspace, specifically in the TMA, many works focused on the sequencing and merging problem and scheduling problem. The former is about to find the best sequence for aircraft flow in order to determine conflict-free situations [12, 24, 25] , the latter is about scheduling of aircraft flow in order to minimize the deviation from the scheduled landing time to the actual landing time [3, 4, 5, 2, 17]. The techniques most utilized were from the operations research arena, since there were implemented many stochastic optimization models, moreover, due to the complexity of the problems, for many of them some heuristics were implemented in order to find sub optimal solutions. Just to mention some, the aircraft scheduling problem was studied by Beasley at al. [3, 4, 5] these researchers developed a mixed-integer one-zero problem and then they extended it employing two heuristics respectively for the static and dynamic case. Other relevant works use Costrained position shifted (CPS) such as the work by Balakrishnan at al. [2], they improved the sequence of aircaft by changing the position of the aircraft in order to minimize the makespan, these authors employed a dynamical programming to get a sub optimal solution, Hu and Chen [9] instead proposed a receding horizon control (RHC) technique where the scheduling and sequencing problem was treated in a dynamic way, they introduced a Genetic algorithm in order to solve it. Regarding the ground side, most of the studies are related to the optimization of the gate assignment, the scheduling of departing aircraft and taxiing operations, with the objective of avoiding congestion situations and favouring a smooth flow of aircraft in the taxiways. In the work of Dorndorf [7] they present a survey about the techniques used to cope with the gate assignment problem, among others we can find the work of Bolat [6] in which a branch and bound alghoritm was combined with a two heuristics, a Coloured petri net (CPN) technique was proposed by Narciso and Piera [18] in order to calculate the number of stands needed to absorb the traffic. In other studies pushback control strategies were propsed in order to determine the best sequence of departures without incurring in congestion situations [19, 23, 10]. As it can be seen for the previous work cited so far, the most implemented techniques refer to analytic and heuristic models, and there is a clear distinction between airspace and ground side. In this work the problem is treated from a holistic view in which both airspace and ground side are taken into account, a methodology has been developed that permits optimizing airport performance following a structured way. The initial approach focuses in performance measured as delay incurred. It uses Discrete Event Simulation (DES) together with statistical techniques for identifying the most influencing factors in the performance of the airport. The final objective will be to develop an optimization algorithm for the whole system. DES is an approach that is used in many applications like logistic and manufacturing [11]. Recently DES was also applied to the aviation field with the scope of modelling the airport operation for both airspace and ground, even inside the terminal [13]. Using this approach, it has been possible to make the analysis and evaluation of airport performance [14, 20, 21]. The methodology proposed uses statistical tools like the Design of experiments and the ANOVA test for identifying the factors that impact the system the most and that can be used at a later stage for the optimization algorithm.

The paper is organized as follows, in section 2 the methodology developed is presented, in section 3 the results from the design of experiments and from the ANOVA can be read, finally in section 4 conclusions are presented.

2 Methodology

In order to make an efficient use of the resources at airports and make a deep analysis of the impact of the factors that play an important role in the performance of the system, a novel methodology was developed. This methodology is based on different phases in which we perform a model-based analysis for identifying the main factors that affect the performance of the airport under study. The first phase performs the identification of the factors that affect the performance of the airport using an objective function. During this phase we identified the significance of the different factors that affect such performance and then in the second phase the model is combined with an optimization algorithm for performing the improvement of the system under study in which the decision variables are the ones that affect the objective performance. In the initial phase, the system is represented by a stochastic model based on DES in which we couple different elements of the system such as the Terminal manoeuvring area and the airside of the airport so that the big picture gives us a better opportunities for improvement. DES is an approach that is used for modeling systems of dynamic nature in which there is strong interaction between the different processes of the system and stochasticity is one of the characteristics that define them. It allows identifying emergent dynamics and also integrating the inherent stochasticity which in some situations hinder the smooth behaviour of the system under study. This approach has been sucessfully used in logistics and manufacturing systems for identifying emergent behaviour, the impact of variability and uncertainty and for bottleneck identification among other characteristics [16]. Until recently, scientific community has been taken simulation as a serious tool for evaluating systems performance during the planning phase of facility development [22]. In the aviation field the studies concerning systems performance and capacity evaluation are quite recent but its potential has been recognized by international institutions and also as consultants which are becoming keen for the use of the methodology for performing studies [14, 20, 21].

2.1 Simulation-Optimisation: the right approach

For coping with operative problems when the identification of causal relationships is necessary for the identification of bottlenecks and problems it is necessary to have robust techniques that allows verifying the potential of improvement of the system. The potential for improvement can be identified through the use of evaluative techniques such as simulation-based analysis and then with the complement of other techniques the relevant parameters can be manipulated to drive the system to a configuration of better performance. However, the use of evaluative techniques with mathematical improvement techniques is a novel approach that has been studied by some authors [15, 1]. These combination has some drawbacks as well as benefits. On one hand optimization based methods and tools have proven their efficiency to deal with operative problems in complex fields such as logistics or manufacturing systems but there is a discussion about the lack of flexibility when modelling operational problems. In most cases, the stochasticity inherent to systems is not included in the developed models, thus reducing their applicability for real scenarios. On the other hand, simulation approaches have great flexibility and allow the modeller the development of high-detailed models to face the problems under a different scope including not only stochastic elements in the models but also the interactions between entities that generate emerging dynamics which influence the behaviour of the real system. Nevertheless, in most simulation-based cases the level of optimization achieved depends on the number of scenarios evaluated, which in general are just a small fraction of the whole available configurations. Thus, optimality is not ensured with the standalone simulation approach likewise suitability is not ensured with the standalone optimization approach. In this paper we present a methodology that aims at overcoming these shortcomings combining optimization techniques with simulation-based analysis. The combination of both techniques results in a robust and structured approach in which the system is progressively improved. The methodology proposed can be illustrated by Fig. 1

As the reader can notice, the methodology presents in the first phase the modelling and simulation of the system under study. The main outcome of this phase corresponds to the identification of the different parameters that affect the performance of the system. Once the identification has been performed, the focus will be put on the development of an optimization algorithm that uses the identified parameters as decision variables. Those parameters that were identified as non-relevant will not be included in the optimization algorithm. The papers presents the current developments for a case study of Lelystad which is a regional airport in the Netherlands that will be upgraded to handle commercial traffic [22].

2.2 Model Development

The model has been developed using a modular DES approach in which different modules of the system were developed such as stand operations, airside movements, taxiing, and airspace. These modules were

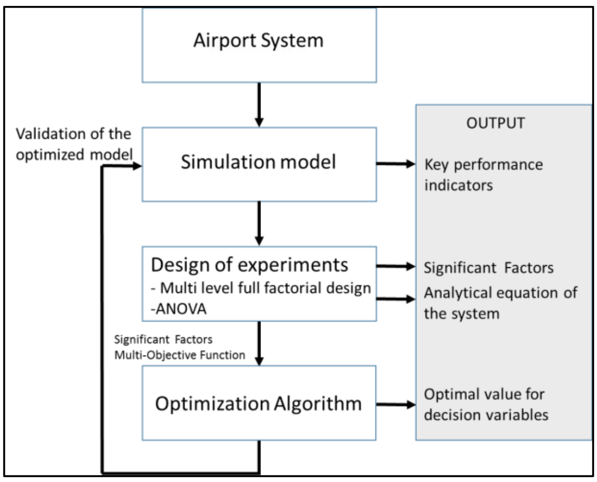

Figure 1 Methodology for assessing and improving the performance in aviation

merged afterwards for having a complete model that included all the required elements for the operations. Then rigorous techniques were put in practice for identifying the most relevant parameters that impact the performance indicators of the system.

2.3 Simulation model

In order to be able to represent the airport system, a simulation model was developed. The model includes the main components of the ground side and airspace like:

- Runway system
- Taxiway system and stands
- Approaching and departing routes
- Airspace

The model was developed using a modular approach [21] which allowed to create the diferent components separately and then integrate them to have a complete view of the system. This allows to make different analysis by taking into account each module aside. In Fig. 2 the architecture of the model is depicted. As it can be appreciated the airside is composed by the runway model and the turnaround model, andthis module interact directly with the one of the airspace making a complete representation of the TMA of the airport of the study.

Each module includes the correspondent technical restrictions and also stochastic ones such as the weather behaviour in which wind direction plays an important role in order to set the runway configuration besides the strength of the crosswind which in some conditions will not allow landings thus reducing the capacity of the system. The model performs the most relevant operations within an airport of small dimensions, in Fig. 3 the main elements of the airport can be seen.

Once the model was developed, it was possible to evaluate performance indicators (PI) like number

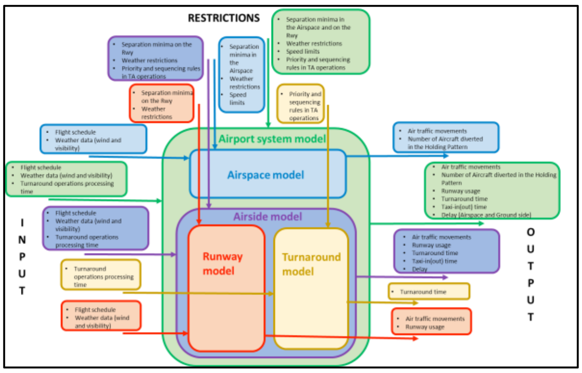

Figure 2 Modular Architecture

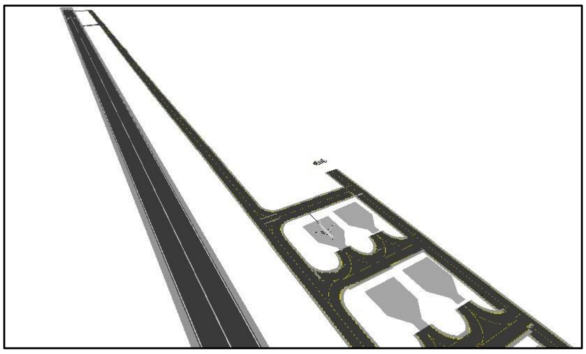

Figure 3 View of the taxiway

of movements, data about turnaround time and about delay under different scenarios. As an initial approach focus was put on the analysis of incurred delay which is an important PI of concern for the different players in the system (airports, airlines, passengers, ATCs). the following subsection presents the design of experiments for evaluating the aforementioned PI.

2.4 Design of the experiments

Design of experiments is a technique that permits to identify the main parameters, or factors within a system. With this technique, it is possible to evaluate what the main effects of the factors involved are, and also their interactions. This technique allows identifying the main effects for each factor. For each factor different values were assigned, called levels, and for each combination of factor level a response is evaluated and an analysis is performed in order to identify if the factor is statistically significant for the output variable (in our case the PI). In the airport system, the initial hyphothesis was that different variables impacted the overall delay namely air traffic, available vehicles for the turnaround, and stand allocation. These three factors were the ones initially evaluated with the use of the model, for the first and the second factors we set three levels, and two levels for the last. The reasons to pick these variables were because in the case of the traffic is already known that the systems have limits and we were interested in identifying what the capacity limitations were for the sytem under study. In the case of the vehicles for the turnaround it is obvious that they are part of the important resources that need to be managed in the best way so that the turnaround time (TAT) is minimized. And finally the selection of the stand allocation is based on the logic that the farther from the vehicle depots the aircraft are located the more probability of lateness for the vehicles that perform the TAT. Our task up to this point was to identify the level of impact of those factors in the overall delay.

To conduct the design of experiments it was used the Design-Expert software which helps performing the multi-level factorial design and ANOVA.

2.4.1 *Multi level design*

A multi level factorial design was performed in which three factors were designed. The factors chosen were:

- Number of incoming aircraft
- Apron's entering mode
- Number of vehicles involved in the turnaround process

In this analysis 10 simulation runs were made for each level. In table 1 the factors with the value of each level are summarized.

2.4.2 *ANOVA*

Once we have run the different experiments, the data of the different treatments with the model was used to perform the one-way ANOVA test to verify the impact of the different parameters. In addition it was possible to develop the quadratic equation that represents the dependency among the studied variables. Table 2 presents the results obtained with the ANOVA test.

3 Experimental Results

After performing the experiments, we applied the ANOVA test and we obtained results about the effect of the factors and their interactions on the response. The dependencies can be plotted in a response surface so that the influence is clearly seen. Besides the results and the graphs that represent the behaviour we could represent the dependency through a quadratic function that could be used as a representation of the model under study. The following figures and tables present the main results from the first stage of the methodology. In Fig. 4 is represented the Half-normal plot, that shows which are the main factors that affect the response of the system. The X axis displays the absolute value for all effects, and the Y axis di splays the half-normal probability percentage. In this case the more the factors differ from the fitted line, that follows a half-nornal distribution, the more they are relevant for the system. Basically, the ones in the right hand side are the most relevant, in this case it can be seen that the factor A, incoming flow of aircraft, plays a dominant role in the value of the response. Other relevant factors are the interaction between factor A and Factor B, Incoming flow of aircraft and Number of vehicles respectively, and factor B. Factor C, Apron's entering mode, results to be non relevant together with all the other interactions.

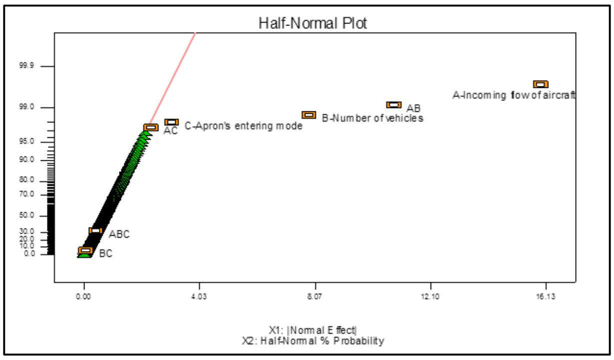

Figure 4 Half-normal plot

Table 2 shows for each factor the value of P, that is the probability of accepting the null hypothesis, when this value is less then 0.0001 means that the factor is significant for the system. From the table we can see that the factors that are significant are the same as the ones identified from the Half-normalplot.

With the response surface depicted in Fig. 5 and 6, we have a better insight about the influence of the factors in the response. We have two response surfaces, one where the level of Apron's entering mode is set to be Left-Right and the other response surface where the level is set to be Center-Out. In particular we can see that when we switch from Left-Out to Center-Out configuration total delay increases.

Table 1 Factors for the multi-level factorial design

Factors	Level 1	Level 2	Level 3
A - Incoming flow of aircraft (/day)	92	132	180
B - Number of vehicles	2	5	8
C - Apron's entering mode	Left-Right	Center-Out	-

Table 2 Analysis of the Variance

Factors	DoF	F - Value	P - Value
A - Incoming flow of aircraft	1	47.87	<0.0001
B - Number of vehicles	1	61.29	<0.0001
C - Apron's entering mode	1	8.58	0.0039
AB	1	88.69	<0.0001
AC	1	2.87	0.0920
BC	1	0.082	0.7754
A^2	1	5.482E-004	0.7754
B^2	1	2.84	0.0937

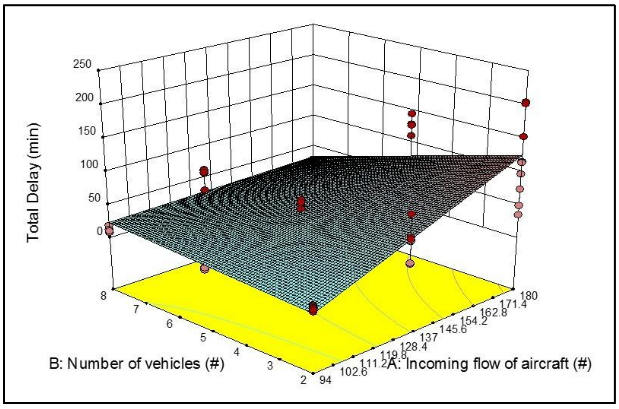

Figure 5 Response surface with Apron's entering mode fixed at level 1 (Left-Right)

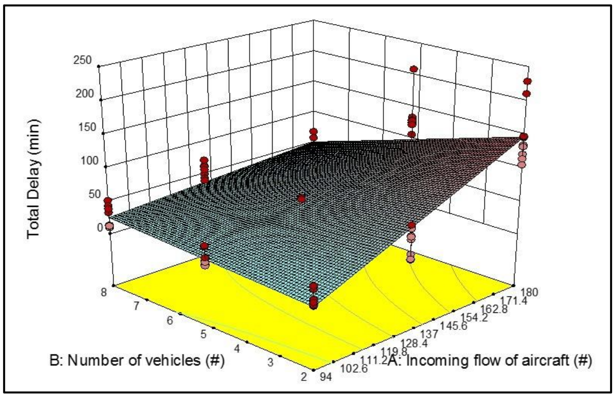

Figure 6 Response surface with Apron's entering mode fixed at level 2 (Center-Out)

It can also be seen how the delay decreases when we change the level of the Incoming flow of aircraft factor, in particularly, we see that the point with the highest value of total delay can be found when Incoming flow of aircraft is set at the highest level and the number of vehicles at the lowest. When we have a low level for Incoming flow of aircraft the factor number of vehicles does not play a relevant role in the value of the response.

From the ANOVA it was possible to determine a metamodel representing the system response in function of the values of the input factors. This equation is interesting because it integrates in a numerical way the dependencies measured during the experiments. Below the final equation of the system can be found.

$$Totaldelay = 57.32 + 36.99 * A - 19.34 * B$$
$$+ 5.91 * C - 28.40 * AB + 4.17 * AC$$
$$- 0.71 * BC + 0.10 * A^2 - 7.21 * B^2$$

4 Conclusions and future work

In this paper a methodology combining simulation and optimization techniques was presented inorder to make an efficient use of resources for an airport system. The results presented in this paper correspond to the simulation phase of the methodology. The study was focused in a regional airport in The Netherlands that is going to accommodate commercial traffic in the next coming years.

It was taken into account the airport system as a whole, including airspace and ground side. The performance of the system were evaluated using a DES approach and then the factors that have a major impact to the response of the system were identified. It was also obtained as a result the impact of the interactions represented as a quadratic equation. The analysis showed that the factor that most impact the system was the incoming flow of aircraft, therefore the amount of traffic inbound plays a crucial role in the airport performance.

We found also that the interaction between incoming flow of aircraft and number of available vehicles on the ground is critical for the performance of the system. In this case when the traffic is increased, we need to increase the number of vehicles in order to reduce the delay. Finally we could also identify the level of influence in the performance played by the stand allocation in which from left to right was the one that gave the best performance. The finalanalytical equation represents the dependencies in numerical terms and can be used as a decision support tool for the planning phase of the airport.

As future work the study will be extended to a multi-objective analysis and for the identification of the operative limits of the airport under different circumstances. In addition the work will continue with the development of the optimization technique that will include the different decision variables for optimizing the performance under different perspectives (airport, airlines or passenger).

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