A COMPLEX SYSTEMS APPROACH TO ASSESSMENT OF AIRPORT FLEXIBILITY, PREDICTABILITY, AND EFFICIENCY

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Abstract

Airport performance monitoring is an important element of current efforts to modernise the ATM system. However, there is no general consensus as to how performance may be measured or even defined, especially in terms of flexibility, predictability, and efficiency. In addition, most previous work assesses the performance of a large system by studying subsystems separately, which can result in difficulties in integrating the results for the separate subsystems. In this work, a complex, large-scale, interconnected, open, sociotechnical (CLIOS) model of the airport is presented. Novel definitions are proposed for the flexibility, predictability, and efficiency of the airport as a whole based on a review of literature and the airport CLIOS model. A first step is also made towards developing methods to quantify these aspects of performance. A highly simplified simulation model of the airport system has been developed. It is the intention that the simulation model will be further developed and that it will be used to further explore the assessment of flexibility, predictability, and efficiency using the complex systems approach as presented in the paper.

1 Introduction

Within the Air Traffic Management (ATM) community, there is strong interest in the performance of the ATM system [1, 2, 3]. This interest exists not only in terms of new developments, which is important to ensure that future demands on the ATM system can be met [2], but also in terms of performance monitoring, which is important to ensure that daily operations are carried out in a satisfactory way. For airports, this latter approach is addressed in programs such as Total Airport Management or TAM [4].

Performance is expressed within the context of the Single European Sky Air traffic management Research (SESAR) programme [2] by means of eleven Key Performance Areas or KPAs. This is based on the approach proposed by ICAO [1].

Until recently, operational concept validation questions were mainly related to the KPAs capacity and safety. Within the domain of airports, new concepts are being developed now that address deficiencies related to, for instance, the KPAs efficiency, predictability and flexibility. There is, however, no general consensus as to how they may be measured and this has resulted in different approaches to measuring them [1, 2, 3, 5, 6].

In addition to the above, addressing the performance of a system like the airport as a whole tends to be difficult [7]. A common procedure to analyse a large system is to decompose the system into subsystems and analyse each subsystem separately. This approach can result in difficulties to integrate the results for the separate subsystems so as to obtain a result for the system as a whole. Especially for *complex* systems, which are typically characterized by many interactions between subsystems, high uncertainties, and significant human involvement [8], this can be

problematic [9]. This problem is at the core of the HERBERT project, which is a project currently being carried out at EUROCONTROL and which this work is part of. The HERBERT project's aim is to explore a complex systems approach for modelling the ATM system.

This paper aims to develop a novel method to assess flexibility, predictability, and efficiency for the airport as a whole. To this end, the paper proposes to model the airport as a "complex, large-scale, interconnected, open, sociotechnical (CLIOS)" system using the method proposed in [8]. This is intended to help understanding the structure and behaviour of the airport system and is considered a necessary step before the performance of the airport can be described.

After the CLIOS model is presented, the paper defines in general terms the KPAs flexibility, predictability and efficiency for the airport as a whole, and not for subsystems. This is based on studying a wide range of literature and considering the nature of the airport system as illustrated with the CLIOS model. It is subsequently considered how these KPAs can be quantified.

A highly simplified but quantified simulation model of the airport will then be presented that is developed based on the airport CLIOS model. The current state of the airport simulation model will be demonstrated with some simple validation simulations. It will also be explained how it is intended to assess the performance of the airport as a whole in this new way using the simulation model.

2   Airport CLIOS Model

2.1   The Nature of the Airport KPAs

It can be expected that the airport KPAs will be influenced by a large number of factors in a way that may not necessarily be intuitive. This is because it is believed the airport can be considered to be a CLIOS system, which comprises not only the airside (directly linking to the rest of the ATM system) but also the landside, including for instance the passenger processes.

Also, the KPAs may not only be influenced by factors relating to the airport itself, but also by factors outside the immediate domain of the airport.

2.2   The Basic Form of the Model

A CLIOS model [8] in general shows the main elements in the system, the relationships between them, and the roles of actors in the system. Using the CLIOS approach, a so-called physical model of the airport system has been developed as shown in Figure 1. The relationships between the actors and the physical airport system are shown in Figure 2. The actors make up what is called in the CLIOS terminology the 'institutional sphere'. A solid-line arrow from one element to another indicates that the first element influences the second element in some way. A dashed-line arrow from an actor to an element means that the actor can influence this particular element.

The airport model has been constructed by identifying the actors, elements, and interactions that are thought important for airport operations. This is based mostly on [10], the EUROCONTROL ATM Process Model [11], and on expert discussions.

The CLIOS model developed so far provides only a starting point to understanding the behaviour of the airport system. It does identify important relationships that exist in the system but does not specify how elements and actors influence each other quantitatively.

2.3   Processes and Factors as Elements of the Model

The physical airport model consists of elements, using the terminology from the CLIOS approach. In this case, two different types of elements have been identified:

- *processes*, and

- *factors*.

We distinguish processes and factors by considering that processes take up system
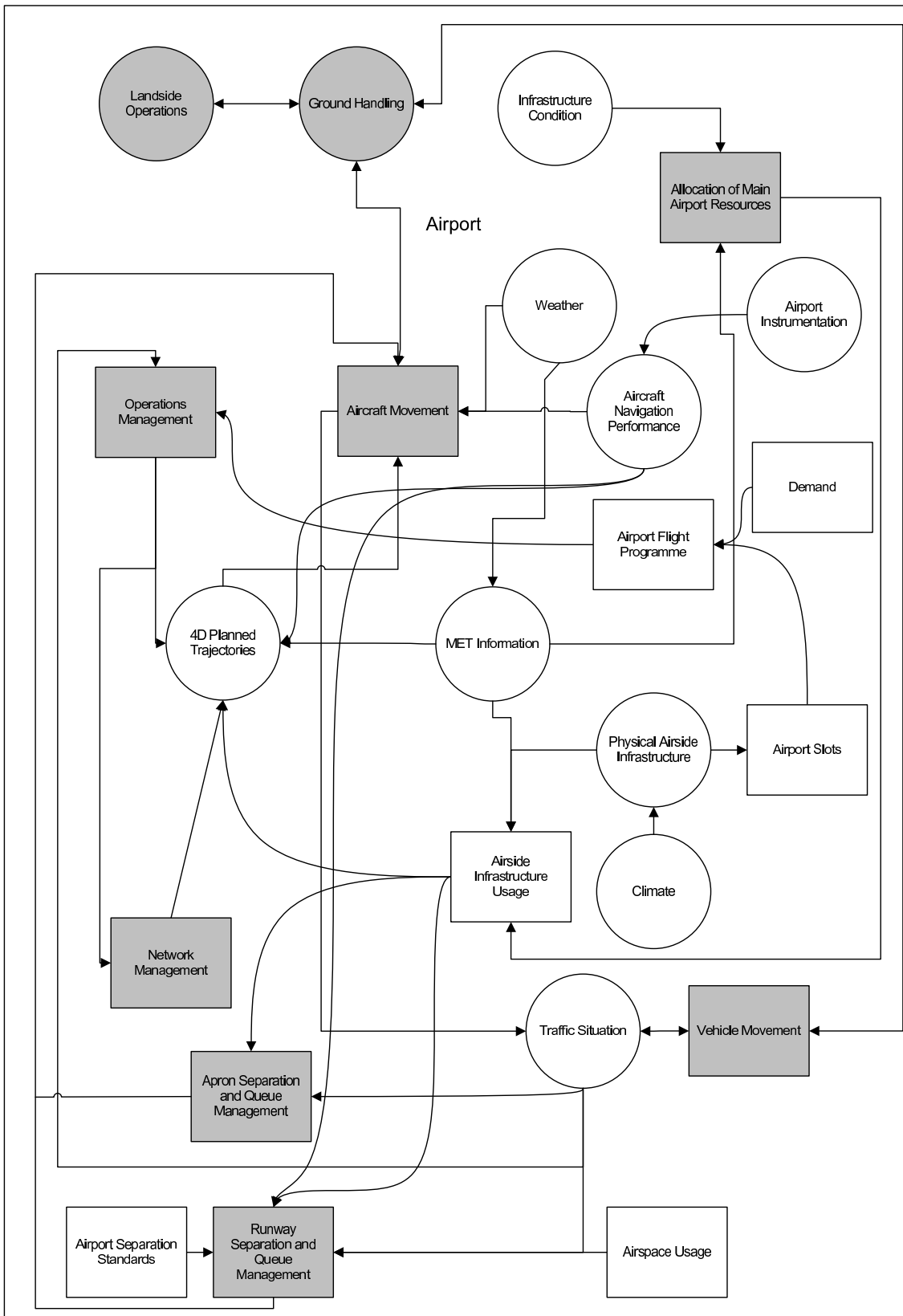
Fig. 1 Model of the Physical Airport Subsystem Using the CLIOS Process.

Fig. 2 Model of the Actors and the Physical Airport Subsystem.

Symbol	Meaning
Grey-filled shape	Process
Un-filled shape	Factor
Box	Element that can be directly influenced by an actor
Circle	Element that can not be directly influenced by an actor

Table 1 Symbols and Meanings.

resources, whereas factors do not. Table 1 shows how these are indicated in Figure 1 and Figure 2.

2.4 Concluding Remarks on the CLIOS model

It is concluded from the developed CLIOS model that many interactions between the elements in the airport system exist, that feedback loops exist, and that many human operators are involved. We conclude from this that a KPA describing the entire system should be developed based on a description of the system as a whole as opposed to descriptions of subsystems.

It is considered in [12] that demand-capacity balancing is the central process via which an airport functions, and that this process takes place at a number of different time horizons. It is considered here that this process of demand-capacity balancing will be carried out primarily in the form of allocating resources. The presence of many different processes in the airport system using resources (see Figure 1) clearly demonstrates the importance of resources. We hypothesize based on this that the allocation of resources will be the primary mechanism that drives the KPAs. It is anticipated that the CLIOS model can further help to identify which resources are involved in this mechanism and what their role is.

The following sections will aim to provide general definitions for the KPAs flexibility, predictability and efficiency for the airport system as a whole. It is aimed below to formulate the definitions on the basis of the hypothesis that the allocation of resources is the primary mechanism that drives the airport KPAs.

3 Flexibility

3.1 Definition

A wide range of literature has been studied, which include the domains of air transportation, information technology infrastructure, business processes, space systems, problem solving in education, behavioral psychology, complex systems, and nuclear science.

It appears that the most commonly used definition in literature of flexibility is: "the ability to change or react with little penalty in time, effort, cost, or performance" [13]. It was concluded in earlier studies also that the idea of minimal penalty is important for flexibility and that this idea is fundamental in most existing definitions of flexibility [13].

We propose to capture the element of low penalty by using the notion of changing 'effectively', meaning with low penalty. Also, the definition of flexibility denoted above does not make it clear what kind of change is meant or what the system reacts to. It is assumed here that flexibility is needed for the airport because the operational environment of the airport may change.

Taking into account that resource allocation is hypothesized to be the primary mechanism that drives the airport's KPAs, it is considered here that the airport reacts to the changes in its operational environment by allocating resources in a different way. We then propose the following definition: **flexibility is the ability of the airport to react effectively to changes in its operational environment by allocating resources differently**.

3.2 Quantification

It is concluded from the referenced literature that a range of system characteristics can indicate flexibility in the system, as detailed in [14]. From all these criteria, it is concluded that the fundamental factor behind all these characteristics is *the presence of knowledge about multiple, efficient strategies to solve problems* [15]. Here, the *efficiency* of a strategy refers

to the cost associated with implementing the strategy.

We aim to apply this approach to quantifying flexibility for the airport. A possible approach could be to measure the level of flexibility as the number of solutions to the equations that describe the system as a whole, which is similar to the approach taken in [16] for a linear system of equations. This work has not been further detailed yet but we expect that such an approach will allow to describe flexibility for the airport system as a whole, and not only for subsystems.

4 Predictability

4.1 Definition

Literature has been studied in the domains of air transportation, cognition, system behaviour, and chaos theory.

In the literature the following aspects are found to be important for predictability:

- System behaviour, meaning, for instance, if a system behaves in a linear way or chaotically [17, 18]

- The accuracy of predictions, such as for a planned or predicted 4D trajectory [2, 19]

- The variation present in the system, regardless of any predictions made [20, 6, 2]

- The propagation of disruption effects through the system (also referred to as stability) [2]

It is proposed to capture all the above aspects in the following definition: **predictability is the ability of making accurate predictions about the future situation**.

4.2 Quantification

Similar to flexibility, it is concluded from the referenced literature that a range of system characteristics can indicate predictability in the system. It is concluded in [14] from the literature

study that the fundamental factor behind these indications for the predictability of the airport system as a whole is *the strategy that the system's behavior follows*, similar to [17] and [18].

The strategy that a system's behaviour follows as discussed above may be described in different ways. In flight dynamics, for example, the aircraft's eigenmotions or characteristic motions are often studied [21]. The eigenmotions such as the phugoid, short period, and spiral mode are characteristic for the aircraft's behaviour in general.

In dynamic system theory, a similar approach is followed. A quantity called the Lyapunov exponent [22] has been developed that essentially measures how a disturbance to the system gets amplified or attenuated over time. A dynamic system can have multiple Lyapunov exponents and, similar to the eigenmotions for an aircraft, they characterise the system's behaviour in general. Particularly, the system's largest Lyapunov exponent is considered to measure the total predictability of the system [23]. In a similar way, we propose to measure the predictability of the airport system as a whole by calculating the largest Lyapunov exponent of the airport system.

5 Efficiency

5.1 Definition

In ATM, efficiency has been considered mostly to refer to delays and excessive fuel consumption due to flying a non-optimal trajectory [2, 20]. Within the ATM Airport Performance (ATMAP) project at EUROCONTROL efficiency was defined as 'acting or producing effectively with a minimum of waste, expense or unnecessary effort (good input to output ratio)' [7].

It is fairly common in other domains to consider that efficiency refers to Pareto [24] optimality [25, 26]. Essentially, this approach means that a situation would be efficient if it is impossible to improve the performance from one point of view without decreasing it from another point of view. This approach is similar to the ATMAP approach.

The difference between considering the effects of flying a non-optimal trajectory and considering Pareto optimality can be illustrated as follows. In some cases, for example, delays cannot be avoided in an operational sense because of excessive demand on for instance a runway. This would make the system automatically inefficient in the first approach, whereas it does not in the second.

Taking into account that resource allocation is hypothesized to be the primary mechanism that drives the KPAs, it is proposed here to use the following definition of efficiency: **efficiency is the degree of Pareto optimality of allocation of the airport's resources**.

5.2 Quantification

In the field of economics and building on the concept of Pareto optimality, it has been stated that an inefficient system contains a certain amount of *distributable surplus* [27]. In the field of economy specifically, this surplus can be seen as the set of mutually beneficial (or at least not harmful) trades between any parties that have not been undertaken [26].

Assessment of efficiency may then take the form of assessing the amount of distributable surplus in the system. Considering the hypothesis of the central role of resource allocation in the airport system, the amount of distributable surplus may be seen here as the amount of resources that are used unnecessarily, i.e., without which the system performs equally well or better. It remains to be studied how this surplus can be quantified for the airport system.

6 Airport Simulation Model

6.1 System Dynamics

The field of study that describes complex systems as a whole in a way that they can be analysed reasonable quickly and in a comprehensible way without going into the details at lower levels is the field of *system dynamics* [28].

A system dynamics simulation model of the airport will be developed here in order to explore the assessment of flexibility, predictability, and efficiency proposed above further and in a quantitative way.
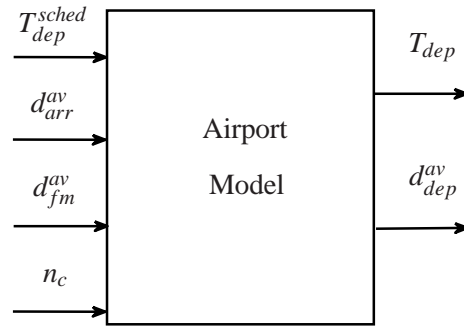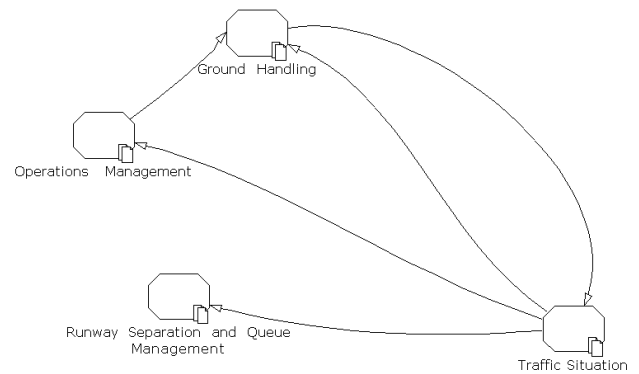

Fig. 3 Inputs and Outputs of the Airport Model.

Fig. 4 Top-level Diagram of the Airport Model.

The following sections will present the model, its current status and a simple validation.

6.2 The Current State of the Model

Currently, a highly simplified version of the airport CLIOS model has been implemented in system dynamics modelling software (Powersim Studio 8 in this case), which allows model-based simulations to be carried out.

The model currently takes as inputs the scheduled departure throughput (T_{dep}^{sched}), the average arrival delay (d_{arr}^{av}), the average flow management delay (d_{fm}^{av}), and the number of home-base carrier delayed arrival flights that are considered candidates for swapping with other
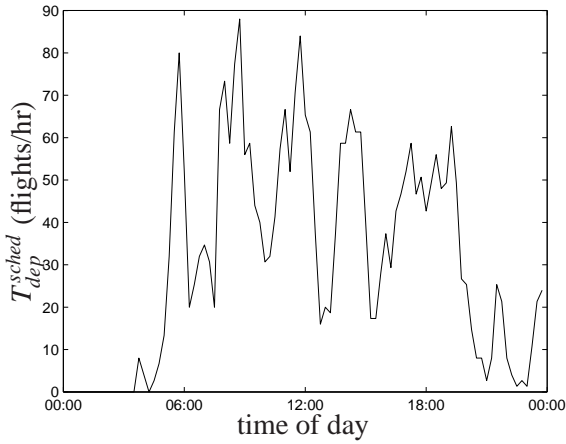
Fig. 5 Scheduled Departure Throughput.

Fig. 6 Recorded Average Arrival Delay.

flights (n_c). It produces the throughput (T_{dep}) and average departure delay (d_{dep}^{av}), as shown in Figure 3.

For the moment, the simulation model only includes the elements shown in Figure 4, which also shows the main relationships included. The quantification of the model is detailed in [14].

6.3 Traffic Sample

A set of recorded traffic data has been obtained to feed the simulation model, containing data from the Central Flow Management Unit (CFMU), the Central Route Charges Office (CRCO), and operators.

The data set contains real traffic data for Paris Charles de Gaulle airport for one day. For illustration purposes, the scheduled departure throughput T_{dep}^{sched} and average arrival delay d_{arr}^{av} as used for one day (11 May 2009) are shown in Figure 5 and Figure 6.

6.4 Validation

The recorded traffic data is also used to initially validate the simulation model, which is done by comparing output from the simulation model with the real data. In this case, this is done by comparing the actual and simulated throughput (T_{dep}) and average departure delay (d_{dep}^{av}). The results are shown in Figure 7 and Figure 8.
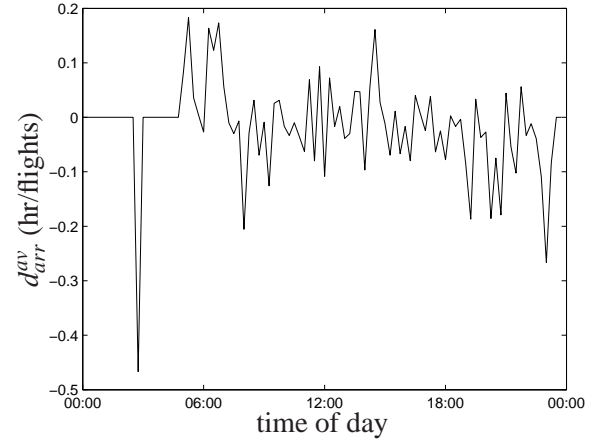

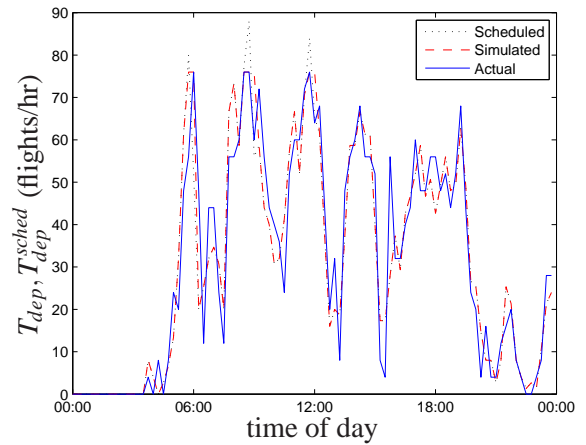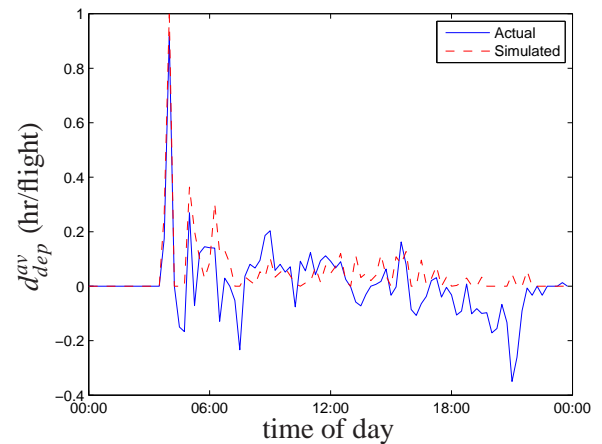**Fig. 7** Actual and Simulated Departure Throughput.

Fig. 8 Actual and Simulated Departure Delay.

From this preliminary analysis, it is concluded that the order of magnitude of the simulation results is appropriate. In fact, the simulation results are generally rather accurate. This is to some degree due to the significant effect that flow management delays, which are an input to the model, have on departure delays. For instance, the peak in departure delay around 04:00 hrs as observed in Figure 8 is almost entirely explained by flow management delays. Because flow management delays are an input, the simulated delay follows the actual delay well. It may also be noted that negative delays are not considered in the model.

6.5 Further Exploration of Flexibility, Predictability, and Efficiency with the Simulation Model

It is the intention that the simulation model will be further developed to explore the approach to performance assessment presented above.

For flexibility, this is expected to result in exploration of possible solutions to the equations that describe the airport system. For predictability, this is expected to result in assessment of the airport's Lyapunov exponents. For efficiency, this is expected to result in assessment of the amount of resources used unnecessarily.

7 Conclusions

A complex, large-scale, interconnected, open, sociotechnical (CLIOS) model of the airport system has been presented, describing the main elements and actors in the system and the main interactions between them. The model contains feedback loops and both airside and landside aspects.

Based on previous research and the CLIOS model, novel definitions for the airport's flexibility, predictability, and efficiency were proposed. Subsequently, a first step has been made towards developing methods to quantify these aspects of performance, following the proposed definitions. The major advantage of the approach followed in the paper is that it should ultimately overcome the difficulties of integrating the performance for subsystems into performance for the system as a whole.

A simplified simulation model of the airport system has been developed. Initial simulation results were obtained and a simple validation process shows the model produces appropriate results.

It is the intention that the simulation model will be further developed to explore the assessment of flexibility, predictability, and efficiency using a complex systems approach in a quantitative way.

Acknowledgments

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