A Proposal of a Framework for Measuring Airport Traffic Runway Parameters

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ABSTRACT: *A project in Europe called Endless Runway was carried out for which we proposed a modelling framework for the analysis of circular runway. We took some inputs from the project indicators and used the air traffic policies. We have considered the Petri Nets that use Stochastic process.*

Keywords: Modelling, Generalized Stochastic Petri Nets, Performance Analysis, Aircraft Traffic, Circular Runway

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1. Introduction

As the global economy is becoming more and more connected, passenger air travel is expected to maintain positive growth rates up to 2030, despite a number of challenges faced by the aviation industry, like the sluggish economic growth worldwide and the high jet fuel prices. It is believed that between 2017 and 2036, the number of airline passengers is expected to grow at a compound annual growth rate (CAGR) of 4.7%. More precisely, in 2017, global air traffic passenger demand increased by 7.5% on the year before, and by the end of 2018, traffic is projected to grow with another 6% [1].

Such intense dynamics in the demand poses quite new challenges vis-à-vis the operational performances of all affected players in the aviation sector, including aircraft manufacturers, aircraft operators, travel agencies, and especially the existing and future airports, which have to cope successfully with the ever-increasing number of flights.

2. The Concept of a Circular Runway

The concept of the circular or endless runway is not an entirely new idea. It has been explored since the early days of aviation. In France, the first circular take-off took place at the end of the 19th century. US Navy has launched such project back in the 1960s, and consequently, many successful landings and take-offs with propeller and jet planes were made between 1964 and 1965 [2]. However, commercial circular runways have never been built, nor tests with passenger aircraft have been conducted so far.

Recently, Dutch researchers have revived the concept of a circular runway, this time for civil airports, based on the idea of Henk Hesselink, senior R&D engineer in the Netherlands Aerospace Centre (NLR). Researchers at "the Endless Runway", a project funded by European Commission, believe circular runways could have several benefits, including being more environmentally friendly and less noisy [3]. The group proposes constructing a 3.5 km wide circular runway with banked sides divided into 18 runway segments, with an airport hub situated in the center of the circle, along with four terminals (A, B, C, and D) with total capacities of 81, 81, 66, 66 planes, respectively. The length of the circular runway would be equal to three straight runways while being able to handle the air traffic of four. Circular runways will allow planes to land and take off at any point in the circle. Pilots will be able to land in directions with the most favorable weather conditions while avoiding difficult maneuvers and situations such as strong crosswinds. The circular design will also mean aircraft coming into land circle above the airport fewer times, thus using less fuel. The design allows for three planes to land and take-off at the same time. Because of the centripetal forces, aircraft will automatically go slower and move towards the center of the runway. Circular runways could also limit noise pollution by spreading it more evenly around the airport. Besides, they take up a third of the space of typical airports, making them better for both the environment and travelers. It is also noteworthy to mention that the Netherlands Aerospace Centre aims to make it a reality by 2050, which could revolutionize air travel.

3. Generalized Stochastic Petri Nets

Generalized Stochastic Petri Nets (GSPNs) [4-5] are recognized as a widely-known tool for performance analysis of distributed systems, which utilizes the graphical notation introduced by ordinary Petri Nets (PNs). In GSPNs some transitions are timed, whilst others are immediate. Random, model. GSPNs are isomorphic to semi-Markov processes, i.e. their quantitative analysis can be performed on a reduced Embedded CTMC (Embedded Markov Chain, EMC), defined solely on a set of tangible states, or by reducing the GSPN to an equivalent Stochastic Petri Net (SPN) [5]. The stationary distribution of the underlying stochastic process is usually a basis for obtaining a plethora of performance metrics, like calculating the probabilities of specific state conditions, resource utilization, expected throughputs, expected number of clients (active resources), expected waiting times, etc. On the other hand, transient analysis is a basis for investigating the system behaviour over time, i.e. it describes the evolution of the observed system at a given time and thus it can be used for obtaining specific performance metrics such as probabilities of reaching particular states and probabilities of satisfying assigned deadlines [5].

4. The Proposed GSPN Simulation Model

The concept of the endless runway has been already evaluated using simulations. Three different areas have been identified to be evaluated, including the runway itself, the surrounding terminal maneuvering area (TMA), and the ground movement area (GMA). For the runway, a special simulation tool was set up by Office National d'Études et de Recherches Aérospatiales (ONERA) to optimize the usage. The TMA was simulated with TrafficSim, a Deutsches Zentrum für Luft- und Raumfahrt (DLR) in-house solution, whilst the GMA was implemented and evaluated in Simmod Pro!. All three areas have been evaluated separately by the used simulation tools. Different parameters like delays or capacities have been used to get the first glimpse into the feasibility of the concept [6].

The proposed GSPN-based simulation model is not aimed to replace the existing specific in-depth simulation models that deal strictly with the technical aspects of the implementation and the feasibility of the concept. It is rather intended to serve as a framework for carrying out performance analysis of the aircraft traffic dynamics, taking into account the known input parameters, including aircraft arrival rate (λ), aircraft departure rate (μ), total capacities of the particular terminals (C1, …, C4), aircraft mean landing delays ($1/\rho$), aircraft taxiing delays from the eighteen runway entry points towards particular terminals ($1/\varphi$) and vice-versa ($1/\beta$), aircraft mean waiting times at particular terminals ($1/\varepsilon$), aircraft mean waiting times to take-off ($1/\omega$), aircraft mean take-off duration ($1/\theta$), mean duration of aircraft movements at ground level ($1/\delta$), etc. Our approach is based on the assumption that the circular runway airport can be viewed as a complex Discrete-Event Dynamic System (DEDS), where activities belong to five phases: (1) Aircraft arrivals and landings; (2) Aircraft taxiing from landing points to airport terminals; (3) Aircraft operations at airport terminals; (4) Aircraft taxiing from airport terminals to departure points; (5) Aircraft take-offs and departures. In addition, since such DEDS is characterized by discrete (countable) state space and events in the presence of concurrency, cooperation, synchronization, blocking etc. vis-à-vis queuing, servicing, and routing of aircraft, a convenient formalism for their representation and performance evaluation is the class of GSPNs. Due to the complexity of the proposed solution, the GSPN model is divided into five sub-models, one per phase.

Figure 1 depicts the activities related to phase #1. Aircraft arrivals follow the Poisson distribution with an arrival rate of λ

(transition *T_arrival*). When ready to land (a token in the place *P_ready_to_land*), the arriving plane has to choose a single entry point *Ri* out of 18 possible ones (transitions *T_choose_entry_Ri*, i = 1, …, 18). However, since maximum three planes are allowed to take-off or land simultaneously (place *P_max_planes*), a plane will be allowed to start landing (place *P_start_landing_Ri*) only if the chosen entry point *Ri* is clear (a token in the place *P_Ri_clear*) and there are no more than three planes in the air (the place *P_max_planes* is nonempty). Otherwise, the transition *T_stay_in_air* will be enabled, and the plane will have to stay in the air (transition *T_circling*) until the landing conditions are met. After the landing (firing of a transition *T_landing_Ri*), a single token is put back into the places *P_max_planes* and *P_Ri_clear*, for the chosen *i*, i.e. *Ri*. The durations of landings and the circling of planes in the air are assumed to be exponentially distributed with means of $1/\rho$ and $1/\nu$, respectively.

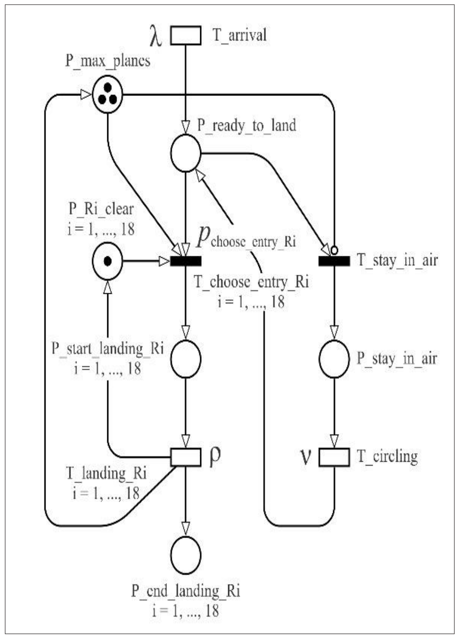

Figure 1. GSPN sub-model of aircraft arrivals and landings (phase #1)

After landing at a chosen entry point *Ri* (i = 1, …, 18), denoted by a token in the place *P_end_landing_Ri*, a plane starts taxiing to a chosen airport terminal *Tj* (j = 1, …, 4), as depicted in Figure 2 (phase #2). This would be possible only if the capacity of the chosen terminal, *Cj* (j = 1, …, 4), is not exhausted (i.e. the place *P_Tj_capacity* is not empty). The taxiing to the chosen terminal *Tj* is assumed to take an exponentially distributed time with a mean of $1/\varphi$. The firing of the transition *T_taxiing_to_Tj* for the chosen *j* puts a single token into places *P_start_waiting_Tj* and *P_move_from_Tj*: a token in the first one denotes that the plain will reside at the chosen terminal *Tj* for an exponentially distributed time with a mean of $1/\varepsilon$ (transition *T_waiting_Tj*), whilst a token in the second one will allow a plane to move from the current terminal to another one during the next phase.

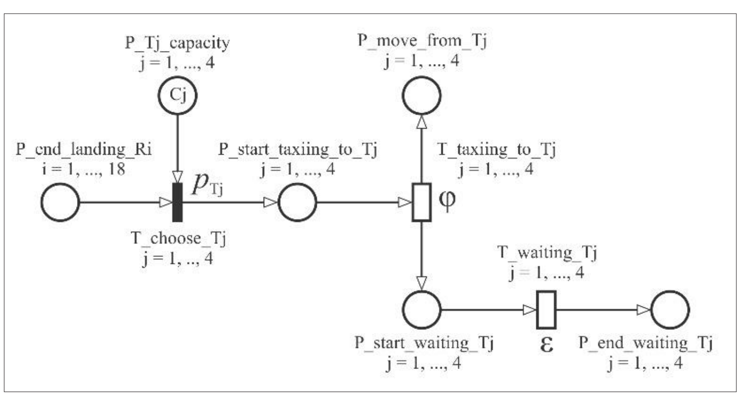

Figure 2. GSPN sub-model of aircraft taxiing to airport terminals (phase #2)

Phase #3 describes aircraft activities at ground level. Figure 3 describes the GSPN segment explicitly related to the terminal T4. Corresponding logic has to be applied for terminals *T*1, *T*2, and *T*3. After residing at the terminal *T*4 for a certain amount of time (a token in the place *P_end_waiting_T4*), each plane can move either to another terminal (transitions *T_move_T4_T1*, *T_move_T4_T2,* and *T_move_T4_T3*), or stay at the current one (transition *T_move_T4_T4*). Each moving from T4 to other terminals takes away a single token from places *P_move_from_T4* and *P_Tk_capacity* (k = 1, 2, 3). Choosing to stay at T4 takes away a single token solely from the place *P_move_from_T4*. Moving from a given terminal to another one takes some time, exponentially distributed with a mean of 1/δ (transitions *T_move_T4_to_Tk*, k = 1, 2, 3). The firing of any of these transitions puts a single token back into the place *P_T4_capacity*, as well as into the place *P_start_departure_Tk*, for a chosen k (k = 1, 2, 3).

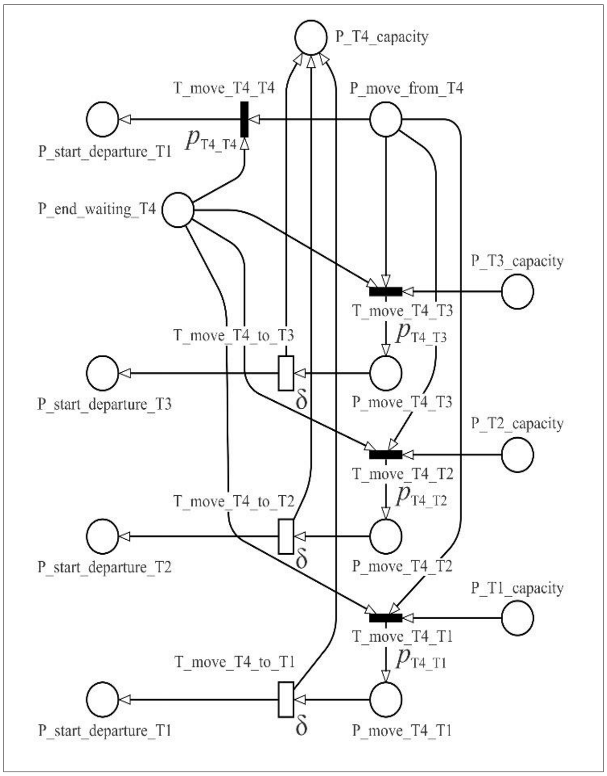

Figure 3. GSPN sub-model of aircraft operations at airport terminals, for the airport terminal T4 (phase #3)

During phase #4, planes departure from any of the four terminals (a token in the places *P_start_departure_Tj*, j = 1, …, 4). The exponential transition *T_departure_Tj* (j = 1, …, 4) fires with a departure rate of μ (Figure 4). First, for any given terminal *Tj* (j = 1, …, 4), departing planes choose an exit point *Ri* (i = 1, …, 18), by firing the corresponding immediate transition *T_choose_exit_Ri* with a probability of p_{choose_Ri}. Next, the plane starts taxiing to the chosen exit point (place *P_start_taxiing_to_Ri*, i = 1, …, 18), an activity that lasts, on average, 1/β. Because more than one plain can consequently choose a particular exit point *Ri*, they will be represented by an equivalent number of tokens in the place *P_wait_for_takeoff_ Ri*. Besides, each firing of the exponential transition *T_taxiing_to_Ri* for a chosen exit point *Ri* puts a token back into the place *P_Tj_capacity* for a given terminal *Tj* (j = 1, …, 4), meaning that a plane has left the terminal and waits in a queue to take-off at the circular runway.

Planes wait for a take-off at an exit point *Ri* (a token in the place *P_wait_for_take-off_Ri*) an arbitrary time that is exponentially distributed with a mean of 1/ω, until the chosen exit point is clear (a token in the place *P_Ri_clear*), as shown in Figure 5 (phase #5). As soon as the last condition is met, the take-off from the exit point *Ri* starts (a token in the place *P_start_take-off_Ri*, i = 1, …, 18), but only if the number of tokens in the place *P_max_planes* is non-zero (i.e. if there are at most three planes landing or taking-off on the circular runway at the moment). The duration of the take-offs is exponentially distributed with a mean of 1/¸ (transition *T_take-off_Ri*, i = 1, …, 18). The firing of this transition puts a single token back to places *P_max_planes* (to denote that the plane has flown away) and *P_Ri_clear* (to denote that the entry/exit point *Ri* is clear for

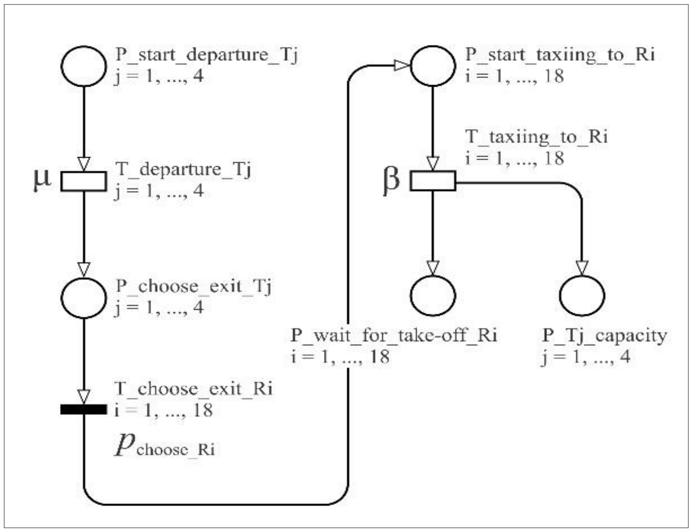

Figure 4. GSPN sub-model of aircraft taxiing from airport terminals (phase #4)

future landings/take-offs), for a particular terminal *Tj* (*j* = 1, …, 4) and chosen exit point *Ri* (*i* = 1, …, 18). It also puts a single token into the place *P_end_departure_Ri*, for the chosen *Ri*, to denote that a departure of a plane has occurred at the exit point *Ri*. In order to avoid cumulating tokens in the place *P_end_departure_Ri*, it is connected to an immediate transition *T_departure* with an arc having a multiplicity of #*P_end_departure_Ri*. In such a way, tokens are immediately removed from the places *P_end_departure_Ri*, *i* = 1, …, 18.

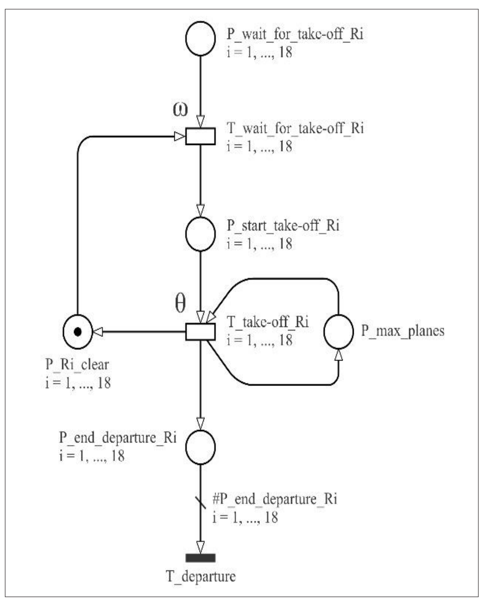

Figure 5. GSPN sub-model of aircraft take-offs and departures (phase #5)

5. Conclusion

The operation of commercial airports with circular runways in terms of aircraft traffic dynamics is highly complex. The existence of multiple stochastic processes justifies its treatment as a DEDS, characterized by discrete (countable) state-space and a number of events, each lasting for a random time. The complexity found among various DEDS components suggests considering the evolution of such system as a stochastic process that can be used to assess its performance. Since stochastic processes can be successfully captured and described by the wide gamut of stochastic Petri nets, the class of GSPNs has been chosen as a modelling formalism, mainly for several reasons: (1) Arrivals and departures of aircraft follow the Poisson distribution, where inter-arrival and inter-departure times are exponentially distributed with parameters λ and μ, respectively. As such, the underlying stochastic process is a Continuous Time Markov Chain (CTMC), which is also an underlying stochastic process of GSPNs; (2) GSPNs are often used for modelling and evaluation of transport and traffic systems; (3) In order to keep the model structure as simple as possible, the durations of all events are supposed to be random times, exponentially distributed, i.e. the times between events conform the Poisson process where events occur continuously and independently at constant average rates; (4) The methodology for an analytical solution of GSPNs is well known and documented; (5) There are multiple dedicated software packages today, like TimeNET, GreatSPN, or WebSPN, that offer both modelling and numeric simulation/evaluation of GSPNs.

The proposed GSPN-based modelling framework is quite complex, and that was the reason for its partitioning into submodels by particular phases. Each GSPN sub-model, corresponding to a particular phase, can be analyzed either as a stand-alone part or in conjunction with other sub-models. The proposed solution can be successfully utilized for obtaining numerous performance measures vis-à-vis the circular runway airport traffic, including the average number of planes waiting at the terminals, the average number of planes at the airport, the average sojourn time of planes at terminals, the average so journ time of planes waiting for takeoff, the utilization of the airport, etc. All of these can be evaluated against different values of the arrival (λ) and departure (μ) rates. Besides the performance evaluation, it can be successfully utilized for addressing additional critical issues related to the circular runway airport, such as correctness analysis, reliability evaluation, design optimization, scheduling (performance control), monitoring & supervision, traffic efficiency, implementation, system tuning, bottleneck identification, workload characterization, capacity planning, forecasting the performance at future loads, evaluation of airport design alternatives, etc.

Validation, as a process of checking whether the specification of the proposed solution captures the actual customer's needs, is an extremely subjective process. As per verification, all the activities vis-à-vis the production of a high quality performance evaluation model (testing, inspection, analysis etc.) can be carried out by using dedicated software.

The limitation of the proposed modelling framework is that the GSPN-based model does not make any difference between two major classes of aircraft regarding their size, as being originally anticipated within the project. This could be accomplished by utilizing the class of Colored Petri Nets (CPNs). Yet another limitation of the proposed solution is that, structurally, it does not take into account particular stands at any of the four terminals (294 in total). The inclusion of such information will significantly improve the accuracy of the simulation model, but it will also make its structure extremely complex and, possibly, computationally intractable due to the state-space explosion.

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