MODELING OF TURNAROUND PROCESS USING PETRI NETS

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ABSTRACT

The paper presents a model of the aircraft turnaround process at airport apron. Airlines have an interest for an efficient and reliable turnaround process which allows them to maintain schedules. The process should also be as fast as required so that aircraft are flying rather than sitting on the ground, incurring losses and extra costs. This is the reason why the turnaround process needs to be studied, planned and executed in an efficient manner.

This turnaround process model has been developed to investigate different resource allocation strategies (aircraft stands, equipment, personnel, etc.) and sensitivities to perturbations, their possible prevention or mitigation of their effects. The model is a rather sophisticated one, using Petri nets as a powerful tool for modeling and simulating discrete processes with concurrent events. This type of model could also easily be incorporated into a larger scale model of airport operation. The model's capabilities are illustrated using real life examples from the Belgrade airport.

KEYWORDS**:** Petri Nets, modeling, aircraft turnaround, ground handling

INTRODUCTION

Delays of aircraft turnaround process have direct negative effects on airlines incurring losses by decreasing aircraft usability[1] and generating extra costs like non-productive fuel consumption, labor costs, maintenance costs, passenger compensation costs[2], etc. As the latest study on propagation of air transport delays shows, between 40% and 50% of delays in Europe are actually reactionary or knock-on delays and in some cases an initial delay can increase up to tree times trough propagation of delay **(Jetzki, 2009)**. Therefore it is crucial to predict their primary occurrence (up to 70% are related to turnaround process **(EUROCONTROL, 2009))** and determine possible cause in order to prevent or mitigate their effects. Airport and air traffic control operations are also affected by delays of turnaround process causing schedule disruption and therefore decreasing capacity utilization efficiency.

The aim of research presented in this paper was to develop a model of the aircraft turnaround process at airport aprons in order to investigate its sensitivity to changes of available resources (aircraft stands - gates, equipment, personnel, etc.), aircraft arrival delays, as well as different gate assignment strategies. As ground operation must be performed with limited number of crew and equipment, which is often shared by several gates, there is typically a concurrence of turnaround processes at an apron. Because of the concurrent nature of turnaround process, Petri Nets were employed as very powerful tool for modeling and simulating discrete systems with concurrent events. The specific class of Petri Nets used in this research is the Hierarchical Stochastic Colored Timed Petri Nets.

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[1] usually described as reduction of airline productivity

[2] include handling and accommodation costs, reimbursements (ticket refunds), rebooking costs, expenses for meals, refreshments, etc incurred by loss of passengers connections as result of delay **(Jovanovic, 2006).**

The proposed model can be helpful at a number of operational levels. On a tactical and implementation level such model can be used to ensure stable and smooth operations under particular configuration (exact traffic data, amount of resources, etc), while at strategic and pre-tactical level (main purpose) it can be used to point out the critical features of the operations, like bottlenecks, deadlocks, interdependencies, etc. and therefore help in designing measures to prevent or mitigate possible negative effects. Additional value of the model is reflected in the fact that it can be carried out at any level of details and modularity, and could be easily added to some broader model of airport operation (airside and/or landside).

The organization of the paper is as follows. The first section contains general definition of Petri Nets. Then the description of aircraft turnaround process is presented, followed by a model of the system. In the last section the model's capabilities are illustrated using real life examples from the Belgrade airport and conclusions are drawn and discussed.

1. PETRI NETS

By definition Petri Nets (PNs) are a graphical and mathematical modeling tool. Graphical representation of PNs model consists of a network formed by *places*, *transitions* and *arcs*. They also have a formal, mathematical representation with a well-defined syntax and semantics. However, for the practical use of PNs, it suffices to have an intuitive understanding of the syntax and semantics.

The structure of PNs (see Figure 1) is represented by a directed bipartite graph made up of *nodes* (places and transitions) and arcs (directed arrows). Transitions (t) represent events that should take place or operations to be carried out, and are usually displayed as rectangles. Places (p) represent the cause/result of the events, but also can be a buffer which stores information or other resources required for the execution of operations. Places are graphically displayed as circles or ellipses. Arcs (a) run from a place to a transition or vice versa, but never between two nodes of the same kind. Each arc is associated with a natural number called *weight* or *valuation function* (if omitted it is assumed to equal 1). According to PNs structure it appears that PNs are state- and action-oriented language, because it gives an explicit description of both possible states and possible actions **(Jensen, 1997)**.

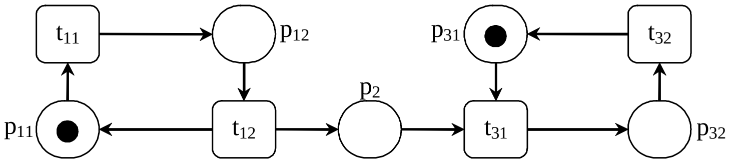

Figure 1: Petri Nets example with initial marking M_0

In following formal definition, based on **(Jensen, 1997)**, Petri Nets is fourt-tuple *(P,T,A,W),* where:

$P=\{p_1, p_2,..., p_n\}$ set of places,

$T=\{t_1, t_2,..., t_n\}$ set of transitions,

$A\subseteq(P\times T)\cup(T\times P)$ set of arcs,

$W: A\rightarrow \mathcal{N}$ valuation function,

$\mathcal{N}$ is the set of natural numbers, $P\cap T=\varnothing$ and $P\cup T\neq\varnothing$.

Each place in PNs can contain one or more *tokens*. The distribution of tokens on the places of a network defines the state of the system at a given moment of time and is called a *marking* (M). A change in net marking represents the change in a system state which is the result of a sequence of transition firings. A transition is said to be *enabled* and may *fire* if each *input place* (place that is connected with transition by input arc) contains tokens equal to or greater than the input arcs weight. When enabled transition fires, tokens equal to input arc weights are removed from each input place while new tokens equal to output arc weights are added to each output place. Net on Figure 2 represent system state after transition t_{11} in marking M_0, showed on Figure 1, fires.

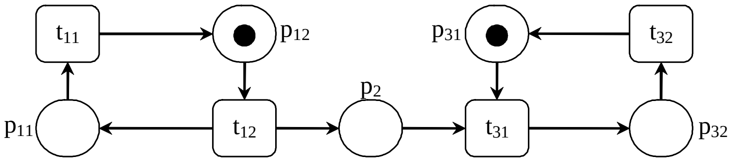

Figure 2: Petri Nets example with marking M_1

The dynamic behavior of modeled system is described by the following dynamic properties, which can be used to investigate the logical correctness of a modeled system i.e. to verify a model:

- Reachability – gives answer to where certain marking M_N is reachable from the initial marking M_0;
- Coverability – shows all distinct markings reachable from initial marking M_0 during net evolution (occurrence graph);
- Boundedness – a PN is said to be bounded if number of tokens in any place does not exceed a finite number k for any marking reachable from M_0. This property is very useful during the net verification phase, especially when some places are used to model resources. By checking that the net is bounded, it is guaranteed that there will be no over-flows in resources **(Abbas-Turki et al. 2004)**;
- Liveness – a Petri Net is said to be live if doesn’t contain deadlocks. Deadlock is a state of the system, represented by certain marking M_N, where there are no enabled transitions;
- Reversibility – a net is reversible if the initial marking M_0 is reachable from all possible markings i.e. states of the system.

Although the original model of PNs is often sufficient to model real systems, the practical use of PNs to describe complex systems has clearly demonstrated a need for a more powerful net type. Over the years many PNs extensions (usually called high-level Petri Nets) emerged and their development continues. Some of them, used in this research, are as follows:

- **Coloured Petri Nets (CPN) – (Jensen, 1997)** Contrary to classic (low-level) PNs, tokens may be differentiated in CPN by equipping each with a *colour*. It makes PNs possible to handle additional information or data, without making the net structure more complex. Although the net structure is still made up of places, transitions and arcs, the *net inscriptions*[1] in CPN become more complex: arc valuation functions will no longer be simple natural numbers but complex functions whose results take into account the colour of input tokens; guard function can be attached to transitions; etc.
- **Timed Petri Nets (TPN) –** In order to evaluate the performance of a system it is convenient to specify how different activities ‘consume’ time. This is done by introducing transition delay i.e. time between removal of input token and creation of output token.
- **Stochastic Petri Nets (SPN) –** This PNs extension allows the assignment of probabilities to net inscription.

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[1] Various text strings attached to the elements of the net structure defining their behavior

- **Hierarchical Petri Nets –** This PNs type introduce a structure in the net so that a number of individual nets, called pages, are related to each other in a formal way. It is a very suitable way to represent complex systems, especially ones that contain repetitive sequences of action.

2. DESCRIPTION AND MODELING OF THE TURNAROUND PROCESS

The turnaround of an aircraft comprises the sequence of ground operations required to service the aircraft between two flights, from the time the chocks (rubber blocks to prevent aircraft from moving) are put in front of the wheels after it lands, to the time the chocks are removed and the aircraft is ready to depart. There are a number of key activities carried out during an aircraft turnaround such as: air-bridge positioning/removal, passengers deplaning/boarding, potable water, galley and lavatories service, cabin cleaning, unloading/loading baggage and/or cargo, aircraft refueling, etc. It should be noted that the servicing arrangements and turnaround tasks vary for different aircraft and different operators (ground handlers). While some activities cannot start before others ends (sequential activities), there are activities which can be done simultaneously (concurrent activities). For example, at some airports, for safety reasons, aircraft refueling cannot start before all passengers have left the cabin; it is physically impossible to load baggage before the end of unloading process; oppositely, galley and lavatories services can be performed simultaneously. Therefore, turnaround process has to be performed according to certain schedule in order to both meet the safety requirements and make the process as efficient as possible.

Based on the duration[1] of turnaround tasks and task-schedule it is possible to calculate, using the *Critical Path Method* (CPM) or other methods, idealized time required to complete turnaround process of an aircraft. Figure 3 shows one sequence of dependent ground service activities, forming the so-called *critical path*, which determines the length of a turnaround process. *Schedule buffer time*[2] (t_s) included in the ground time is used for compensation of time losses due to operational disruptions of a turnaround process or other delays.

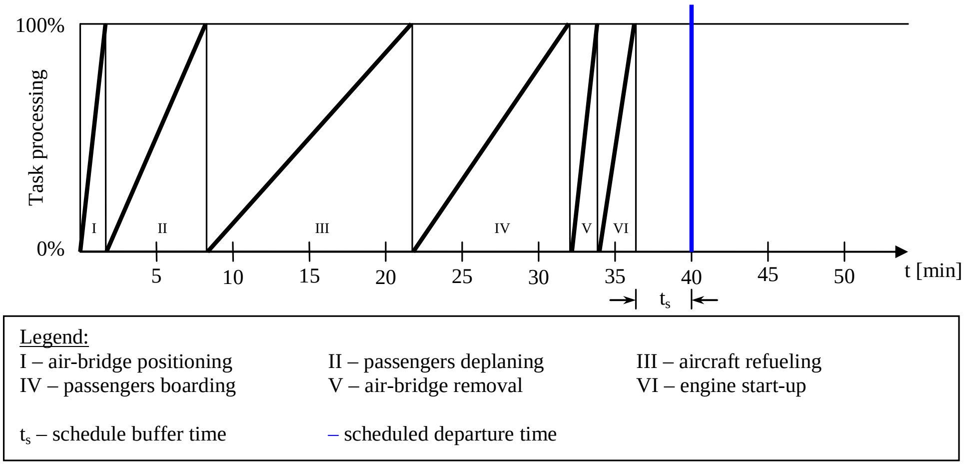

Figure 3: Turnaround process critical path

Operational disruptions to turnaround process such as: equipment failure, lack of labor and/or equipment, missing checked-in passengers, late checked-in passengers, late baggage and cargo, etc, lead to extension of turnaround activities and may influence the departure

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[1] Idealized duration is published by aircraft manufactures in the “Airplane Characteristics for Airport Planning Manual”, for each aircraft type, with certain assumptions (load factor, number of luggage per passenger, amount of fuel to be refueled, etc.)

[2] Time difference between scheduled turnaround completion moment and scheduled push-back moment

punctuality of turnaround aircraft only when total duration of service activities on critical path exceeds the scheduled turnaround time plus scheduled buffer time. In an example shown at Figure 4, fuel tank failure caused t_d time units extension of refueling process and turnaround process as a whole (taking into account that refueling activity is on critical path, see Figure 3). Since disruption time is greater than the scheduled buffer time, it caused departure delay equal to t_Σ time units ($t_\Sigma = t_d - t_s$). In another example (Figure 5), a delay of cabin cleaning activity causes the change of turnaround process critical path and therefore extends the process. However, since duration of realized turnaround process is less than scheduled duration of turnaround process plus buffer time, cabin cleaning delay will not cause departure delay.

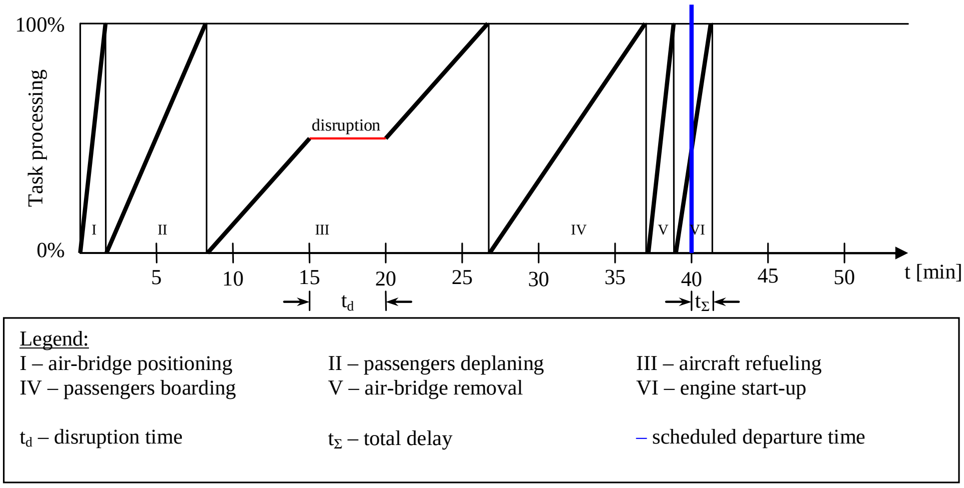


Figure 4: Change in turnaround process critical path (fuel tank failure)

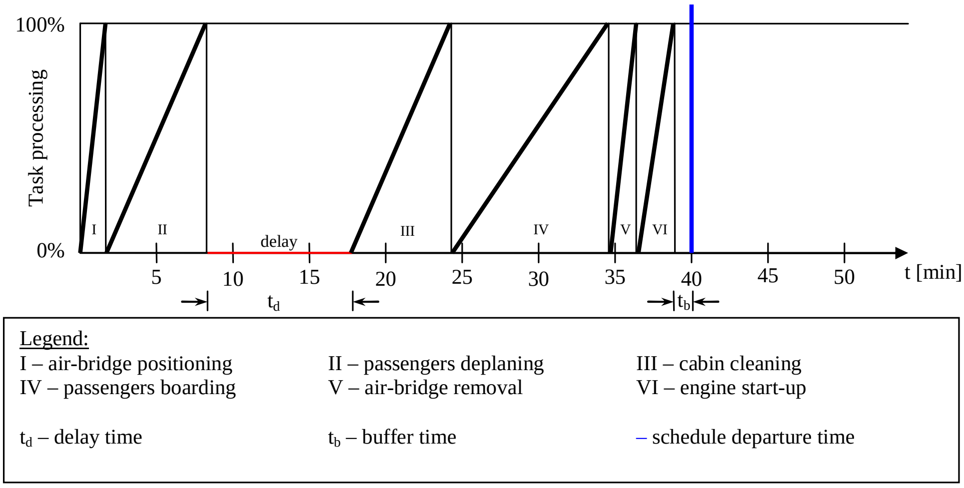


Figure 5: Change in turnaround process critical path (delay of cabin cleaning)

Delays due to aircraft turnaround process have adverse impact not only on airlines but also on airports which is of main interest in this paper. Due to high demand for airport slots, some airports (major hub airports) are working at the limits of their capacity. In such conditions, delay of turnaround process of an aircraft can cause disturbance in handling other aircrafts (e.g. gate has been occupied longer than planned, and the next aircraft is not able to park). In addition, hub airports affect dozens of other airports through reactionary delays and in 56% of cases an initial delay returns to hub airport after first delayed flight **(EUROCONTROL, 2009)**. This line of reasoning was a motivation for development of modular and flexible turnaround process model, containing both sequential and concurrent activities, in order to comprehend effects of operational disruptions of turnaround process on aircrafts departure punctuality as well as on airport operations.

Although it is beyond the scope of this paper, it should be noted that the apron turnaround system is not an independent system. Many of turnaround activities are coupled with the rest of airport and airline systems, and therefore gate departure delay is not only influenced by individual turnaround processes but also by delay occurring in the rest of the system.

2.1. Conceptual model of the system

After landing, aircraft taxis toward apron and aircraft stands. Stop bar, located at the entrance of the apron, was chosen to be the boundary of the system. At the stop bar aircraft waits until the allocated aircraft stand and apron taxiway are free, before it can continue with parking procedure. After aircraft is parked and chocks are put, turnaround process begins. When aircraft turnaround is finished and aircraft is ready to leave according to schedule (departure time has come), aircraft pilot contacts ATC and waits for the clearance to begin push-back procedure. Aircraft leaves the modeled system at the exit of the apron.

On the basis of simulation model description a conceptual model is developed.

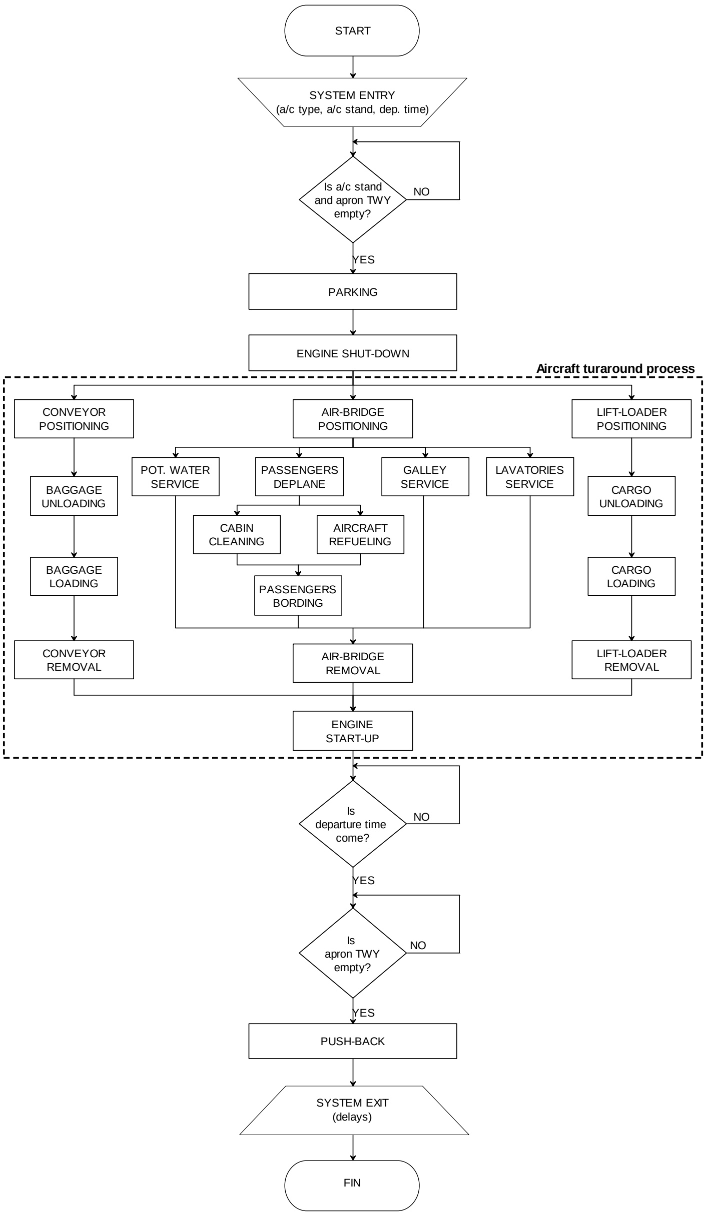


Figure 6: Conceptual model of the system

2.2. CPN model of the system

CPN model of turnaround process is structured in three hierarchical levels, as shown at Figure 7.

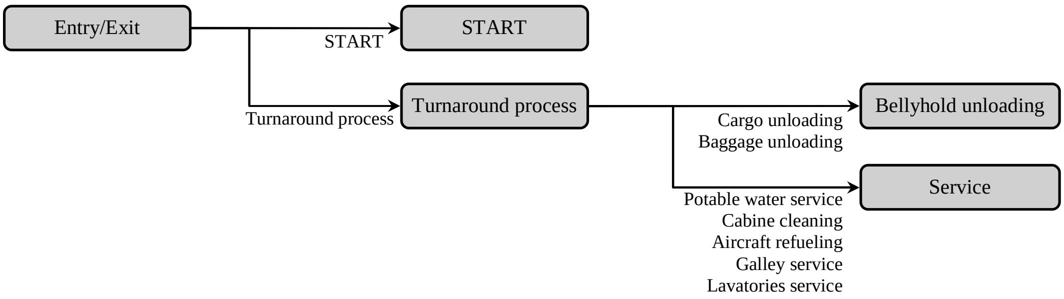


Figure 7: Hierarchical graph of CPN model of turnaround process

At the highest hierarchical level there is a supernet called **Entry/Exit** (Figure 8) which models: aircraft arrival (entering the system), parking, entering turnaround process queue, push back and departure (leaving the system). In Figure 8 elliptical places represent the state of aircraft in the system, while round places represent resources. At the beginning of simulation an ‘initial marking’ is set by loading data such as *daily operational plan* (DOP) and available equipment (resources) from input files. In the initial marking each token in place called ‘Incoming aircrafts’ represents one aircraft in DOP and contains information of schedule arrival time, aircraft type, allocated stand, schedule departure time, but depending on the simulated scenario it may contain other information too: number of passengers onboard, baggage, cargo, etc. Aircraft enter the system at the stop bar located at the entrance of the apron (hereinafter called point A). Parking procedure can begin, and transition representing this activity can fire, only if apron taxiway and allocated stand are free i.e. if places ‘apron TWY’ and ‘Empty stands’ contain required tokens. Otherwise a queue of aircraft is formed at the point A. Aircraft are served by FIFO rule, which means that aircraft which arrived later have to wait for preceding aircraft to be parked before they can continue, no matter their allocated stands may already be free. When an aircraft is parked and engines are shut-down, the turnaround process can begin. This state is represented with place ‘Aircraft ready for turnaround’. After the turnaround process is finished and the aircraft is ready to leave according to schedule, the push-back procedure can begin if apron taxiway is free; if not a departure queue is formed (place ‘Aircraft ready to leave’). Aircraft leave system at the point A.

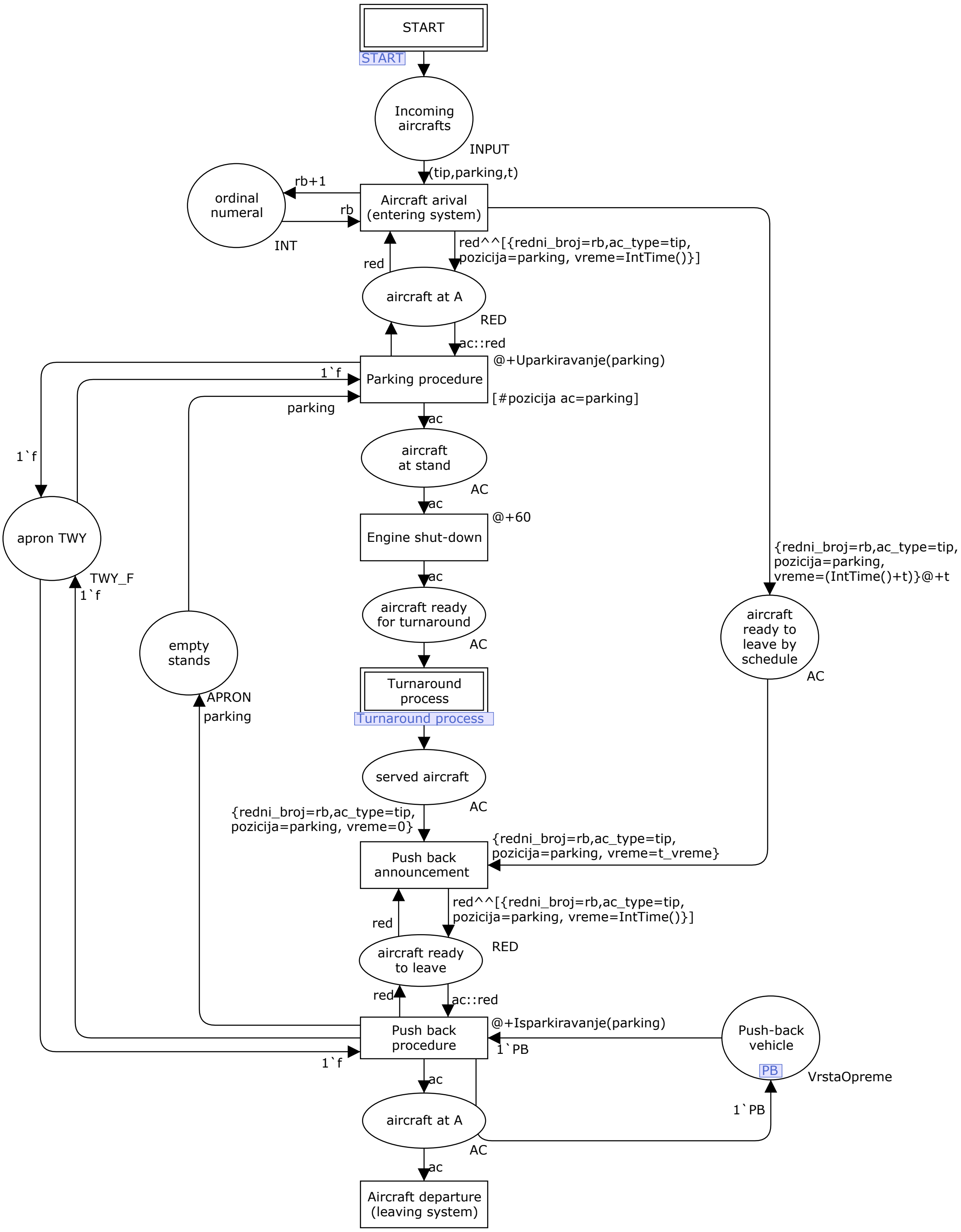


Figure 8: Supernet Entry/Exit

Supernet is connected with two subnets labeled **START** and **Turnaround process**. Subnet **START** is an auxiliary net used for data input (DOP and available resources) from the input files. The other subnet of hierarchy level 2, called **Turnaround process,** models all activities of aircraft turnaround process and it is connected with two hierarchy level 3 subnets: **Service** and **Bellyhold unloading**, which models ground service and cargo/baggage handling activities in detail.

3. ILLUSTRATION OF THE MODEL APPLICATION

Application of the CPN model of turnaround process is illustrated on a Belgrade airport case. Based on real life traffic data, an increased traffic sample has been created in order to test system performance and sensitivity to perturbations. During this research two experiments and several scenarios were defined and were all simulated using the same traffic flow, shown at Figure 9. Each line at Figure 9 represents one aircraft with scheduled arrival and departure time.

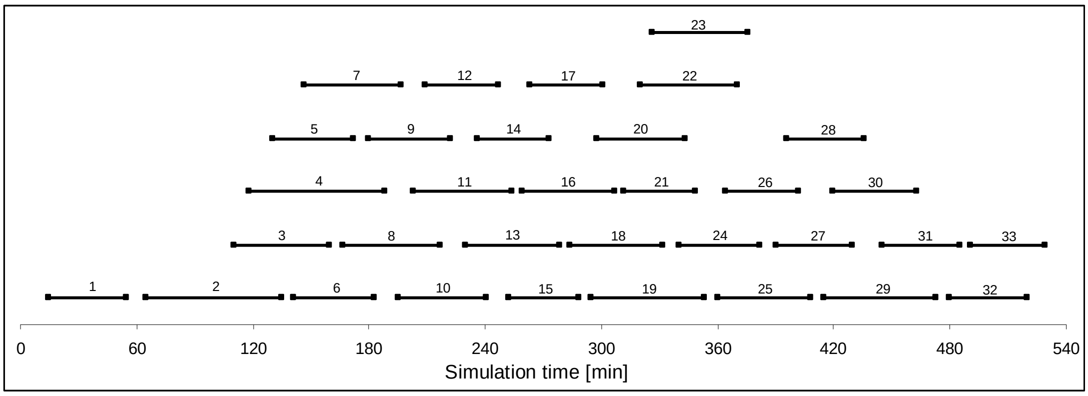


Figure 9: Generated traffic example

Experiments differ in terms of gate-assignment strategy. In the first experiment gates were dedicated to aircraft according to gate assignment plan, while in the second experiment gates were automatically assigned during aircraft arrival. Each scenario is designed to illustrate possible applications of the model in airport operations.

Scenario1 is a baseline scenario and it considers turnaround process as idealized deterministic reliable system with unlimited availability of ground handling equipment (as much as needed and as long as needed). Hence, it is obvious that all operations are performed according to plan and there are no delays in this idealized system. Although this is a largely unrealistic assumption, it can nevertheless be used to estimate the required volume of ground equipment for a given traffic volume, and for staff planning process. Figure 10 shows that maximum of four galley service equipment were employed during simulation. Taking into account maximum number and distribution of employed equipment, the airport planning division can decide on the sufficient volume of equipment and ground crew needed for given traffic.

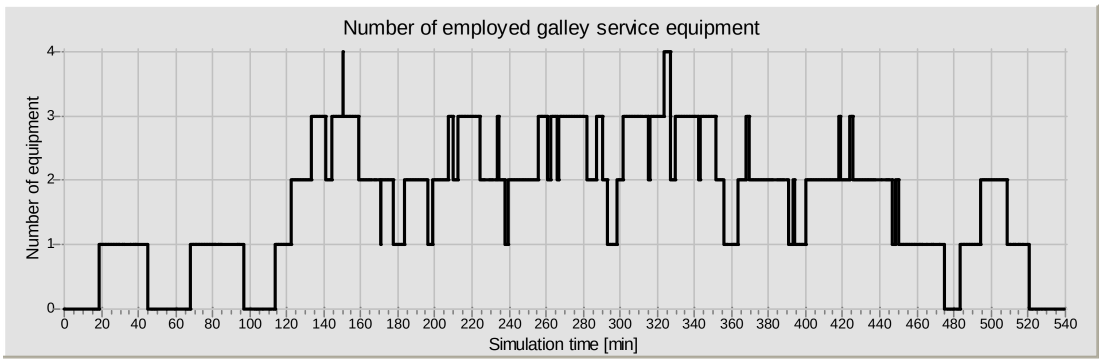


Figure 10: Scenario1 – Distribution of employed galley service equipment

Scenario2 assumes lack or failure of ground handling equipment, in order to foresee its effect on airport operations. Figure 11 shows airport traffic flow in the case where three galley service equipments were employed. Taking into account that galley service is not on the critical path of the turnaround process, it is obvious why there are no delays have arisen (scheduled and actual departure times equals).

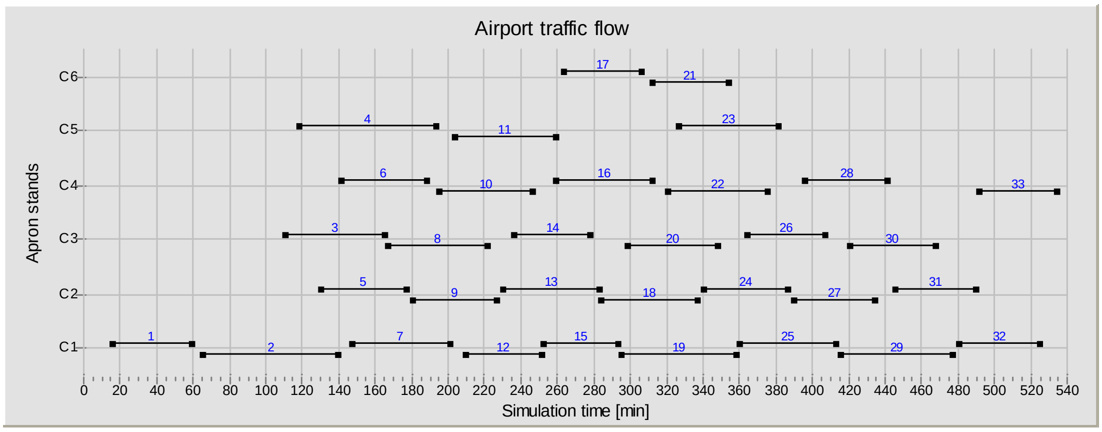


Figure 11: Scenario2 – Airport traffic flow

On the other hand, Figure 12 shows disruption of aircraft number 7 turnaround due to lack of fuel tank which lasted 20 minutes and caused more than 15 minutes departure delay (red line represents delay of turnaround activity and blue vertical line scheduled departure time; each activity is labeled with its number). It also caused departure delay of aircraft number 12 although its turnaround process was performed according to the schedule (Figure 13). In total, the lack of fuel tank caused 97 minutes of turnaround delay of all aircraft, while total departure delay was 317 minutes.

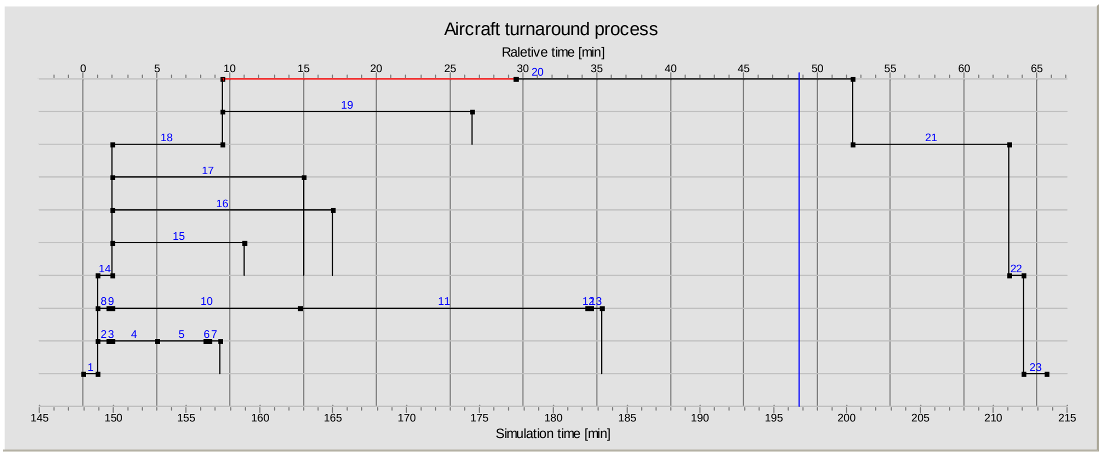


Figure 12: Scenario2 – Aircraft number 7 turnaround

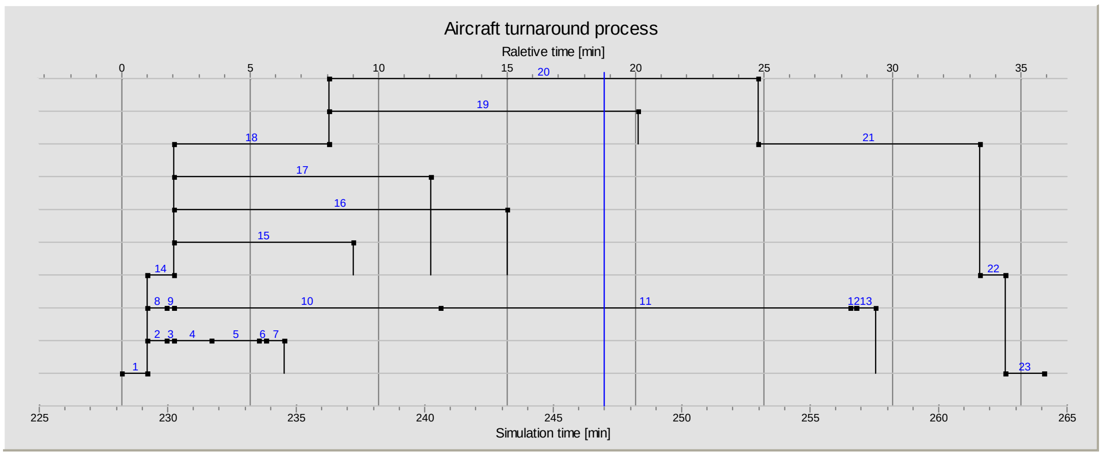


Figure 13: Scenario2 – Aircraft number 12 turnaround

Scenario3 assumes aircraft arrival time as a random variable with uniform distribution (scheduled time +/- 5 minutes). There are no delays of turnaround process, in order to investigate only effects of random aircraft arrival time on airport operations. Due to small variation of arrival time, much of arrival delay (35 minutes in total) was compensated trough turnaround process and 8 minutes of total departure delay were encountered.

Scenario4 assumes variable passenger deplaning and boarding time, aiming to reflect different situations which can arise in practice, such as different number of passengers onboard, late checked-in passengers, late transfer passengers etc. Figure 14 shows traffic flow from which it can be seen that arrival (parking) delay of some aircraft (yellow color) is caused by departure delay of others (red color; caused by extension of turnaround process).

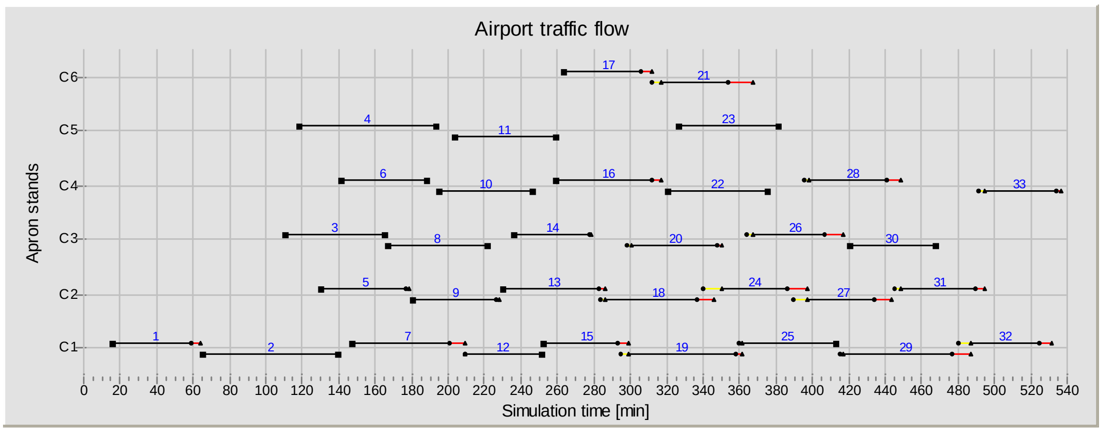
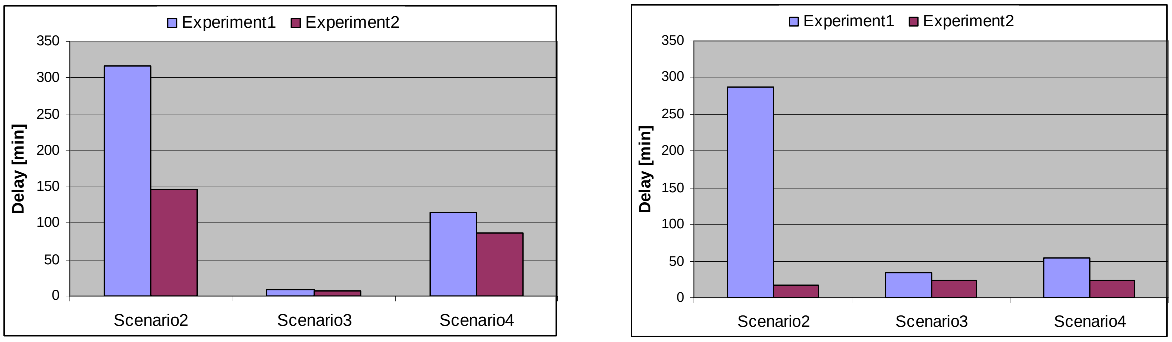


Figure 14: Scenario4 – Airport traffic flow

Finally, through analysis it has been clear that gate-assignment strategy where gates are dedicated to aircrafts according to gate assignment plan leads to additional delays when operations are perturbed. Figure 15 shows that departure delay for each simulated scenario is always smaller when using automatic assignment strategy (experiment2) than using strict gate assignment strategy (experiment1). It also shows that arrival delay (including parking delay) is influenced by the gate assignment strategy. This is of great importance, especially at hub airports where most of the passengers are transfer passengers whose inbound flight delays will cause delays of outbound flights (this is however beyond the scope of this research as landside operations were not modeled). Beside positive effects of automatic assignment strategy it should be noted that the change of gate assignment close to aircraft arrival will usually result in a longer turnaround (need to transfer outbound baggage, cargo and passengers, etc.).



Departure delay **Arrival delay**

Figure 15: Comparison of experiment1 and experiment2 simulation results

CONCLUSIONS

This paper presented the development of aircraft turnaround process using Petri Nets. The motivation for the development of this model was to comprehend and measure the effects of operational disruptions of turnaround process on airport operations. Model application capabilities are illustrated on Belgrade airport case. Simulated scenarios were intended to show that the developed model can be used at tactical and implementation phase as well as at strategic and pre-tactical level. Other than that, the model could also be used to investigate effects of structural (construction of new gate, taxiway, etc.) and organizational changes to airport operation. In addition, the aim was to make a model which could easily be added to some broader model of airport operation (airside and/or landside).

Finally, this research reconfirms the potential of Petri Nets, as a powerful tool for modeling systems with sequential and concurrent activities. Additional advantage is that performance of the system can easily be evaluated over wide range of system parameters.

REFERENCES AND BIBLIOGRAPHY

[1] Abbas-Turki A., Bouyekhf R., Grunder O. and El Moudni A. (2004), “On the line planning problems of the hub public-transportation networks”, International Journal of Systems Science, vol. 35, number 12, 10. October 2004, pp.693-706

[2] EUROCONTROL (2009), “Performance Review Reports – PRR 2008”, Performance Review Commission, Brussels, May 2009

[3] Feron E., Hansman R. J., Odoni A. R., Cots R. B., Delcaire B., Feng X., Hall W. D., Idris H. R., Muharremoglu A., and Pujet N. (1997), “The Departure planner: A conceptual discussion”, Massachusetts Institute of Technology, Cambridge, December 1997

[4] Jensen K. (1997), “Coloured Petri Nets”, vol. 1, second edition, Springer, February 1997

[5] Jetzki M. (2009), “The propagation of air transport delays in Europe”, PhD Thesis RWTH Aachen University, published by EUROCONTROL, Brussels, December 2009

[6] Jovanović R. (2006), “Effects on airline delay costs of delayed passengers”, MSc Thesis, University of Westminster, London, 2006

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