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CPN-SIMULATION METHODOLOGY FOR THE BOARDING PROCESS OF AIRCRAFT

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ABSTRACT

The boarding process of an aircraft is one of the identified bottlenecks in the turnaround when the aircraft arrives to an airport. The present article presents a methodology that models the key aspects of a boarding process using coloured Petri nets in order to understand in detail what are the main micro-dynamics and cause-effect relationships that hinder the smooth boarding process. Then the different models are integrated at a different level using a discrete-event program to simulate in detail the boarding process. The combination of both techniques reinforce mutually in such a way that the development process is very efficient for developing micro-models when the dynamics are difficult to understand. This kind of approach can be used for testing different boarding configurations and improve the efficiency of the studied process while reducing the cost associated to the process.

Keywords: simulation, discrete event simulation, coloured petri nets, aircraft boarding process

1. INTRODUCTION

The turnaround of an aircraft is the temporary space between consecutive flights when the aircraft is in the airport. Depending on the type of company, the time and space available, the turnaround will be more or less long (Bazargan 2004). Furthermore this length will depend upon the business model of the company as all flight schedules are different and the operations vary from business model to business model. In addition, the times of the ground handling operations result very difficult to homogenise due to the different factors that influence the operations such as handling agents, congestion at the airside, etc.

The steps followed by a typical stopover of an aircraft are:

- Prior preparation for boarding: the lines of passengers are organised and all their hand luggage and documentation is checked.
- The plane arrives at the parking stand.
- Block-In is performed.
- The passengers and bags disembark.
- The plane is fuelled.
- Whether there is a scheduled cleaning, the cleaning team will proceed to clean the plane.
- When the last passenger leaves and the cleaning services have finished, the passengers for the next flight shall be boarded. Simultaneously the bags shall start to be loaded for the new flight.
- During the boarding of passengers, the coordinator shall deliver the necessary documentation to the captain.
- As soon as the plane is loaded with fuel, bags and passengers, the doors are closed.
- The chocks are removed.
- The plane performs the taxiing towards the corresponding runway for the take-off.

The business model of the low cost carriers (LCC) forces them to take out some of the operations in order to reduce turnaround times and thus making them more competitive. For this reason the boarding/deboarding operations acquire more and more importance since those operations are the ones that consume most of the time when the aircraft is performing the stopover. Figure 1 illustrates the different processes that compose the turnaround of an aircraft (Airbus 2014).

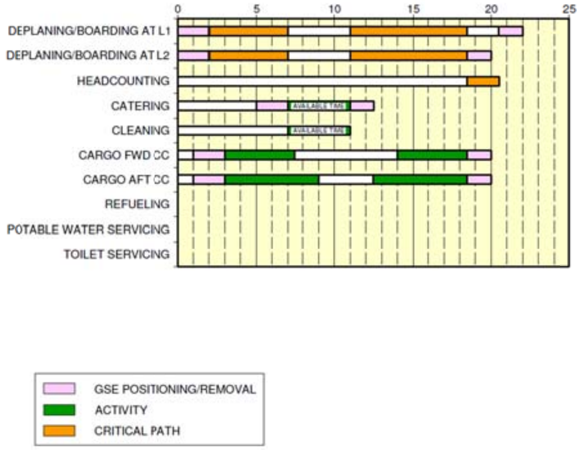


Figure 1: The outstation turnaround time for the A-320

From Figure 1 it can be noticed that the boarding and deboarding operations are currently in the critical path. Therefore in order to make the operations more profitable it is necessary to reduce the turnaround operations.

The current paper presents a methodology that will be useful for improving the boarding process using a combination of coloured Petri nets with simulation.

1.1. Review on Boarding Operations

Different authors have put focus on ways to improve the boarding process. Most of them put their efforts in managing the seats and the schedule of the boarding process in the best possible way. Some of the initial efforts for testing the seat scheduling are the ones presented by Marelli, Mattocks, and Merry (1998). These authors simulated the allocation of seats by two different states (On-Off). Using this approach they analysed the results when the boarding is performed using a window, middle aisle (WILMA) scheme. Their conclusion is that the boarding time can be decreased compared to a random assignment boarding. That experiment was followed by defining a different one for the WILMA BLOCK, which uses the same approach but enhanced with separating the boarding in blocks, first the ones at the back, then the ones in the middle, and then those in the front.

Another relevant study is the one presented by Van Landeghem and Beuselinck (2002), through the use of EXCEL and ARENA they simulated some scenarios and conclusions were drawn from the discrete event approach focusing mainly on the boarding time.

Other authors have put focus on policies that could help reduce the boarding time and they use different techniques to test their policies. One interesting example is the work done by Steffen (2008), in which he finds the optimal allocation of passengers using an approach that uses Markov Chains and Monte-Carlo Simulation. Furthermore Soolaki et al. (2012) present an approach that models the problem using linear programming and genetic algorithms. Finally, Steffen and Hotchkiss (2012) tested different configurations using a real-size fuselage of a Boeing 757 for improving the use of the aisle to reduce the boarding time.

The review performed reveals that most of the studies have used different modelling techniques ranging from abstract models developed using linear programming to real-size sets that try to copy the real boarding situations. In the previous years the studies focused mainly on the boarding strategies while in recent years scientific community is paying more attention to the main drivers that are behind the processes that could reduce the boarding times. These drivers are inherent to human nature such as age, companions, family relationships, passengers with bags, disabilities, and even psychological conditions. For these reasons the researchers are investigating with scenarios that are as close as possible to a real situation. However real-size experiments cannot be performed anytime the researcher wants because they are expensive and it would result difficult to coordinate all the needed elements. This situation puts in evidence the need for the use of digital models that allow the researchers to integrate more characteristics that play a role in the process and result close to real situations. The paper will focus on a methodology that avoids using the traditional abstract approaches such as Monte Carlo simulation or linear programing. Instead, the approach goes one step further using coloured Petri nets (CPN) together with simulation for integrating in a straight forward way the characteristics that play an important role in the boarding process and at the same time allowing the modeller to integrate as much elements as needed.

2. CPN-SIMULATION APPROACH

In this paper CPN is used together with simulation for developing a methodological approach that allows modellers to cope with the inherent complexity present in systems whose performance depend on multiple factors. The advantage of using a modelling formalism with the simulation approach is that the different micro-dynamics can be easily understood and the simulation model can be developed in a structured fashion. Different situations, such as the ones present when the passengers with bags must allocate them in the upper compartments of the cabin, or those that appear when the passengers already sit block the ones that need to sit in the same section, can be modelled in a structured way resulting in a more reliable and robust simulator.

2.1. Coloured Petri Nets

Coloured Petri Nets is a simple yet powerful modelling formalism that allows to properly modelling discrete-event dynamic systems that present a concurrent, asynchronous and parallel behaviour (Moore and Gupta 1996; Jensen 1997; Christensen, Jensen, Mailund, and Kristensen 2001). CPN can be graphically represented as a bipartite graph which is composed of two types of nodes: the place nodes and the transition nodes. The entities that flow in the model are known as tokens and they have attributes known as colours.

The formal definition is as follows (Jensen 1997):

$$CPN = (\sum, P, T, A, N, C, G, E, I) \tag{1}$$

where:

- $\sum = \{C_1, C_2, \dots, C_{nc}\}$ represents the finite and not-empty set of colours. They allow the attribute specification of each modelled entity.
- $P = \{P_1, P_2, \dots, P_{np}\}$ represents the finite set of place nodes.
- $T = \{T_1, T_2, \dots, T_{nt}\}$ represents the set of transition nodes, such that $P \cap T = \phi$, which normally are associated to activities in the real system.

- $A = \{A_1, A_2, \dots, A_{na}\}$ represents the directed arc set, which relate transition and place nodes such as $A \subseteq P \times T \cup T \times P$.
- N is the node function $N(A_i)$, which is associated to the input and output arcs. If one is a place node then the other must be a transition node and vice versa.
- C is the colour set function, $C(P_i)$, which specifies the combination of colours for each place node such as $C : P \rightarrow \Sigma$:

$$C(P_i) = C_j : P_i \in P, C_j \in \Sigma \qquad (2)$$

- G is the guard function, associated to transition nodes, $G(T_i)$, $G : T \rightarrow EXPR$. It is normally used to inhibit the event associated with the transition upon the attribute values of the processed entities.
- E is the set of arc expressions, $E(A_i)$, such as $E : A \rightarrow EXPR$. For the input arcs they specify the quantity and type of entities that can be selected among the ones present in the place node in order to enable the transition. When it is dealing with an output place, they specify the values of the output tokens for the state generated when transition fires.
- I is the initialization function, $I(P_i)$. It allows the value specification for the initial entities in the place nodes at the beginning of the simulation. It is the initial state of a particular scenario.
- $EXPR$ denotes logic expressions provided by any inscription language (logic, functional, etc.)

The state of every CPN model is also called the *marking*, which is composed by the expressions associated to each place P and they must be closed expressions i.e. they cannot have any free variables.

3. THE CPN-SIMULATION APPROACH

A discrete-event system (DES) model has been developed in which the micro-operations such as identifying a person in the block seat, moving forward-backward, putting the luggage on the overhead compartment, or defining different attributes for the type of passenger that board the aircraft are based on the CPN modelling formalism. The advantage of developing a DES simulation model based on the CPN model is that the different micro-operations that vary depending on the type of passenger are clearly identified and therefore a robust simulation model can be developed, which would be too complex for a DES simulator alone. The CPN elements have been mapped and implemented using the technique presented by Mujica and Piera (2011). Following the same logic, the simulation model has been developed using the software SIMIO.

The CPN model models the different interactions that a passenger experience when they are boarding the aircraft. The initial interactions modelled are the ones that appear when a passenger needs to sit in his respective seat and he is blocked by passenger that previously have arrived. These relations are modelled using the CPN model and they illustrate that if more interactions are identified then is just necessary to modify the respective transition in the CPN model and then implement it in the simulator. After the interactions have been identified and modelled with the CPN model then the implementation in the simulation model is straightforward.

As it has been mentioned, the interactions modelled are the ones at the seat-level in the aircraft. The relations will be implemented in a model of the seat of the aircraft and the total simulation model will be constructed using the simulation program and replicating the seat models so that a final model of the cabin is obtained. Figure 2 illustrates the methodological approach.

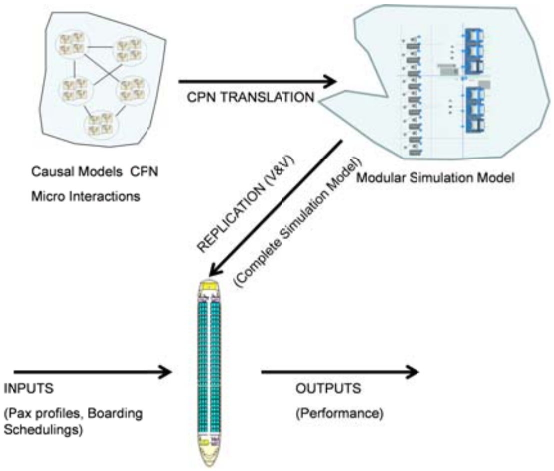


Figure 2: The methodological Approach

The CPN model of the seat-interaction is composed by 16 transitions and 3 place nodes. The definition of colours is presented in Table 1.

Table 1: Colour Definition and Description

Colour	Definition	Description
X	Integer	It describes the row number of the seat block
Y	{000, 001, 010, 100, 011, 101, 111}	It describes the seats occupied by the passengers
Z	Integer	It represents the amount of people waiting in the aisle for the passenger to sit.
R	Integer	It represents the row where the passenger is supposed to be sat.
W	{001, 010, 100}	It represents the seat location of the passenger.
D	{0,1}	It represents if the waiting person is seated in the middle.

The information related to the place nodes is presented in Table 2.

Table 2: Definition of Place Nodes

Place	Colour Set	Description
S	Product X*Y	This place represents the information of the left block of seats of one row of the cabin.
W	Z, D	This place holds information about the passengers standing up and waiting for the passenger to sit.
P	Product R*W	This place holds the information of the passenger.

The following figures present examples of the different transitions that compose the model. These transitions are grouped in the transitions that model the different sitting situations that a passenger can face when boarding a plane. The remaining interactions are modelled taking advantage of the characteristics of the simulation program once the replication of the modules has been performed.

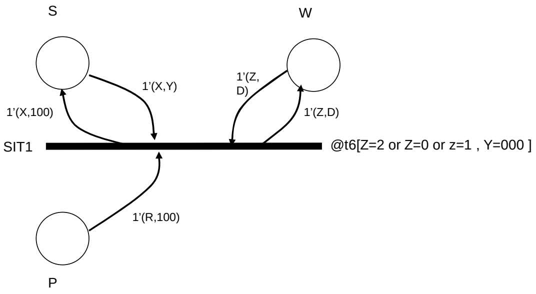


Figure 3: Transition for Sitting

Figure 3 illustrates the situation when a passenger has to sit at the window and the row of seats is empty. This situation is modelled by the value of the colour W for the passenger (W=100). In this example 100 means that the passenger seat is the one in the window and the other two are not his (using a binary coding). The value of the variable Y is 000 which represents that the row is empty and the value of the colour Z can be either 2, 1 or 0. For this situation the result is the same, either no one is waiting for the passenger to sit or there are passengers that stood up for letting the passenger reach the window (Z=1 or Z=2) . In this example the corresponding time consumption can be associated to the value of the variable t6, but it would depend on the correspondent study and maybe on the characteristics of the passenger sitting. Once the passenger is sat, the new colour value for Y is assigned with the output arc to S (Y=100).

Another example is presented in Figure 4, which represents the situation in which a passenger must sit at a window seat (W=100) and the middle seat is occupied by another passenger (Y=010) who was previously sat and must walk out to let the former reach his window seat.

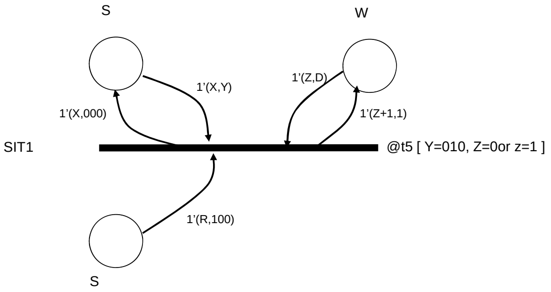


Figure 4: The Walking Out of a Passenger Seated in the Middle

In this model a unit is added to the colour Z of the token in the waiting place node and the variable D turns to 1; in this way track is kept for the number of passengers waiting until the correspondent passenger is seated. Once this event takes place the correspondent person has left the middle seat (Y=000) and the corresponding time consumption is modelled by the value of t5. For the remaining transitions the authors encourage the reader to contact them but using the same logic the model can be developed.

Using the CPN approach it is possible to identify clearly the cause-effect relationships that sometimes hinder the smooth flow of passengers inside the cabin during the boarding or deboarding process. Moreover the colours can also be used to model characteristics such as age, size, number of bags, disabilities etc. and those characteristics can be used to simulate in a more accurate way the micro-processes that generate emergent dynamics once the people is interacting with each other.

4. IMPLEMENTATION OF THE CPN MODEL

The CPN models can be integrated with the software tool making a mapping or implementing some logic such as the one presented by Mujica and Piera (2011). In this example the micro-simulation of the interaction present in the system is implemented following the methodology previously presented. Since the software uses an object-oriented modelling paradigm the simulation of the complete cabin is performed efficiently. As it has been mentioned, firstly, the different transitions of the CPN model are used to develop the modular object that represents a row inside the cabin. Secondly, advantage is taken from the use of a modular approach when the different rows of the cabin are put together in order to make a complete model for the cabin that takes into account not only the micro-interaction between passengers but also the interaction that occurs at higher levels e.g. aisle blocking, speed reduction duo to the passengers, etc.

Figure 5 illustrates the elements used in the module that simulates the interaction of people at seat-level. The methodology proposed by Mujica and Piera (2011) is used to implement the different transitions that occur during the seating process. The transitions implemented in the model are evaluated using the *Separator* objects from SIMIO. The elements are configured in cascade using *Connectors* so that the logic associated to each object (CPN transitions) is evaluated at once and only those transitions that satisfy the different restrictions are fired thus performing the simulation with high accuracy. In Figure 5 the *TransX* objects correspond to transitions 1 to 10 and the logic behind each transition is implemented using the processes window of SIMIO.

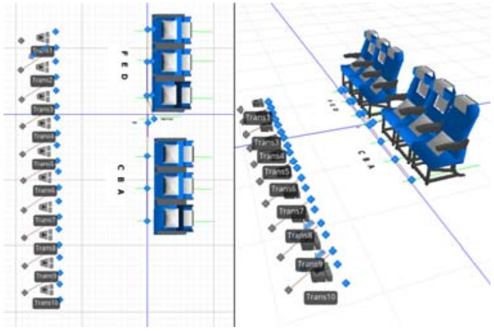
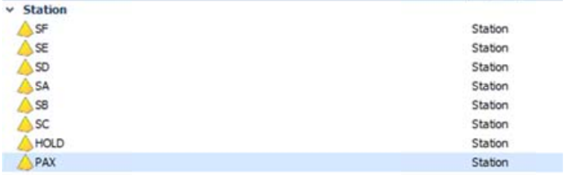


Figure 5: The Elements of the DES Software Model

Some SIMIO elements are used to model the place nodes and transition nodes. As mentioned earlier, the logic behind the transition nodes is coded using different *steps* within the *Processes* windows from SIMIO and the place nodes are modelled using the elements called *Stations.* Figure 6 presents the different stations used in the object; some of these stations are just used to store the entities that simulate that passengers sat in the cabin seats. Other stations, namely *HOLD* and *PAX*, are used to represent the place nodes *W* and *P* of the CPN model, respectively.



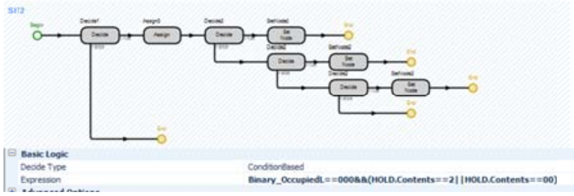
Station	
SF	Station
SE	Station
SD	Station
SA	Station
SB	Station
SC	Station
HOLD	Station
PAX	Station

Figure 6: Station Elements

Figure 7 illustrates the implemented logic for transition called SIT2 (General Sit). First the step *DECIDE* evaluates if the passenger wants to sit **(ModelEntity.Seat=100)**, and if the seat row is empty (**Binary_OccupiedL=000**) and if the people waiting is zero, one or two **(Hold. Contents)**:

```
ModelEntity.Seat=="100"&&Binary_OccupiedL==0&&(Hold.contents==0||Hold.contents==1||Hold.contents==2)
```

If the condition is fulfilled then the new values are assigned (*ASSIGN*) to the variable that stores the availability of the row. The remaining steps are used to send the entity to the corresponding seat and the time is consumed depending on the characteristics of the entity and the length of the path (this is managed by the software itself).



Basic Logic

Decide Type	ConditionBased
Expression	Binary_OccupiedL==000&&(HOLD.Contents==2||HOLD.Contents==00)

Figure 7: The CPN Logic Coded in SIMIO Steps

Once the module of the row is constructed, the development of the whole cabin is performed in a straightforward way. The top figure of Figure 8 illustrates the whole model of a cabin once the different row-modules are put.

Every time an entity (passenger) enters to a module the CPN logic behind the model will govern the simulation while the rest of the time the dynamics will be governed by the interaction of the entities themselves and with the different objects. Furthermore and for aesthetic purposes it is possible to hide those elements of the module such as the *Separators* that evaluate the different conditions of the transitions. In the bottom part of Figure 8 the sequence when the passenger needs to sit in the middle is illustrated. In the first snapshot 2 passengers are sit in the first row while another one approaches. The second snapshot illustrates the situation when the passenger in the aisle has to stand up so that the approaching passenger can get to his seat and in the following snapshots the passengers sit and let the remaining ones to continue to their corresponding seats. All of those events were modelled at the micro-level using the CPN model.

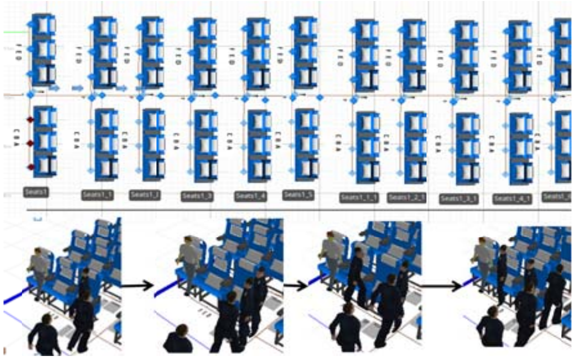


Figure 8: The different modules put together

5. CONCLUSIONS

A methodology for developing high-detailed simulators for the different operations at a cabin has been presented. Using this methodology is possible to construct detailed simulation models considering interactions between elements that otherwise could not be taken into account, such as age, disabilities, number of bags etc. The cause-effect relationships present between the different elements are modelled using the coloured Petri net formalism and afterwards the CPN models are integrated with a discrete-event software called SIMIO to evaluate the emergent dynamics once the elements that participate in the boarding process are put together. The advantage of using this approach is that using the CPN formalism, the cause-effect relationships are revealed and modelled in a straightforward way, so that is very easy to integrate them in the digital model when developing the commercial simulator. Using this approach it would be possible to take these kinds of simulations one step further for analysing and optimizing processes where the interaction of small elements becomes important for the optimisation of the whole procedure.

The model presented here only uses the most basic micro-interactions such as passenger blocking, passenger standing up, speed of passengers however future implementations will take into account particular characteristics of the passengers such as carried luggage, aptitude for boarding, familiar relationships among others and those will be easily implemented using the CPN-Simulation approach.

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