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CPN-DES MODULAR SIMULATOR FOR ASSESING BOARDING PERFORMANCE OF AIRCRAFTS

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ABSTRACT

The boarding process of an aircraft is part of the critical path in the turnaround process of an aircraft. The present article presents a simulator based on a methodology that uses coloured Petri Nets with discrete event systems. The combined approach allows to efficiently model the casual relationships that participate in the boarding process and with the properties of the discrete event approach it is possible to evaluate the emergent dynamics which play an important role in the performance of the boarding process of an aircraft. The coloured Petri net approach allows to model in detail what are the main micro causal relationships that hinder the smooth boarding process. Once the causal relationships are modelled with the modelling formalism they are implemented in a module of a discrete event simulator which in turn will become the building blocks for a more complex object such as the cabin of an aircraft. The combination of both techniques reinforce mutually in such a way that the final simulator is very efficient for analysing and understanding the dynamics that govern the performance of the boarding process.

1 INTRODUCTION

The turnaround time (TAT) 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 (Basargan, 2004).

In addition, the business model plays an important role since the stop over takes a different length of time as the operations vary from one business model to business model for example the TAT of a Low Cost Carrier (LCC) is much smaller than the one for the Full Service Carrier (FSC). For this reason it is very difficult to homogenize the times of all the ground handling processes when the aircraft has already arrived at the airport.

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

- Prior preparation for boarding: the passengers are organized and all their hand luggage and documentation is checked.
- The plane arrives at the parking stand.
- Block-In is performed. This step consists of putting chokes at the landing gear so the aircraft remains static during all the process.

- The passengers and bags disembark.
- The plane is fuelled.
- When 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, a 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.

In the particular case of LCC, some of these steps are taken out during the TAT. For this reason the boarding/deboarding operations acquire more and more importance than for the case of the FSC. Figure 1 illustrates the different processes that compose the turnaround of an aircraft (Airbus 2011).

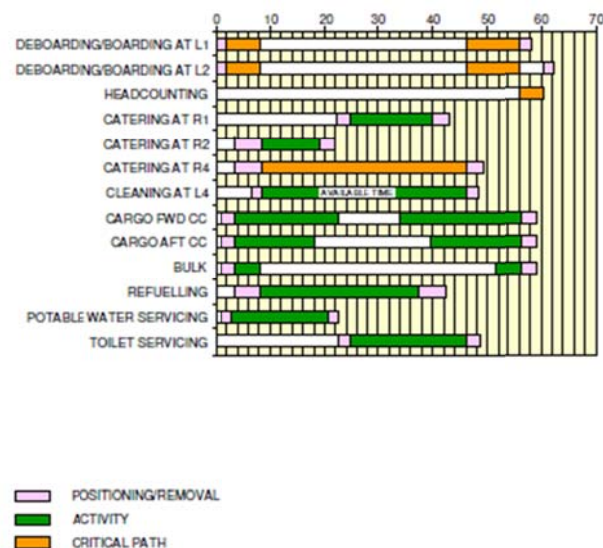


Figure 1. The turnaround time of the A-320-200

In order to reduce the TAT it is necessary to reduce the time as much as possible of the steps that compose the critical path. For the LCC the boarding and deboarding processes are key for this objective, that is why scientific community has put focus in different policies and methods for reducing these processes. The current paper presents a methodology that goes a step further than the current studies related to this process. The methodology used in this work allows to integrate in an efficient way the interactions of passengers during the boarding process at the seat level and also during the movements in the cabin.

1.1 Related Studies

Different authors have put focus on the way to improve the boarding process. Most of them put their efforts in managing in the best possible way the seats and the schedule of the boarding process. The different improvements are achieved through different strategies such as the ones presented by Marelli, Mattocks, and Merry (1998) tested in a simulator with two different states for each one of the seats (On-Off). They presented the improvements obtained when the boarding is performed using a window, middle

aisle (WILMA) scheme; for this case a boarding time can be decreased compared to a random assignment boarding. Further methods have been defined and tested such as the one known as 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.

In the study presented by Van Landeghem and Beuselinck (2002) they shown that the fastest boarding method is a random one using as parameters for allocation the row and seat of the passengers; on the other hand Steffen (2008) claims that he finds the optimal allocation of the passengers using Markov Chains and Monte Carlo Simulation. In recent approaches different techniques have been used to improve the allocation of passengers such as the work presented by Soolaki et al. (2012) where the authors present an approach using linear programming and genetic algorithms. Again Steffen and Hotchkiss (2012) tested different configurations in 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 simulation focusing mainly in the boarding strategy, and recently scientific community is taking into account other individual factors that have an influence in the boarding speed such as age, companions, family relationships, passengers travellers with bags, disabilities etc. From the review performed it is clear that in order to improve the boarding/deboarding processes it is necessary either to perform real-time experiments or use digital models that allow integrating more characteristics that play a role in the process and not only the sequence or policies of boarding. The current methodology presents a Coloured Petri net (CPN) approach together with DES software that allows integrating the characteristics that play a role in the boarding process and also the stochasticity inherent in the process such as speed of passengers, number of bags, and even age.

2 CPN-SIMULATION APPROACH

In this paper, DES simulation is integrated with CPN for a more robust approach. The advantage of using a modelling formalism with the simulation model with a DES software is that the modeller can first develop the causal relationships with the CPN approach and then they can be used for governing the behaviour of the DES model. The result is a high-detailed simulator that can be extended with more characteristics than the one that can be achieved using either CPN or DES alone.

2.1 Coloured Petri Nets

Coloured Petri Nets is a simple yet powerful modelling formalism which allows to properly modelling discrete-event dynamic systems which present a concurrent, asynchronous and parallel behaviour (Moore et al. 1996, Jensen 1997, Christensen et al. 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 (Jensen1997):

$$CPN = (\Sigma, P, T, A, N, C, G, E, I)$$

Where

- $\Sigma = \{ C_1, C_2, \dots, C_{nc} \}$ represent the finite and not-empty set of colours. They allow the attribute specification of each modelled entity.
- $P = \{ P_1, P_2, \dots, P_{np} \}$ represent the finite set of place nodes.
- $T = \{ T_1, T_2, \dots, T_{nt} \}$ represent the set of transition nodes such that $P \cap T = \emptyset$ which normally are associated to activities in the real system.
- $A = \{ A_1, A_2, \dots, A_{na} \}$ represent the directed arc set, which relate transition and place nodes such as $A \subseteq P \times T \cup T \times P$
- $N =$ It 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 functions, $C(P_i)$, which specify for the combination of colours for each place node such as $C: P \rightarrow \Sigma$.

$$C(P_i) = C_j \quad P_i \in P, C_j \in \Sigma$$

- G = Guard function, it is associated to transition nodes, $G(T_i)$, $G: T \rightarrow \text{EXPR}$. It is normally used to inhibit the event associated with the transition upon the attribute values of the processed entities.
- E = these are the arc expressions $E(A_i)$ such as $E: A \rightarrow \text{EXPR}$. 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 = 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-DES APPROACH

A discrete-event system (DES) model has been developed in which the micro-operations such as identifying a person in the seat, moving forward-backward to let the other passengers reach their seats among different attributes for the type of passenger that board the aircraft are based on the CPN modelling formalism. The advantage of developing a model that uses DES with CPN is that the causal relationships are formalized using the CPN approach and they can be verified testing different behaviour properties of the formalism such as boundedness, liveness (deadlock analysis) among others. These properties allows to verify that the conceptual model of the future simulators are well constructed and when they are implemented in the DES software the resulting simulator is a more robust one that needs less maintenance if the analyst wants to extend it with more characteristics. The first integration of the CPN models in a DES tool has been presented by the author in (Mujica and Piera 2011). Following the same methodology, the simulator of a cabin has been developed using CPN with a DES software that allows to develop modules whose underlying behaviour is ruled by the CPN models.

The CPN model is composed by 16 transitions and 3 place nodes. These transitions are the ones that model the different events performed at one row of the cabin. The formal definition of colours is presented in Table 1.

Table 1. Colour definition and description

COLOUR	DEFINITION	DESCRIPTION
X	Integer	It is the row number of the seat block
Y	{000,001,010,100,011,101,111}	It describes the seats occupied by the passengers. 000 means no passenger seated, 001 represents one passenger sit in the position closest to the aisle, 010 is used for representing a passenger sit in the middle and 100 represents a passenger sit in the window.
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 sit.
W	{001,010,100}	It represents the seat location of the passenger. It is similar to Y
D	{0,1}	It represents if the waiting person is seated in the middle (0 for either window or aisle and 1 for middle) and it is

		also used to represent that the passenger belongs to the right block (0) or the left block(1)
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The information related to the place nodes and the colour sets are presented in Table 2.

Table 2. Definition of Place nodes

Place	Colour Set	Description
SEAT	Product $X*Y*D$	This place represents the information of how is occupied the row. The first colour is used for the row number, the second for the seat occupancy and the last colour for the side of the block used.
AISLE	Product $Z*D*D$	This place holds information about the amount of passengers standing up in the Aisle waiting for the seat, if they are sit in the middle, and which side they belong to. Z represents how many passengers are standing, the first D is used to mark if some passenger belongs to the middle, and the second D is to keep track of the side of the block the passenger belongs to.
PAX	Product $R*W*D$	This place holds the information of the passenger. The first colour refers to the number of row, the second refers to the position of the passenger in the seat block (window, middle, aisle) and the third one is the information about which side of the row he belongs to.

The following figures present examples of the different transitions that compose the model. As it has been mentioned, the model is composed by 16 transition nodes and 3 place nodes. The initial CPN model can be constructed and analysed using tools for CPN such as CPNTools (www.cpntools.org) which has some behavioural analysis tools for verifying the good behaviour of the model prior to its integration with the DES software. The transitions model the different situations that a passenger face when he looks for its seat such as (finding the seat, moving out to let other people reach their seat, sit, stand up, wait in the aisle to let people reach their seat etc.).

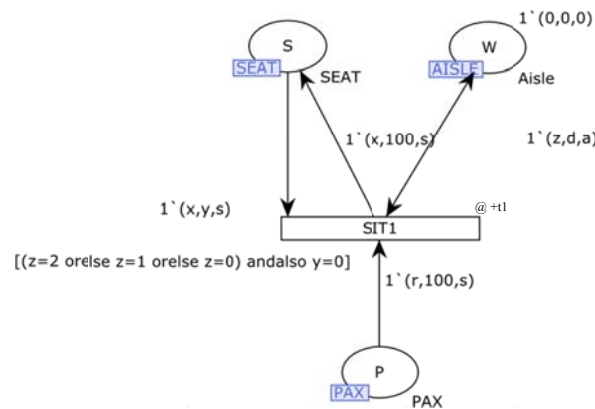


Figure 2. Transition for Sitting

Figure 2 illustrates one event when a passenger has to sit at the window ($w=100$) and the row of seats is empty ($y=0$). This could be the case either because of two situations, one is because nobody has sit yet ($z=0$) or because there were passengers already sit but they had to stand up to let the passenger to sit in Place W ($z=2$, $z=0$ or $z=1$). In this case the corresponding time consumption can be associated to the variable $t1$, but it would depend on the correspondent study. Once the passenger is sit, the new colour value is assigned via the output arc to the place node S with the value of variable w which in this example is 100 $[1'(x,100,s)]$ modelling that now the passenger has reached his seat.

Another example is illustrated by Figure 3 which represents the situation where a passenger must get to the seat at the window (w=100) and the middle seat is occupied by another passenger who was previously sit (y=10) , this passenger must walk out so that the passenger at the window can reach to its seat.

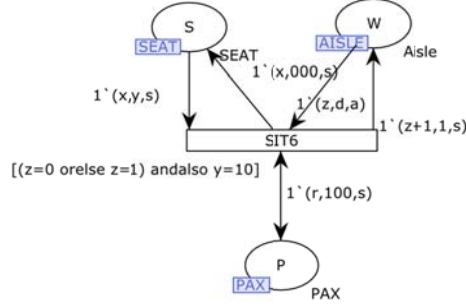


Figure 3. walking out of a passenger seated in the middle

In this model a unit is added to the colour z ($z+1$) of the token in the waiting place (Place node AISLE) and the variable d turns to 1 (1 represents that the passenger that stood up was from the middle) and the value s is used for keeping track of what side of the row the passenger belongs to. The token in the **PAX** place node do not change values since the event is that the passenger in the middle goes out. Finally with this event the token in the place node **SEAT** changes its y value to 000 to represent that the seat is now empty.

Using the CPN approach it is possible to clearly model the cause-effect relationships that sometimes hinder the smooth flow of passengers inside the cabin during the boarding or deboarding process. In addition, more colours can also be added to the model to represent characteristics such as age, size, number of bags, disabilities etc. and those characteristics can be used to simulate events in a more accurate way and then the emergent dynamics that appear once the model is developed are more accurate to reality. The total model is composed by 16 transitions that represent all the events that appear during the seat of the passengers at one row of the cabin. Figure 4 presents the different transitions of the CPN model.

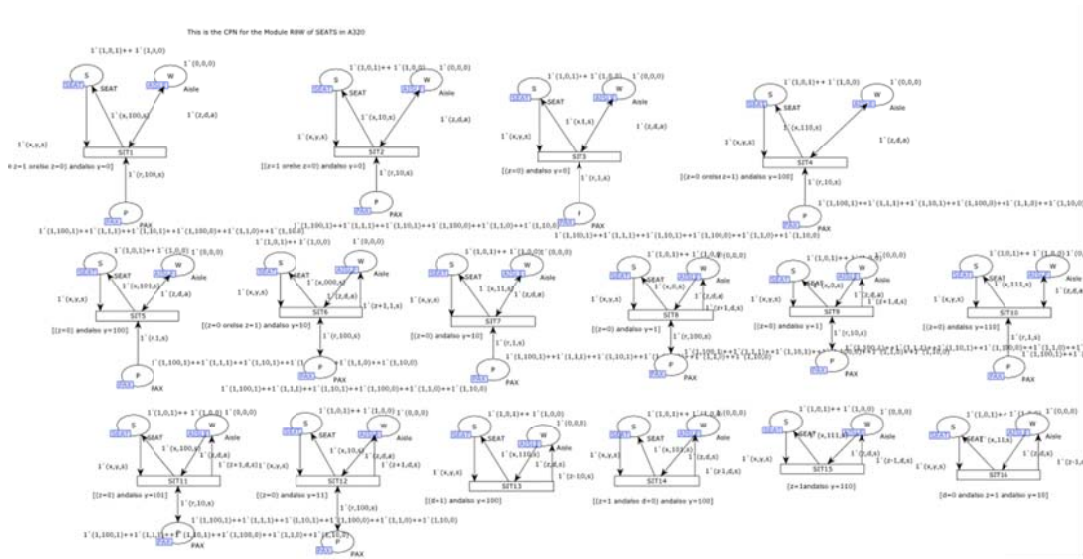


Figure 4. The transitions of the CPN model

4 MODULAR INTEGRATION OF CPN MODELS

The CPN models previously developed are in turn integrated in a DES software tool called SIMIO following the rules and implementations presented by the author in a previous work (Mujica and Piera 2011). The CPN model can be integrated for taking advantage of the symmetry presented in a cabin. The cabin can be simulated using a module that represents one row and then the module (governed by the CPN) can be instantiated to develop a complete model of the cabin. SIMIO is very efficient for this approach since it has an object oriented approach in which modularity is inherent in it, but the approach can be easily implemented using another DES tool such as ARENA or ANYLOGIC. The resulting simulator models with high accuracy the micro interactions between passengers and the emergent dynamics are assessed when the total model is developed. IT is fair to mention that the implementation allows also to take full advantage of the software capabilities and simulate accurately the stochasticity inherent in the system.

Figure 5 illustrates the methodology used for the developing of the aircraft cabin.

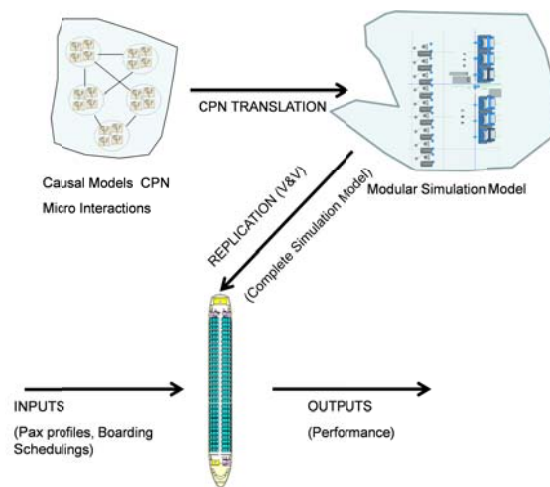


Figure 5. Modelling approach for the cabin model

First, it is necessary to implement the different activities (transitions) in a module that simulates one row inside the cabin. Second, 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 (at row level) but also the interaction that occurs at higher levels e.g. in the aisle, walking speeds, aisle blocking etc.

Figure 6 illustrates the elements for the row-module in which the CPN model rules the evolution of activities and events during simulation time. 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 *Separator* objects from SIMIO in which the CPN transition logic is implemented to evaluate the different events that occur in the module. The transitions are evaluated concurrently using *Connectors* which do not consume simulation time so the logic associated to each object (CPN transitions) is evaluated all at once and only those that satisfy the different restrictions are fired thus performing the simulation with high accuracy. In the figure the *Trans* objects correspond to transitions 1 to 10 and the logic of those transitions are implemented using the processes window of SIMIO.

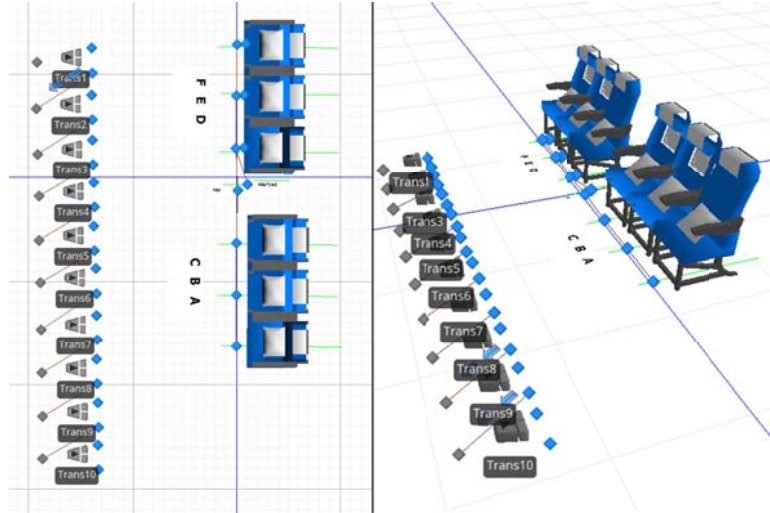


Figure 6. The elements of the DES software model

Other SIMIO elements are used to model the place nodes and transition nodes. For the place nodes, the *Stations* elements are added for holding the entities (passengers) and their status are used to model the transitions of the CPN models. Figure 7 presents the different stations used in the object; some of those stations are just used to store the entities that simulate the passengers sit in the cabin seats while others namely HOLD and PAX are used to represent the place nodes AISLE and PAX respectively of the CPN model.

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

Figure 7. Station elements

Figure 8 is an example of the logic for transition SIT6 (Transition6) of Figure 3. First the step DECIDE evaluates if there is a passenger waiting for a seat (**PAX.Contents>0**) and if the seat is occupied at the middle (**Binary_OccupiedL=010|| Binary_OccupiedR=010**) and that there is either no one or one passenger waiting for a seat (**WaitingPeople==0||WaitingPeople==1**). If that condition is fulfilled then the next condition checks whether the passenger goes to the left side (**ModelEntity.side==1**) and that the passenger needs the window (**ModelEntity.Seat==100**). The second SEARCH step looks for the SE.contents that is the passenger blocking and then through the set node and the transfer node it is sent out of his seat. The remaining steps are used to update the values of the different variables used.

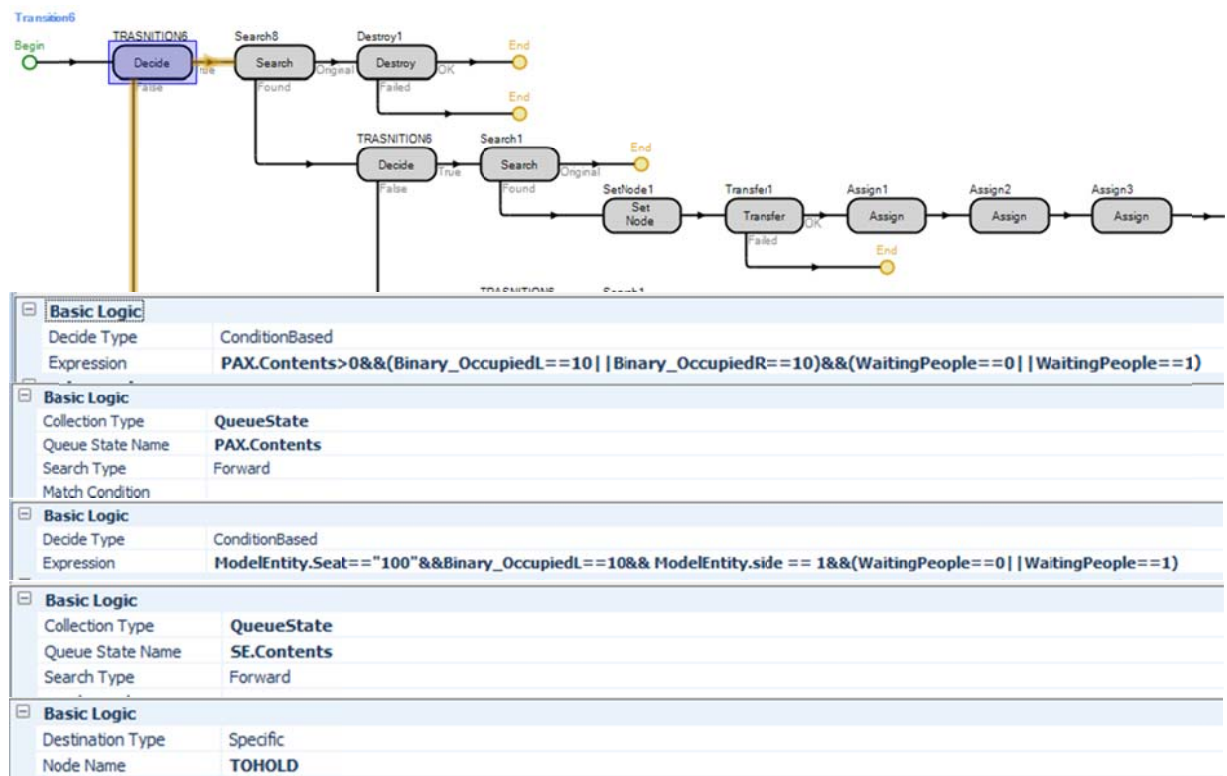


Figure 8. The CPN logic coded in SIMIO steps

A similar coding is performed for all the different transitions of the model and they are coded for developing the module that represents the row of the cabin. Once the module of the row is constructed, the whole cabin is constructed by just making instantiations of the module and connecting them together using the capabilities of the DES software. Figure 9 illustrates the whole model of a cabin once the different instantiations of the row module are put together. 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 DES simulator. In Figure 9 the final result of the cabin simulator developed using this approach is presented together with some snapshots of the simulation, in particular the snapshots illustrate the situation when the passengers need to move out so that the arriving passenger reaches his place at the window, and it also shows in the last snapshot that while the passengers are letting the arriving one passes to get his seat they are blocking the aisle thus generating a queue as a consequence of these events.

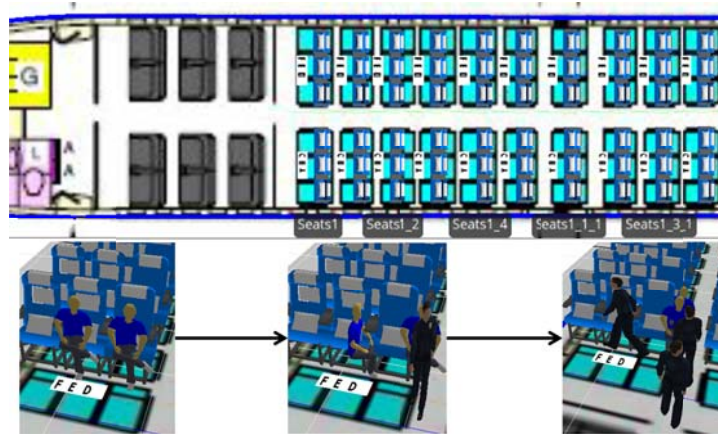


Figure 9. The different modules put together

5 EXAMPLE CASE

In order to illustrate the capacities of the approach, a model of the cabin of the A320-200 (Airbus 2005) has been developed. The model can be used to evaluate and verify the results reported in literature and what is the difference when micro-dynamics are included in the model. As it has been discussed, the current studies did not take into account characteristics that might become important when the objective is to reduce the boarding time such as the interaction between passengers, differences in walking speed during the process which might be related to physical characteristics of the passengers such as age, disabilities, etc.

The power of this approach lays in its capabilities of including not only the layout profile of the cabin, the interactions between different elements during the boarding but also the stochasticity of the processes that play a role in the total time it takes to perform the boarding. The latter characteristics can be easily evaluated using the capabilities of the DES software while the micro-interaction at the row-level are modelled by the CPN and then when the modules are integrated to construct the cabin, the final simulator is a robust one that can be used to evaluate and analyse the boarding and deboarding through different perspectives. The different assumptions and characteristics are presented in Table 3.

Table 3. Stochastic Parameters

Parameter	Assumed Values	Description
Passengers speed during the boarding process	0.5-1.0 m/s	This parameter is based on measured speeds during boarding.
Speed of passengers when they move in/out the seat.	0.125 m/s	This is one of the assumptions when the passengers have to go out or move in if they need to let other passengers reach their seats.
Inter arrival time	Uniform(3,5) sec	This parameter models the time difference between passengers due to the boarding pass control.
Boarding type	RANDOM	It is assumed that they are boarded in a random fashion.

5.1 Results

The developed model has been implemented for an aircraft of 138 passengers in which the parameters of the previous table have been implemented. It has been tested to verify that the results are similar to the one reported in literature and also to verify the potential of the simulator for evaluating other interactions between the passengers.

After running 20 replications of the model using three configurations we could assess the values for the boarding time using this approach.

Table 4. Results of the test model

Configuration	Output		Average	Minimum	Maximum
Random Pax Speed (0.5-1) m/s	Total Time	Boarding	10.00 mins	9.86 mins	10.25 mins
Random Pax Speed (0.3-0.7) m/s	Total Time	Boarding	10.76 mins	10.59 mins	10.95 mins
Pax Speed (1-1.4) m/s	Total Time	Boarding	9.61 mins	9.43 mins	9.77 mins

6 CONCLUSION

A methodology for developing simulators based on the modular approach of CPN-DES models for the boarding of a cabin has been presented. The cause-effect relationships due to particular interactions of the passengers are modelled using the coloured Petri net formalism, afterwards the CPN models are integrated in a DES module software to evaluate the emergent dynamics and the impact of the stochasticity of the system. Using this methodology it is possible to evaluate the interactions based on CPN models that can be integrated with DES simulators for the developing of simulators of high detail. The approach allows to efficiently develop simulators since CPN formalism has some analytical tools that allows to assess the correct behaviour of the CPN model that later on will be integrated with the DES software. The use of the DES software allows not only assessing the boarding performance depending on the boarding policy but also analysing the impact of stochasticity and the emergent dynamics which could not be possible to achieve using CPN or DES alone. In the paper, the example of an A320-200 cabin has been presented in order to illustrate the implementation using this approach. As a future work different boarding policies will be tested with the simulator so that we can evaluate if the stochasticity and emergent dynamics play an important role in the boarding time of an aircraft which is an important process in the turnaround time.

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