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Discrete Event Simulation Applied to Aircraft Development Cycle

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Abstract

The trend in aerospace industry is to increase product complexity, reduce costs and integrate processes along the aircraft lifecycle. Discrete event simulation provides an important support to this challenge. Discrete event simulation techniques are a flexible tool for the evaluation of solutions, comparison of productive scenarios, analysis the impact of modifications and introduction of new processes. However, the selection of the modeling method and simulation tool is not trivial. It impacts not only on the results but also on the effort required to run the simulation. In this context, this paper analyses the applicability of two modeling and simulation approaches in different phases of the aeronautical product lifecycle. It considers the use of event oriented simulation based on Petri nets and process oriented simulation, based on the commercial tool QUEST.

Keywords: *Discrete Event Simulation, Aircraft Industry, Aircraft Lifecycle, Petri nets.*

Introduction

The importance of simulation for the aircraft development is highlighted by the investments of the aircraft industry on simulation tools and the conception of virtual aircraft environments. In this context, this paper discusses two solutions for discrete event simulation considering its application to the aircraft development lifecycle.

This work is motivated by the Brazilian aircraft industry, which faces a highly competitive scenario. The introduction of better and more sophisticated products is a constant need for maintaining the current position in a global market. The rapid and efficient development of new products is a fundamental issue when the time-to-market of aircrafts is shortening. For this purposes, paradigms such as simultaneous engineering and PLM (Product Lifecycle Management) must be fully incorporated into the aircraft industry.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

Simultaneous engineering can be understood as a systematic approach for the integrated and parallel development of products and processes, including manufacture (SCHÜTZER and SOUZA, 1999). The integration of people, processes and tools that is necessary for the simultaneous engineering is supported by the Product Lifecycle Management concept, known as PLM (MOELLER and ROLF, 2001). The key point of PLM is the management of all data and information related to the product. A successful PLM solution provides rapid access to complete information for decision making, reducing costs and time (CLEMENTS, 2003). A PLM solution must provide data sharing among a set of computational tools with different purposes such as, CAD (Computer Aided Design), CAM (*Computer Aided Manufacturing*), PPM (*Project and Portfolio Management*) and also discrete event simulation tools (SUN *et al*, 2004). Discrete event simulation tools can be applied to different processes, such as design, manufacture, distribution, support and maintenance and product disassembly, and along all the phase of an aircraft life cycle (CATES, 2004). Examples of discrete event simulation projects related to aircraft industry are Bazargan and McGrath (2003) and Lee *et al* (2003).

This paper aims to compare two different solutions for discrete event modeling and simulation of processes from different phases of aircraft lifecycles. The two solutions are (1) event-driven simulation based on Petri nets and (2) process-driven simulation based on the use of the commercial tool QUEST. The purpose is to determine the advantages and drawbacks of each solution according to the features of the problem under analysis. For this purpose, the two solutions are applied to simulation projects in each phase of the aircraft lifecycle.

This paper is organized as follows: Section 2 presents the aircraft lifecycle and discusses the use of simulation tools in each phase of the aircraft lifecycle. Section 3 details the two solutions under analysis in this paper. Section 4 proposes a systematic approach for conducting simulation projects in aircraft industry. This approach is based on a customer-supplier relationship. Section 5 presents and discusses the simulation projects developed for comparing the two simulation solutions. Finally, Section 6 rounds off the work presenting conclusions.

Aircraft Lifecycle Phases

A modern aircraft is an extremely complex equipment class and has thousands of safety-critical parts that are challenging to design, integrate, manage and maintain. Its lifecycle is typically divided in four main phases: (1) preliminary, (2) development, (3) serialization and, finally, (4) phase-out.

The preliminary phase starts with poor details about the product. Typically the target times are from a few weeks to a month and normally a multidisciplinary team of a few specialists are involved in order to maintain the confidentiality and present the product study results. If these studies present feasible return of investment, the product project can go ahead to the development phase. Otherwise, it must be re-evaluated or refused. In order to mitigate the high risk of achieving incorrect results,

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

and reduce the number of prototypes, the simulation tools must focus on providing approximated results in a fast way. The typical scenario of a simulation project is characterized by absence of statistic data and short time. The presentation of the simulation project results is usually in common language and aims for a public of different technical knowledge and hierarchical levels.

The development phase is characterized by the product and process refinement and by the definition and involvement of the product suppliers and partnerships. The level of details and the number of specialists increase. The development phase requires an integrated design model in order to achieve improvements through the team collaboration, both internally and with suppliers. The flow of information among the production chain is intensified in order to reduce costs and time. Information technologies support simultaneous engineering. Engineers have access to computational tools to model and simulate product and processes without the need of physical models and mock-ups. Simulation supports the visualization and verification of faults on the product assembly, collision among components, determination of free space for cables and accessories, etc. All the information about the product is organized in a common database and shared among different simulation tools. Different from the preliminary phase, the simulation projects of the development phase are supported by a large amount of information about the product and must provide precise results in order to not compromise the next phase (BROWN, 2004).

In the serialization phase, the project level of detail is high, and the companies manage vast amounts of data, project planning, innovation, budgets, resources, and many other factors that affect all businesses. In order to address these needs, discrete-event simulation is normally used to simulate their existing processes, expecting to be able to improve quality, save money, improve efficiency, or obtain consistency. Normally, the serialization processes are modeled to represent the system properties that are relevant to the business in terms of operability, structures, performance and data quality. The structure category includes a solid body representation of the project and derived characteristics including the coordinate definition of various subsystems and their constraints. The performance category describes the execution accuracy of the project including scheduling, information processing, and data transmission. The operation category specifies the operation modes of each subsystem and their resource usage profiles and constraints. In addition to decision making, on-line simulation may use a real time link between a simulation model and the production system as a direct method of process control.

In the phase out, the customer support is the main business of the aeronautical companies. Solutions for new services must be elaborated in order to bring benefits to the airline business. In this case the management system is used to collect all data necessary to the study, and also to guarantee the configuration management of the product. The simulation tools use this database, and must increase the product quality by verifying the customer processes and the impact of the product design modifications, or even confirming new customer requirements by simulating customer operations before the beginning of an airline service.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

The phase of the aircraft lifecycle determines some of the important features of a simulation project that impacts on the choice of the simulation tool. Table 1 presents a relative and qualitative analysis of these features.

Table 1 - Features of simulation projects according to aircraft lifecycle phase.

	Preliminary	Development	Serialization	Phase-out
Information available for the simulation project	Low	Medium	High	High
Financial resource available for the simulation project	Low	High	Medium	Medium
Acceptable uncertainty in the simulation results	High	Medium	Low	Low
Complexity of the simulation models	Low	Medium	High	High
Time available for the simulation project	Low	Medium	High	Low
General purpose of the simulation project	Approve business plan	Detail product and processes	Optimize product and processes	Add product value

Simulation Solutions under Analysis

This section characterizes the two simulation solutions under analysis in this paper.

The first point to consider when analyzing simulation tools is how it models the system that must be simulated. A model is an abstraction of the real physical system. This abstraction must contain all the relevant features to the problem under analysis, and, desirably, should not contain irrelevant features that must difficult the modeling and simulation process (BANKS et al, 2009).

In the case of discrete event simulation, the system under analysis is modeled as a discrete event dynamic system, which is characterized by causality relationships that relates the occurrence of events to the system evolution (LAW and KELTON, 1991). The dynamics of discrete event system is driven by the occurrence of instantaneous events, which modify the state of the system in a discrete way. The time interval from the beginning to the end of an event is not relevant for the system dynamics when compared to the time intervals between events.

For simulation purposes, a model of discrete event dynamic system can be defined as being composed of entities, activities and processes. Each component of the system that requires an explicit representation is an entity (PIDD, 1994). The purpose of the simulation is to reproduce the activities of the model entities and obtain conclusions about the system behavior and performance (LIMA, 2005).

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

One way of classifying discrete event simulation approaches is to organize them in event oriented simulation and process oriented simulation.

In the discrete event simulation, the system model explicitly contains the effect of each discrete event on the system state. The modeler must determine all the events that can change the system state and then develop the dynamic logic associated to each event. The simulation is the result of the execution of the logic associated to each event in an ordered time sequence (PIDD, 2004).

This class includes all the simulation tools based on mathematical formalisms that models discrete event dynamic systems, such as automata, Petri nets, Markov chains, etc (HO, 1987). These formalisms do not associate an interpretation to the events and states. They do not support the definition of entities or the association between a state and an entity of the system. Similarly, they do not support the definition of activities or the association between an event and the beginning or ending of an activity. This association between states and entities or events and activities is under the responsibility of the system modeler and is not explicitly incorporated in the modeling formalism.

Process oriented simulation is based on the description of the processes performed by each entity. A process is a sequence of events with a particular meaning. The basis of the process oriented simulation is the assumption that most of the system behavior can be organized in standard sequences of events, such as a queue of entities waiting for a server. The logic associated to these sequences of events is generalized and associated with a component of the modeling language. These components are used to model the entity behavior.

The advantage of process oriented simulation is the facility to build a new model, once that the logic of the standard components does not need to be defined. On the other hand, the model is restricted to the set of components of that particular language. Comparing to event oriented simulation, the modeling flexibility is limited.

In order to evaluate the two approaches, a simulation tool is selected from each class.

Among the tools available for process oriented simulation, those based on Petri nets are particularly considered because of their well-known advantages of Petri nets for representing process features such as concurrency, conflict, synchronization and asynchronous behavior.

Petri nets (MURATA, 1989) are a modeling formalism proposed by Carl Adam Petri in 1962 for modeling distributed systems. They were rapidly recognized as a promising formalism, due to its adequacy to represent a number of features of discrete event dynamic system behavior. A Petri net is a directed, weighted, bipartite graph with two kinds of nodes: places and transitions. The places of a Petri net contain a positive integer number of tokens. The distribution of tokens over the places is the Petri net marking and indicates the current state of the system. Each transition of a Petri net is associated with an event of the system. The system behavior is simulated

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

by the firing of transitions, which corresponds to the occurrence of an event. In the same way as an event affects the system state, when a transition fires, it modifies the Petri net marking. A detailed description of the Petri net formalism can be found in Murata (1989).

The Petri net simulation tool used in this work is HPSIM. It is a free tool available at the Internet. Among it features, it supports the association of time intervals to transitions, which can be deterministic or stochastic.

Among the tools available for process oriented simulation, the selected one is QUEST, from Dassault Systèmes' DELMIA software suite. The reason for this choice is its adoption by the Brazilian aeronautic industry.

The main process model used by the tool is a queue, from the queuing theory (ALLEN, 1997). The system is abstracted as a queuing network. Each queue is characterized by an arrival process and a service process. Other process models are incorporated into the tool to provide flexibility. In the selected tool, the queuing theory and other details about the process models are hidden from the modeler by a user-friendly interface. The modeler defines the system as composed of parts, buffers, routes, machines, part sources and sinks. The tool also provides a programming language for specifying operation and routing logic.

The model simulation is based on the process execution. The simulator maintains a list of future events in chronological order. When the simulation clock is updated, the processes associated to the events of the current time are performed, resulting in the updating of the system state and the addition of new items to the list of future events.

Differently from the Petri net simulator, QUEST provides a 3D environment to illustrate the system behavior.

The Modeling Approach

In order to compare the two simulation solutions, a systematic approach is proposed for conducting simulation projects in an aircraft industry. The need of a systematic approach for developing simulation project is highlighted by other works, such as (RANDELL *et al*, 1999), (RANDELL, 2002). This approach is based on a customer-supplier relationship. The customer is a working group of the aircraft industry that needs a discrete simulation study. The supplier is another working group that has been specialized in discrete simulation projects and develops the simulation study in partnership with the customer. The modeling approach is composed of a set of activities (Figure 1) that are organized in six steps. The steps cover the main activities pointed out in traditional references as part of discrete simulation process (CHIFF and MEDINA, 2010).

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

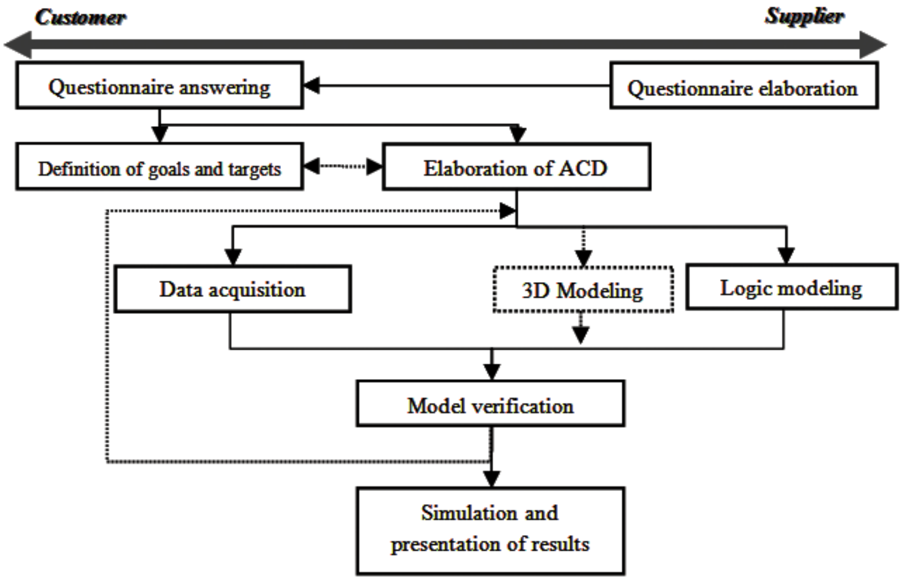

Figure 1 - Modeling approach.

Step 1 - Problem Definition

In the aeronautic industry, the problems normally contain a great number of variables, different kinds of parameters, relationships, restrictions and goals. However, not all the features of the system under study are relevant for the simulation problem. Details that do not influence the simulation results may not be included in the model in order not to overcharge the modeling and simulation activities.

This step is strongly based on the interaction between the two working groups of the aeronautic organization [1]. The customer identifies the problem and contacts the supplier. Based on this first contact, the supplier organizes a questionnaire to be answered by the customer. This questionnaire must provide basic information about the simulation study, such as scope, level of detail, available source of data, complexity of data, requested precision and accuracy of the results, available time to perform the simulation study, among others.

An example of questions from this questionnaire are:

- Why the simulation study is being requested?
- What are the expected results?
- Which kind of decisions will be taken based on the results?
- What are the affected working areas?
- Who will make the simulation plan?

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

Step 2 - Definition of Goals and Targets

In this paper, targets are the results to be obtained by discrete simulation. The supplier is responsible for reaching the targets. Examples of targets are performance analysis, capacity analysis, comparison of solutions, sensitivity analysis, etc. On the other hand, goals are related the application of the simulation results for solving a broader problem. The customer is responsible for achieving the goals.

Targets and goals are closed related and must be defined by the customer.

This is step is performed in parallel with the Step 3. This parallelism is motivated by the frequent ignorance of the customer about the simulation capabilities and resources.

Step 3 - Understanding the System

Once the problem is identified, the supplier translates the problem into the ACD (Activities Cycle Diagram) model. The ACD language is composed of two kinds of entities that interact: queues and activities (Figure 2). The arrows model their precedence.

Figure 2 - Symbols of ACD.

The ACD provides a first model of the system, in a high level of abstraction and with no dynamics. The elaboration of the ACD is performed by the supplier in close interaction with the customer.

Step 4 - Building the System Model

This step is broken down into two activities, which are performed in parallel: the model specification in the simulation tool and the data acquisition. The first one is usually simpler and requires less effort than data acquisition.

The data acquisition can be performed on an existing system and based on stored historical data of similar systems. It is performed mainly by the customer, which usually has a deep knowledge about the system. The ACD elaborated in Step 3 assists the data acquisition. The data acquisition phase establishes the relationship between the level of detail of the model and results obtained from simulation.

On the other hand, the model specification in the simulation tool is performed by the supplier, which has a deep knowledge of the modeling language and the resources provided by the tool. When necessary, it includes the building of three-dimensional model of the system.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

Step 5 - Model Verification

The model verification consists of varying the input parameters and analyzing the coherence results, assuring that the model is a good abstraction of the real world. The results provided by the model are compared with the expected behavior of the real system.

Step 6 - Simulation and Results Presentation

Multiples simulations must be performed in order to obtain an accurate result. The simulation scenarios are defined according to the targets defined in Step 2. In the case of stochastic simulation, the RIRO (Random Input, Random Output) rule is adopted. These results are then formatted and presented to all the project participants.

The Case Studies

The approach described in Section 4 has been applied to four case studies, one from each phase of the aircraft lifecycle. They are described in the next sections.

Case Study 1 - Preliminary Phase

The purpose of this case study is the identification of potential bottlenecks and queues in the production line of a new aircraft that are caused by the limited availability of resources. Using the simulation model, variations of the original proposal must be analyzed in order to achieve a better configuration for the production line. The goal of this simulation project is to support the viability analysis of the new aircraft production plan.

The ACD of this case study is presented in Figure 3.

Although the aircraft of this case study is a completely new one, the fabrication processes are well known by the aircraft industry and production times can be estimated from production lines of existing aircrafts. The simulation used only deterministic times, which are original from different sources such as process plans, maintenance reports, among others.

Due to the low level of detail required by this case study, the modeling activity in both simulation tools was simple and rapid. The structure of the Petri net model was closer to that of the ACD than the QUEST model, requiring less effort. The 3D graphic interface provided by QUEST was not used because it would aggregate no important information to the simulation study and could not be performed in the available time. The results obtained in both simulation tools are equivalent and the functions available in both solutions were sufficient for the analysis of the problem. These are common features of most of the simulation studies of the preliminary phase.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

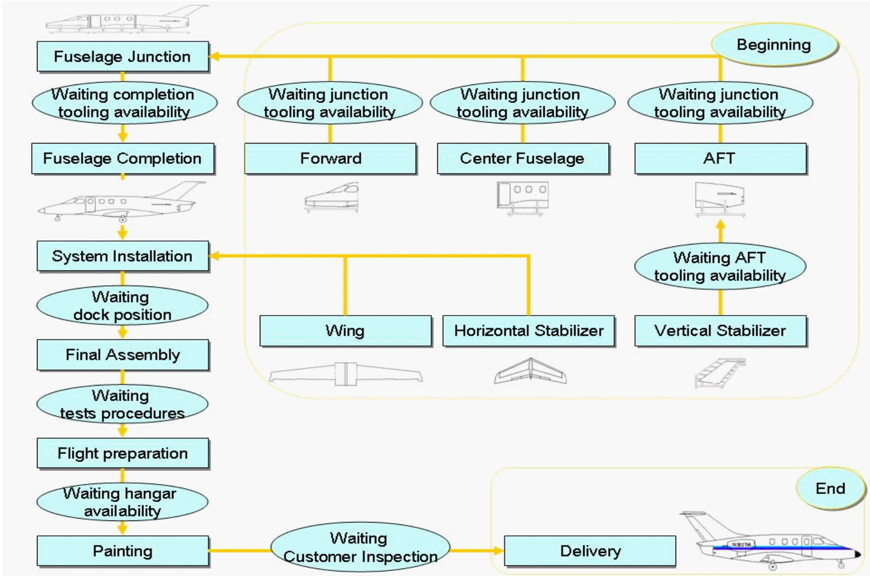

Figure 3 - ACD of Case Study 1.

The HPSIM and QUEST models are presented in Figure 4 and Figure 5.

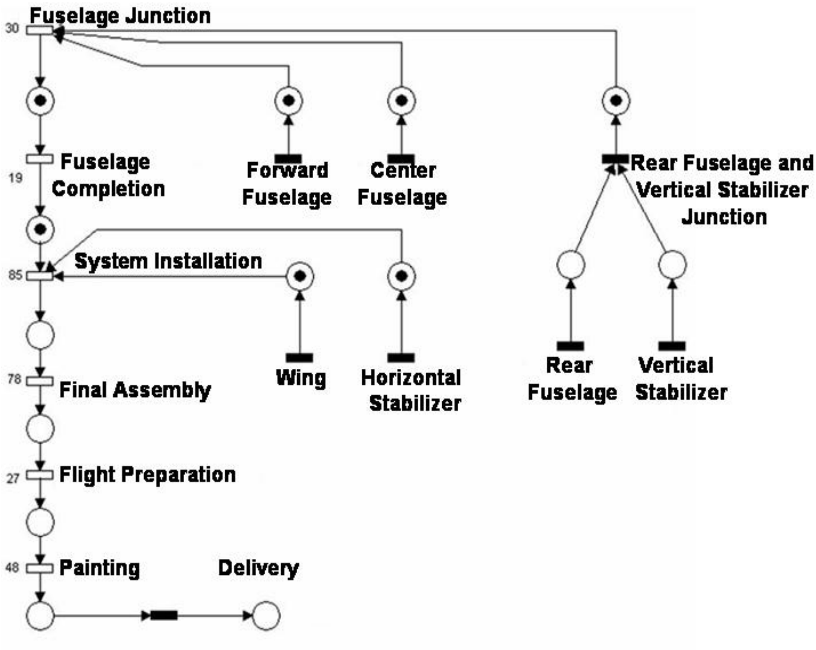

Figure 4 - HPSIM model of Case Study 2.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

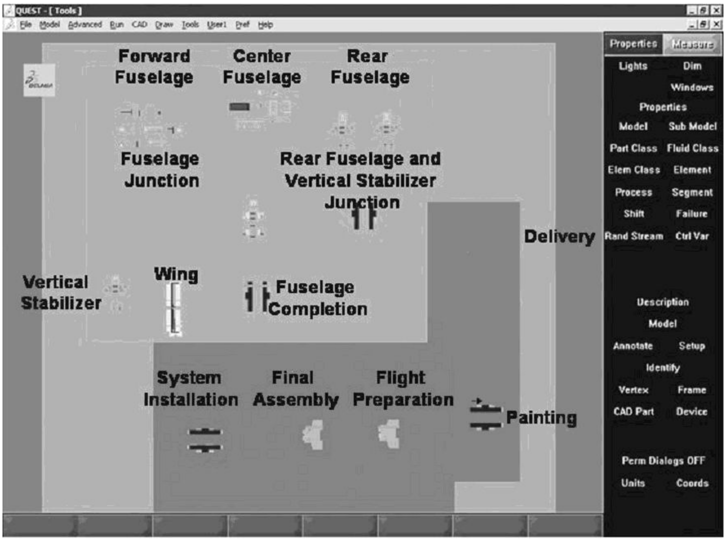

Figure 5 - QUEST model of Case Study 2.

Case Study 2 - Development Phase

This case study analyses the material reception and storage system, considering different input data. New operation rules and strategies must be evaluated and tested. The goal of this project is to provide information for establishing a common strategy between the planning of logistic operations and the stock control in order to avoid the permanence of material in the quarantine area for more than 4 days. The ACD of this project is illustrated in Figure 6.

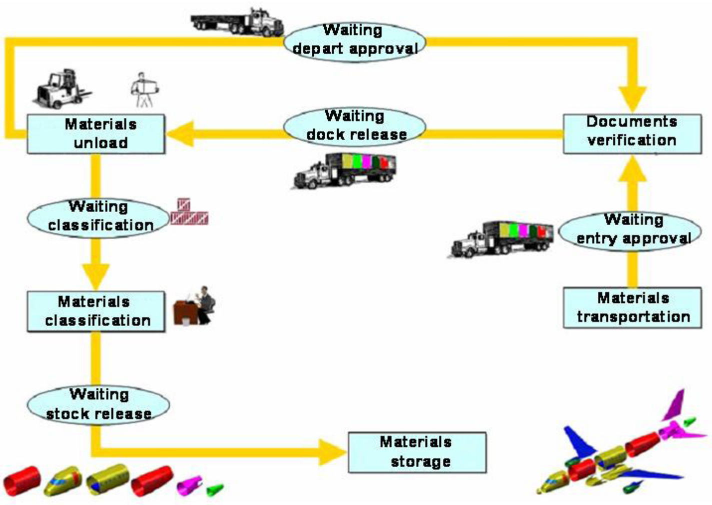

Figure 6 - ACD of Case Study 2.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

The HPSIM model is presented in Figure 7. The QUEST model is presented in Figure 8. The logic of the HPSIM and QUEST models must include a number of details which do not appear in the ACD, such as the differentiation between the processing of different kinds of materials (electrics, mechanics, equipment, others), the sharing of resources (operators) among the activities, and other restrictions about the entities behavior.

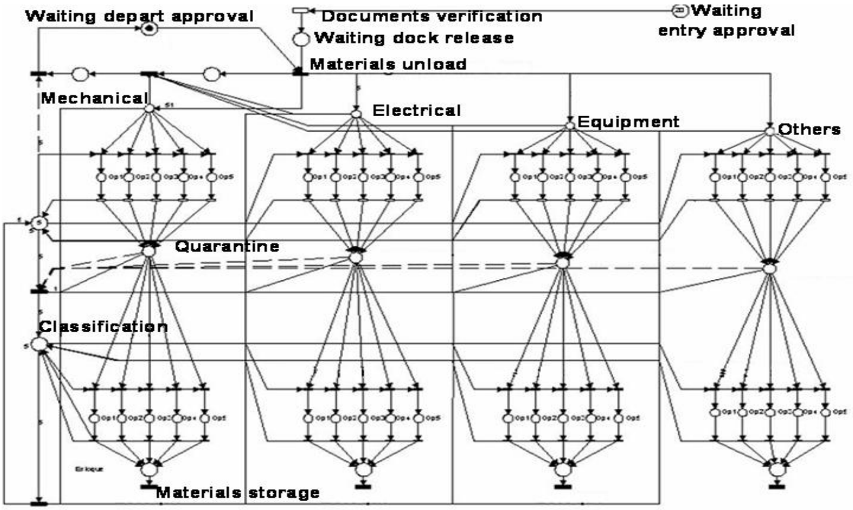

Figure 7. HPSIM model of Case Study 3.

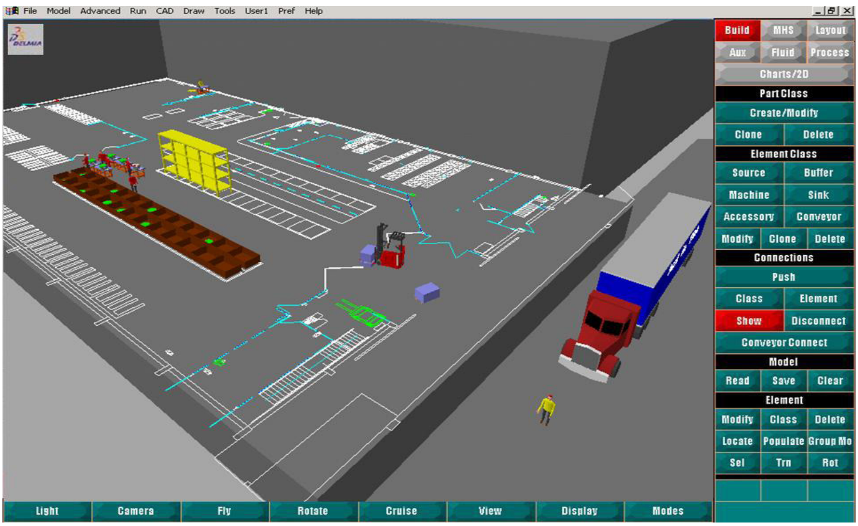

Figure 8. QUEST model of Case Study 3.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

The input data for the model were obtained by measuring time intervals in the real system during one year. The stochastic distributions were then adjusted to the collected data. The kinds of stochastic distributions were limited to the ones available in each simulator.

The following points were highlighted by this case study:

- The modeling of stochastic behavior in HPSIM is limited. Some limitations are imposed by the Petri net language, which only allows the association of stochastic distribution to transition times. In order to model a variable number of parts in each truck, the stochastic distribution must be associated to the weight of a Petri net arc, which is not possible in the Petri net formalism. Other limitations, such as the kind of stochastic distribution, are imposed by the chosen simulation tool (HPSIM) and may not be found in other Petri net simulators.
- The HPSIM, such as other Petri net simulators, allows the visualization of the discrete state of the model in a detailed and precise way. At each moment it is possible to see the number of tokens in each place and how each transition firing modifies the net marking. This graphical interface helps the model building and the error detection. On the other hand, it is not easily understood by a person that is not familiar with Petri nets. The visualization of the QUEST simulation is a 3D animation that is easily understood by anyone with a basic knowledge of the system, but it hides details about the programmed logic.
- The building of the HPSIM model from the ACD is not straightforward as in Case Study 1. It must include a detailed trajectory for each entity, the limited capacity of the working stations, the sharing of resources, and the resource routing in the system. Although some refinement rules can be specified for the elaboration of the HPSIM model, this step requires a significant effort from the modeler when the simulation project requires a model with high level of detail.
- HPSIM does not have any function for off-line analysis of the simulation results. The only available way to analyze the simulation history is to load it in a spreadsheet editor, such as Microsoft Excel. The data provided by the simulator is a list of place markings and transition firings. This limitation is also found in many other Petri net simulators and is a consequence of the generality of the Petri net modeling language.
- The QUEST model is built by firstly defining the physical layout of the system. Then the working stations, buffers, material reception points and other locations are defined. In this case study, the close relationship between the real components of the system and the QUEST elements available for the system modeling made the modeling process easier and simpler in QUEST than in HPSIM.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

- QUEST embeds the routing logic and the causality relationship among activities in the programming language available for the process definition. The programming language provides flexibility. However, differently from the Petri net model, the causality relationships are not evident in the 2D or 3D visualization of the system.
- QUEST provides more flexibility for modeling stochastic behavior than HPSIM. Basically, the stochastic distributions can be associated to any variable of the model using the programming language.
- The tools provided by QUEST for the analysis of the simulation results simplify and reduce significantly the processing of the simulation results and generation of reports.

Case Study of the Serialization Phase

The purpose of this case study is the determination of the boarding time of an aircraft for a specific configuration of the distribution of seats inside the aircraft. The case study aims to provide the client of the aircraft industry with adequate comprehension of the boarding process and stimulate the definition of boarding strategies that minimize the permanence of the aircraft at land.

The ACD of this case study is presented in Figure 9. The HPSIM and QUEST models are illustrated in Figure 10 and Figure 11.

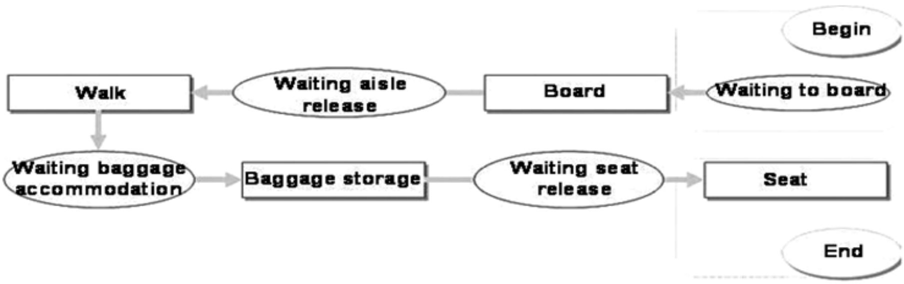

Figure 9 - ACD of Case Study 3.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

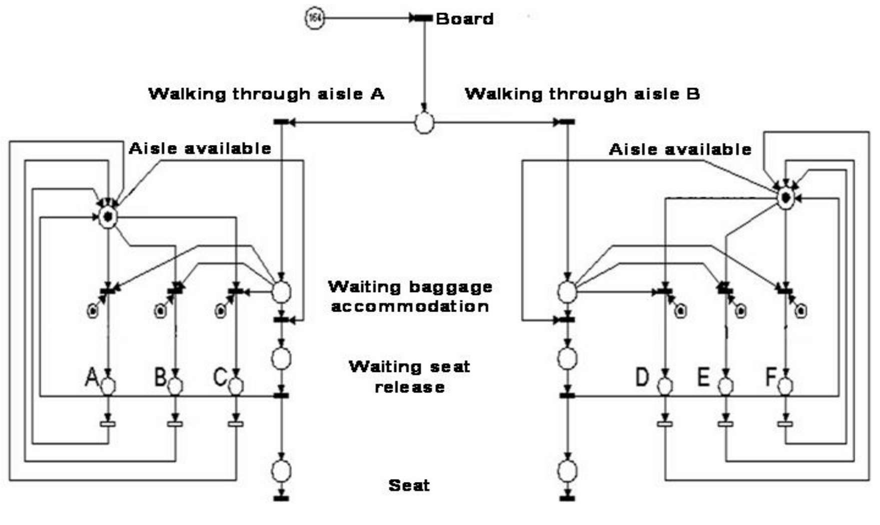

Figure 10 - HPSIM model of Case Study 3.

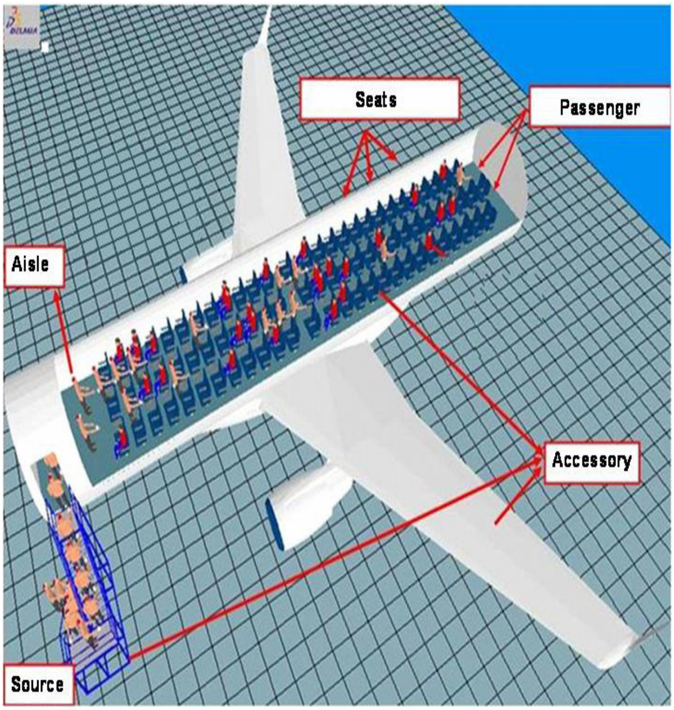

Figure 11 – QUEST model of Case Study 3.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

The following conclusions are obtained from this example:

- The Petri net model is composed of a large number of places and transitions (Figure 9 presents only the model of the first row). The size of the model makes the visualization of the simulation impossible. This problem is due to the fact that the event oriented modeling (adopted by HPSIM) requires a large level of details than process oriented modeling (adopted by QUEST).
- As the boarding process has behavior requirements that are different from those of conventional manufacturing systems, this case study allowed the evaluation of the modeling flexibility provided by the simulators. Particularly, QUEST presents some limitations. In order to model the boarding process, it was necessary to create invisible entities that are carried by the passengers to the aircraft, in the same way that parts carried by operators from an input buffer to a machine.
- The 3D interface provided by QUEST was essential for the visualization and comprehension of the boarding process. At this stage, the aircraft industry already has all the CAD models of the aircraft; the creation of the 3D simulation environment does not require any significant effort.

Case Study 4 - Phase-Out

When comparing to the serialization phase, the phase-out is marked by a high interaction with the clients of the aircraft industry. It is characterized by resource optimizing problems.

The case study of this phase is the modeling of the boarding and travelling time for a specific route, considering different aircraft configurations. The purpose is to provide the client with the necessary data for selecting among the aircrafts.

The ACD of this Case study is presented in Figure 12. Figure 13 and Figure 14 illustrate the HPSIM and QUEST models.

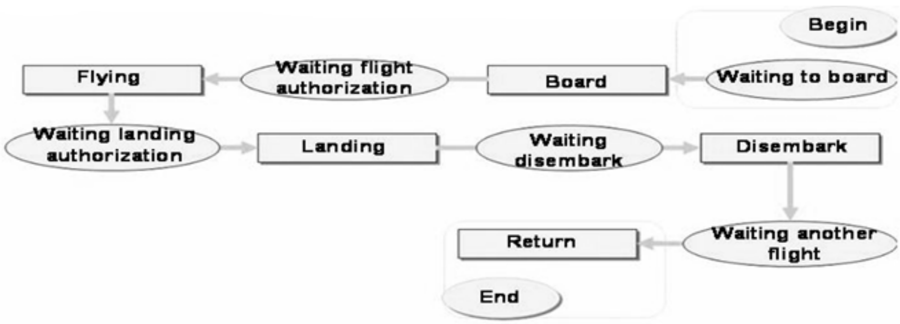

Figure 12 - ACD of Case Study 4.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

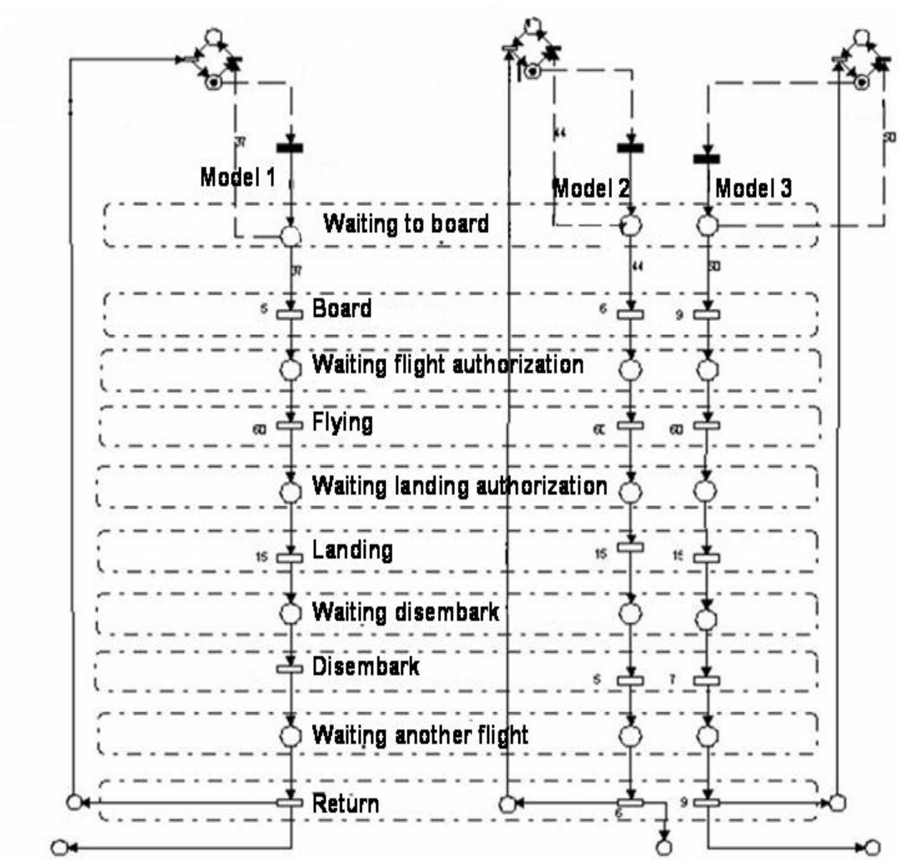

Figure 13 - HPSIM model of Case Study 4.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

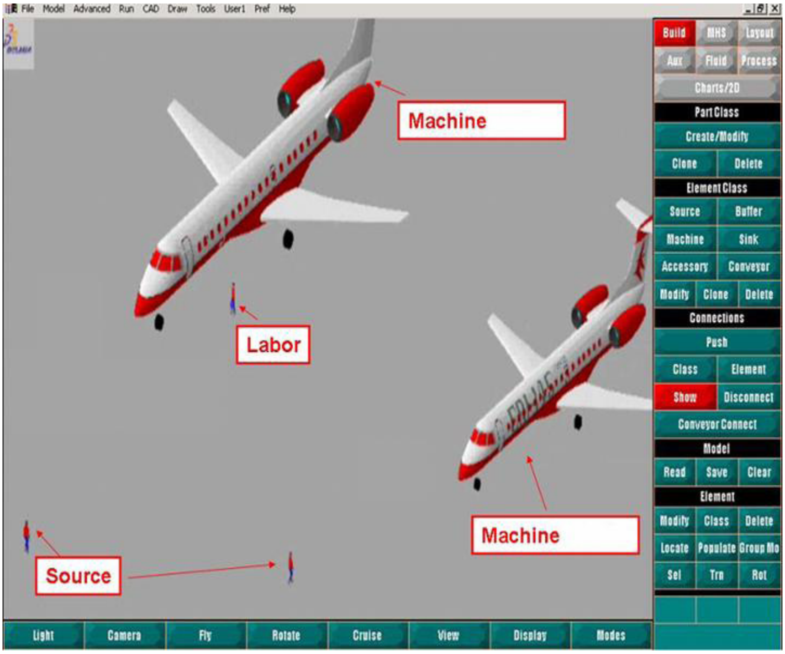

Figure 14 - QUEST model of Case Study 4.

The data used in this case study are deterministic. The model is simpler than the ones built for the development and serialization phases. These are common features of discrete simulation projects in the phase out and are a consequence of the limited financial resources available in this phase.

As a consequence of the model simplicity, both HPSIM and QUEST models are quickly built. The HPSIM model has the advantage of having a structure similar to the ACD. The 3D interface of the QUEST model is not significant for the results comprehension in this case.

Comparison of Case Studies

In order to compare the case studies presented in this section, Table 2 present some numerical data related to the complexity of the models. The ACD model is represented by the total number of queues and activities. The effort required in the data acquisition phase is represented by the number of deterministic and stochastic parameters. These parameters are used in both Petri net and QUEST models. The Petri net models are represented by the total number of places and transitions. In the QUEST models, the number of elements includes entities, machines, places, operators, sources and sinks.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

Table 2 - Case study comparison.

	Phase A / Case 1	Phase B / Case 2	Phase C / Case 3	Phase D / Case 4
Number of queues and activities of the ACD model	22	10	9	10
Deterministic / stochastic parameters	6/0	10/8	5/6	15/0
Number of places and transitions of the Petri net model	28	149	1340	51
Number of elements of the Quest model	37	35	304	28

The data of Table 2 is consistent with the description of the aircraft lifecycle phases presented in Section 2. The analysis of the number of stochastic parameters shows that the accuracy of the discrete simulation models is higher in Phases B and C, because of the available information about the aircraft. The complexity of the ACD model is similar in all the case studies.

It is interesting to observe that the size of the QUEST model for Phases A, B and D is similar, although the model of Case Study 1 is significantly simpler than the others. On the other hand, the problem of Case Study 3 is not easily modeled either in Petri nets or QUEST. Although the ACD and the problem is not particularly complex, the models for both simulators are excessively large. For the Petri net model, the net that represents one row should be copied the number of rows of the aircraft. Similar, in the QUEST model each seat is modeled as a machine and a place, enlarging the model.

Conclusions

This paper compares two solutions for discrete simulation projects in the aircraft industry. The first solution is based on a simple and free Petri net simulator, HPSIM. The second solution is based on the use of the commercial tool QUEST. Both solutions are applied to problems in different phases of the aircraft lifecycle, allowing the identification of the advantages and disadvantages of each solution, according to the problem features.

In order to organize the development of the simulation projects, the paper proposes a modeling approach that is composed of six steps: (1) definition of the problem by answering a questionnaire, (2) definition of goals and targets, (3) building an Activity Cycle Diagram (ACD) of the solution, (4) building the system model in HPSIM or QUEST, (5) model verification and (6) simulation and results presentation. This approach is applied to four case studies, using the two simulation tools. Each case study came from a different phase of the aircraft lifecycle.

Some of the conclusions obtained in the case studies are due to simulation approach (*process oriented* or *event oriented*). Others are specific for the tool used in the comparison (HPSIM or QUEST). The main points highlighted by the case studies are the following.

Brazilian Journal of Operations & Production Management
Volume 7, Number 2, 2010, pp. 131-152

The event oriented simulation aims at the explicit representation of parallelism, concurrency, synchronism and resource sharing. It usually provides more flexibility because it allows the definition of any relationship between a state and an event. It is not restricted by pre-defined processes and entities. On the other hand it usually requires more effort to build the system model. The case studies appointed that the main advantages of the Petri net solution are for simple problems, when the Petri net model is similar to ACD model. For these problems, the use of HPSIM requests less time than the use of QUEST. Because the QUEST model is composed of elements that cannot be mapped directly in the ACD elements.

One important advantage of process oriented simulation is scalability. When the problem requires the incorporation of a high level of detail in the model, the Petri net model can easily become of a size that makes it impossible to understand and manipulate, as happened in Case Study 3. The QUEST model is more compact and has a 3D graphic interface that helps on the communication between people involved in the problem.

Generally, the data handling in event oriented simulation is more time consuming than in process oriented simulation. Even if another Petri net simulator with advanced functions for data handling would have been used in this work, QUEST would still be better for data handling. The reason is because QUEST defines the entities of the system and, as a consequence, can provide tools for automatic calculation of the entity attributes, such as percentage of use. On the other hand, HPSIM defines only places and transitions, so the kind of data that can be provided automatically are mean number of tokens in a place, mean time between fires of a transition, etc. The user has to manually manipulate these places and transitions data in order to obtain the entities attributes. As a consequence, QUEST is better for problems that require extensive data handling.

Finally, it is important to emphasize that the choice of the best simulator depends on matching the features of the simulator, with the ones of the simulation problem. Among the parameters that must be considered are: the budget and time that will be necessary to complete the study, the skills required from the simulation people, the size and level of detail of the model, the experimentation range, and the presentation of results.

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