Official URL:
https://doi.org/10.1108/02656710310461341

To cite this version:

Pérès, François and Grenouilleau, Jean-Christophe *Spare parts supply modelling: application to a space station.* (2003) International Journal of Quality & Reliability Management, 20 (3). 360-377. ISSN 0265-671X

Spare parts supply modelling: application to a space station

François Pérès
Laboratoire Productique Logistique, Ecole Centrale Paris,
Châtenay-Malabry Cedex, France
Jean-Christophe Grenouilleau
European Space Agency, D\MSM-EOI, Delft, The Netherlands

Keywords *Spare parts, Space planning, Performance measurement, Logistics, Supply chain, Modelling*

Abstract *The work deals with the topic of spare parts management in a space system. The paper is divided into three parts. The first one is dedicated to the characterization of the system structure and presents the particularities related to the spare-elements procurement. Modelling is the object of the second part. After having exposed the bases of the problem to be solved, a macro-model is introduced. Each of the three elements of an orbital system, namely ground, flying and transport, is then described with a Petri net. Operation specificities of every element are then listed and integrated into the model. A concrete application of this modelling is given in the last part. It concerns the Columbus laboratory of the International Space Station. A representative function is selected and several supply strategies are evaluated.*

1. Introduction

The ability of a system to be repaired plays an important role in the control of the performance and costs. The dependability methods usually take into account an ideal operational environment, i.e. the availability of maintenance resources is instantaneous and with unlimited capacity. Within the framework of operational and economical performance evaluation of the system during its useful life, these assumptions may not be acceptable. As they are integrated in the design process, the logistic support analyses (LSA) allow, in particular, the verification of the assumption of the ideal availability of maintenance resources and consequently to identify the cost-performance problems as early as possible to redirect the options already taken.

Among the resources that are necessary to achieve maintenance tasks by replacement or repair, the spare elements take a very specific place due to the potential impact of their unavailability. The teams that are involved in the preparation of the operational phase pay special attention to the management of their supply. Defined in accordance with the maintenance policy, the supply management strategy mainly determines the range of spare elements and their supply mode as well as their geographical dispatch.

The research works summarized in this article deal with the development and the use of decision-making tools in the context of an inhabited spatial system in the design phase. The work is divided in three parts.

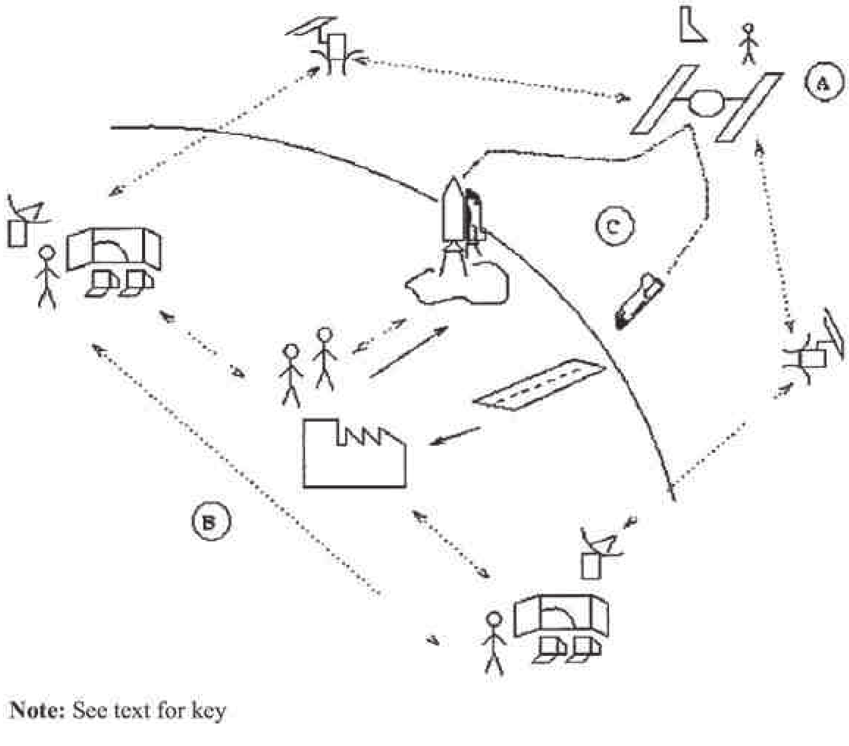
We start with a presentation of the spare parts supply in a spatial context. After having briefly described the components of an orbital system we characterize the particularities of such a system, capable of influencing the supply management. We then develop an evaluation method of the spare parts supply during the operating phase. We show that the problem can be formulated in terms of looking for the best compromise between, on the one hand, the unavailability time of a function in the absence of a spare element and, on the other hand, the cost related to the selected strategy. We then develop a model for the spare parts supply based on the use of the Petri nets. Finally, we suggest an illustration of the method through the application of the spare parts supply strategy to a function of the Columbus laboratory of the International Space Station.

2. Spare element supply of an orbital station

2.1 Structure of a spatial system

A spatial station system is generally defined by many interacting blocks called segments (see Figure 1):

- A flight segment (A), which includes the orbital infrastructure and crew as well as the communication means.
- A ground segment (B), which includes the infrastructure and the means necessary to monitor the flight segment (control and communication centres), the industrial structure that allows the support of the operation



Note: See text for key

Figure 1.
Components of a spatial system

as well as the infrastructure dedicated to users (preparation units of the elements to be launched and operated).

- A transportation segment (C) which allows the transport between the station and the ground of the crew, the results of experiments, the necessary resources and other failing elements. It includes the launchers, the cargo vehicles, the infrastructures of launch preparation and eventually return preparation.

2.2 Specifics of spare parts supply of a spatial system

2.2.1 The need for spare parts. The feedback of previous experience concerning the maintenance of spatial systems (and consequently the supply of spare parts), is limited and the rare data collected constitute an estimation to be taken with precaution because the systems and equipments developed are most frequently unique. In the preliminary phases, then, one must frequently resort to analogies with past programs in order to evaluate the needs in terms of replacement. Several works have estimated the needs of an orbital station in this way. A conservative estimate based on experience indicates that the spare-elements requirement represents annually 5 percent of the total mass of the system. However, this depends on the level of repair that is opted for. A rather low level of repair (i.e. repairing as many elements as possible, even down to the most basic) requires more tools and higher skills but, in return a lower mass at the time of restocking.

2.2.2 Stock. They are organized in what we define as stock echelons which means that the place of storage can be either on the ground (in the launch area or at the manufacturer's) or in orbit. One must keep in mind that storage on board an orbital space station is very much constrained in terms of available space, which has been confirmed by the Russian experience. Even though volume is limited, this is not the only hindrance to storage in the station. Let us note that the Apollo missions gave up on storing elements on board lunar modules because of the lack of knowledge about effects of radiation and space environment on the material. Replacing a failing element with another whose condition could not be guaranteed was judged too risky and the adopted solution was then to specify early in the design phase the element with higher reliability. Concerning the ground stock, the geographic distribution may be very diverse: the elements could be stored at the user's base, could stay in a centralized depot at the manufacturer's, or again, be distributed between the two. The stock may concern goods at diverse levels of nomenclature (spare elements, repair items).

2.2.3 The elements to be supplied. Only a limited number of industrials are interested in contracts of a very small volume of parts. Very often, the development and manufacturing times are very long. Because of the manufacturing lead time constraints, the supply of elements needs to be performed at the same pace as the manufacturing in order for the spare elements to be available when the system is started. Moreover, the rapid evolution of the market associated with a considerable time required to design the system often implies that many elements will be obsolete by the end of the preliminary conception phase.

2.2.4 The repairs. As far as repairs in orbit are concerned, the main constraint is the astronaut's qualification. Often, one makes the hypothesis that the low-level repairs (e.g. a welding) are too complex and their quality too uncertain to be performed on board. Thus, the replacements are more generally performed by a total exchange of orbit replaceable units (ORU). When a failing element is brought back from orbit, it is generally restored into its original condition. Indeed, because returns for repair are rare, the elements are often totally dismantled and inspected to collect as much information as possible. According to Batteau and Marciano (1976), the cost of a repaired element in the case of the Space Lab laboratory reaches between 70 and 75 percent of the cost of a new element, which means a gain of 25 to 30 percent compared to the cost of a new element. However, this gain could be greatly diminished by the cost of the shuttle return transport.

2.2.5 Transport. The frequency of transport (90 days for the International Space Station) is the fruit of a compromise between the fuel needs of the station and the load capacity of the space shuttle. It takes also into account a margin of security in case a restocking cannot be done. Shuttle launching data indicate that the major reason for postponement of a launch is of a meteorological nature. One complex transport problem in the context of space flight, is the existence of a lead time for loading. Because of the complexity of the evaluation process involved in the loading of space shuttles, the possibility of modifying the composition of the supply to be loaded is improbable. The continuous operations concept, such as the one envisaged for the International Space Station, poses serious difficulties when an urgent demand for supply is necessary. The potential impact on the planning of several flights, as well as the international aspect of the operations necessitates considering a mechanism of priorities (Blagov, 1993). Furthermore, because of the analyses of the required load, (among others the determination of the centre of gravity and moments of inertia), modifications are progressively impossible depending on the weight of elements to be added or withdrawn from the cargo.

2.2.6 Tests. The state of onboard systems of a space system is controlled almost permanently by means of telemetry and reports carried out by the astronauts. Consequently, failures are immediately communicated. The passive redundancies and the stored elements pose, nevertheless, some difficulties. Theoretically, the periodical test of elements increases the probability of failure. It is necessary, then, to arbitrate between the risk of keeping an element which is potentially out of order and the risk of causing its failure during the test.

3. Modelling the policies of spare parts supply

3.1 Formulation of the problem

Because of the uncertainties of demand and the capacity of the logistic chain, it is acceptable to think that the risks of seeing a deferred request are never negligible. We are, then, interested in seeing that the cost and availability objectives are reached. The search for an acceptable risk, in the economic sense of the term, necessitates the finding of a compromise between what the user is ready to invest a priori in order to reduce the risks of not attaining the objective, and what the user must spend a posteriori if the selected measures are not sufficient. One can envisage the construction of a curve showing the maintainability relevance (Figure 2). Let us consider the random variable X, representing the average time of unavailability of the function. We note Pr(X > Objective), the probability that this average time exceeds the objective fixed by the user. It is accepted that there exists a zone where the variations around the objective are economically acceptable. We propose to construct this curve in order to proceed with the evaluation of the spare elements supply policies. Representing the influence of the decisions concerning the logistic chain requires taking into account the set of supply management parameters in the modelling that we propose:

- the storage echelons envisaged (in orbit, on the ground, at the manufacturers);
- the stock nomenclature (complete elements, sub-elements, parts);
- the supply possibilities (supply parts that were stored or parts that have been repaired or manufactured); and
- the management decisions (When to supply? Which elements and what quantity? Under which condition?).

Because each selected combination is a potential solution, the problem may be difficult to resolve. The choice of a model and a resolution technique is the result of a compromise between the representation power, the handling power

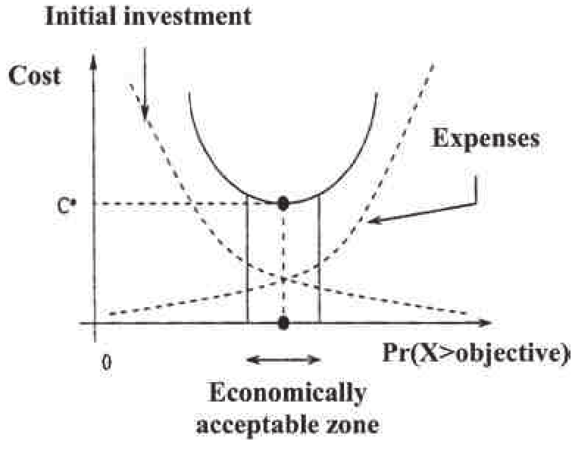


Figure 2.
Relevance of the efforts of maintainability

and the ease of implementation (Pérès, 1996; Noyes, 1987). The complexity of the analytical forms induced by the diversity and complexity of the phenomena that take place led us to choose the route of simulation. Among the available tools we selected the Petri nets because they are easy to use, they can adapt rapidly to structural or organizational modifications, and they integrate stochastic and determinist phenomena.

Little work, to our knowledge has been based on the Petri net for establishing models of logistic support (Ereau, 1997; Ereau *et al.*, 1997). In the majority of cases, the authors limit themselves to the evaluation of the number of operators to put in place in order to insure the availability of an installation. Ereau (1997) and Ereau *et al.* (1997) propose, however, a simple description of logistic support of a constellation of satellites. Leroy and Signoret (1992) propose as well the concept of logistic mobilization for petroleum platforms. However, one can think that the representation of the supply chain could be much more complex. With this in mind, van der Aalst (1992) proposed models for logistic systems of distribution. We found it interesting to use the Petri net for modelling not only the orbital system, but also for the logistic support network. The models are developed and applied with the help of the Moca-RP tool (Cordier *et al.*, 1997; Signoret, 1999). We propose an interpretation of the Petri nets which permits the representation of the supply policies management and its impact on the system performance. We will show how to represent the orbital system as well as the spare parts logistic chain of supply.

3.2 Modelling

Figure 3 gives a sketched view of the modelling structure. In the following, we will successively describe the orbital system, the transportation system and the logistic chain. For more details on this modelling work, please refer to Ereau (1997) and Ereau *et al.* (1997).

3.2.1 The orbital system

3.2.1.1 ORUs. Each replaceable element can be found in three states:

Standby: this is the state when the element is not used. The transitions between the running state and the failure state are run by external promptings (start or stop impulsions). The start time can be immediate or tempered,

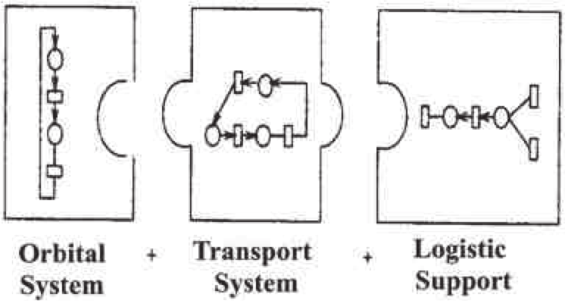


Figure 3. Architecture of the whole model

eventually controlled by a usage function. This is the original state of the element.

(1) *Running*: this is the nominal state of the element that allows it to fully ensure its function. In this paper we do not take into consideration elements that would be in a deteriorated functioning state. The time before the transition towards a failure state can be represented by different distributions (Dirac, exponential, Weibull, etc.).

(2) *Failure*: this is the state of the element that experienced a failure. Even though the successive damages can be contemplated, we assume that the transition is immediate. Return to the standby state happens after some replacement lead time that depends on the availability of the spare element. We consider this lead time for the replacement in orbit as negligible compared to other lead times taken into account.

Figure 4 shows a view of the related Petri nets.

The elements of an onboard system can be redundant (Pages and Gondran, 1980; Ushakov and Harrison, 1994). Ereau (1997) and Ereau *et al.* (1997) suggested a modelling for redundant satellites. In this case several failures are necessary to put the element in the failure state. The following restrictions will be taken into consideration:

- the redundant systems are passive ones, meaning that they are in a waiting state, ready to fulfil their part;
- the commutation on the redundancy is totally reliable; and
- the failure of redundancies from the waiting state are not announced.

We give a representation of a material redundancy in Figure 5.

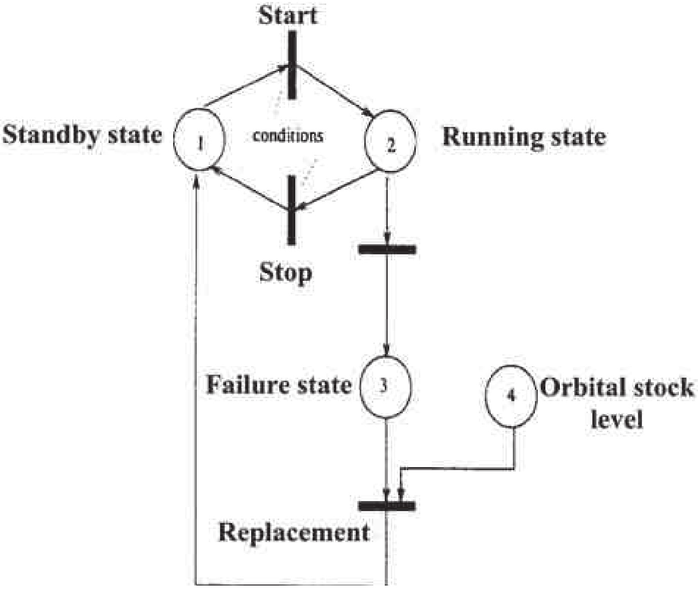


Figure 4.
Representation of a replaceable element

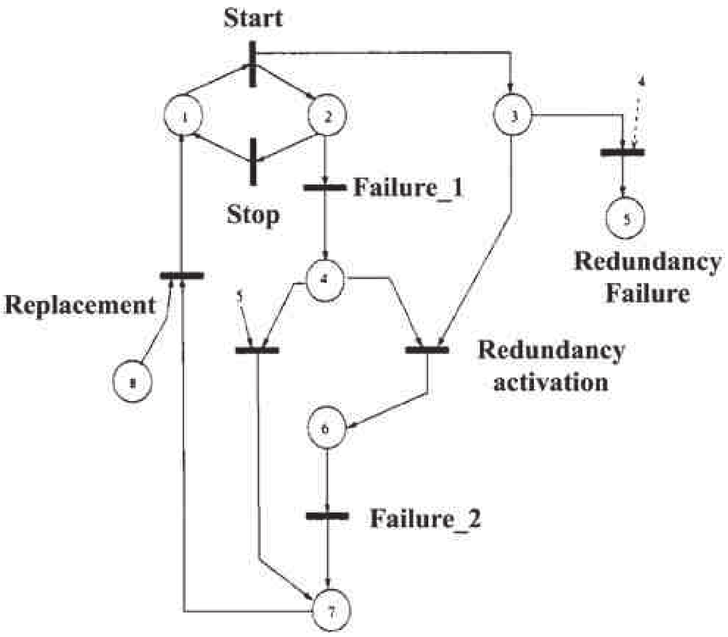


Figure 5.
Representation of a material redundancy

The replacements of elements are determined by maintenance policies that have been selected by the designers (Figure 6):

- *Corrective maintenance only*: the replacement is performed at the nearest opportunity; the failures from the running state are reported by information released when the element goes through the related transitions; here the information related to the failures from the standby state are not taken into consideration.
- *Preventive and corrective maintenance*: the replacement is scheduled to be performed at a predetermined moment. Two cases can then occur: either this date is reached with no failure, or a failure occurs before.

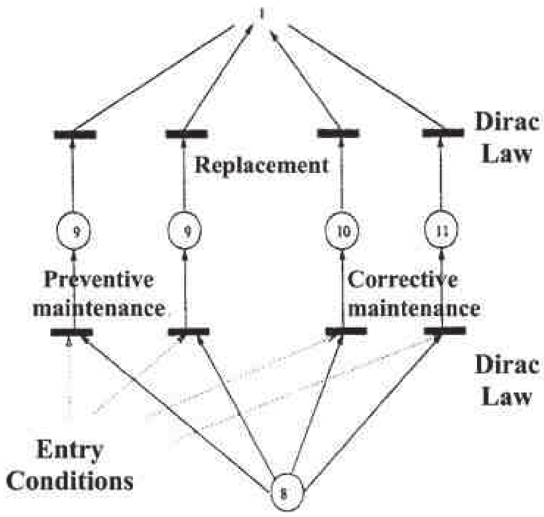


Figure 6.
Representation of the maintenance policies

Let us now take the following scenario into consideration: the failure of an element occurs and there is no spare part available. If an identical element is present in the system, fulfilling a less important application, one can imagine exchanging elements between applications. It can then be represented by adding a transition between the waiting places of the similar elements. These transitions become valid if there is no stock.

Sherbrooke (1994) that the cannibalization can have a negative effect on the availability of the system if it is explicitly considered as an operation strategy and not used during the operation. We will then recommend that this strategy be avoided in the first place.

The phenomenon of cannibalization is sketched in Figure 7.

3.2.1.2. Functions fulfilled by the system. Let us now consider all of the functions fulfilled by the orbital system. From the point of view of the function it is required for, the state of the element is binary (running, failure). In relation to the model which we have described for an element (see Figure 4), this means that the standby and failure states are to be considered equally. From our knowledge of the system operating conditions we can deduct the Petri net of the function. The transformation of these operating conditions described by reliability diagrams is possible. Based on this, Signoret (1999) recently proposed a method that allows the building of the Petri net of a system according to its production levels.

In Figure 8 we consider a function composed of two elements (1 and 2). We assign one place in the Petri net to each level of performance of the system. The entry conditions in the places are determined when transmitted messages are received at the time when a token passes through a transition.

3.2.2 Transport system

3.2.2.1 A basic model. The transport vehicle may be in two different states according to whether it is on the ground or in orbit. We consider the delay between the launch of the shuttle in orbit and its arrival at the station to be

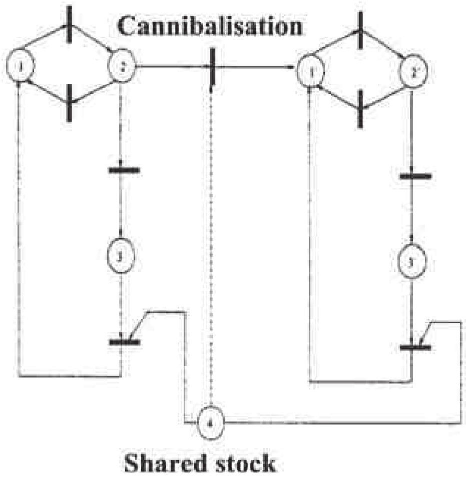
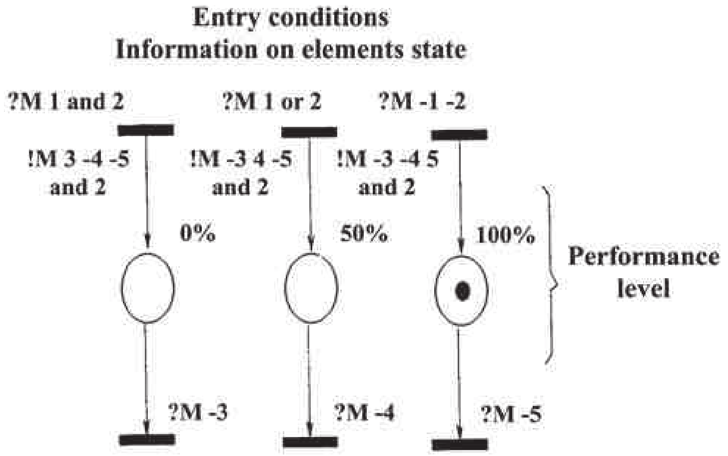


Figure 7.
Cannibalization between two elements



Note: We also take into account the possibilities of a functional redundancy

Figure 8.
Modelling of a function

negligible (in reality this delay is two or three days). Consequently, when the shuttle is in orbit, we assume that it is docked. A place is assigned to each of the two preceding states. The vehicle is represented by a token. The evolution of the marked places of this network represents the state of the shuttle and therefore the movements of the vehicle between its orbit and the ground (see Figure 9).

3.2.2.2 Integration of loading constraints. The loading and unloading activity is represented by transitions of varying lengths of time. We have chosen to consider these periods of loading as negligible compared to other constraints which cause delays of a much longer duration. In order to load an element, three conditions are necessary (see Figure 10):

1. the part must be available in sufficient quantities (marking of place number 12);
2. the shuttle must be on the ground and accept the load (marking of place number 14); and
3. intermediate storage in orbit must be possible (marking of place number 8).

It is possible to transport each element to the orbiting shuttle, but also from the orbit to the ground. It is then necessary to make a distinction between the

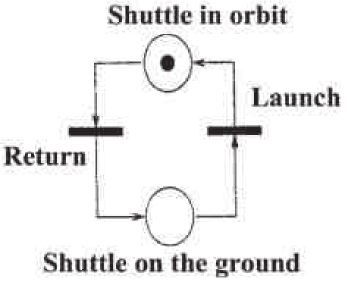


Figure 9.
Representation of the transport

ascending and descending elements. Consequently, the representation of an element must be modified to represent this (addition of a place standing for "descending stock"). A capacity constraint may be taken into consideration (Proth and Xie, 1994) by adding a place with limited capacity which would contain as many tokens as the number of marks in the storage places. The studies carried out at the ESA indicate that the part allocated to Europe for the restocking of maintenance supplies (400kg/year) is not restrictive (Passaro *et al.*, 1999). Therefore, we will not verify this constraint further. If necessary, however, we would take a capacity limitation into account. On the other hand, there is a heavy constraint caused by the limited lead time after which it is no longer possible to carry out the loading. This lead time depends essentially on the mass of the element. One can consider a standard lead time by adding a place which corresponds to the state of "end of loading time" reached when going through a deterministic time transition. Note that the case of variable lead times according to mass has also been dealt with.

Let us note that other constraints such as the maximum number of round trip cycles by elements or the notion of priority element can be taken into account by Petri nets (coloured petri nets as far as the second constraint is concerned).

3.2.3 The ground segment. In order to represent the supply chain, we added, in the Petri nets, the flow of operations (supply, distribution, loading, manufacture, repair), the flow of information (regarding stock, failures, transport), as well as the flow of decisions (regulation actions, loading, unloading, purchase).

3.2.3.1 Operational level. Our representation takes into account different stock echelons as well as their in and out flows. We consider the following construction bases (see Figure 11):

- a stock echelon is represented by one place; the number of tokens in that place corresponds to the stock level, that allows the introduction of a capacity constraint;
- the supply activities are represented by transitions of any time length; and
- the weight given to the arcs gives information about the quantity supplied.

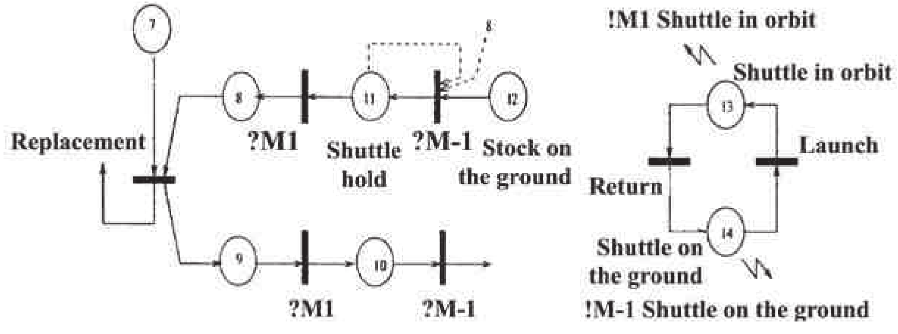


Figure 10.
Representation of loading constraints

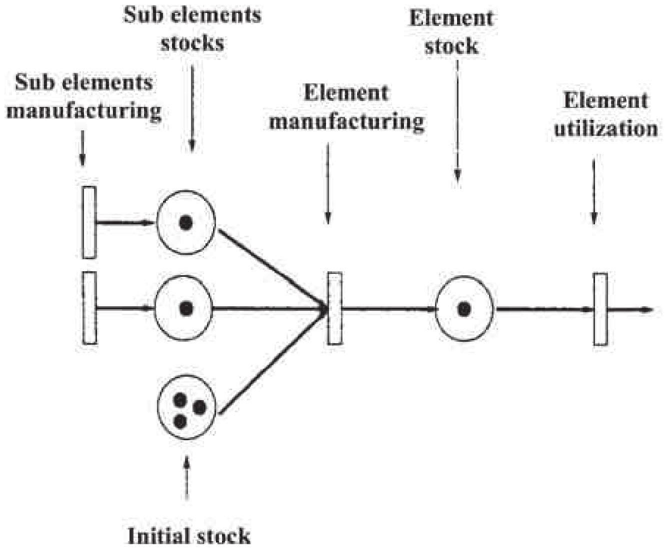


Figure 11. Standard supply structure

From then on, it is possible to model numerous structures. Let us remember that the need for supplies may be responded to in different manners: from a stock echelon, a manufacture on demand (transitions and conditions), or after the assembly of sub-elements (places and transitions). The supply of stock may be achieved by the dispatch of either newly manufactured or repaired elements. Supply by the manufacturer may have capacity or time restrictions (lifetime of aline of fabrication). The repair structure consists of a place standing for the operator, and a transition representing the repair time, no matter the type of distribution. The constraints of this structure, such as the number of operators available or the capacity of the repair centre are classic and easily integrated into the models.

3.2.3.2 Decision and information levels. The management of the supply chain gives an answer to the questions we posed at the beginning of this section: Is it preferable to stock supplies? If so, where? Which elements must be supplied? When? In which quantity? And under what form? Should we repair?

The decisions concerning the supply of stock in orbit are linked with the system operational strategy. It is, then, principally the information regarding failures and deadlines which activate supply from the ground. We will show how to represent three standard policies (see Figure 12):

1. *Static policy:* most often concerns elements for which supply is later impossible.
2. *Calendar policy:* this policy consists in supplying at a predetermined date, the fixed or variable quantity.
3. *Threshold policy:* contrary to the static policy, it permits the control of the quality of service because of its dynamic character – if the demand increases, so also does the frequency of supply.

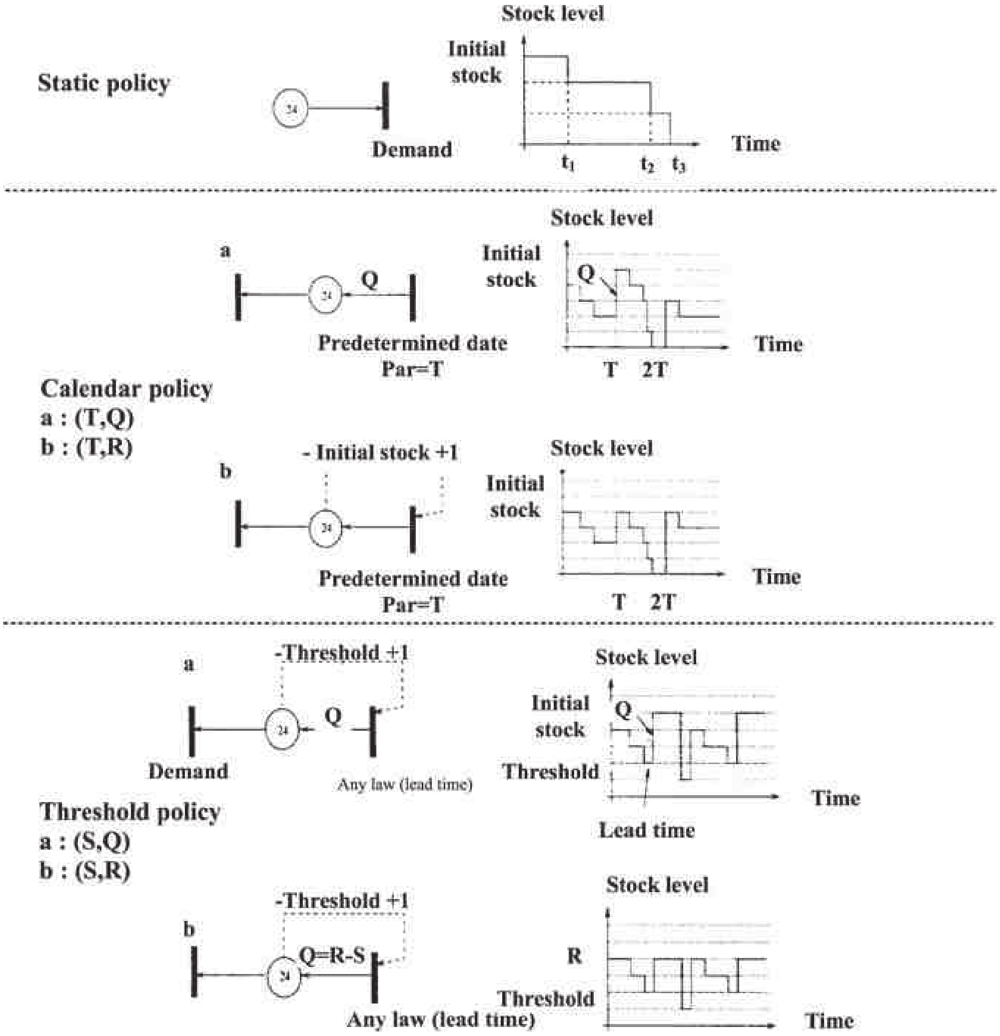


Figure 12.
Different supply policies

It is obvious that the number of possible combinations is not limited to what we propose here. However, the rules of construction for representing structures more complex remain similar and the modelling stays open to new structures.

3.2.4 Assembly of models. In order to represent correctly the functioning of the space system and its support, it is first necessary to make their physical flows correspond. In the present case, the transportation plays exactly this part, by carrying the spare elements from the support system to the orbital system. The physical assembly of the models is performed through the transport network that enables the synchronization of the two other networks. The supply events have then to be coordinated with the events that happen in orbit. To do that, one has to identify the data that flow in the system to activate the support actions. Finally, the choice of a policy determines both the physical structure that has been set up and the use of the data to manage the physical flow.

4. Application to the Columbus laboratory

4.1 Description of Columbus

The International Space Station recently became a reality with the successful launching and docking of its first two modules. Europe actively participates in this technological and scientific development by building many elements and in particular the orbital Columbus laboratory (see Figure 13). The laboratory is a pressurized habitable module designed to provide for ten years a multifunction laboratory able to welcome all the scientific disciplines related to micro gravity: technological and scientific research as well as industrial applications. The detailed design review of the laboratory is now under process and the launching of the laboratory is scheduled for October 2002.

The average availability objective for the laboratory functions can be different depending on whether it regards security functions (99.9 percent on 90 days during 10 years) or operating functions (94 percent on 90 days during 10 years). Reaching this objective requires the support of maintenance activities and in this perspective the laboratory carries about 300 replaceable elements representing 65 different types. Only 15 percent of these elements are subject to preventive maintenance, which consequently emphasizes the role of the logistic support system.

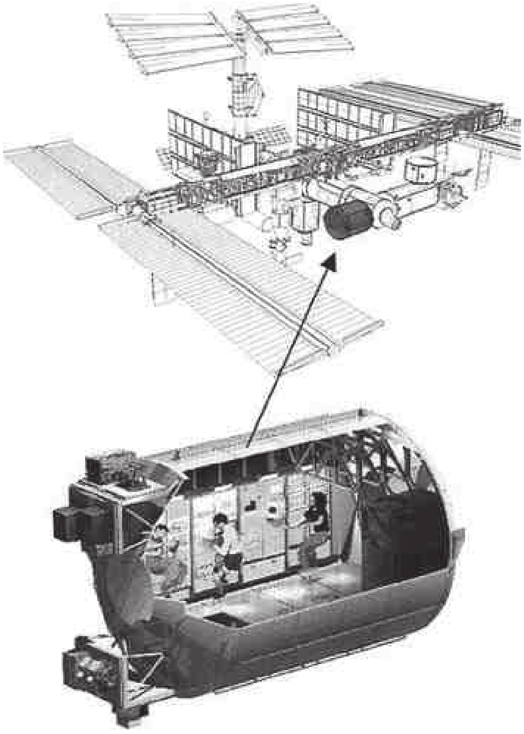


Figure 13.
The International Space Station and the Columbus laboratory

4.2 Evaluation of the supply policies of a selected function

4.2.1 Selection of a study function. No scientific experiment can be run without electrical energy, this is the reason why the "payload power supply" function has been selected. This function is also interesting because of its relatively simple architecture that allows a rapid illustration of the model's implementation. The systems of the International Space Station provide the laboratory with direct current (120V DC) through two buses (see Figure 14).

Each bus feeds a Power Distribution Unit (PDU). The two elements receive electrical power and provide the connections, the distribution, as well as the protection of all the experiment racks. The power supply of the PDUs are also cross-strapped in order to compensate for the loss of a bus of the station. Each PDU is redundant and feeds two power supplies (nominal and auxiliary) which dispatch the power to the racks. This function, also belonging to the power distribution to the onboard systems, has to be available on average 99.9 percent on 90 days during 10 years because of its great impact on the laboratory security.

4.2.2 Modelling. The modelling of each of the PDUs is performed as described in paragraph 3. The replaceable elements have been integrated in the model by taking into account the possibility for the standby redundancy to fail. As far as the maintenance during the flight is concerned, the dimensions and the weight of the element make its orbital storage impossible. Because the cannibalisation is not considered, the astronauts will replace the element when it becomes available. This replacement will be performed either to restore the redundancy or after a complete failure.

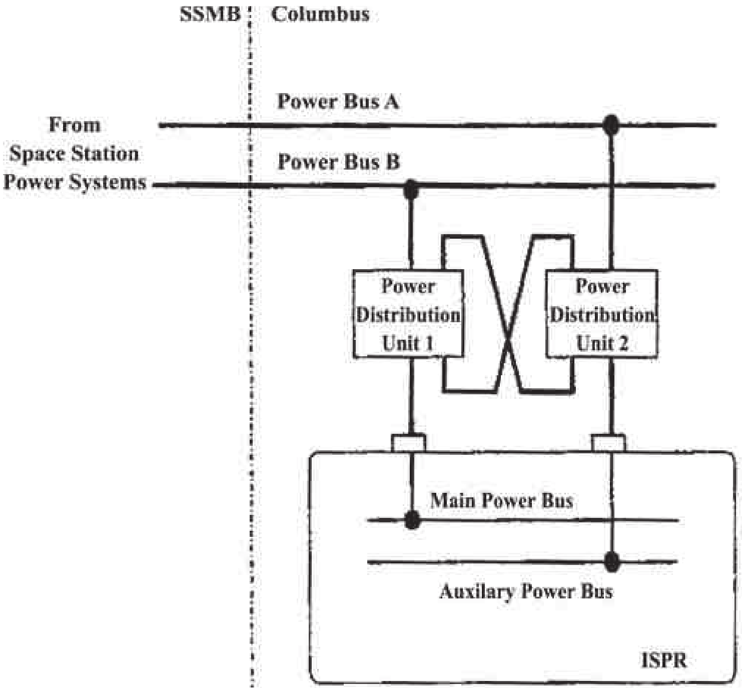


Figure 14.
Simplified view of the "payload power supply" function

We consider the three following states for the power supply function:

(1) running on auxiliary power: from the PDU 1;
(2) running on auxiliary power: from the PDU 2; and
(3) not running: PDU 1 and PDU 2 failure.

As regards the subnet that represents the transport, the closure of the loading capacities happens 45 days before launching. The length of the orbital stay is set to 12 days (288 hours).

The first supply policy for the elements of the power supply function consists in supplying first the stock on the ground with one element and then to proceed with the return of failing elements in orbit for repair. The second policy is a static one where the first supply takes into account the number of expected failures during the lifetime.

4.2.3 Evaluation and discussion on the results. We can now deal with the analysis of the technico-economical performance of the supply policies. In order to do that, we first run a simulation (100,000 stories) which allows us to evaluate the selected indicators. The processing of the simulation results leads to the curve of the function average unavailability (see Figure 15).

We can directly visualize the probability of not meeting the average objective by plotting the related limit (99.9 percent on 90 days, i.e. approximately 2.2 hours of unavailability), still keeping in mind the extreme nature of the selected operation policy. It can be stated that the two policies are quasi identical as far as performance. Thanks to the simulation we can then proceed with the evaluation of the average costs of each of these policies. The results are as follows:

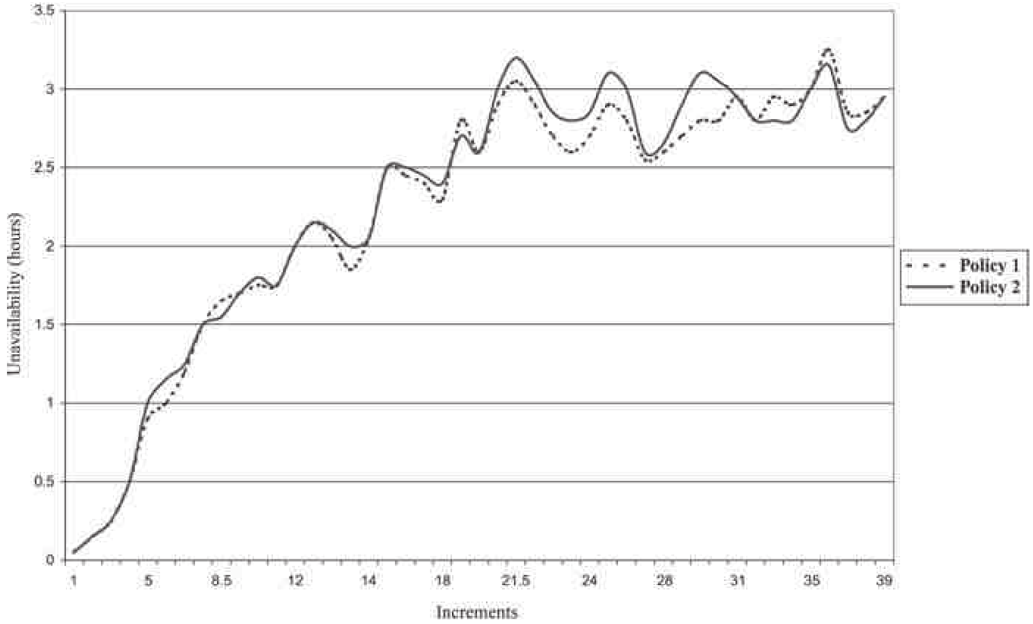


Figure 15.
Evolution of the power supply unavailability

- policy no. 1 ≅ €14.2 million; and
- policy no. 2 ≅ €20 million.

One can see that the two policies are close in performance but not in cost. Let us note that this result does not confirm the intuition of the designers of the orbital laboratory. They thought that the repairs would not be economically worth the cost of transport.

5. Conclusion

The use of the Petri nets for the specification and analysis of logistic support systems seems to be a research perspective full of promise. With the help of coloured or uncoloured stochastic and deterministic Petri nets related to each support element, future works will lead to the development of a Logistic Support Analysis. The development of such a tool will allow the finding of a partial solution to the difficulty of implementation of this type of analysis. The work which has been presented in this paper goes in this direction. The modelling of the supply logistic chain and the evaluation of the technico-economical relevance of its structure and control became possible. A logical follow up of this work will consist in using formal tools and optimisation methods to analyse the Petri nets that represent the system and its logistic support. It will be then possible to detect, in the structure of the Petri nets, the potential problems of the support system in order to improve the relevance of the undertaken efforts. Eventually let us also mention that this work is currently being applied to the other functions of the Columbus laboratory where it is used as a guiding decision tool.

References

Batteau, P. and Marciano, J. (1976), *Probabilités et Décisions dans l'Incertain*, Presses Universitaires de Fance, Paris.

Blagov, V. (1993), "Orbital space stations mission control", paper presented at the Mir Space Station Symposium, 27-28 July.

Cordier, C. *et al.* (1997), "Integration of process simulations in availability studies", *Reliability Engineering and System Safety*, Vol. 55, pp. 105-16.

Ereau, J.-F. (1997), "Réseaux de Petri pour l'étude de la disponibilité opérationnelle des systèmes spatiaux en phases d'avant-projet", PhD thesis, Université Paul Sabatier de Toulouse, Toulouse.

Ereau, J.-F., Saleman, M., Valette, R. and Demmou, H. (1997), "Petri nets for the evaluation of redundant systems", *Reliability Engineering and System Safety*, Vol. 55, pp. 95-104.

Leroy, A. and Signoret, J. (1992), *Le Risque Technologique, Que-Sais-Je?*, Presses Universitaires de France, Paris.

Noyes, D. (1987), "Approches méthodologiques pour l'aide à la conception et à la conduite des systèmes de production", PhD thesis, Institut National Polytechnique de Toulouse, Toulouse.

Pages, A. and Gondran, M. (1980), *La Fiabilité des Systèmes*, Collection de la Direction des Etudes et Recherches d'Electricité de France, Eyrolles.

Passaro, R. *et al.* (1999), ”Colombus spares and support equipment provisioning documentation”, technical report, Alenia Aerospazio, Divisione Spazio.

Pérès, F. (1996), “Outils d’analyse de performance pour stratégies de maintenance dans les systèmes de production”, PhD thesis, Université Bordeaux I, Bordeaux.

Proth, J. and Xie, X. (1994), *Les Réseaux de Petri pour la Conception et la Gestion des Systèmes de Production*, Masson, Paris.

Sherbrooke, C. (1994), *Optimal Inventory Modeling of Systems: Multi-echelon Techniques*, John Wiley & Sons, New York, NY.

Signoret, J. (1999), “Des diagrammes de fiabilité aux réseaux de Petri et aux calculs de productivité”, technical report, Groupe d’études Moca-RP.

Ushakov, I.A. and Harrison, R.A. (Eds) (1994), *Handbook of Reliability Engineering*, John Wiley & Sons, New York, NY.

van der Aalst, W. (1992), “Timed coloured Petri nets and their application to logistics”, PhD thesis, Université Technique d’Eindhoven, Eindhoven.

Further reading

Bertrand, R., (1998), “Conceptual design and flight simulation of space stations”, PhD thesis, Institut fur Raumfahrtsysteme, Universitat Stuttgart, Stuttgart.

Grenouilleau, J.-C. (1999), “Modélisation de politiques d’approvisionnement en eléments de rechange pour le laboratoire orbital Colombus”, PhD thesis, Ecole Centrale Paris Laboratoire Productique Logistique, Paris.