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## Optimizing end-of-life system dismantling strategy

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The management of end-of-life systems is becoming a major concern for systems manufacturers as the negative impact of these systems on the environment is a matter of increasing public awareness and their appropriate treatment offers economic opportunities. In this context, the disassembly of these systems in order to recycle their components is a possible and sound option that can make it possible to sustain economical progress while respecting environment requirements. The work undertaken in this paper considers modelling and optimizing issues of such disassembly activities. An integrated approach is proposed to model and optimize the selection of valuable components of end-of-life systems, their recycling options and the way to obtain them. Because the framework of such problems is highly uncertain, we propose the use of Bayesian networks and their extension in terms of influence diagrams as mathematical tools for structuring and managing uncertainties. This approach allows taking into account uncertainties rising from different sources on one hand and as a support for optimization on the other hand.

Keywords: Disassembly strategy, end-of-life modelling, Bayesian networks, optimization.

### 1 Introduction

Because of sustainable development concerns or considerations (Presley *et al.* 2007), the stakes related to the final step in the life cycle of systems - that is their retirement from service - have increased considerably. End-of-life systems must be disassembled in order to satisfy environmental issues. Valuable components must be selected according to technical, economic, and environmental criteria and ultimately a disassembly system has to be optimized enabling these components to be obtained.

Disassembly strategies must then respond to all decision issues raised during the stage of system retirement. In a disassembly strategy, the way to obtain and to recycle components is what we refer to as disassembly trajectory in this paper. When this trajectory is known,

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3 decision-makers can then specify the internal disassembly process, identify the needs for the  
4 repatriation logistics chain and identify and select recycling channels. A disassembly  
5 trajectory is defined with a set of products (elementary products or sub-assemblies) and a set  
6 of activities on these products. These activities could be disassembly activities, which can be  
7 destructive or not, or recycling activities which generally include:  
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- 10 • functional recycling that consists of introducing disassembled products into the  
11 process of new system production or into the exploitation process (maintenance for  
12 instance) of existing systems;
- 13 • material recycling that generates material from components of the end-of-life system  
14 in the production process of new systems;
- 15 • energy-oriented recycling in order to produce energy;

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Dangerous products and/or components that cannot be recycled may be stocked in safe  
places that respect environmental requirements.

Disassembly is undertaken in an uncertain context that needs to be characterized when  
defining a strategy. Uncertainties to be considered are mainly related to:

- the state of end-of-life systems when their deconstruction moment comes;
- the system withdrawal date;
- the withdrawal conditions and repatriation modes of the system;
- the duration of the disassembly and recycling activities and the nature of resources  
needed;
- the recycling channels that depend on demands of disassembled products and on their  
adequacy with the recycling techniques.

Our purpose is to provide the decision-makers with decision support tools that first  
allow the determination of disassembly trajectories based on various decision problems  
encountered in disassembly and second, makes it possible the management of uncertainty.

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3 Different kind of decision problems may be encountered when defining a disassembly  
4 trajectory. The first one concerns the definition of a disassembly path. It enables the  
5 determination of the intermediate sub-assemblies that have to be generated to obtain the final  
6 components. Graph theory (Lambert and Gupta 2005), AND/OR graph and Petri nets (Tang *et*  
7 *al.* 2002) are the most used modeling tools to represent this kind of problem. Graph search is  
8 used to find optimal solution according to economical criteria. These models are not sufficient  
9 to represent sequence-dependant cost (i.e. cost of a sequence of operation determines the  
10 order of operation) when parallel disassembly operations need to be achieved with the same  
11 resource (Kang 2005). This is the second kind of decision problem. It is currently modeled  
12 and solved with linear programming on the basis of a disassembly path model that specifies  
13 precedence constraints between operations (Kang *et al.* 2001, Lambert and Gupta 2005). In  
14 (Moore *et al.* 2003) specific Petri nets are proposed to model this problem in which pre-  
15 conditions for beginning each operation are modeled. Some sub-assemblies of an end-of-life  
16 system can be recycled and do not need to be disassembled. For each sub-assembly, decision-  
17 makers have to choose between disassembly and recycling. This leads to the third type of  
18 decision problem called disassembly depth. It necessitates the representation of the potential  
19 recycling values of sub-assemblies. Petri nets are most commonly used to represent this  
20 problem (Zussman and Zhou 1999, Tiwari *et al.* 2002, Reveliotis 2007) and AND/OR graph  
21 are also used in (Kang 2005) (Lambert and Gupta 2005). Indeed, these models allow  
22 integrating sub-assembly recycling values into their optimal search algorithms. The fourth  
23 type of decision problem that decision-makers may encounter in disassembly concerns the  
24 selection of a single recycling option from a set of possible options for each selected  
25 component. Petri net and associated search algorithms are also currently used to model this  
26 problem (Zussman and Zhou 1999, Tiwari *et al.* 2002). Indeed, only a few modifications are  
27 necessary to integrate various recycling options for each component in order to adapt Petri  
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3 nets used for modeling disassembly depth and path. In the disassembly of end-of-life system,  
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5 destructive disassembly operation is an efficient alternative to reduce operation time and cost.  
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7 However, very few studies deal with this problem. Destructive disassembly of a component is  
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9 performed when the component is too damaged (Gungor and Gupta 1998). In (Das and Naik  
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11 2002), the authors propose a specific process model to represent destructive operations that  
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13 generate recycling components and carcasses (component or sub-assemblies that cannot be  
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15 recycled). Generation of material fragments is considered in (Kanai *et al.* 1999) as the result  
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17 of destructive operations. Tree structure is used to model the material fragments that compose  
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19 the system to be disassembled. In (Duta *et al.* 2003), the authors suggest integrating  
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21 destructive operations in disassembly Petri nets. Through this study, Petri nets seem to be the  
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23 most flexible tool to model the different decision problems linked to the disassembly  
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25 trajectory definition (Table 1).  
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32         Uncertainties are inherent in the deconstruction activity and more generally in end-of-  
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34 life systems management tasks. As far as we know, few models of the literature actually take  
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36 them into consideration and, when they do, very often only one type of uncertainty is dealt  
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38 with. In most cases, sources of uncertainty concern the different levels of the state of  
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40 degradation. In (Krikke *et al.* 1998), probability distribution is associated with each  
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42 component and a dynamic programming procedure allows the determination of an optimal  
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44 trajectory in a tree-based representation of the end-of-life system. A similar approach is  
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46 proposed in (Salomonski and Zussman 1999), (Reveliotis 2007) based on Petri nets and with  
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48 learning approaches to determine probabilities. The same Petri net structure is used in  
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50 (Turowski *et al.* 2005) but the authors model uncertainties with fuzzy logic. The failure of a  
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52 disassembly operation is a consequence of product state uncertainties (degradation or  
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54 constitution). A Bayesian network is proposed in (Geiger *et al.* 1996) to model the state of the  
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56 system and the risk of failure of disassembly operations. In (Zussman and Zhou 1999, Duta *et*  
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3 *al.* 2003), a probability of failure is associated with each disassembly operation and integrated  
4 into the optimal search algorithm. Operation times and cost (disassembly and recycling) are  
5 also non deterministic since they are the result of various disassembly operations. The  
6 component states and their nature make these parameters highly uncertain (Turowski *et al.*  
7 2005, Kang 2005). In (Kang 2005), the author also proposes to take into account the variation  
8 in recycling revenue to select an optimal disassembly trajectory. One of the principal  
9 limitations of the approaches presented so far is that they do not integrate many uncertainty  
10 sources encountered in the end-of-life systems management processes.  
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22 Table 1 sums up the related work we have analyzed. To model and solve disassembly  
23 trajectory problems, Petri nets seem to be the most flexible modeling tool. They represent  
24 every type of disassembly decision problem. Nevertheless, one of the principal limitations of  
25 the approaches based on this tool is that they do not integrate the various uncertainty sources  
26 traditionally encountered in the end-of-life system management processes. In this paper, we  
27 propose a new approach to model and determine optimal trajectory that resumes modeling  
28 flexibility of Petri nets and allows the integration of various sources of uncertainty. In section  
29 2, a Bayesian network-based model for disassembly is presented. From this model,  
30 optimization principles are presented in section 3. An illustrative example is proposed in  
31 section 4.  
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## 47 **2 Disassembly strategy modelling**

### 48 **2.1 Bayesian networks for disassembly modelling**

49 It has been shown in (Godichaud 2009) that Bayesian networks may constitute a privileged  
50 modelling tool to represent various sources of uncertainties in disassembly. In (Godichaud *et*  
51 *al.* 2009), a modelling procedure is proposed to define a disassembly Bayesian network on the  
52 basis of a Petri net. This model seems quite interesting since it has the advantages of the  
53 disassembly Petri nets but also because it uses the capacity of Bayesian networks to deal with  
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3 uncertainty management. Apart from this ability of the model to represent uncertain  
4 situations, the model makes it possible to return to the causes and advance to the  
5 consequences as well as to update probabilities based on knowledge of the context. For a  
6 precise description of Bayesian networks see for instance (Pearl 1988, Jensen and Nielsen  
7 2001). Let us point out however that the data required to fill in the Conditional Probability  
8 Table required to assess the situations described by the model can be obtained using statistics  
9 and / or learning as well as expert judgment.

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20 In order to represent decision problems, decision and value nodes can be introduced in  
21 a Bayesian network. Such models are called influence diagrams. They are an extension of  
22 Bayesian networks for the representation of uncertain decision-making problems (Howard *et*  
23 *al.* 1981, Jensen and Nielsen 2001).

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29 Three types of nodes characterize an influence diagram (see Figure 1):

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- *chance nodes*, (generally represented by circles) represent problem variables;
  - *decision nodes*, (generally represented by rectangles) stand for the different choices available to decision-makers,
  - *utility or value nodes*, (generally represented by diamonds) enable the numerical evaluation of decision consequences.

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Edges or arcs connecting a chance node to a decision node correspond to information available to the decision-maker when making his decision. There are various algorithms to solve decision problems represented by influence diagrams, see for instance (Lauritzen and Nielsson 2001, Jensen and Nielsen 2007).

## 2.2 *Problem representation*

The disassembly trajectory problem is represented by Bayesian networks (BN). Indeed, they enable all the elements of this decision problem to be represented. Generally speaking, system disassembly modelling with Bayesian networks is described by the following items:



- “*product*” nodes representing end-of-life system components that have one or more recycling option
- “*activity*” nodes representing disassembly operations or recycling action on each product,
- arcs characterizing precedence and exclusion relationships between activities,
- node parameters that make it possible to characterize disassembly process progress.

Decision variables are attached to each product. They indicate the direction of the disassembly trajectory towards one option (disassembling or recycling). Constraints are specified by the arcs. Economical parameters are associated with “*activity*” nodes by means of utility nodes. They represent costs and incomes potentially generated by the realization of an activity. They enable the economic profit of the various trajectories to be evaluated. The set of nodes of the Bayesian networks disassembly model is noted  $N$ . The following subsets of nodes characterize the model structure:

- $N_P$  is the set of “*product*” nodes with :
  - $P$  an element of  $N_P$ ,
  - $S_C$  the node representing the whole system
  - $S_P$  the set of modalities of node  $P$ ,
- $N_A$  is the of “*activity*” nodes with :
  - $N_{A^d}$  subset of “*activity*” nodes representing disassembly operations and  $N_{A^r}$  representing disassembly operations on  $P$ ,
  - $N_{A^c}$  subset of “*activity*” nodes representing recycling action and  $N_{A^e}$  representing recycling action on  $P$ ,
  - $A$  an element of  $N_A$ ,
  - $S_A$  the set of modalities of node  $A$ ,

- $N_U$  is the set of utility nodes. They are associated with each activity and  $U_A$  is the utility node associated with the activity modelled by node  $A$ .

Based on the generic representation of an activity in a process, an example of disassembly trajectory is presented on Figure 2. The deconstruction of a system modeled by node  $S_C$  is considered. This node corresponds to the input flow of the activity modeled by node  $A_1$ . It is a disassembly operation which generates the products modeled by nodes  $P_2$  and  $P_3$ . Product  $P_2$  can be recycled by carrying out the activity  $A_2$ . Two activities are then possible on product  $P_3$ : material recycling (node  $A_3$ ) or functional recycling (node  $A_4$ ). Only one activity must however be selected. A decision node  $C_1$  represents the selection between both activities.

Purposes of the disassembly model are:

- representing the disassembly processes,
- taking into account various origin uncertainties,
- evaluating disassembly trajectories.

### 2.3 Modelling of the disassembly process

The modality set of an “activity” node (disassembly operation and recycling action) corresponds to the various realization modes of the modeled activity. In the most straightforward configuration corresponding to the description of the chaining of the process activity, two modalities are necessary:

- “ $r$ ”: activity is carried out,
- “ $nr$ ”: activity is not carried out.

Main input and output elements in a disassembly trajectory correspond to the components of an end-of-life system (sub-assemblies or elementary components). To describe the realization of a disassembly trajectory, a minimum of two modalities is necessary for the “product” node corresponding to an input or output element:

- “**a**”: the element is activated i.e. the beginning conditions of an activity are realized,
- “**na**”: the element is not activated.

The basic mechanism to be modeled is characterized by the repetition of the following phases: product activation and activity realization. Product activation is modeled by the arcs going from “*activity*” nodes to “*product*” nodes. The mechanism to be modelled works as follows:

- when the activity is not realized (modality “**nr**”), the output products are not generated or activated (modality “**na**”),
- when the activity is carried out (modality “**r**”), the output products are generated or activated (modality “**a**”).

In cases where there is no uncertainty, the element activation is modelled in conditional probability tables (CPT) of the “*product*” nodes as illustrated in Table 2 which must be read in the following way:

- $Pr(P = a \mid A = r) = 1$ , i.e. the “*product*” node **P** takes the modality “**a**” with probability equal to 1 when the activity node takes modality “**r**” (deterministic case),
- $Pr(P = na \mid A = nr) = 1$ , i.e. the “*product*” node **P** takes the modality “**na**” with probability equal to 1 when the activity node takes the modality “**nr**”.

Following the same principles, activity realization is modelled by “*activity*” node CPT according to arcs going from “*product*” nodes to “*activity*” nodes. An activity can be realized only if the product to be transformed is activated. The specification of the activity realization modelling is presented in Table 3.

## 2.4 Handling disassembly uncertainties

### 2.4.1 System state uncertainties

System state uncertainties are taken into account in “product” nodes. Degradation levels of each component of an end-of-life system have to be characterized. To consider various possible states of the products obtained through disassembly operations, the set of “product” node modalities are modified. The modality “na” (not activated) is used to model the process realization progress. Modality “a” is modified for products that can have different degradation levels. A “product” node  $P$  will be thus characterized by the modality set  $S_P = \{m_1^P, \dots, m_k^P, \dots, m_{K_P}^P, na\}$  if  $K_P$  degradation levels have to be taken into account.

### 2.4.2 Disassembly operation uncertainties

Another uncertainty source is related to the nature of disassembly operation. Systems are not necessarily designed to be disassembled and operations are not standardized. Thus there are intrinsic uncertainties when determining disassembly effort. To handle uncertainties relating to disassembly operation realization modes, the modality set of “activity” nodes is modified. Modality “nr” is used to model the process realization logic. Modality “r” can be replaced by others modality values characterizing different realization modes. If  $K_A$  realization modes have to be taken into account, modality set  $S_A = \{m_1^A, \dots, m_k^A, \dots, m_{K_A}^A, nr\}$  will be associated with “activity” node  $A$  representing a disassembly operation (this modality set may include subset of modality  $S_{A^P}$  representing the disassembly mode associated with component  $P$  for this operation).

For instance, if three realization modes  $K_A = 3$  are possible for a node  $A$  representing a disassembly operation, the modalities could be:

- $m_1^A = n$  nominal realization mode ; operation duration and resources correspond to forecast ;

- $m_j^A = s$  degraded realization mode ; operation duration is longer and/or the resources used are modified (destructive disassembly operation can be a degraded realization mode of a disassembly operation) ;
- $m_j^A = g$  operation failure when the operation duration becomes too important or when it is not realizable ;
- $nr$  : not selected operation.

There is no generic situation for parameter specifications on “activity” nodes. Nodes representing disassembly operations can indeed be conditioned by various other nodes according to the operation environment. Three current situations can however be highlighted:

- direct evaluation: uncertainty is relating to not modeled factors i.e. the node is not conditioned by another: the user will evaluate the probabilities  $Pr(A = m_j^A), j \in \{1 \dots K_A\}$ ,
- evaluation according to product conditions: state of disassembled product can influence operation realization ; probabilities associated with a node  $A$  are then conditioned by a node  $P$ : the user has to evaluate  $Pr(A = m_j^A / P = m_l^P), j \in \{1 \dots K_A\}, l \in \{1 \dots K_P\}$ ,
- evaluation according to the resource used: when various resources can be used for an operation, they can influence its realization: if  $R$  represents a resource, the user has to evaluate  $Pr(A = m_j^A / R = m_k^R), j \in \{1 \dots K_A\}, k \in \{1 \dots K_R\}$ , where  $K_R$  is the number of possible using mode of the resource.

#### 2.4.3 Recycling action uncertainties

Recycling action uncertainties are taken into account on the associated “activity” nodes and, if necessary, on nodes representing the demand for disassembled products. Modelling principles of increasing value actions are the same as those used for the disassembly operations. An

“activity” node  $A$  is associated with each identified action. Its modality set  $S_A = \{m_1^A, \dots, m_k^A, \dots, m_{k_D}^A, nr\}$  represents the activity realization modes. These various modes characterize the duration as well as the required resources needed to recycle the product.

Recycling action generates an income if the related product is subject to a demand. Demands are determined by forecasts which can be uncertain. Nodes characterizing the demand are then integrated into the disassembly model. Demand uncertainties imply considering storage of product inducing handling costs as presented in the next section. Modelled uncertainties can, for instance, being related to demand dates or cancellation. In this case, a node  $D$  modelling the demand for a product will have modality set  $S_D = \{m_1^D, \dots, m_k^D, \dots, m_{k_D}^D\}$  where  $m_k^D$  corresponds to possible demands:  $m_{k_D}^D$  corresponds to demand cancellation and  $m_k^D$  may represent the probabilities of demand at a given period.

### 2.5 Economic evaluation

Disassembly strategies can be evaluated from an economic point of view through elements relating to:

- disassembly operation costs,
- recycling action costs (realization and storage),
- recycling value incomes.

These economic elements are modelled by utility nodes attached to each disassembly process activity as illustrated in Figure 3. Economic parameters are then specified in the utility table attached to each utility node.

A utility function is associated with each utility node. This function gives a value for each configuration of parent nodes of the considered utility node. If a node  $V$  is considered with the set  $pa(V)$  of its parent nodes, utility of  $V$  is noted  $U(pa(V))$ . A utility  $U(A)$  of a utility node associated with an “activity” node  $A$ , characterizes costs and incomes of the

activity modelled by  $A$  according to its different realization modes. The general shape of a utility table  $U(A)$  is given in Table 4.

The model enables other elements that have an impact on costs to be taken into account, such as product state conditions or a particular context (demand for the product for instance). Different situations are presented in Figure 3(b) and (c). Utility table elements correspond then to  $U(A = m_j^A, P = m_i^P)$  and  $U(A = m_j^A, D = m_k^D)$ , with  $j \in \{1 \dots K_A\}, i \in \{1 \dots K_P\}, k \in \{1 \dots K_D\}$ , namely the evaluation of activity according to activity realization modes and to the state of the product or the demand respectively. If  $c_A(m_i^A)$  is the realization cost of activity  $A$  in mode  $m_i^A$  and  $\pi_A^P$  is the income generated by recycling  $P$  through  $A$ , utility values associated with  $A$  will be  $U(A = m_i^A) = \pi_A^P - c_A(m_i^A)$ . If recycling incomes depend on product state, the utility values become  $U(P = m_j^P, A = m_i^A) = \pi_A^P(m_j^P) - c_A(m_i^A)$ . In Figure 3(c), demand has an impact on recycling cost because there are storage costs. If  $c_S(m_k^D)$  is the storage cost then  $U(D = m_k^D, A = m_i^A) = -c_S(m_k^D) - c_A(m_i^A)$ . We can retrieve the utility form of Figure 7(a) by applying the equation [1] (used in optimization described in the following section):

$$U(A = m_i^A) = \sum_{k \in \{1 \dots K_D\}} \text{Pr}(D = m_k^D) * U(D = m_k^D, A = m_i^A) \quad [1]$$

The purpose of the model proposed in this section is to represent the problem of disassembly trajectory determination i.e. a set of activities with their connexions. It also enables these various activities to be analyzed and specified in order to serve as a support for optimization mechanisms which are presented in the next section. The optimisation mechanism consists then in tracking each product model in a recursive way going from the elementary component models to the global end-of-life system.

### 3 Disassembly trajectory optimization

#### 3.1 Product disassembly generic model

The model presented above represents the whole disassembly trajectory that the decision maker has identified. The model is a network and the objective is to find an optimal trajectory within this network that for each product, given its state, what the best activity would be. In this network,  $Succ(P)$  represents the set of successors of “product” node  $P$  (i.e.  $N_{A_P} \cup N_{A_P}^*$ ) and  $Succ(A)$  represents the set of product node successors of a disassembly activity  $A$ . A disassembly policy model is drawn from the global model to evaluate each product separately. It enables the required defining recursive equation to be obtained to determine the optimal disassembly trajectory.

Disassembly policies are modelled by decision nodes associated with each product. These nodes are integrated in the model as presented in Figure 4 (node  $PL_P$ ) which gives a generic model representation (integration of all the elements required to determine a policy). The considered product is modelled by node  $P$  and modalities of node  $PL_P$  characterize all the possible options likely to be selected on the product. Utilities  $U(Q), Q \in Succ(A), A \in N_{A_P}^*$  (i.e.  $Q$  is a component of  $P$ ) represent the evaluation of product components generated by each disassembly operation. A policy model being associated with each product, these utilities correspond to the optimisation result of the product component policies.

#### 3.2 Reduction rules for optimization

Given the modelling generic structure proposed in Figure 4 and the model specificity (activation principles of variables), the method using diagram progressive reduction is appropriate. Indeed it shows how recursive techniques can be applied to evaluate trajectories by considering each valuable component of the system. Consequently, resolving and analyzing the disassembly of a given system is made easier.



We introduce the resolution technique in this section in order to apply it to the generic model used for the assessment of a product valuation policy.

The resolution method is made up of four generic operations (Jensen and Nielsen, 07) that are applied to the influence diagram. These operations enable the progressive reduction of the model and step by step resolution until only one utility node remains. This node stands for the expected utility of the end-of-life system, given that at each decision node the best solution has been selected. The four reduction operations are: merging utility nodes, removing chance nodes, removing decision nodes, changing arc direction. The use of these four rules enables the resolution of any influence diagram:

- (R1) *Merging several utility nodes*: Let us consider a set of utility nodes  $U_1 \dots U_n$  of an influence diagram. These nodes can be merged into a single utility node  $U^*$  whose conditional expectation is given by :

$$U^*(pa(U_1) \cup \dots \cup pa(U_n)) = U_1(pa(U_1)) + \dots + U_n(pa(U_n)) \quad [2]$$

- (R2) *Removing chance node*: Let us consider a node  $X$  father of a single utility node  $U$ . Given the node  $X$  is represented by the probability distribution  $Pr(X/pa(X))$  and node  $U$  is described by its conditional expectation  $U(pa(U))$ , node  $X$  can be removed by modifying the conditional expectation of node  $U$  as followed:

$$U(pa(X) \cup pa(U) \setminus X) = \sum_X Pr(X/pa(X)) * U(pa(U)) \quad [3]$$

- (R3) *Removing decision nodes*: Let us consider a decision node  $D$  father of a single utility node  $U$  whose predecessors are also predecessors of node  $D$  (predecessors of node  $U$  are presumed to be known at the time the decision is made). Given that the policy  $\delta_D$  relating to node  $D$  has to be evaluated and that node  $U$  is described by its

conditional expectation  $U(pa(U))$ , node  $D$  can be removed by modifying the conditional expectation of node  $U$  as follows:

$$U(pa(D) \cup pa(r) \setminus \{D\}) = \max_D (U(pa(U))) \quad [4]$$

strategy  $\delta_D$  is then defined as follows

$$\delta_D = \operatorname{argmax}_D (U(pa(U))) \quad [5]$$

- (R4) *Changing arc direction*: when none of these rules can be applied, some arcs can be reversed in order to reach to a situation where the previous rules can be used. To this end, rules belonging to the probability theory must be applied. Some examples are presented in (Tatman and Shachter 1990, Jensen and Nielsen 2007).

### 3.3 Application to the disassembly model

Given the policy model presented in Figure 4, evaluation of a product  $P$  in state  $m_{k_P}^P$  and its optimal policy are defined by equations [6] and [7], with  $i \in \{1 \dots K_A\}$ ,  $j \in \{1 \dots K_P\}$ ,  $k \in \{1 \dots K_Q\}$ :

$$U(P = m_i^P) = \max_{A \in \text{Succ}(P)} \left[ \sum_j \Pr(A = m_j^A / P = m_i^P) * \left[ U(A = m_j^A) + \sum_{Q \in \text{Succ}(A)} \sum_k [\Pr(Q = k \right. \right. \quad [6]$$

$$PL_P(m_i^P) = \operatorname{argmax}_{A \in \text{Succ}(P)} \left[ \sum_j \Pr(A = m_j^A / P = m_i^P) * \left[ U(A = m_j^A) + \sum_{Q \in \text{Succ}(A)} \sum_k [\Pr(Q = k \right. \quad [7]$$

If the costs and/or incomes of an activity are dependent on product state, utility  $U(A = m_{k_A}^A)$  must be replaced by  $U(P = m_i^P, A = m_{k_A}^A)$ . If the costs of a recycling action are dependent of a demand  $D$  for the product then equation [1] could be used to retrieve the shape of equations [6] and [7].

1  
2  
3 These equations can be justified by a step-by- step analysis of the policy model. Let us  
4  
5 apply the different reduction rules previously introduced (equations [2] to [5]) in order to  
6  
7 optimize the dismantling trajectories represented by influence diagrams. To this end we will  
8  
9 proceed to the optimization of the generic model of Figure 4. This model can be used at each  
10  
11 decomposition level of the end-of-life system. The evaluation method consists of processing  
12  
13 each elementary model in a recursive way by going from the basic components to the product  
14  
15 to be recycled as presented on Figure 5. The generic resolution method is made up of different  
16  
17 stages corresponding to the application of a reduction rule on a variable or a set of variables of  
18  
19 the same nature.  
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27 The generic resolution method is made of different steps corresponding to the  
28  
29 application of a reduction rule on a variable or a set of variables of same nature. These  
30  
31 different steps are the following:  
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33

- 34 (S1) Removing nodes representing the recycling action;  
35  
36 (S2) Removing utility nodes linked to nodes representing the disassembly operations;  
37  
38 (S3) Removing nodes representing the dismantling operation;  
39  
40 (S4) Merging utility nodes relating to the given policy;  
41  
42 (S5) Removing decision node representing the policy;  
43  
44 (S6) Removing node representing the product to be recycled.  
45  
46  
47

48 Input data correspond to:  
49  
50

- 51 • probabilities  $Pr\left(\frac{A}{P}\right)$  for all activities  $A$  (disassembly and recycling) that can be  
52  
53 performed on  $P$  ,  
54  
55  
56  
57 • probabilities  $Pr\left(\frac{Q}{A}\right)$  for all components  $Q$  of  $P$  generated by disassembly operation  
58  
59  
60  $A$  ,

- utilities values for disassembly operation  $U(A = m_j^A) = -c_A(m_j^A)$  that correspond to disassembly operation costs,
- utilities values for recycling activities  $U(A = m_j^A) = \pi_A^P - c_A(m_j^A)$  that correspond to difference between incomes and recycling action cost.

The first step (S1) corresponds to the determination of the utility of a recycling action  $A$  given that product  $P$  is in state  $m_{k_P}^P$ . These nodes  $A$  can be removed since they have as single successor, utility nodes (rule R<sub>2</sub>). Parameters are modified as follows:

$$U(P = m_i^P, PL_P = A) = \left( \sum_{j=1}^{K_A} [\Pr(A = m_j^A)] /_{P = m_i^P} \right) * U(A = m_j^A) \quad [8]$$

If  $P$  is an elementary component, it is associated with recycling action only. Utilities and the corresponding policy can be determined directly after this step.

The second step (S2) relates to the determination of the utility of a disassembly operation  $A$  given that product  $P$  is in state  $m_i^P$ . It depends on disassembly cost  $U(A = m_j^A) = -c_A(m_j^A)$  and utilities  $U(Q)$  for all components  $Q$  generated by  $A$ . Utility nodes  $U(A)$  and  $U(Q)$  connected to the same node  $A \in N_{A_P}^d$  representing a disassembly operation can then be merged (rule R<sub>1</sub>):

$$U(A = m_j^A) = U(A = m_j^A) + \sum_{Q \in \text{Succ}(A)} \sum_{k=1}^{K_Q} \Pr(Q = m_k^Q / A = m_j^A) * U(Q = m_k^Q) \quad [9]$$

At this step, nodes representing disassembly operations can be removed, given that they have as successors only utility nodes  $U(A)$  (rule R<sub>2</sub>). Utilities of each disassembly operation  $A$  on  $P$  is then given by (step (S3)):

$$U(P = m_i^P, PL_P = A) = \left( \sum_{j=1..K_A} \frac{[\Pr(A = m_j^A)]}{P = m_i^P} \right) * \left[ U(A = m_j^A) + \sum_{Q \in Succ(A)} \sum_{k=1..K_Q} \right] \quad [10]$$

The set of utility nodes has now the same parents  $P$  and  $PL_P$ . They can be merged in the fourth step into a single utility node  $U_P$  (rule R<sub>1</sub>). The fifth step (S5) consists of determining the activity for P. Utility and policy for P is then:

$$U(P = m_i^P) = \max_{A \in Succ(P)} U(P = m_i^P, PL_P = A) \\ PL_P(m_i^P) = \operatorname{argmax}_{A \in Succ(P)} U(P = m_i^P, PL_P = A) \quad [11]$$

It corresponds to [6] and [7] if we express  $U(P = m_i^P, PL_P = A)$  with equation [8], [9] and [10]. Eventually, (S6) corresponds to the removal of node  $P$ .

## 4 Illustrative example

### 4.1 System layout

The problem we want to tackle concerns the valuation trajectory of an airplane turbine represented in Figure 6. The system is made up of seven elementary products (P<sub>1</sub> to P<sub>7</sub>) and sub-assemblies are: SA<sub>1</sub> = {P<sub>2</sub>, P<sub>3</sub>, P<sub>4</sub>, P<sub>5</sub>, P<sub>6</sub>} ; SA<sub>2</sub> = {P<sub>2</sub>, P<sub>4</sub>, P<sub>5</sub>} ; SA<sub>3</sub> = {P<sub>3</sub>, P<sub>5</sub>, P<sub>6</sub>}. The connection graph on Figure 6(b) is used to identify the disassembly operation and the precedence relationships. The method of analysing a connection graph is presented in detail in (Lambert and Gupta 2005) for instance and its application to the example is developed in (Godichaud 2009).

For the system considered here, all the elements are recapitulated in Table 5 which gives a rapid overview of the model nodes. Disassembly operations concern only sub-assembly and two types of recycling action are considered: material recycling and functional recycling.

#### 4.2 *Building the model*

Nodes are interconnected according to the system structure and the relation highlighted in the connection diagram in Figure 6. The general form of the model is presented in Figure 7. Each identified product has the same generic structure introduced in Figure 4. It is customized according to the disassembly operations and recycling action likely to be performed on the product. For the SA<sub>1</sub> product for instance, one comes across the nodes corresponding to the recycling action MR<sub>1</sub> and FR<sub>1</sub> as well as the nodes relating to the disassembly operations DO<sub>2</sub> and DO<sub>3</sub>.

The states of the nodes of the model are defined in Table 6 in a generic way for each type of node. The states of the decision nodes characterize the possible activities for each product. Consequently, a decision node representing a policy has a number of states standing for the different activities associated with the considered product.

Utility nodes stand for the performances which depend on a costing model, itself based on the parent nodes. To each configuration of the parent nodes a value is defined.

The model input parameters correspond, on the one hand, to the uncertainties relating to activity realization as well as to the state of the products and, on the other hand, to activity costs and incomes. All the model input data of the valuation trajectory is presented in Table 7 for the “activity” and “utility” nodes. Table 8 shows the “product” nodes.

#### 4.3 *Optimization result*

An algorithm based on the recursive relations [6] and [7] has been implemented with the graph of Figure 7 and its parameters as inputs. It proceeds by beginning the evaluation with elementary components P1 to P7 and the sub-assembly SA2 which cannot be disassembled. Sub-assembly SA3 can then be evaluated since all its components were evaluated. It is then the sub-assembly SA1 which can be evaluated and finally the complete system.

The graphical representation of the optimal trajectory is given on Figure 7 in bold. The optimal trajectory is drawn in bold lines. It shows that the best solution consists of obtaining

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3 products  $P_1$ ,  $SA_1$ ,  $P_7$ ,  $P_2$ ,  $P_4$  and  $SA_3$ . For each product, the optimal strategy is indicated in the  
4  
5 decision nodes (rectangles). For product  $SA_1$ , for instance, it shows that activity  $DO_3$  has to be  
6  
7 selected. For product  $P_1$  and  $P_2$ , it depends on their state. If the products are in a deteriorated  
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9 state “d”, the trajectory is indicated with black non-bold lines (the non-selected trajectory  
10  
11 being represented by a dotted line).  
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15 The result of optimisation is presented on Table 9 for each product. All the products  
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17 (component and sub-assemblies) are listed in the first column. The second column states  
18  
19 whether or not each product is in the optimal disassembly trajectory. The third and fourth  
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21 columns give the policies for each product given their states (normal state  $PL(P=n)$  or  
22  
23 degraded state  $PL(p=d)$ ). For instance, the policy for S consists in realizing disassembly  
24  
25 operation  $DO_1$  whatever its state. Utility values for each product given its state are presented  
26  
27 in the last column. The disassembly utility of S is 243.3 (monetary unit here because costs  
28  
29 have been considered as utility values) if it is in normal state and 231.23 otherwise. If 100  
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31 arrivals of systems S are expected at a given period with a probability of 0.5 of having a  
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33 normal state or degraded state then the expected incomes for this period are 23758.  
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39 The optimal trajectory is presented on Figure 8 with the probabilities (percentages) at  
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41 each node. For each “*product*” node, the values correspond to the probabilities of generating  
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43 this product in various states (normal or degraded) and the probabilities of not generating this  
44  
45 product (especially when the trajectory fails upstream). For each “*activity*” node, the values  
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47 correspond to the probabilities of realizing this activity in various modes (normal or slow),  
48  
49 stopping it or not realizing it. For instance, if 100 arrivals of systems S are expected on a  
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51 given period with a probability of 0.5 of having a normal state or degraded state, the product  
52  
53  $P_7$  is expected to be 92.4 times in a normal state, 5.12 times in a degraded state and it is not  
54  
55 generated 2.5 times. Furthermore, the recycling activity  $FR_9$  of  $P_7$  is expected to be realized  
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3 67.7 times in a normal mode, 24.6 times in a degraded mode and stopped 5.13 times (not  
4 realized 2.5 times).  
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## 8 **5 Conclusion**

9 The end-of-life system disassembly strategies are based on the determination of trajectories  
10 completely defined by the products subject to increasing value actions, their mode of  
11 obtaining as well as their valuation circuits. Trajectory modelling and optimizing methods  
12 within an uncertain context have been proposed in this article. The model structure provides  
13 the guidelines for analyzing the trajectories. It also enables the consideration of uncertainties  
14 of various natures in the problem representation and optimization as they generally appear in  
15 the dismantling context of end-of-line systems.  
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27 The working perspectives concern first the consideration of uncertainties likely to  
28 evolve with time (duration of an activity, date of arrival or request ...). This type of modeling  
29 will enable the planning of several arrivals of end-of-life systems to be disassembled. Within  
30 this framework, Bayesian dynamic networks provide an interesting modeling solution.  
31  
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36 We have used an economic criterion to evaluate the quality of a disassembly  
37 trajectory. Other criteria must be taken account in order to have better control over the  
38 disassembly process. These are environmental criteria based on the ecological impact of the  
39 disassembly process. Multi-criteria optimizing approaches could be used for this purpose.  
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46 Another perspective deals with the model deployment on a real industrial case. At the  
47 moment the model is being applied in the field of airplane recycling. The industrial partner is  
48 the company Tarmac Aerosave (Tarbes Advanced Recycling and Maintenance Aircraft  
49 Company). It must be said that the number of aircraft to be recycled due to age will exceed  
50 6000 over the next 4 years. High stakes for research...  
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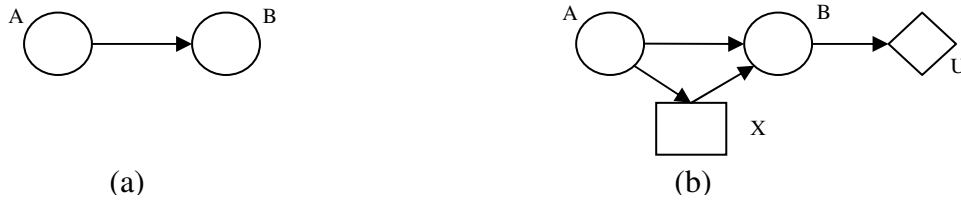


Figure 1. Example of Bayesian network (a) and influence diagram (b)

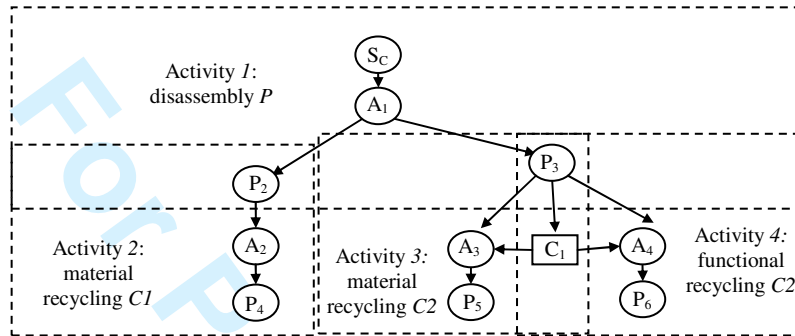


Figure 2. Disassembly process representation with a BN

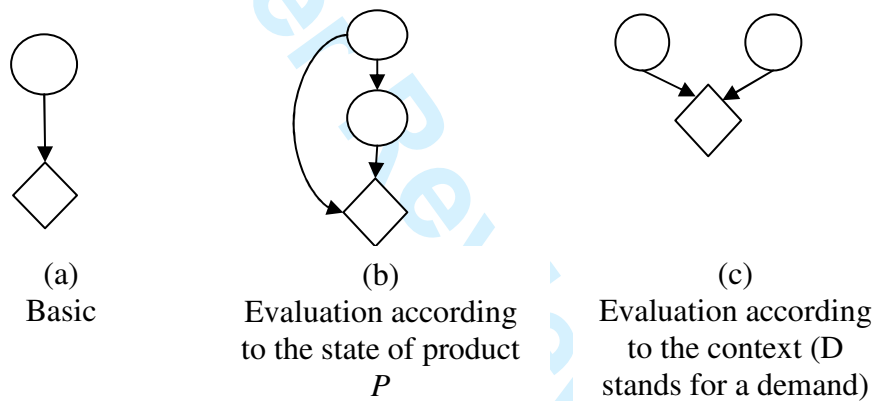


Figure 3. Activity evaluation specification

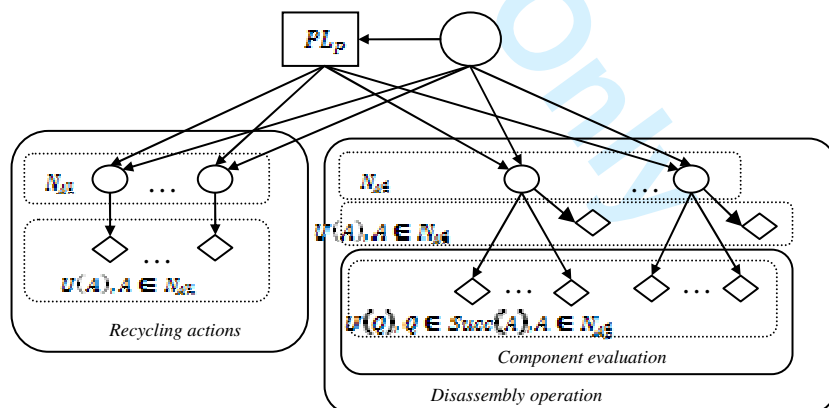


Figure 4. Disassembly policy model

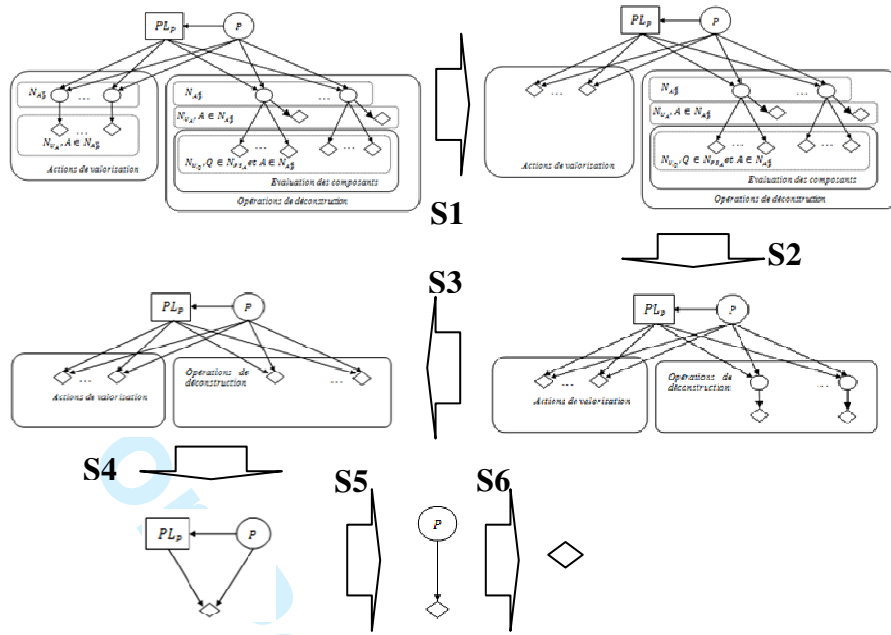


Figure 5. Progressive graphical modification through reduction rules application

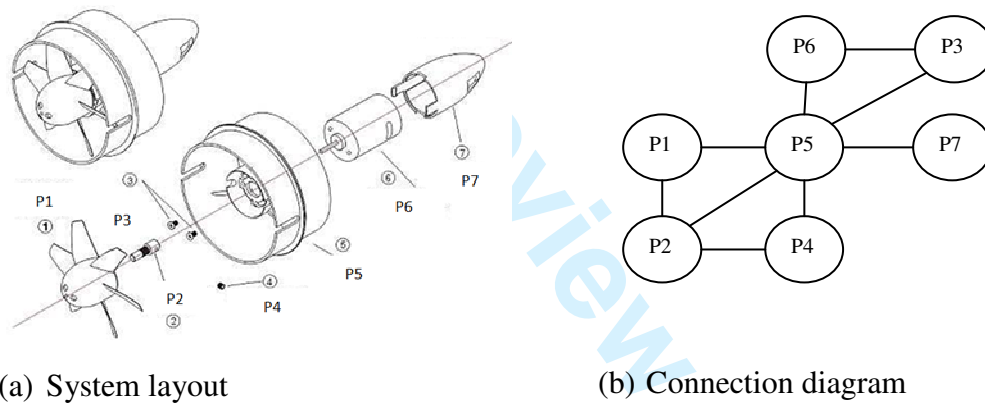


Figure 6. Representation of the system to be disassembled.

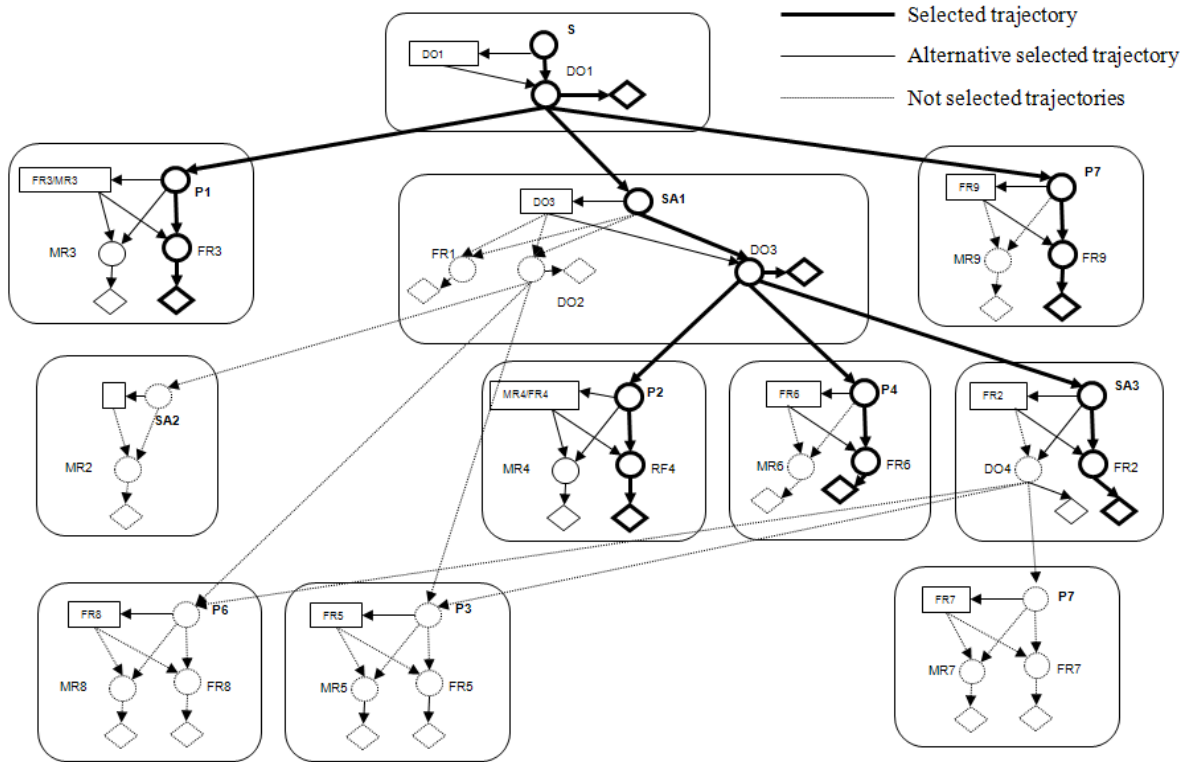


Figure 7. Disassembly trajectory representation

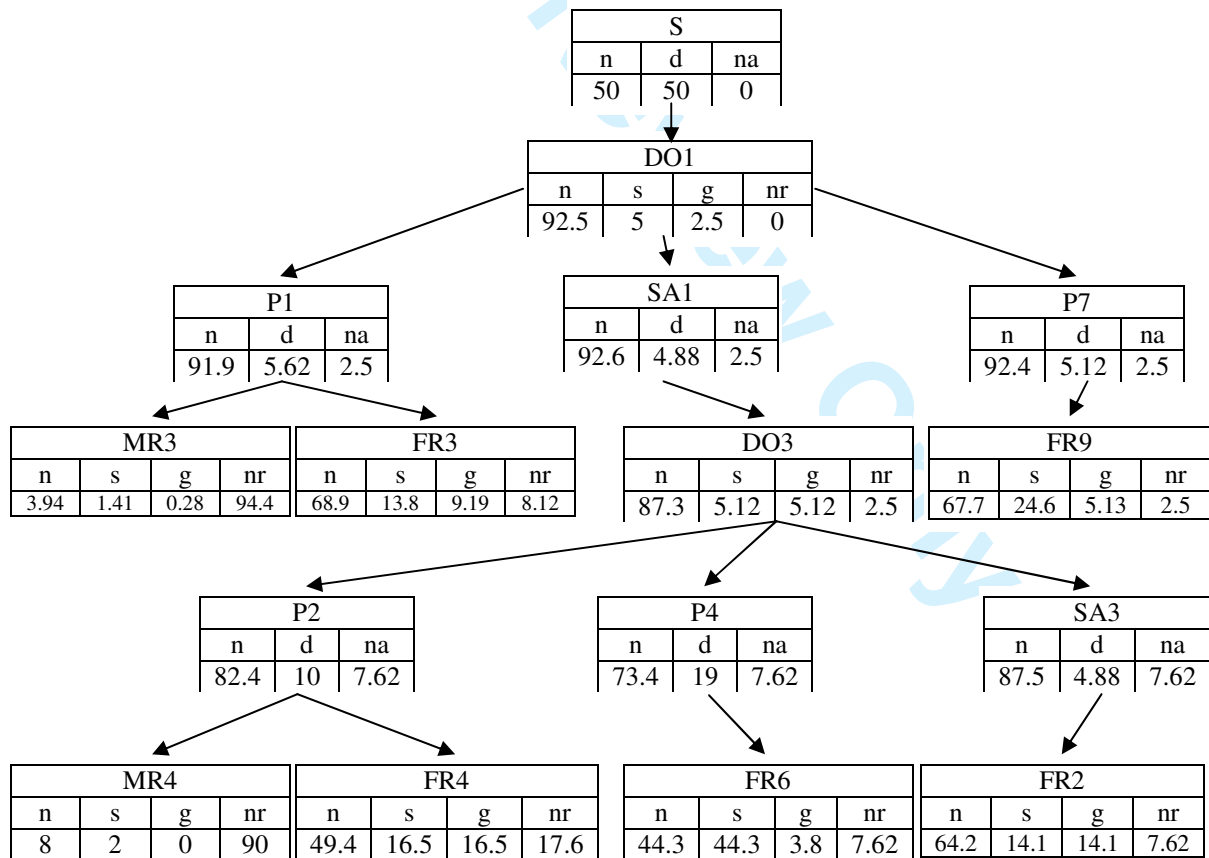


Figure 8. Optimal trajectory probabilities

	Decision problem					Uncertainties				Kind of model
	Path	Sequence	Depth	Recycling option	Destructive operation	No uncertainties	Component degradation	Disassembly operation failure	Operation times	
Geiger <i>et al.</i> 1995	✓						✓			Bayesian network AND/OR graph Probability
Gungor and Gupta 1998	✓				✓		✓	✓		Heuristic
Krikke <i>et al.</i> 1998			✓	✓			✓			Tree Dynamic programming Probability
Zussman and Zhou 1999	✓		✓	✓				✓		Petri nets Probability
Kanai <i>et al.</i> 1999	✓		✓		✓	✓				Tree and Petri nets
Salomonski <i>et al.</i> 1999	✓		✓	✓			✓			Petri nets Probability
Kang <i>et al.</i> 2001		✓	✓			✓				Graphs Mathematical programming
Tang <i>et al.</i> 2002	✓		✓			✓				Tree, AND/OR graphs and Petri nets
Tiwari <i>et al.</i> 2002			✓	✓		✓				Petri nets
Moore <i>et al.</i> 2003		✓				✓				Petri nets
Kang 2005		✓	✓						✓	Graphs Mathematical programming Interval
Turowski <i>et al.</i> 2005			✓				✓		✓	Petri nets Fuzzy logic
Lambert and Gupta 2005	✓	✓	✓			✓				AND/OR graphs Mathematical programming
Duta <i>et al.</i> 2003	✓		✓		✓			✓		Petri nets Probability, decision tree
Reveliotis 2007			✓	✓			✓			Petri nets Probability / Q learning
Das <i>and al.</i> 2002			✓	✓	✓	✓				Tree

Table 1. State of the art on tools used to model the different aspects of disassembly trajectory definition.

	$P \in N_{S_A}$	
$A$	$a$	$na$
$r$	1	0
$nr$	0	1

Table 2. CPT of a “product” node  $P$  with an “activity” node  $A$  as an input.

	$A$	
$P \in N_{S_A}$	$r$	$nr$
$a$	1	0
$na$	0	1

Table 3. CPT of an “activity” node  $A$  with a “product” node  $P$  as an input.

	$A$					
	$m_1^A$	...	$m_{k_A}^A$	...	$m_{k_A}^A$	$nr$
$U$	$U(A = m_1^A)$	...	$U(A = m_{k_A}^A)$	...	$U(A = m_{k_A}^A)$	0

Table 4. Utility table: general shape.

Product	Disassembly operation	Material recycling	Functional recycling
$S$	$DO1$	-	-
$SA1$	$DO2 ; DO3$	-	$FR1$
$SA2$	-	$MR2$	-
$SA3$	$DO4$	-	$FR2$
$P1$	-	$MR3$	$FR3$
$P2$	-	$MR4$	$FR4$
$P3$	-	$MR5$	$FR5$
$P4$	-	$MR6$	$FR6$
$P5$	-	$MR7$	$FR7$
$P6$	-	$MR8$	$FR8$
$P7$	-	$MR9$	$FR9$

Table 5. Nodes used in the model.

Nodes	Meaning	Notations
Product	Deterioration level	$n$ : normal
		$d$ : deteriorated
		$na$ : not activated
Activity	Activity realization mode	$n$ : nominal
		$s$ : slow
		$g$ : giving up
		$nr$ : not realized

Table 6. Possible node values.

	$Pr(A=n/P=n)$	$Pr(A=s/P=n)$	$Pr(A=g/P=n)$	$Pr(A=n/P=d)$	$Pr(A=s/P=d)$	$Pr(A=g/P=d)$	$U(A=n)$	$U(A=s)$	$U(A=g)$
DO1	0.95	0.05	0	0.9	0.05	0.05	-5	-7	-10
DO2	0.9	0.1	0	0.8	0.1	0.1	-5	-10	-15
DO3	0.9	0.05	0.05	0.8	0.1	0.1	-8	-10	-12
DO4	0.95	0.05	0	0.9	0.05	0.05	-10	-15	-20
MR1	0.3	0.3	0.4	0.3	0.3	0.4	30	10	-5
MR2	0.9	0.1	0	0.8	0.2	0	60	30	-3
MR3	0.8	0.15	0.05	0.7	0.25	0.05	35	15	-5
MR4	0.8	0.2	0	0.8	0.2	0	20	10	-2
MR5	0.8	0.1	0.1	0.7	0.2	0.1	30	15	-2
MR6	0.9	0.1	0	0.8	0.1	0.1	20	10	-1
MR7	0.9	0.1	0	0.8	0.15	0.05	20	10	0
MR8	0.9	0.1	0	0.8	0.1	0.1	20	10	-2
MR9	0.8	0.15	0.05	0.75	0.15	0.1	30	10	-5
FR1	0.6	0.2	0.2	0.2	0.3	0.5	50	25	-10
FR2	0.7	0.15	0.15	0.6	0.2	0.2	200	35	-4
FR3	0.75	0.15	0.1	0.2	0.3	0.5	40	20	-3
FR4	0.6	0.2	0.2	0.4	0.3	0.3	30	10	-5
FR5	0.9	0.1	0	0.5	0.25	0.25	40	30	-6
FR6	0.5	0.5	0	0.4	0.4	0.2	60	10	-10
FR7	0.8	0.1	0.1	0.5	0.25	0.25	45	35	-4
FR8	0.6	0.4	0	0.5	0.25	0.25	50	25	-5
FR9	0.7	0.25	0.05	0.6	0.3	0.3	50	20	-5

Table 7. "Activity" and "utility" node parameters.

		$Pr(P=n/A=n)$	$Pr(P=d/A=n)$	$Pr(P=n/A=s)$	$Pr(P=d/A=s)$
DO1	P1	0.95	0.05	0.8	0.2
	SA1	0.95	0.05	0.95	0.05
	P7	0.95	0.05	0.9	0.1
DO2	SA2	0.9	0.1	0.85	0.15
	P6	0.9	0.1	0.9	0.1
	P3	0.9	0.1	0.85	0.15
DO3	P2	0.9	0.1	0.75	0.25
	P4	0.8	0.2	0.7	0.3
	SA3	0.95	0.05	0.9	0.1
DO4	P6	0.95	0.05	0.9	0.1
	P3	0.95	0.05	0.8	0.2
	P5	0.95	0.05	0.9	0.1

Table 8. "Product" node parameters.

P		PL(P=n)	PL(P=d)	U(P=n)	U(P=d)
S	✓	DO <sub>1</sub>	DO <sub>1</sub>	243.93	231.23
SA <sub>1</sub>	✓	DO <sub>3</sub>	DO <sub>3</sub>	177.63	167.44
SA <sub>2</sub>		MR <sub>2</sub>	MR <sub>2</sub>	57	54
SA <sub>3</sub>	✓	FR <sub>2</sub>	FR <sub>2</sub>	144.65	126.2
P <sub>1</sub>	✓	FR <sub>3</sub>	MR <sub>3</sub>	37.2	28
P <sub>2</sub>	✓	FR <sub>4</sub>	MR <sub>4</sub>	19	18
P <sub>3</sub>		FR <sub>5</sub>	FR <sub>5</sub>	39	26
P <sub>4</sub>		FR <sub>6</sub>	FR <sub>6</sub>	35	26
P <sub>5</sub>		FR <sub>7</sub>	FR <sub>7</sub>	39.1	30.25
P <sub>6</sub>	✓	FR <sub>8</sub>	FR <sub>8</sub>	40	20
P <sub>7</sub>	✓	FR <sub>9</sub>	FR <sub>9</sub>	39.75	34.5

Table 9. Product evaluation results