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ORIGINAL ARTICLE

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End-of-Life Decision making in circular economy using generalized colored stochastic Petri nets

Gautier Vanson^{1*} , Pascale Marangé¹ and Eric Levrat¹

Abstract

Circular economy enables to restore product value at the end of life i.e. when no longer used or damaged. Thus, the product life cycle is extended and this economy permits to reduce waste increase and resources rarefaction. There are several revaluation options (reuse, remanufacturing, recycling, ...). So, decision makers need to assess these options to determine which is the best decision. Thus, we will present a study about an End-Of-Life (EoL) decision making which aims to facilitate the industrialization of circular economy. For this, it is essential to consider all variables and parameters impacting the decision of the product trajectory. A first part of the work proposes to identify the variables and parameters impacting the decision making. A second part proposes an assessment approach based on a modeling by Generalized Colored Stochastic Petri Net (GCSPN) and on a Monte-Carlo simulation. The approach developed is tested on an industrial example from the literature to analyze the efficiency and effectiveness of the model. This first application showed the feasibility of the approach, and also the limits of the GCSPN modelling.

Keywords: Circular economy, Sustainability, Decision making, Generalized colored stochastic Petri net, Monte-Carlo simulation

1 Introduction

According to the world population growth curve, we observe that the increase in the world's population is similar with the increase in energy, materials consumed and CO₂ in the atmosphere [1]. The transition of companies to Industry 4.0 brings new technological advances with a greater source of information to solve some of these issues. Nevertheless, product customization and planned obsolescence both generate today a significant end-of-life (EoL) product stream and for a long time [2].

The concept of circular economy based on the pillars of sustainable development is defined by the Ellen Mc Arthur Foundation as follows: circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating nat-

ural system (<https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy>). In circular economy, the goal is to reduce the waste produced by consumer society, in a circular cycle composed of a set of processes such as reuse/refurbishment/remanufacturing/recycling/... These loops enable a product to be renewed, reconstituted and to extend its life cycle. Nevertheless, one question seems essential: how does one choose the optimized process of revalorization? In fact, the process that allows a product to be regenerated for the longest time and at the lowest cost will be favored among all the possibilities offered to companies.

An analysis of the literature shows that there are many papers on these different processes, but very few that group these different processes into a unified process. The objective of our work over the last few years is to propose a global vision of product regeneration. In Diez 2015, we defined the regeneration paradigm as [3]: "set of actions, natural or technical, to restore a waste or its constituents

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to an acceptable state (functional and operational) allowing to extend its life cycle". Nowadays this process is not yet industrialized and regeneration activities are mainly handmade [4]. When a manufacturer decides to regenerate a product, it should consider that revalorizing the product enables to reduce implicit costs such as the end-of-life product management costs, which are more and more regulated, and to reduce the manufacturing costs such as operating costs and raw material purchases. So, industrializing regeneration provides economic advantages with reduced implicit costs and makes it possible to reach a new clientele potentially demanding regenerated products, which are by definition less costly than new products. From an environmental point of view, a life cycle analysis of the product and in particular at the end of its life would ensure the ecological advantages to regenerate a product in such or such revalorization process. However, there is no doubt that extending the life of a product by reusing it, repairing it, remanufacturing it and recycling it allows reducing the depletion of natural resources and waste volume. So, the objective of this paper is to propose a methodology and a decision making tool to determine the best regeneration to perform, based on the product health state, on information regeneration processes and market needs.

In a sustainable point of view, we assume to assess each product in an individual way to find the best regeneration trajectory for each product. Indeed, if we assess a product set, the best regeneration trajectory mean could be not appropriate for all products. The second assumption is to work with products with high value added and multi-components to justify an individual assessment to each product. In addition, some regeneration processes are divergent because they require a partial or complete decomposition (reconditioning, remanufacturing, disassembly, ...). Thus, the decision making tool must also be sequential to be able to diagnose and assess each decomposed element. The third assumption is that there are several regeneration alternatives for a product. Furthermore, we consider that these alternatives are prioritized from an environmental and economic point of view. For example, reuse is the smallest recovery loop, therefore the least expensive and with the best environmental impact compared to remanufacturing and recycling. Thus, if reuse is not possible for a product then the next option such as remanufacturing can be considered. This assumption could be in opposition with current market but not from a sustainable development point of view.

Regarding these assumptions, the decision making must be able to adapt the decision according to different variables and parameters impacting the decision. Thus, this work considers complete loops in the regeneration cycle (Collect product, Assess product and Regenerate prod-

uct) for decision-making and the assessment of different regeneration alternatives depending on the product health state, regeneration processes (reuse, remanufacturing, recycling, ...) and information on the market. The health state is built for a product, as a function of functional, operational and dysfunctional variables. Indeed, when considering an EoL product, the health state depends on the information collected throughout the product use phase. To take into account these uncertainties, a modeling method for regeneration decision making is proposed using generalized stochastic Petri net modeling (GCSPN) combined with Monte-Carlo simulation. We obtain a decision making tool to estimate the best regeneration trajectory.

The paper is structured as follows: a review of decision making in the regeneration process is proposed in Sect. 2. Section 3 develops the proposed decision making method for the EoL product. Section 4 is devoted to the application of the method on an example from the literature and its analysis. Section 5 concludes the paper and proposes several perspectives for future research.

2 Literature review: decision making in regeneration process

The regeneration objective is to reuse products waste (products, sub-assemblies and components) to remain in use phase as long as possible (extend the product life cycle) and delay the dismantling phase. This process is composed of several activities as we can see in Fig. 1. The decision activity is an indispensable building block to assess the different regeneration alternatives and to choose the best regeneration decision. Indeed, the assessment result will depend on variables collected over the entire product life cycle, but also on regeneration activities like refurbishment, cleaning, disassembly, rework or re-assembly. So, the assessment must take into account all the elements that may impact the regeneration trajectory, as well as product, processes and market variables and parameters. In addition, the decision making must consider that some variables and parameters are uncertain. Thus, we propose a literature review to answer the following questions:

- What does the end-of-life product assessment cover?
- What are the variables and parameters used in decision making?
- What are the tools used for decision making?
- What are the assessment criteria?
- Do the models take uncertainty into account in the assessment?

From the articles presented in Table 1, it is clear that there are several assessment methods (graphical or algorithmic). Each paper uses heterogeneous product, process, market variables and parameters to perform assessment. As the regeneration process has an input stream that is

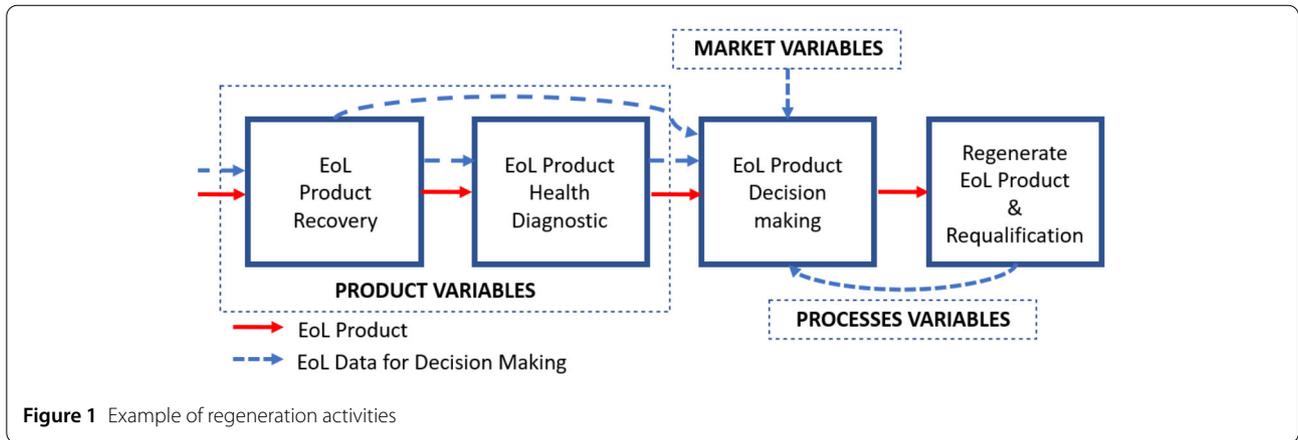


Figure 1 Example of regeneration activities

Table 1 End-of-life decision-making methods in literature

Assessment type	Target	Variables parameters	Modeling tool	Solving tool	Criteria	Uncertainty
EoL assessments	The best EoL alternative [5]	Market/Process		A multicriteria decision-aid	Economic/ Environnemental	No
	The optimal EoL option [6]	Product/Process/ Market	PESTEL	Analytic hierarchy process and Cost/benefit analyses	Economic/ Environnemental	No
	The best EoL alternative [7]	Process/Market	A Product Recovery Multi-Criteria Decision Tool		Economic/ Environnemental/ Social	No
	The best circularity strategies for a product and/or service [8]	Product/Process	A multi-criteria decision-making method		Environmental/ Economic/Social	No
Disassembly assessments	The optimal disassembly sequence [9]	Product	Fuzzy Reasoning Petri Nets (FRPN)	Reasoning algorithm based on FRPN	Economic	Yes
	The optimal disassembly sequence [10]	Product/Process	FRPN/matrix operation	A reasoning algorithm of formalisation	Economic	Yes
	The best disassembly sequence [11]	Process	A mathematical model	Heuristic SS algorithm	Economic	No
	The best disassembly sequence [12]	Product/Process	A mathematical model	A stochastic program	Economic	Yes
Other assessments	The optimal strategy between manufacturing or remanufacturing [13]	Product/Process	A mathematical model with prioritization	Tabu search/scatter search/neural networks	Economic	Yes
	The best collection strategy [14]	Market	Fuzzy Coloured Petri Net models	Model simulation	Economic/ Environmental	Yes
	The optimal facility locations and flows between facilities [15]	Product/Process/ Market	A mathematical model	A stochastic multi-objective model/Pareto-optimal solution	Economic	Yes
	The best PSS scenarios [16]	Process		A multi-criteria analysis/"ELECTRE I" method	Environmental/ Economic/Social	No
	The best design for new products from post-used components [17]	Product		Multiagent systems	Economic	No

not controlled, it is essential to consider the uncertainty on the product variables but also the effect of the regeneration actions. As shown in Table 1, many papers do not take uncertainty into account in their models. The applications only deal with product or subassembly level equipment. Another observation is that only 4 papers in Table 1 assess more than three regeneration processes [5–8]. Else other articles focus solely on one theme as disassembly or collect or PSS scenario [9–17]. However, only papers working on the disassembly activity such as [9, 10] and [11] propose a customized decision making for each product to determine the best disassembly sequence with an industrialization perspective. On the contrary, papers [5, 6] and [7] assess several regeneration options for a product individually but at a strategic, static level, i.e., without considering the product's health state but only according to the product's characteristics such as its nomenclature and/or its composition in terms of material. Therefore, it is not possible to use these decision making tools for the purpose of industrializing regeneration. So, to increase profit, the best regeneration trajectory for each product should be determined in a personalized way rather than using the statistical optimization of many products [12]. Indeed, even if statistical optimization allows to reduce the importance of the assessment time, this could lead to slowdowns in the regeneration chain because the trajectory of a few products assessed globally could disrupt the process. The majority of the papers studied in Table 1 do not specify calculation times – which is an important omission – given that the time criterion is crucial for the implementation of profitable industrialization for manufacturers. So, [18] provides a review of decision making work in the solid waste management area. In this review, several critical decision-making points are highlighted: for example, most critical issues are the assumptions and selection of evaluation criteria and further the selection of the criteria weight values. In Table 1, the criteria column shows that all papers use economic criteria, four papers use environmental criteria, and three papers use criteria in all three sustainability categories. The economic criteria are important because they provide evidence for companies to demonstrate the economic feasibility of product regeneration. In addition, the articles using the most criteria are the articles assessing several end-of-life alternatives. While the articles assessing the disassembly activity focus only on the economic criteria. In our work, we defined assumptions and the criteria type (environmental, economic) in introduction. We proposed consider all assessments with product, process and market variables. Thus, the assessment trajectory of an EoL product is more relevant since the variables used concern the whole regeneration cycle. Thanks to this global

vision, it is obvious that the assessment of the regeneration trajectory will be more accurate and more profitable.

3 Decision making method for EoL product

Following the state of the art, we will propose a decision making approach that allows to determine the best regeneration strategy for a product depending on its health state but also on the regeneration process and market information. To do this, the proposed approach is divided into 3 steps:

- Identification of the variables that influence the health state and those that are related to the regeneration process and the market.
- Instantiation of the proposed models.
- Evaluation of the strategies by Monte-Carlo simulation.

As a reminder and to complete the assumptions mentioned in introduction: with an industrialization point of view, we consider a single type of product, complete (containing all its components), which arrives in the cycle through a push flow (suppliers randomly provide EoL products). In this way, products can arrive with information about their usage, either provided by the supplier or integrated into the product (smart product), or most frequently any information requiring diagnosis and tests to assess EoL product health state. Thus, we assume that it's feasible to collect EoL product information with a certain cost. To industrialize regeneration, the following activities must be implemented (Fig. 1):

1. EoL products recovery through users or other collectors.
2. Diagnose the product health state:
 - (a) by recovering information on the product by collecting all the information available on the product and provided by the supplier. If necessary, carry out additional tests to retrieve missing information for decision making.
 - (b) by assigning a class to the product based on the data collected, which allows the product to be categorized to facilitate its assessment.
3. Determine the best regeneration route for the product to be regenerated according to its condition, criteria and constraints (cost, customers needs, environmental impact...). According to its assessment, the waste product will be oriented towards the most adapted process for its regeneration (reuse/remanufacturing/recycling/...).
4. Regenerate the EoL product and requalify it according to its new health state. The requalification objective is to position the product in a class in view of its reinsertion in remanufacturing or resale.

It is important to specify that the activities described for regeneration are recursive for certain trajectories with product decomposition. Indeed, for each decomposed el-

ement, activities 2 to 5 are repeated because the process can deteriorate the product. Moreover, the diagnosis of the physical and/or functional aspect at the lower level of the nomenclature is not necessarily possible before decomposition. Thus, the decision-making is important because it is necessary to assess the regeneration trajectory for each decomposed element. Nevertheless, before designing a decision making system, it is required to identify and analyze the variables and parameters impacting the decision making.

The first sub-section proposes a formalization in order to identify the variables influencing the decision making. The second, a modeling into Petri Net following the regeneration activities. Finally, to obtain a decision making tool that allows to determine the best regeneration trajectory according to the product's health state, process and market, a Monte-Carlo simulation is used. With this tool, we obtain the best regeneration trajectory, success probability and potential gain.

3.1 Variables identification impacting the decision-making

So, the need to identify variables and their influence on the decision making is essential. Figure 2 presents a causal loop diagram [19] which contains a non-exhaustive list of variables/parameters impacting the decision making. Thus, as presented in the previous section and with a global vision, three groups are identified: product variables, process vari-

ables and market variables. The interactions that exist between the identified variables are modeled through cause-effect relationships. These interactions are represented by polarized arrows. This polarity describes the type of influence that one variable has on another. The "S" (Same) polarity means that the two variables evolve in the same direction. Conversely, the "O" (Opposite) polarity means that the two variables move in opposite directions. During its regeneration, a product can be decomposed into several elements, the causal loop diagram (Fig. 2) is instantiated recursively for each sub-assembly and component of a product.

The variable *DECISION MAKING* is therefore influenced:

- by the variable *PRODUCT HEALTH STATE* with a "O" polarity because if the health state is acceptable and the product is still in use, then there is no need to take a decision.
- by the parameters of the regeneration processes grouped by the *REGENERATION PROCESS* variable to make the model more comprehensible with a "S" polarity.
- by the var *MARKET DEMAND* with a polarity "S" because the market demand prioritizes the regeneration processes. For example, if customer acceptability of regenerated products is low then the

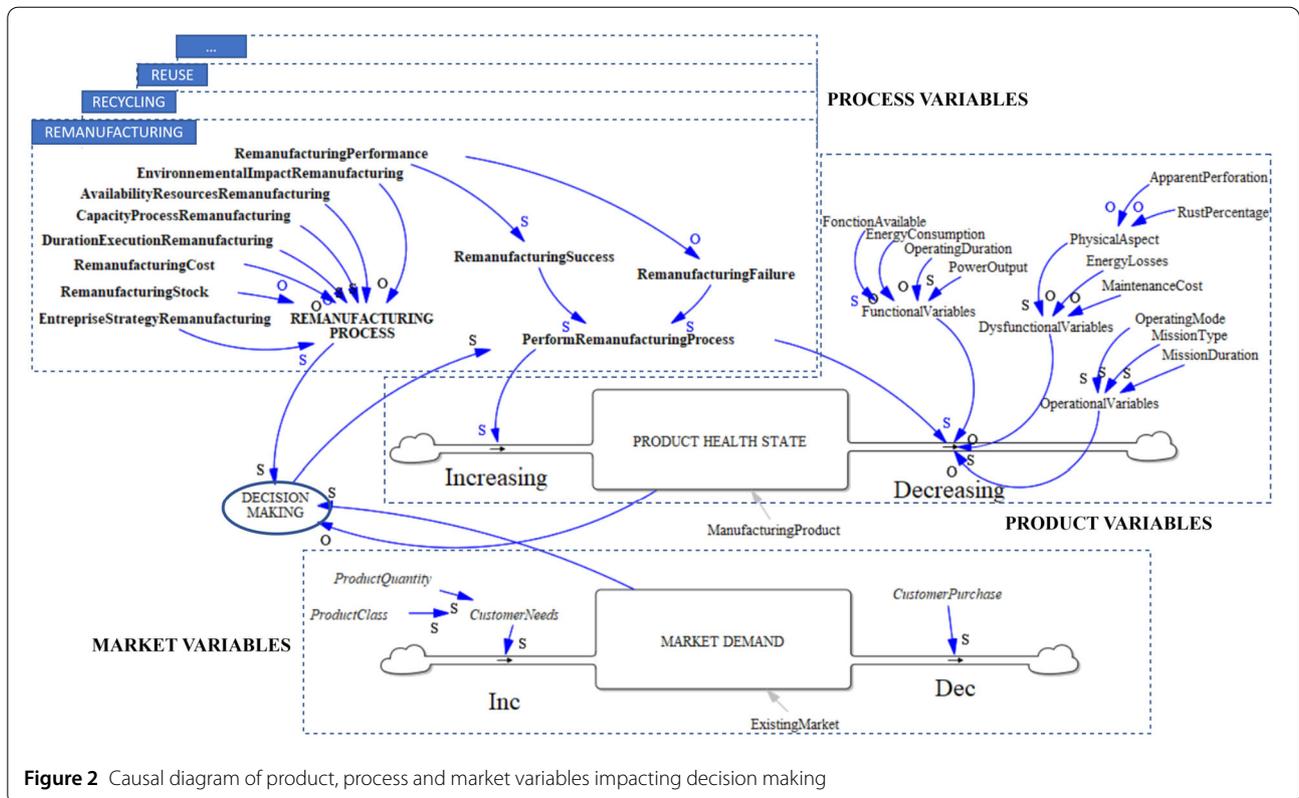


Figure 2 Causal diagram of product, process and market variables impacting decision making

recycling process will be preferred over remanufacturing.

3.1.1 Product variables

The *PRODUCT HEALTH STATE* stock variable represents the real state of a system in a vector indicators form of various kinds. These variables can be deterministic, uncertain and/or unknown. So, product variables are defined according to the following families: functional, dysfunctional and operational for each level of the element to be regenerated (equipment/sub-assembly/component). The work of [20] proposes product prioritization to establish health assessment at each level, and a method to reconstruct the health state of the higher level or to project for the lower levels. This principle is reused in disassembly/reassembly activities.

In Fig. 2 the *PRODUCT HEALTH STATE* stock variable is seen as a stock that can be filled through the “Increasing” valve and emptied through “Decreasing”. The *PRODUCT HEALTH STATE* stock variable evolves according to the phase of the life cycle it is in. During the first manufacturing phase the health state is maximal, during the use phase the product’s health state is reduced while the regeneration actions increase its health state.

Thus, in the use phase we find the different functional, dysfunctional and operational variables that are direct indicators of the health state. Two types of variables are used: Boolean variables for all-or-nothing indicators (example: is the move function for product still available? YES/NO) and real variables for performance, rate or percentage indicators (example: *OperatingDuration*, *RustPercentage*...). Moreover, the polarity of the arrows allows to know how the variables interact. For example, if we consider the *OperatingDuration* variable its polarity with *FunctionalVariable* is “O” because the more the operating duration increases the more *FunctionalVariable* will decrease. For the *FunctionAvailable* boolean variable, it evolves in the same way as *FunctionalVariable*, if the function in question is no more operational then *FunctionalVariable* will decrease.

3.1.2 Process variables

Depending on the availability, capacity, performance, environmental impact, cost and other indicators of each regeneration process, the decision on the trajectory will be different. In addition, these variables evolve over time and must be continuously updated so that the decision making system can determine the best regeneration trajectory for each product. For example, remanufacturing process variables such as the component inventory, the process availability, or the process environmental impact can influence the decision to remanufacture the product following this

process and thus potentially improve the product condition. Thus, these variables have an indirect influence on the product’s health state, but are crucial in the decision making process.

Process variables in Fig. 2 can be instantiated for each regeneration process (reuse, reconditioning, remanufacturing, recycling...) considered in the model. In addition, it is important to note that each activity in each regeneration process can have a negative influence on the health state. For example, a disassembly activity between two elements can physically damage one or both components. Indeed, the variability of the products’ state to be disassembled makes the operations complex. The difficulty of adapting regeneration operations to the variability of the products justifies taking into account the potential failure of the activity in the decision making process. Thus, this possibility must be considered by inserting uncertainty for each regeneration process modeled in the decision making system. Thus, Fig. 2 shows that if the decision has been made to regenerate the product through the remanufacturing process based on the regeneration process’s performance the product can either go well and thus improve the product’s health state or not go well and further deteriorate the product. Thus, the polarity from “*RemanufacturingPerformance*” to “*RemanufacturingSuccess*” is “S” but is “O” to “*RemanufacturingFailure*”.

3.1.3 Market variable

The *MARKET DEMAND* variable is also seen as a stock that can be filled through the “Inc” valve and emptied through “Dec”. This variable shows that customer demands for the new or regenerated product influence decision making through the target health state for regeneration. This is because the regenerated product health state depends on the market demand in terms of quantity and quality. If there is no demand, there will be no remanufacturing. In addition, as more customers purchase product, the demand will decrease.

3.2 Generalized colored stochastic Petri net formalization

The second step of our approach is to model the product evolution throughout the regeneration process. This model represents the impact of the regeneration actions on the product variables, depending on the product health, the company’s strategy (cost, customer needs, environmental impact, etc.) and the market demands.

The objective is therefore to propose the best regeneration trajectory of a product, considering uncertainties (product and processes) and constraints (ranges, cost, customer requirements, environmental impact...). We propose generalized colored stochastic Petri net (GCSPN) for modelling all the previous aspects [21]. Colored aspect al-

lows information to be added to the tokens, which reduces the complexity and combinatorial explosion linked to the many variables considered in the model. The stochastic aspect allows the introduction of uncertainty when transitions occur (probability laws modelling uncertainty). A GCSPN is defined by: $(P; T; C; Pre; Post; Inh; pri; M_0; W)$ where:

- P is a finite set of places;
- T is a finite set (disjoint from P) of timed transitions and immediate transitions;
- $C : P \cup T \rightarrow \omega$ is the color function that associates to each element $s \in P \cup T$ a color domain $C(s) \in \omega$ where ω is a set that contains finite and non-empty sets of colors. An element of $C(s)$ is called the color of s ;
- Pre, Post and Inh are the incidence and inhibition functions, which associate to each place $p \in P$ and to each transition $t \in T$, an application of $C(t)$ to $Bag(C(p))$ Notes $Bag(X)$: the set of multi sets on X ;
- $pri : T \rightarrow \{0; 1\}$ is the priority function which associates to each delayed transition value 0 and to each immediate transition value 1;
- M_0 the initial marking, is a function defined on P , such as $\forall p \in P; M_0(p) \in Bag(C(p))$;
- $W : \forall t \in T; W(t) : C(t) \rightarrow \mathbb{R}^+$ is a function which associates to each delayed (or immediate) transition, for a given color $c \in C(t)$ a crossing rate (or a weight).

The GCSPN model will allow to model:

- the dynamics of the regeneration process using the place/transition structure of the Petri net;
- The evolution of the product's health state, the different regeneration alternatives and the market needs using token colours;

Token color $C(s)$ is a tuple $(C_{health}^{Level}, C_{route}^{Level}, C_{stock}^{Level})$ allows the following information to be displayed:

- Health state based on the functional, dysfunctional and operational variables in Fig. 2: C_{health}^{Level} and the resulted class from diagnosis. Color C_{health}^{Level} is defined from a variable depending on the level in the nomenclature. Thus, this color is defined for each element of the product nomenclature using the product variables identified by the pattern of Fig. 2.
- Regeneration alternatives: C_{route}^{Level} is an element of the set of regeneration processes identified in Fig. 2 = {reuse, remanufacturing, recycling, ...}.
- Stock based on sub-assemblies and components in reserve and updated by the regeneration processes: C_{stock}^{Level} .

The regeneration evolution is represented by GCSPN. Each transition of this GCSPN corresponds to a regeneration activity or a regeneration process. Figure 3 shows a GCSPN example that provides an overview of the regeneration activities: diagnosis (black), path selection activity (blue), regeneration processes (dark green) and inventory

(brown). The largest place at the bottom is the characteristics of a regenerated product possibly from reuse or remanufacturing. The following paragraph explains each type of activity (diagnostic, trajectory selection, regeneration process, stock) in more detail.

- The health diagnosis updates the product class variable based on the incoming product's health state. To do this, it is necessary to enter the thresholds of each variable upstream, which will allow the product to be categorized by assigning it a class (Fig. 4). Some variables can have a single threshold, for example for a functional variable: either the function is operational or it is not. Other variables can have several thresholds, especially for variables representing a percentage, for example the rust percentage of a product can be divided into three categories thanks to two thresholds: a normal level and an acceptable level. The pattern equation to determine the variable $Classe_{Level}$ in the diagnosis activity must verify equation (1). If the equation is verified, color $Classe_{Level}$ of the token takes the color of the class associated with the equation

$$\left(\bigwedge_{j=1}^K varBool_j == a_j \right) \wedge \left(\bigwedge_{i=1}^L (varThresholds_i \bullet Level_i) \right) == true \quad (1)$$

with a_j Boolean variables, $level_i$ real threshold, “•” represents a comparison operator, K number of boolean variables and L number of real variables.

- The activity that determines the regeneration path comes after the diagnosis activity. The activity determines the regeneration process for the product based on the product class, in-stock assemblies and components, market parameters, and strategic parameters (Fig. 5). For example, strategic parameters can be the prioritization of regeneration processes in terms of environmental impact and/or economic cost. Strategic parameters depend on the company's preferences and their sales strategy. Market parameters can for example indicate what the customer needs are in terms of product class preference. In our study, and according to the second assumption stated in the introduction, the strategy is to privilege the process with the lowest environmental impact, i.e., the smallest regeneration loops as a priority, such as reuse, then remanufacturing and finally recycling.

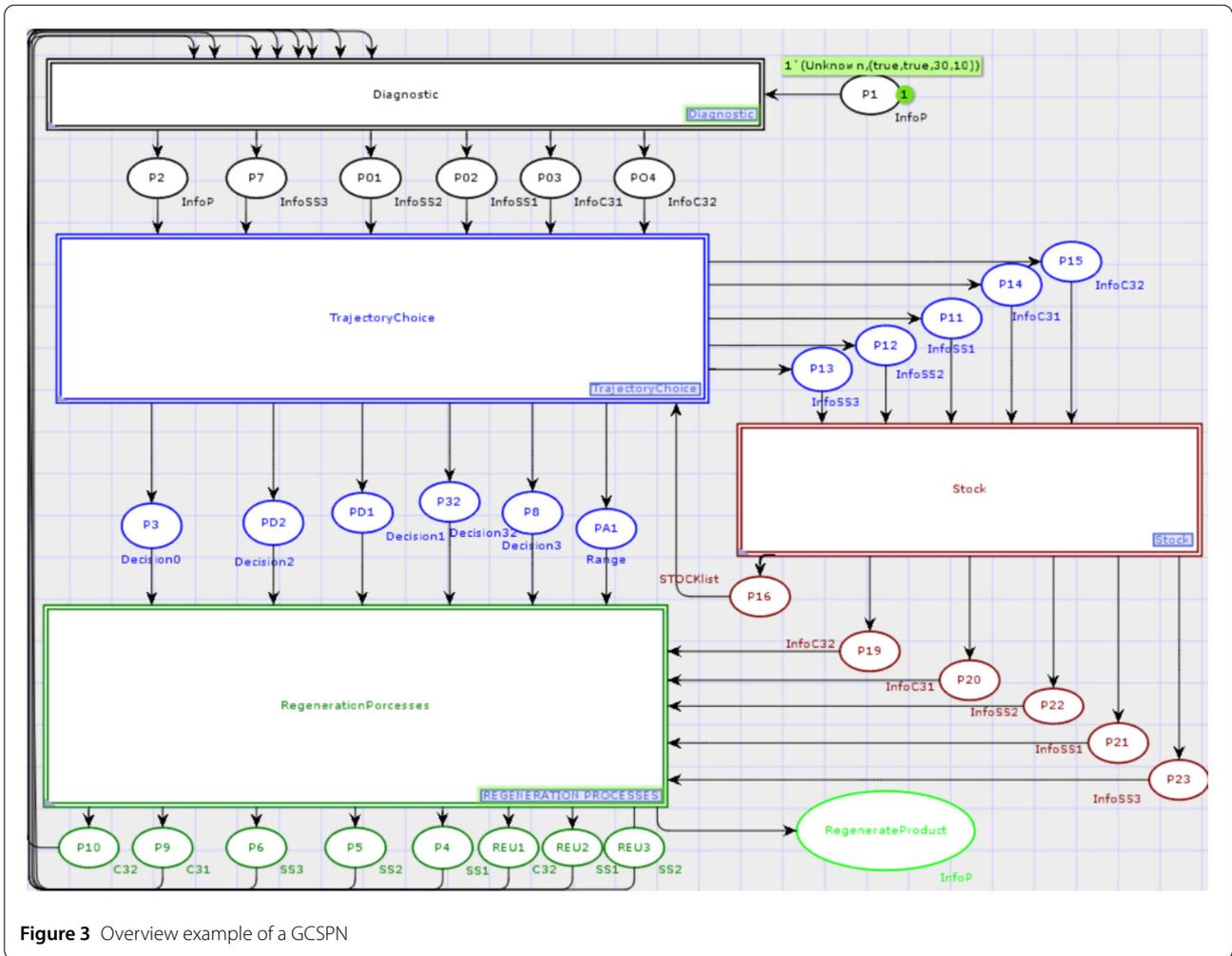


Figure 3 Overview example of a GCSPN

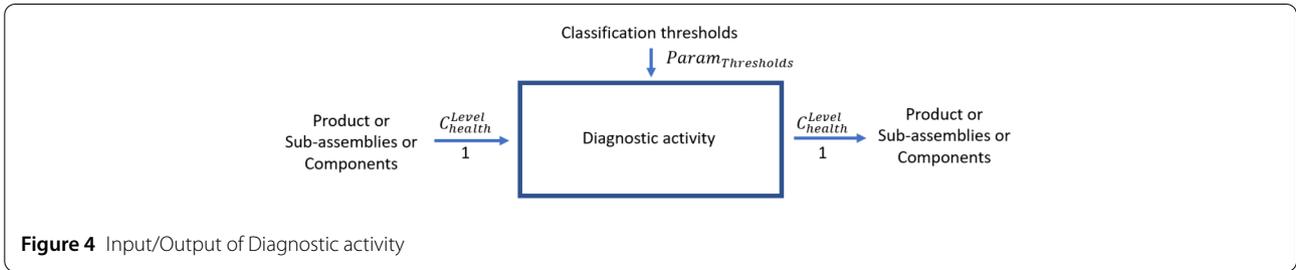


Figure 4 Input/Output of Diagnostic activity

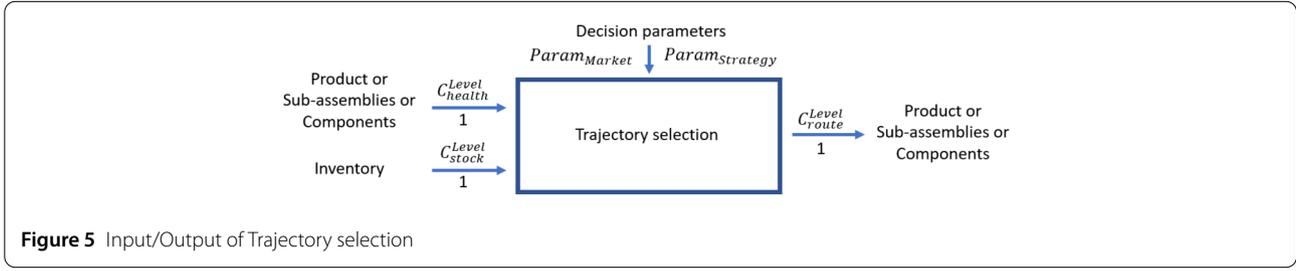


Figure 5 Input/Output of Trajectory selection

To simplify the equation of this activity, we consider that there are as many test conditions as there are regeneration processes to select. In addition, we use a desired state (*DS*) parameter based on the company’s decision-making strategy and market variables. The pattern equation to determine the model regeneration process is defined by the equation (2). If the equation is verified, color C_{route}^{Level} of the token takes the color of the class associated with the equation:

$$C_{route}^{Level} = \begin{cases} \text{if } (\bigvee_{i=1}^O Class_{Level} == Class_{Level}^{Strat_i} \\ \wedge DS == DS^{Strat_i} \\ \wedge StockLevel = StockLevel^{Strat_i}) \\ \text{then (RegenerationProcess1)} \\ \text{else} \\ \dots \\ \text{if } (\bigvee_{i=O+1}^P Class_{Level} = Class_{Level}^{Strat_i} \\ \wedge DS = DS^{Strat_i} \\ \wedge StockLevel = StockLevel^{Strat_i}) \\ \text{then (RegenerationProcessN-1)} \\ \text{else (RegenerationProcessN)} \end{cases} \quad (2)$$

- The inventory is updated if product components have been disassembled and requalified (Fig. 6).

The pattern equation for the inventory activity is therefore the following:

$$C_{stock}^{Level} = \begin{cases} \text{if } (Class_{Level} = A) \\ \text{then } (StockInit_A + 1, \\ StockInit_B, \\ StockInit_C) \\ \text{else} \\ \text{if } (Class_{Level} = B) \\ \text{then } (StockInit_A, StockInit_B + 1, \\ StockInit_C) \\ \text{else } (StockInit_A, \\ StockInit_B, \\ StockInit_C + 1) \end{cases} \quad (3)$$

- Then, according to the determined trajectory, the product is sent to the chosen regeneration process to be revalorized (reuse or remanufacturing or recycling or ...) (Fig. 7).

Reuse: only affects the highest level of the product nomenclature. Indeed, if the incoming product is similar to a new product or corresponds to a “class A” product, then a cleaning action is sufficient before requalifying the product.

Remanufacturing: is defined by [22] as a process which “consists of seven key activities to turn cores into remanufactured products/components including core acquisition, disassembly, cleaning, inspection, reworking, reassembly, and testing”. In this work, we use only disassembly, reworking and reassembly activities (Fig. 8).

- Disassembly: determines the color of each sub-assembly or component obtained after decomposition. Each token has a color that depends on the health state of high level element, the disassembly route and the parameters of the disassembly process.
- Rework: used to increase the health of a sub-assembly or component. The new token has a color that depends on the incoming component’s health state, the regeneration trajectory, and the parameters of the rework activities.
- Assembly: determines the color of the assembly from the health state of n sub-assemblies or components composed high level element, the assembly route and the parameters of assembly process.
- Recycling: is defined by [23] as “a product recovery option that involves techniques for creating new materials from wastes”. The new token has a color that depends on the health state.

GCSPN transitions change the color of the tokens and thus the characteristics of the regenerated product, sub-assemblies and components. In addition, the parameters of the regeneration set of activities and thus the decision making depend on the business strategy of the company’s

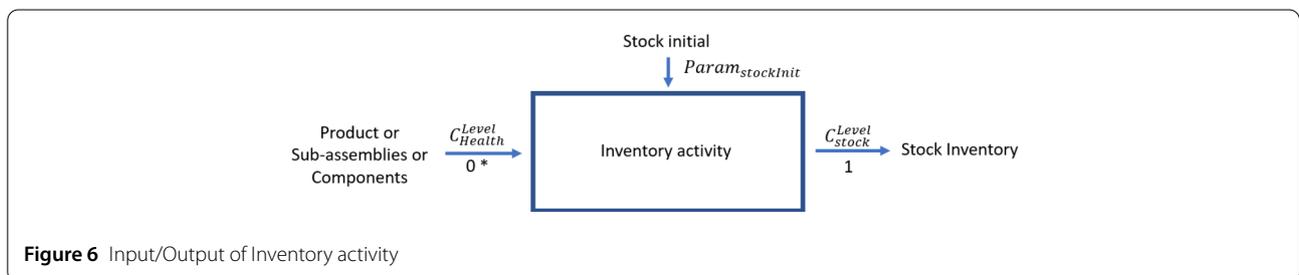


Figure 6 Input/Output of Inventory activity

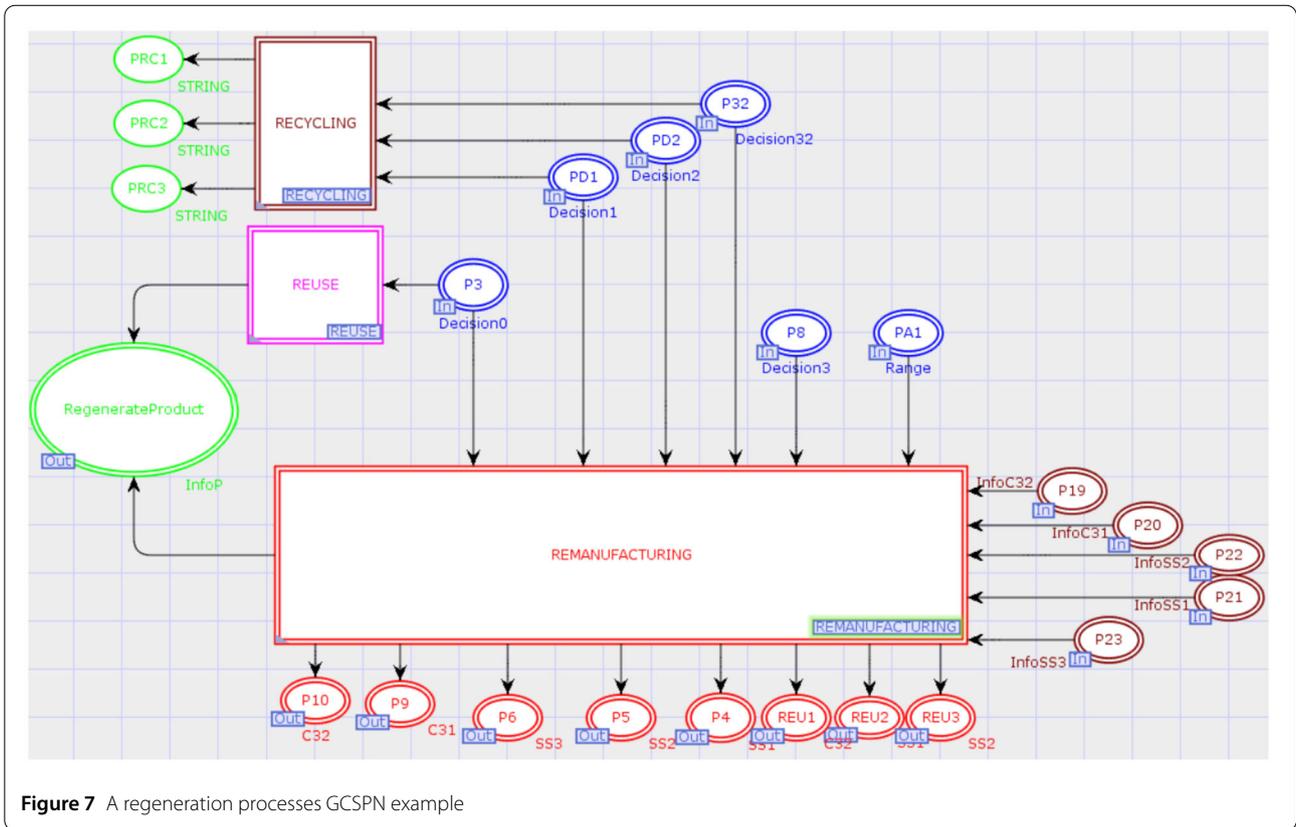


Figure 7 A regeneration processes GCSPN example

resources, the regeneration process performance and the product characteristics and its ability to be regenerated. For example, are all sub-assemblies disassemblable and re-workable? Thus, the structure of the GCSPN and the different parameters depend on the strategy, constraints and resources of the company. So, the decomposition/recomposition equations of the product’s health state must be determined.

In addition, the direction of the arrows for the different variables going to either the “Increasing” or “Decreasing” valves (Fig. 2) allows to know when (in which phase) and how EoL product color variables change through the GCSPN transitions (improvement or deterioration). Once the model colors have been defined, regeneration activities are used to create recursive patterns to form the structure of the GCSPN. Thus, depending on the company’s resources and the regeneration processes compatible with the product, it is possible to integrate new process blocks (Fig. 7) into the model and/or to delete process blocks if a regeneration path is now unusable. This hierarchical aspect of the PN modeling allows to simplify the modeling of the decision making system.

In addition, the variables used to define health state are not always known, some variables are formalized with

an uncertainty. In order to represent this uncertainty, the value of the variable is drawn randomly following a probability law whose parameters depend on the color of the token:

- for unknown variables before disassembly, a value is drawn according to truncated probability laws (normal, uniform, ...) defined which represent the possible values variability. In this study, the probability laws of the stochastic variables are assumed to be known. They can be determined by statistical studies, by experts, from the monitoring of products in real time or by feedback.
- The success probability for a specific process operation, is modeled by discrete laws between 0 and 100%. Depending on the draw and the result of the operation, it is either a success (the variables follow the defined equations) or a failure (the variables are degraded).

The model equation for the regeneration processes takes place in three steps: first, a guard is used to activate or not the regeneration process depending on the regeneration path selected in the upstream activity (Fig. 9). Secondly, actions are associated with the transition to perform the drawing of probability laws. For each activity of a regeneration process there is at least one probability

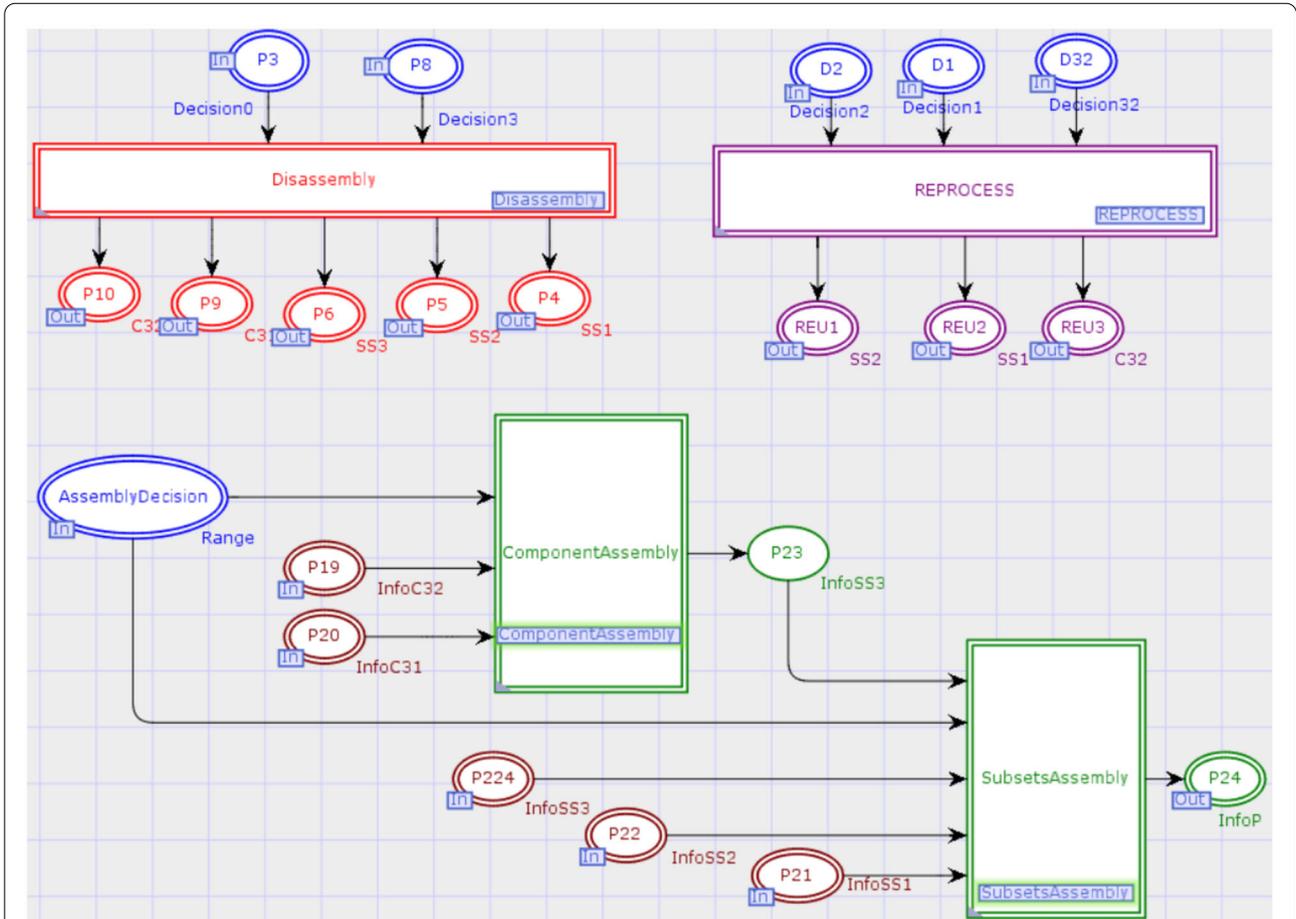


Figure 8 A remanufacturing activities GCSN example

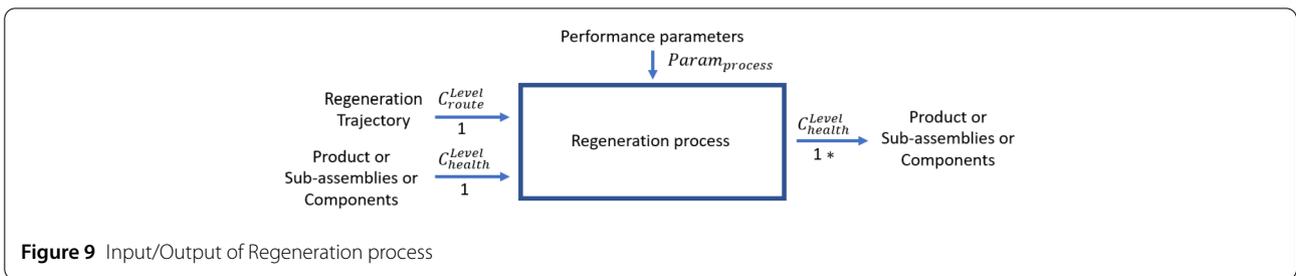


Figure 9 Input/Output of Regeneration process

law ($ProbabilityLaw_i$), the one corresponding to the uncertainty of the success or failure of the activity. Thirdly, according to the law0, the performance parameter of the resource N ($PerfProcess_N$) and the process characteristics: a new color is created if the activity was a decomposition otherwise the input color is updated (improved or deteriorated state if the activity is a failure). In addition, after each pass in a regeneration process, the new color must pass again in the diagnostic activity to be assigned a new class (A, B or C). Indeed, the variables of the element leav-

ing the process depend on the variables of the element entering and the regeneration process:

1. Guard: [$ProcessN = C^{Level}_{route}$] "Transition activation".
2. Action: "Probability law drawing"

$$PerfDrawingProcess_N = ProbabilityLaw_0,$$

$$NewVar1 = ProbabilityLaw_1,$$

...

$$NewVarN = ProbabilityLaw_N.$$

3. Token color changes according to the following equation:

$$C_{\text{health}}^{\text{Level}} = \begin{cases} \text{if } (PerfDrawingProcess_N \leq PerfProcessN) \\ \text{then } (unknown, \\ \quad Var1Bool = a_1, \dots, \\ \quad VarNBool = a_N, \\ \quad NewVar1 + b_1, \dots, \\ \quad NewVarN + b_N, \\ \quad SameVar1 + c_1, \dots, \\ \quad SameVarN + c_N) \\ \text{else } (unknown, \\ \quad Var1Bool = x_1, \dots, \\ \quad VarNBool = x_N, \\ \quad NewVar1 + y_1, \dots, \\ \quad NewVarN + y_N, \\ \quad SameVar1 + z_1, \dots, \\ \quad SameVarN + z_N). \end{cases} \quad (4)$$

Figure 10 shows the GCSPN of the disassembly activity for a product P_A whose health state is defined by $C_{\text{health}}^{P_A} = (var_1, var_2, class_{P_A})$. Product P_A is composed of a sub-assembly S_{AB} and a component C_C . Sub-assembly S_{AB} is composed of 2 components C_D and C_E .

There are two possibilities to disassemble product P_A :

- Route DR_1 : if the health state of P_A is classified B, it is decomposed into S_{AB} and C_C .

- Route DR_2 : if product P_A is classified C, it is first decomposed into S_{AB} and C_C and then S_{AB} is decomposed into C_D and C_E .

In the case of route 1, the following equation is used to determine the health state: $C_{\text{health}}^{S_{AB}} = (var_3, var_4, class_{S_{AB}})$. Component S_{AB} has 2 variables and var_3 is not measurable. Thus, when product A is disassembled to obtain S_{AB} , the normal parameter law (m, σ) models the variable uncertainty. In addition, the disassembly operation is also uncertain. In 70% of cases the operation is a success. In 30% of cases, variables are deteriorated. Function transition is therefore constructed as well as the place $(P_{S_{AB}})$ represented the sub-system S_{AB} with color:

- Parameters for DR1 activity:
 - $ProbabilityLaw_0 = \text{Uniform}(0, 100)$;
 - $ProbabilityLaw_1 = \text{Normal}(50, 10)$.
- Parameters for disassembly S_{AB} :
 - $PerfProcessN = P_{OP1} = 70, a1 = true, b1 = 0, x1 = false, y1 = -30,$

$$C_{\text{health}}^{S_{AB}} = \begin{cases} \text{if } (Perf = \text{Unif}(0, 100)) \\ \leq 70 \\ \text{then } (Unknown, a1, \\ \quad NewVar1 + b1) \\ \text{else } (Unknown, x1, \\ \quad NewVar1 + y1). \end{cases} \quad (5)$$

- Parameters for disassembly C_C :

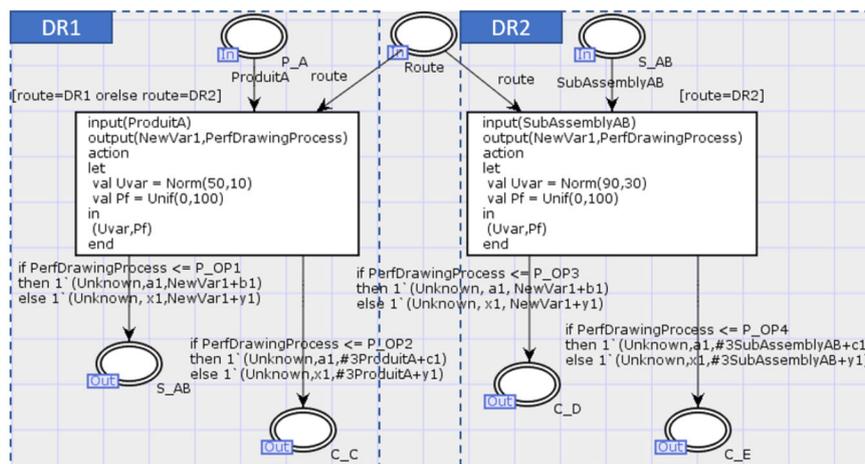


Figure 10 GCSPN for disassembly activity

$PerfProcessN = P_{OP2} = 80, a1 = true, c1 = 0, x1 = false, y1 = -15,$

$$C_{health}^{CC} = \begin{cases} \text{if } (Perf = Unif(0, 100)) \\ \leq 80 \\ \text{then } (Unknown, a1, \\ NewVar1 + c1) \\ \text{else } (Unknown, x1, \\ NewVar1 + y1). \end{cases} \quad (6)$$

Section 3.2 showed how to use the causal diagram formalism in Fig. 2 to construct the colors:

- representing the product and component health state from the identified functional, dysfunctional, and operational variables of each level (C_{health}^{Level}).
- representing the choice of the regeneration path according to the number of regeneration processes available for the product to be regenerated (C_{route}^{Level}).
- representing the number of components, sub-assemblies in stock per class (C_{stock}^{Level}).

Moreover, from the identified process parameters (the performance of the different operations, their capacity to increase the product’s health state or to deteriorate it....) and the different regeneration activities (diagnosis, trajectory selection) the structure of the GCSPN is designed. Once the construction of the model is completed, it must be simulated to obtain results and to make a decision.

3.3 Simulation of the GCSPN

From this GCSPN model, it is possible to generate different regeneration trajectories as reuse, remanufacturing (disassembly and reassembly routes, reworking) and recycling. In order to assess them, a set of criteria such as the potential gain, the probability of reaching the desired state, the class of the remanufactured product, etc. are used. These criteria are added to the previous models in order to assess their value according to the health state of the incoming products and regeneration trajectory decisions.

By simulating the model, many times (Monte-Carlo process) with the same product variables and analyzing the

results, we obtain reliable estimates that allow us to decide on the regeneration trajectory. Indeed, the model repeats the simulation as long as the stopping criteria do not converge below a chosen step. One or more criteria can be chosen to stop the simulation.

To sum up, the stochastic aspect is found at several levels in the model: random drawing of the uncertain variables of the product according to probability laws, random drawing of the process operations by discrete laws and Monte-Carlo simulation.

To summarize, Sect. 3 outlined the methodology for building a decision making tool in GCSPN. The first step was to construct a causal diagram to identify and analyze the variables useful for determining the product’s health state and the different variables useful for decision making. Then, from this formalism it is possible to define the colors and transitions of the GCSPN. Once the model is built, this section explains how to simulate the model to obtain results and to be able to make a decision in a personalized way to each product entering the decision making process. The next part, will highlight the proposed methodology through an application from the literature.

4 Numerical illustration to an industrial case

The model is tested with an example from the literature [12]: a Knorr-Brese EBS 1 Channel Module which allows us to verify the effectiveness and efficiency of the model (Fig. 11). We consider 3 sub-assemblies: the cover, the support which is composed of 2 sub-assemblies (electronic card and the body). The following variables are considered for the Knorr-Brese module level (Fig. 12). So, variables threshold are pre-defined. EBS module F_1 and F_2 functionalities are tested on test benches. The *OperatingDuration* is given by the supplier and the *RustPercentage* is determined by observation of the module. The color of the token corresponding to the EBS module health is formed of 5 variables:

$$C_{health}^{EBS} = (class_{EBS}, F_{1EBS}, F_{2EBS}, D_{EBS}, R_{EBS}). \quad (7)$$

In this scenario, we have 3 functional variables ($F_{1EBS}, F_{2EBS}, D_{EBS}$) and one dysfunctional variable (R_{EBS}). $class_{EBS}$



Figure 11 EBS module and components of the returned module [12]

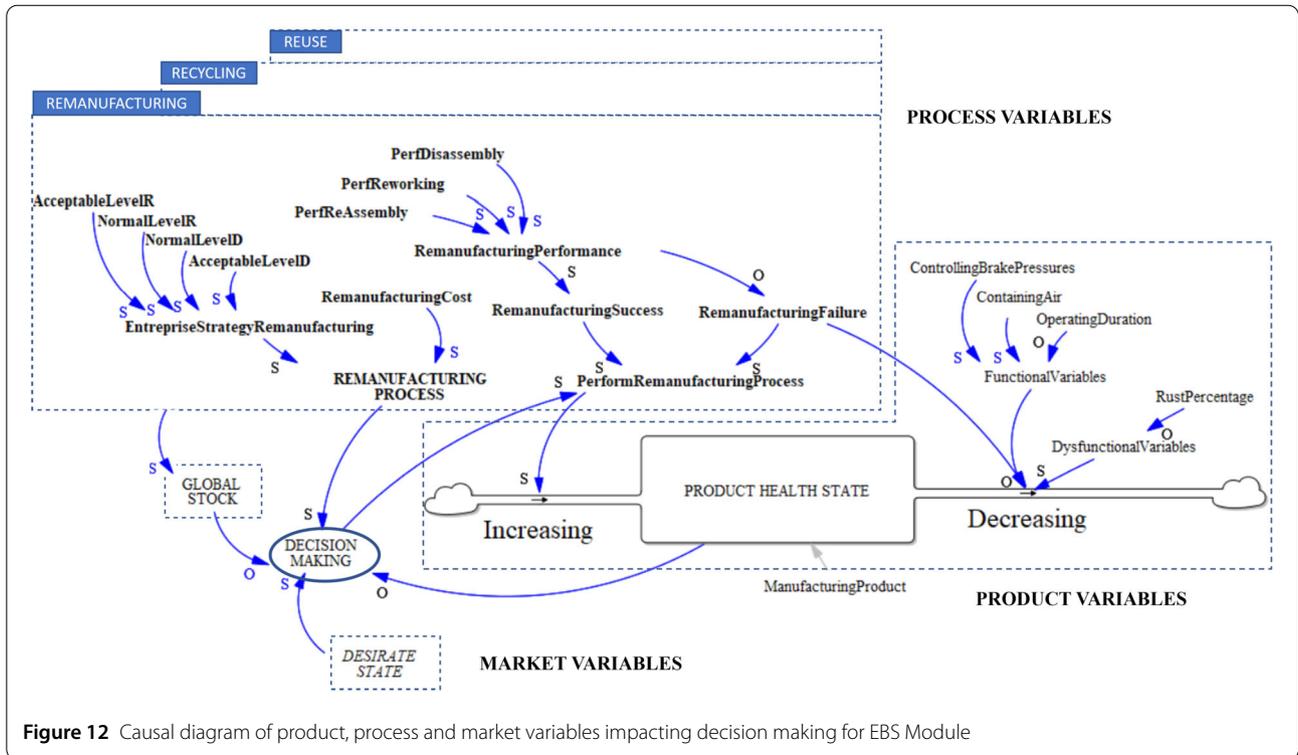


Figure 12 Causal diagram of product, process and market variables impacting decision making for EBS Module

Table 2 Variables for the equipment level: EBS module

Variables	Values
Controlling brake pressures (F_{1EBS})	0: False 1: True
Containing the air (F_{2EBS})	0: False 1: True
OperatingDuration (D_{EBS})	0: $D_{EBS} > \text{AcceptableLevel_D}$ 1: $\text{NormalLevel_D} < D_{EBS} \leq \text{AcceptableLevel_D}$ 2: $D_{EBS} \leq \text{NormalLevel_D}$
RustPercentage (R_{EBS})	0: $R_{EBS} > \text{AcceptableLevel_R}$ 1: $\text{NormalLevel_R} < R_{EBS} \leq \text{AcceptableLevel_R}$ hours 2: $R_{EBS} \leq \text{NormalLevel_R}$ hours

variable of the incoming product is first null and then updated after the diagnostic activity. Table 2 illustrates the variables categorized according to the thresholds determined by the company. The first two variables correspond to functions essential to the EBS module and are categorized with a binary state. Either the function is operational or it is not. For the *OperatingDuration* and *RustPercentage* variables, the threshold parameters must be filled in by the company.

The colors of each sub-assembly and component are defined in the same way. Some variables at module level allow, by deduction, to determine the elements variables (sub-assemblies, components) which represent elements that have just been disassembled (e.g., the usage support is the same for EBS duration). For variables that

cannot be inferred, uncertainty must be introduced (e.g., *TightnessLevel* of the valves).

The next step is to classify the classes (A, B and C) of each element (product, sub-assemblies and components) according to their variables (EBS module example in the Table 3). When crossing the transition and according to Table 3, the transition function determines the health state of the EBS module by the following color and parameters:

- EBS Parameters for *OperatingDuration*:
NormalLevelD = 20,000 hours, AcceptableLevelD = 40,000 hours.
- EBS Parameters for *RustPercentage*: NormalLevelR = 20% rust, AcceptableLevelR = 40% rust.

Table 3 Variables for the equipment level: EBS module

Var	F1		F2		D			R1		
	1	0	1	0	2	1	0	2	1	0
A	X		X		X			X		
B	X		X		X				X	
B	X		X			X		X		
C					If not A and not B					

- Color evolution is defined by:

$$C_{health}^{EBS} = \begin{cases} \text{if } (F_{1EBS} = true \wedge F_{2EBS} = true) \\ \quad \wedge (D_{EBS} \leq NormalLevelD) \\ \quad \wedge (R_{EBS} \leq NormalLevelR) \\ \text{then } (A, F_{1EBS}, F_{2EBS}, D_{EBS}) \\ \text{else} \\ \text{if } (F_{1EBS} = true \wedge F_{2EBS} = true) \\ \quad \wedge (D_{EBS} \leq AcceptableLevelD) \\ \quad \wedge (R_{EBS} \leq AcceptableLevelR) \\ \text{then } (B, F_{1EBS}, F_{2EBS}, D_{EBS}) \\ \text{else } (C, F_{1EBS}, F_{2EBS}, D_{EBS}). \end{cases} \quad (8)$$

The activities: reuse, remanufacturing and recycling must be defined according to the equation (4). Disassembly/reassembly ranges, projection/reconstruction rules, costs, operations yield, stocks, customer demands and the laws of probability most representative of the uncertain variables must be defined. In this application, it's possible to:

- reuse EBS module with some minor cleaning activities.
- remanufacture EBS module. There are 2 ranges of disassembly (DR_1, DR_2) and 2 ranges of reassembly (RR_1, RR_2) possible. DR_1 aims at disassembling the EBS module into three sub-assemblies and DR_2 aims at obtaining the two sub-assemblies cap and cover as well as the two components electronic board and body. Rework is possible for the cap, the cover and the body. The electronic board is considered too complex to be reworked. For the reassembly, the company has the manufacturing resources to integrate the regenerated components in the manufacturing line: electronic board and body to obtain the support. The production line can also integrate the regenerated sub-assemblies to remanufacture an EBS module.
- recycle the EBS module's cap, cover and body. The electronic board is considered too complex to be recycled. So, in this scenario, if the electronic board is disassembled, another partner regenerates it.

Therefore, the color of the route is defined by: (C_{route}^{Level}) is an element of the set: $\{Reuse, DR_1, DR_2, Stock, Rework, Recycle, RR_1, RR_2, No_R\}$.

To simplify the company's decision-making strategy, we use a desired state (DS) parameter determined according to market variables. Thus, depending on the DS , the class of the incoming product and the stock, the decision making process will choose a regeneration process (C_{health}^{Level}).

The assumption in this application is that the remanufactured product market only requires class A or B products and in the event that a product or sub-assembly is diagnosed as C then it is disassembled and then recycled to recover raw material. In addition, for the reassembling process, we don't surpass the class element assembling. For example, for reach a DS product B, we only use sub-assemblies and components from class B. The three possible regeneration routes are defined as follows:

- If an incoming EBS module is class A, the DS is class A and the class A EBS module inventory is below the company's recommended threshold, then the module will enter the reuse process to be cleaned and requalified for resale.
- If an incoming EBS module is class A, the DS is class A but the inventory of class A EBS modules is below the company's recommended threshold, then the module will be disassembled following the DR_1 range to store sub-assemblies for future reassembly. Another possibility for route DR_1 to be chosen is that the incoming product is of class B with a DS equal to B and no matter how much stock of element B there is, or that the product is of class B and the DS is equal to A.
- In the case where an incoming product is class C, disassembly range number two DR_2 is systematically selected with the objective of recycling class C sub-assemblies and components.

These three regeneration route are translated into the equation:

$$C_{route}^{EBS} = \begin{cases} \text{if } (class_{EBS} == A \wedge DS = A) \\ \quad \wedge stock_{EBS}^A \leq normalLevelEBS_A) \\ \text{then } (Reuse) \\ \text{else} \\ \text{if } ((DS = A \wedge class_{EBS} == A) \\ \quad \wedge stock_{EBS}^A \geq normalLevelEBS_A) \\ \quad \vee (DS == B \wedge class_{EBS} == B) \\ \quad \vee (DS == A \wedge class_{EBS} == B) \\ \text{then } (DR_1) \\ \text{else } (DR_2). \end{cases} \quad (9)$$

Decisions regarding the regeneration possibilities of the cap: If the DS is class A and cap is class B then the cap is rework to try to improve the cap's health state regardless of component stock. If the disassembled cap is class C then

recycling is chosen. Else the cap is stored.

$$C_{\text{route}}^{\text{Cap}} = \begin{cases} \text{if } (DS == A \wedge \text{class}_{\text{Cap}} == B) \\ \text{then } (Rework) \\ \text{else} \\ \text{if } (\text{class}_{\text{Cap}} == C) \\ \text{then } (Recycle) \\ \text{else } (Stock). \end{cases} \quad (10)$$

The decision to reassemble is only made once all the elements have been regenerated. In this scenario, the company prioritizes the regenerated components in the reassembly process. If this is not possible, then elements are taken from stock, with a preference for reassembling sub-assemblies (semi-finished product) rather than going through component assembly.

Regarding the body disassembly, 2 variables are uncertain because they cannot be diagnosed before the disassembly (*TightnessLevel* and *RustPercentage*). Thus, for the *TightnessLevel* valve, we use a truncated normal law between 0 and 100% with as parameter a fixed standard deviation assumed to be statistically determined and an average which is a function of the equipment level service life variable (EBS module). Once the parameters of the normal distribution have been determined, a random draw in the distribution assigns a value to the *TightnessLevel*.

Process uncertainty is modelled by discrete laws. Probabilities are defined according to the performance of each operation. Either the operation is a success or a failure. If it is successful, the values of the variables are affected normally according to the rules determined, otherwise the variables are deteriorated by adding or decreasing.

Before simulating, it is necessary to choose the variables of the input product supposedly determined in the diagnostic activity upstream of the decision-making model. We propose 6 possible scenarios:

1. Sc1: a class A product with a class A DS with a stock is supposed to be null for sub-assemblies but not for the components.
2. Sc2: a class A product and a class B DS with a stock is supposed to be null for sub-assemblies but not for the components.
3. Sc3: a class B product and a class A DS with a stock is supposed to be null for sub-assemblies but not for the components.
4. Sc4: a class B product and a class B DS with a stock is supposed to be null for sub-assemblies but not for the components.
5. Sc5: a class B product and a class A DS with null stock.
6. Sc6: a class B product and a class A DS with complete stock.

Table 4 Alternatives costs

Alternatives	Alternatives cost (€)
Reuse	0.5
DR1	1.5
DR2	3.5
Rework Cap	4
Rework Cover	5
Rework Body	9
Recycle Cap or Cover or Body	0.5
RR1	1
RR2	2
No	0

Table 5 Alternatives resale prices per class

Alternatives	Alternatives cost (€)
A	796,6
B	100
C	Not saleable
Material Recovery	1,49€

The alternatives that we are trying to assess, knowing the resale grid, are listed in the following tables. Table 4 and Table 5 are based on the work of [12]. The alternative costs are determined based on the disassembly operation cost which is “0.29 cents of € per second”. The alternatives resale prices per class are determined between 796.6€ which “represents an estimate of its actual average market price” and “the resale value of a remanufactured 1 channel EBS module [which] is about 100 €”. Regarding recycling, “The revenue which can be generated by recovering the material of this product is taken to be 1.49€.”

We observe the potential gain and the probability of reaching the desired state with a stopping step of 0.01 which corresponds to 1 euro-cent for the potential gain and 1% for the probability. As we observe two decision criteria, we have to wait for the two criteria to converge, before stopping the Monte-Carlo simulation. So, after many simulations to reach the stopping criteria and the processing of this data, it can be decided which will be the best regeneration trajectory. To illustrate, Fig. 13 shows for Sc4 scenario the number of Monte-Carlo simulations required for the potential gain and the success probability to converge. Thus, every 10 simulations the average of each criteria is recalculated and compared to the previous one until the difference is lower than the chosen stopping step. To perform the decision-making for the application presented and with an Intel(R) Core(TM)/i7-10850H CPU @ 2.70 GHz/2.71 GHz the time follow this equation: $time = 0.053 \times SimulationNbr$. So, for a product that requires 1000 simulations to converge to the best decision, the decision making time would be: 53 s.

The results presented in Table 6 show that depending on the product’s health state, the DS and the stocks, the regeneration trajectories change and do not necessarily lead to

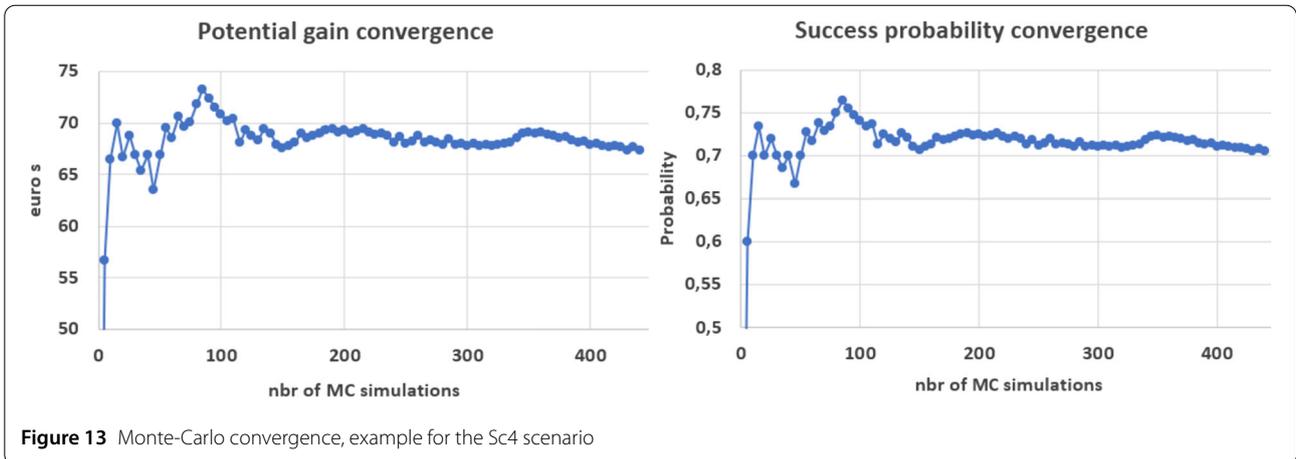


Figure 13 Monte-Carlo convergence, example for the Sc4 scenario

Table 6 Results of the six scenarios

Criteria	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6
Gain€	796.1	-2.39	150,66	67.3	-8.23	787.3
Success%	1	0	0.23	0.7	0	1
Reuse %	1	0	0	0	0	0
DR1 %	0	0.48	0	0.54	0	0
DR2 %	0	0.52	1	0.46	1	1
Rework %	0	0	0.8	0	0.8	0.85
Recycle %	0	0.52	0.78	0.46	0.8	0.81
RR1 %	0	0	0	0.54	0	1
RR2 %	0	0	0.2	0.17	0	0
No %	0	1	0.8	0.3	1	0
nbr of simulations	20	160	860	440	160	180

the production of a regenerated product. Indeed, for Sc2 and Sc5 we obtain a negative potential gain, so, the regeneration decision could be to stock these products and wait for market variables (DS) to be favorable to regenerate them. Nevertheless, in cases where the probability of reaching the DS is less than 50%, for example, it is possible, thanks to the decision making system, to predict which regeneration trajectory has the best chance of leading to a result that is beneficial to the company. In addition, it is noted that the more a product has the possibility of trajectory as for example for Sc3 and Sc4, the more the number of simulation is high. The higher number of simulations can be explained by the fact that in these scenarios, depending on the drawing of the probability laws, several trajectories can be envisaged such as remanufacturing with disassembly, reworking and reassembly activities and recycling. The results show that the simulation number varies to converge and stop the data processing. However, with stopping criteria, no time is lost and the assessment can switch to another product to be regenerated.

One way to reduce trajectory fluctuations would be to reduce uncertainties in both the uncertain product variables and the regeneration processes that can deteriorate the product if the operation to restore the product fails.

In addition, the different scenarios show that the results vary depending on the DS to be achieved, the product condition, and the available inventory. Thus, decision making is needed because there are many possible alternatives. Moreover, the settings of the processes can also influence the regeneration trajectory, in particular the performance of the regeneration operations which, through a discrete draw, determines whether the operation is successful or not.

5 Conclusion

Regeneration processes plays a key role in the EoL's products valorization. They effectively enable used products to be reintroduced directly into the market. In this paper, we have proposed a formalization, in order to identify the variables influencing the decision making. This formalism is the starting point in the methodology to build a tool to help the assessment of the regeneration level by modeling generalized colored stochastic Petri nets. This proposed approach takes into account some uncertainties related to the product's health state and some uncertainties concerning the regeneration processes. The proposed model was applied to an industrial instance of the literature (EBS Module).

A first application showed the approach feasibility, but also the limits of the GCSPN modelling. If the proposed method was applied to large scale systems, the complexity of the model would explode because of a large number of sub-assemblies and components. Indeed, for each disassembled element a decision making activity is required to guide this element towards the most appropriate regeneration process for it. So, the structure of the model is based on the proposed regeneration processes (reuse/remanufacturing / recycling), and the product information is carried out by the token color. This choice of modelling implies redefining all the transition function equations if the product characteristics change. One perspective is to propose generic models regardless of the product nomenclature.

ture and the variables characterizing the health state. This generalization would allow the methodology to be applied to more complex products and processes.

In Sect. 4, the equation's time is determine for the application but this time depends on the capacity of the computer and the transition place number of the GCSPN model. Indeed, for a more complex product with more elements in the model, the simulation time would be longer. Thus, a relation between the number of place/transition in the model should be established to obtain an equation for the execution time. In addition, we should analyse the impact of the execution time in different regeneration processes when a trajectory implies several random drawings in probability laws. A perspective would be to compare this time with another decision making approach with the same product studied. Another perspective is to compare our approach with statistical optimisation approaches such as that of [12] in order to determine the characteristics of the products to be treated by our approach.

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Code availability

Not applicable.

Declarations

Ethics approval

All authors accept the ethical standards of the journal.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors contributed to the study conception and design. All authors read and approved the final manuscript.

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