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Regeneration Management Tool for Industrial Ecosystem

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Abstract: Sustainable development is increasingly present in the international political powers. In response, the circular economy is increasingly emphasized. This economy is also called regeneration paradigm. This paradigm uses a multitude of concepts, which makes it complex to understand. Indeed, it makes each stakeholder (nature, decomposers and user companies) interact amongst themselves to create an industrial ecosystem. However, they sometimes have requirements that oppose. Therefore, this paper proposes a regeneration management tool to coordinate all of these stakeholders. For that, the regeneration requirements are identified. Then, they are modeled to understand their impacts on the product lifecycle and on the company business. These models are based on system dynamics that has been developed to enable a better understanding of complex systems.

Keywords: circular economy, regeneration paradigm, life cycle management, industrial ecosystem, system dynamics, modelling

1. INTRODUCTION

The problematics of sustainable development is based on global warming; increasing scarcity of some raw materials; accumulation of waste etc. They are increasingly present in the political debates (COP 21 and 22, Rio+20, Europe 2020 project). These debates highlight the necessity to change our behavior concerning the environment. One of the solutions to these problems is to turn towards the circular economy.

This economy is in contradiction with the linear economy (take-make-dump), because it considers that resources are limited and that waste do not exist (Foundation Ellen MacArthur, 2014). In other words, waste are transformed into secondary raw materials (make-use-return indefinitely). For this, the circular economy is based on the following schools of thought: (i) Biomimicry (Benyus, 2009), study of nature to design goods and to develop new technologies; (ii) Industrial Ecology (Despeisse et al., 2012), study of the material and energy flow through the industrial system to add value to waste produced by a firm; (iii) Cradle-to-Cradle (McDonough and Braungart, 2010), design of goods in harmony with environment and communities through the term “nutrients”.

In our previous works (Diez et al., 2015), we propose an approach of these concepts through the notion of “regeneration paradigm”. The regeneration term comes from the food web that is circular and reuses all that is produced by each entity being a part of trophic organization. Indeed, some entities (vegetables, herbivores, carnivores) eat others entities and produce organic matters. By eating these matters, decomposers (worm, bacteria and fungi) produce mineral salts that feed vegetables. This cycle is repeated indefinitely and regulates itself. In (Diez et al., 2015), we have shown that by applying the same principles to the industrial world, it is

necessary to add processes to play the role of decomposers, called “technical decomposers” or “decomposition processes”. Unlike to the industrial ecology where companies exchange their waste to use them like resources, the technical decomposers transform unusable items to add them value. This transformation can be operated by the item’s user or by a specialized company. (Foundation Ellen MacArthur, 2014; Govindan et al., 2014) identify four technical decomposers: repair, reuse, remanufacturing and recycling processes. In (Diez et al., 2015), we have added a new decomposer, called detechnification, to create a link between industry and nature. Indeed, when a product cannot be regenerated in the industrial world, it is put back in nature. To do it healthy, the detechnification process decontaminates the non-reusable product and prepares it to be absorbed easily by nature. This decomposer has requirements that come from nature and focus on human and environmental risks.

Each technical decomposer operates different transformations (time, space and/or shape) on a product and preserves its original functionality, except for the recycling and detechnification processes. Decomposers allow increasing the item’s life cycle, especially by maximizing the short loops. Actually, using decomposers having a low impact on the item’s function (repair and reuse process) multiplies the number of users. Nevertheless, each regeneration shall not affect the possibility of using another decomposer, later in the lifecycle. Moreover, in (Diez et al., 2016), we have shown that the decomposers can be applied on each level of an item (product, subassembly, component), but all decomposers are not applicable at every levels. The choice of decomposer raises the question of its own requirements, which must be combined with future user requirements. All these requirements are grouped in the “regeneration requirements”.

This new approach stimulates companies to create an industrial ecosystem between users (supplier and customer) and decomposers. However, it remains theoretical and the companies are unable to project their strategy into this paradigm, to see the benefits of this approach. This new paradigm requires companies to rethink their strategy at all levels. Moreover, no tools are available to help the managers to implement easily the regeneration in a company, and even less in an industrial ecosystem. Therefore, the aim of this paper is to propose a regeneration management tool for industrial ecosystem. Thus, the first part presents the essential elements to understand the regeneration and its modelling. Then, the second part models the behavior of a product through its passage in decomposition processes and exhibits the profits generated by the regeneration. Finally, the last part concludes this paper and proposes some perspectives.

2. MODELING INDUSTRIAL REGENERATION

Regeneration highlights the concept of decomposers. These decomposers receive products to be regenerated and produce regenerated products (Fig. 1) to be used.

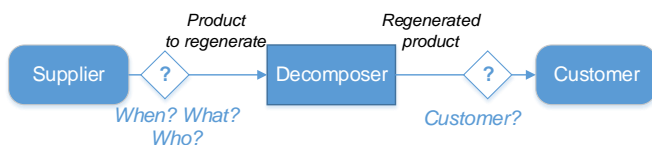


Fig. 1. Environment of decomposer and questions to evolve within decomposers

To be regenerated, a product must meet the requirements of a decomposer. Each decomposer has its own role and does not perform the same transformations on products. They all have different requirements. In the same way, a customer, who also has requirements, uses the regenerated products. All of these requirements are called “regeneration requirements”. These requirements change the requirements of the companies that use the initial product. It is the same for the requirements of the companies that will use the regenerated products (product, by-product, raw materials). For example, the user of a car, who incorporates the regeneration of his vehicle, must take into account the requirements of the decomposer to which he wishes to apply. In parallel, a garage that uses spare parts must review its requirements on the refill parts. For example, a residual or security level of reliability may be required.

Thus, the development of regeneration within the industry involves asking us several questions. Firstly, regeneration influences the using time of a product. In fact, this product must satisfy a set of requirements in order to be regenerated. This involves asking "when to stop using a product and to sell it?" Secondly, (Diez et al., 2016), have shown that regeneration occurred at all levels of a product. This involves asking us "What are the elements of the product that need to be regenerated? Which ones can be resold?" Lastly, the best decomposer must be chosen to regenerate a product. In other words, "who will regenerate this product?" The answer to this question is partially induced by the answer to the second because, for example, only the disassembly makes it possible to obtain spare parts.

To answer “when”, “what” and “who” questions, the regeneration requirements must be defined.

2.1. Regeneration requirements

To precisely define the “regeneration requirements”, we focus on the works that address the second life of a product. In the literature, these works focus exclusively on processes downstream of decomposers (remanufacturing, reassembly, reuse). Some work interests (“Design for” - (Charter and Gray, 2008), (Gaustad et al., 2010)) even the way in which a product should be designed so that it can be easily remanufactured, reused... and propose some requirements. However, the proposed requirements do not directly apply to the processes cited in the “Design for”. Indeed, for example, for remanufacturing, they concern how to design the product so that it can be easily assembled, and therefore previously disassembled. For products manufacturing from recycled raw materials, they concern the quality of the materials. Finally, these requirements are the requirements that must be met in order to enter the manufacturing process. In other words, these are requirements that decomposers must take into account when regenerating a product. These requirements are called “customer requirements” (Table 1) and concern regenerated products.

Concerning the decomposers, few works are interested, except the destructuring process that recycles materials. (Balanca et al., 2014) propose some criteria coming from design for end-of-life guidelines, and associate them at one or more end-of-life processes. Some of these criteria are listed in the (Table 1) as “decomposer requirements” and concern product to regenerate.

To resume, a regeneration requirement is a requirement that comes either from decomposers or from customers. These requirements are complemented by requirements imposed by the government (national standards or laws).

Table 1. Regeneration requirement example

Requirements	Category	Criterion	Definition at regeneration time
Customer	Natural/ Social	Contamination	Harmfulness of the material
		Security	No danger to human
	Technical	Residual Reliability	Probability to fulfill the mission in a given time
		Functionality	Capability to perform the function
Economic	Profitability	Capital/Loss generated by a used product in relation to new product	
Decomposer	Technical	Disassemble	Possibility to access of level N-1 of a product without destroying the structure and its sub-components
		Dismantle	Possibility to access of level N-1 of a product by destroying the structure but by preserving the state of its sub-components
		Adaptability	Possibility to assemble a level N-1 with a level N
		Separability	Possibility to separate all materials
		Composition	Possibility to transform materials in second raw materials
Natural	Biodegradability	Possibility for a material to be processed by living organisms	
+ same requirements than customer			

Table 1 includes some criteria of regeneration distributed according to the categories (technical, natural/social and economic) they meet, and according to the stakeholders who define the “regeneration requirements”. Technical criteria come from the decomposers and customer. Natural/social criteria come from nature, which is a potential customer. Economic criteria come from users (supplier and customer). Each requirement depends on one or more criteria, which are associated to a value goal. The value changes according to the customers requirements. These criteria can be real or boolean. A real criterion need to set thresholds to know if the criterion is met or not. It can have multiple values and evolves continually. A boolean criterion is analytical and has only two possibilities.

In the sequel of this paper, we must focus on an example, the “residual reliability” requirement, to develop a regeneration management tool.

2.2. Modeling impact of an industrial ecosystem

To choose the regeneration actions, the impact of an industrial ecosystem on product life must be modeled. Indeed, an industrial ecosystem is composed of several stakeholders (companies, decomposers and nature) that have specific requirements on the product, according to their own business (reliability level, profitability...). All these stakeholders and their requirements interact between them and affect its regeneration possibilities. In addition, the condition of a product changes over time (mechanical wear...) and through the different product lives.

To model the impact of an industrial ecosystem on product life, we need a tool able to model the interaction between various variables, a state of product and its evolution over time. For this, we propose to use the system dynamics.

2.2.1. System Dynamics

System dynamics is a systemic methodology developed to facilitate understanding and prediction of a complex system’s behavior over time (Sterman, 2000). It is a way of systems thinking which focuses on the internal and external interactions of a system (Forrester, 1961). These interactions allow identifying the key variables and developing some scenarios to evaluate the consequences of a new policy or structure, as regeneration paradigm. This methodology was often used to understand the behavior of waste in recycling and disassembly processes (Chaerul et al., 2008; Golroudbary and Zahraee, 2015).

System dynamics is based on four steps. The first is the creation of causal loop diagram. These diagrams are simple maps that represent the interactions between a system, its environment and its stakeholders. Each interaction is represented by an arrow and can symbolize a positive (variables progress in the same direction) or negative impact (variables progress in opposite direction). These interactions create some feedback loops and determine the behavior of system over time. These feedback loops can be also positive (even number of negative interactions) or negative (odd number of negative interactions). Then, the causal loop diagrams are translated into stocks and flows diagrams (SFd) to have a more detailed analysis. In this step, it is very important to identify clearly the stocks and the flows. The stocks are variables, which measure the accumulation of

physical or not resources. The flows are input and output, which change a stock over time. The third step means instantiating the SFd through mathematical equations, initiate conditions, and parameters. In the last step, these equations are solved numerically to show the behavior of each variable over a period.

2.2.2. Regeneration modelling in system dynamics

In addition to model the behavior of each regeneration requirements, we want to manage the regeneration. By understanding the industrial ecosystem, its impacts on the use phase and its financial interest, it is more easily to implement the regeneration in the companies. For this, we use the software “Vensim” that offers system dynamics features.

In system dynamics, there are four steps. However, in this paper, we do not make the causal diagram. Indeed, this step is to identify the interaction between each requirement, but this work propose to model the behavior of each requirement independently. Therefore, we begin to second step.

The requirements validation is done in relation to monitoring of different criteria. These criteria are real or boolean, and are represented in a different way.

A real criterion is shown by a stock variable. This variable evolves over time with flows variables. For example, flow W empties the stock X , while flow V fills it (Fig. 2 - A). In equation terms, a stock is represented by an integral between its input and output flows (1) with an initialization when $t=0$. All type of mathematical functions (trigonometric, integral, conditional, addition, etc.) can represent the flow variables. However, the output flows must be real. A boolean criterion represents by a standard variable. The variable is equal to 1 when the criterion is met and 0 when it is not. It is conditioned by the state of other variables. For example, the criterion Y is influenced by the e and f variables (Fig. 2 - B) (2).

The variables (a , b , c , d , e , and f) that influence the variables representing boolean criteria (Y) and flows (V , W) can be real, boolean, or other types.

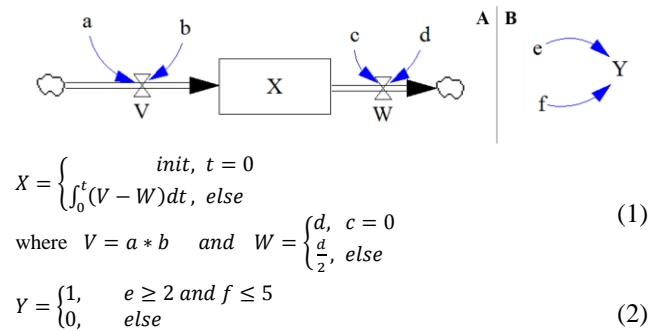


Fig. 2. Real criterion (A) and Boolean criterion (B) representation in SFd with associated equations

3. CASE STUDY

To model the behavior of each regeneration criterion and, to show the interest to regeneration, we model the longevity of a product through the behavior of a regeneration criterion. Then, we model the financial aspect to motivate companies to consider this paradigm in their business policy. For this, we suppose the following hypotheses: (i) Product functionalities are always checked over time; (ii) Each user uses the product

with the same manner, but with a different intensity and with different requirements; (iii) Deterioration is modeled by a deterioration rate that depends on the given criterion; (iv) For each real criterion, each user defines thresholds to buy the product and to sell it; (v) Each scenario is a succession of users and decomposers. When a user changes a product, a decomposer regenerates this product and resells it to a new user; (vi) Between each user and decomposer, there are several waiting-time. These times are technical and commercial; (vii) Regeneration actions are made in function of criteria thresholds of the next user; (viii) Regeneration actions time is proportional to the increasing to do for each real criterion. In our study case, we consider two scenarios. One to show the interest of regeneration, and another one, to show the interest to combine maintenance with regeneration.

3.1. Scenario 1 – Interest of reuse

During its lifecycles, a product goes successively and continually through a use phase and a regeneration phase. When the product does not meet the various company thresholds, it is sold to a decomposer. This decomposer does regeneration actions and sells the regenerated product to a new company, and so on. In this scenario, we restrict our study to only one criterion: residual reliability (called here, reliability), and one decomposer: reuse. Reliability is one of the most important factors to buy a product. Each company wants to be sure that its product will operate for a given time. Reuse process is the first decomposer of the regeneration loop and the one that greatest increases the number of product life. Thus, each company buys and sells product remaining reliability. We consider five companies with different reliability requirements, one for the purchase and another for the sale (Table 2). The “User 1” purchases a product with a reliability equal to 100%. The others buy the second-hand product. For example, the “User 3” buys the product with a minimum of 85% of reliability and sells it if its reliability drops below 55%. However, if the reliability drops below 21%, the product cannot be reused and must move towards another decomposer.

Table 2. Reliability threshold and time to find a client

		User 1	User 2	User 3	User 4	User 5
Reliability Threshold (%)	Purchase	100	90	85	90	60
	Sale	80	70	55	43	20
Time to Find (Month)	Decomposer	1	1	2	2	3
	Next User	/	1	2	1	3

Another point, during a cycle (a use step and a decomposition step), several waiting time appear and cause an immobilization of the product. Before selling its product, the company must find a decomposer. Each company has a different time to find it (Table 2). The others waiting times concern the decomposer, that must find a next company, plan regeneration actions, perform them and characterize the regenerated product. Time to find the next company is different according to each company (Table 2) and those to plan and to characterize are constant. Time to perform regeneration is proportional to the reliability to be added to product. The regeneration is

completely finished when the company is found. Hence, the planning and the characterization are completed, well as the actions are performed.

3.1.1. Reliability behavior

In this case study, the only considered regeneration requirement is linked to residual reliability criterion, that is a real. In SFd, it is represented by a stock variable that decreases, and increases over time. The deterioration and improvement are flow variables (Fig. 3).

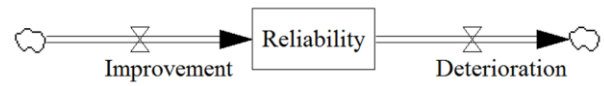


Fig. 3. Basic representation of reliability behavior in SFd

The deterioration flow depends on a failure rate that follows a bathtub curve composed of a decreasing (early failures) and an increasing (wear-out failures) and a constant (random failures) (Fig. 4).

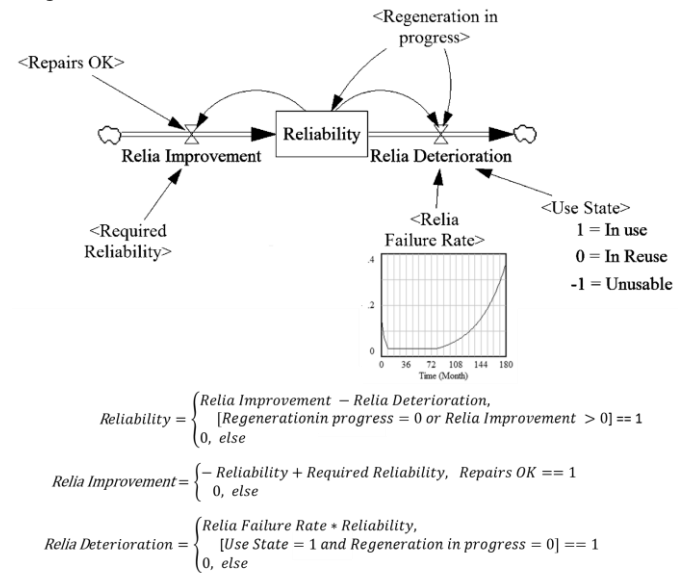


Fig. 4. Reliability, improvement and deterioration behaviour in SFd with associated equations

Reliability can be deteriorated only if the product is used ($Use State = 1$) and if the regeneration does by the decomposer is finished ($Regeneration in progress = 0$) (Fig. 4). Reliability is deteriorated until it reaches the selling threshold. When this threshold is reached, the decomposer regenerates the product reliability by doing some repairs or/and upgrades to standard. Thus, reliability increases. As the deterioration, it can be improved only if the regeneration are finished ($Repairs OK = 1$) (Fig. 4). The percentage improvement depends on the reliability requested by the future company. For example, the “User 2” sells the product with 75% of reliability and the “User 3” wants a reliability of 85%. The decomposer must add 10% of reliability to meet the requirement of “User 3”. To summarize, reliability can be modified only if the regeneration is finished or if an improvement is done.

After simulation on a time scale equal to 180 months, we obtained the following curve (Fig. 5).

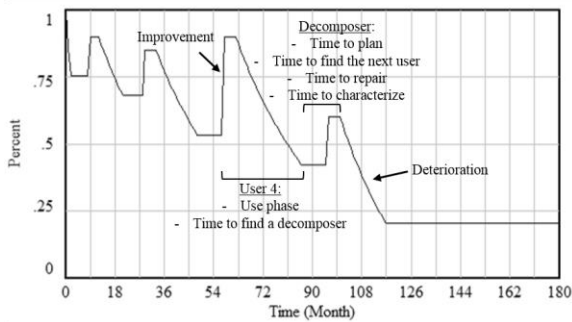


Fig. 5. Reliability curve (period of 180 months and 5 users)

3.1.2. Lifecycle Analysis

To show the interest of reuse process, in product point of view, we compare the possession time for a new product purchase with that of purchasing a second-hand product. This is made to “User 3” and “User 5”. We choose these two examples because the first uses the product when the failure rate is constant and the second uses the product when the failure rate increases. Thus, we can determine for which company it is more interesting to buy second-hand product. As expected, for “User 3”, the possession time for a used product is longer (x2,5) than for a new product. In the case of a used product, when “User 3” buys it, the early failure period is finished and the failure rate is constant, therefore reliability decreases slowly. While, for the new product case, “User 3” suffers the early failure period where the failure rate is raised. Thus, the reliability decreases more quickly than for used product. While for “User 5”, it is the opposite. The possession time for a used product is shorter (x0.5) than for a new product (Table 3). “User 5” buys the used product when it is in the wear-out failure period. Reliability decreases greatly. When he buys a new product, he owns the product along each failure phases, because he has a low sale reliability requirement. Consequently, it is more interesting to buy a used product than a new product, when the product is in its constant failure period. We have to consider next the cost point of view.

3.1.3. Cost Analysis

We consider the financial aspect for a company to meet the profitability requirement represented by the generated capital. We propose to model it with regeneration.

As reliability, generated capital is a real criterion and is represented by a stock variable. It decreases in function of the expenses done by the company and increases by the generated profits. The expenses flow is influenced by the purchasing product, operation cost, and immobilization cost. While the sale product and the sale product made by the product influence the profits flow. Here, a company buys and sells the remaining reliability of a product. Operation and immobilization cost are proportional to the time spent in these phases. The number of manufacturing and sold materials is proportional to the reliability. Indeed, we consider that more reliability declines fewer products are manufactured.

To show the interest of reuse process, in the company point of view, we compare the generated capital for these two cases. In the case of a new product, we consider that when it does not meet the company requirement, it is immediately sold at scrap prices, regardless of the reliability it still has. Thus, the immobilization cost does not exist for a new product. We still

consider “User 3” and “User 5”. We have the same conclusion as in the previous part. “User 3” has higher capital when he buys a used product than when he buys a new product, and in return for “User 5” (Table 3).

This is due to the same reason as above. Indeed, for “User 3”, reliability decreases more slowly for a used product than a new product. Thus, the number of manufactured materials is more important for the used product. Moreover, the purchase of a used- product is cheaper because purchased reliability is lower. The same principle applies to “User 5”.

Table 3. Possession time and capital (new and used case)

	Time Use of system (Month)		Number of systems used on 180 months		Generated Capital (€)	
	New	Used	New	Used	New	Used
User 3	6	15	30	12	89 093	206 251
User 5	36	17	5	10,5	289 295	132 482

3.2. Scenario 2 – Interest of reuse and periodic maintenance

To improve the regeneration and to increase the longevity of a product, we propose to use the type of maintenance. We add a new requirement: doing periodic maintenance to the first scenario. Each company sets a period in which it maintains the product and the percentage it wants to add (Table 4).

Table 4. Maintenance period and reliability added

	User 1	User 2	User 3	User 4	User 5
Maintenance Period (Month)	0	3	5	4	2
Reliability Added (%)	0	4	2	3	3

3.2.1. Reliability behavior

Reliability behavior is the same as in 3.1.1. This scenario still has the succession of users and decomposer, user requirements and the waiting times. The improvement also increases when a periodic maintenance is done. We consider that periodic maintenance are less than one month (Fig. 6).

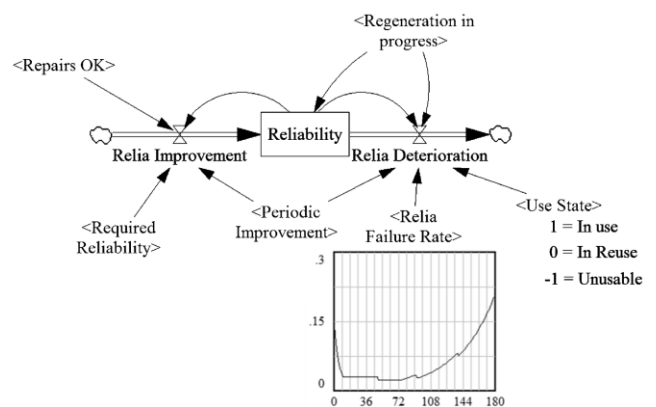


Fig. 6. Reliability modelling with periodic maintenance

Moreover, with periodic maintenance, the failure rate during the constant period of failure rate decreases according to the period chosen to do maintenance (Fig. 6). Thus, more maintenance periods are closed; more the MTTF is low.

3.2.2. Lifecycle Analysis

To show the impact of adding maintenance, in product point of view, we compare the longevity of a product without and with periodic maintenance (Fig. 7). As expected, doing maintenance extends the product longevity. Indeed, there are 52 months between the two cases. Moreover, in the company point of view, with maintenance, companies buy the lowest number of the product (Table 5). For this, we assume that each purchased product is the same and that it is used the same way as the previous one. In our example, during the period, “User 3” need 12 used product without maintenance against 6,2 with. Consequently, considering maintenance in regeneration is interesting to increase the product longevity. This adds new costs for companies, therefore, it is always interesting to make regeneration is this case?

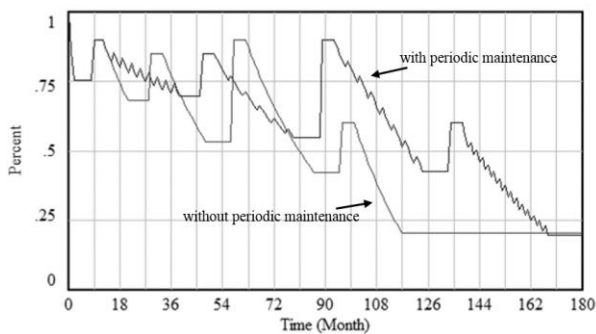


Fig. 7. Reliability curve without and with periodic maintenance

3.2.3. Cost Analysis

As for reliability behavior, the calculations of generated capital is the same as in 3.1.2. Nevertheless, we add the periodic maintenance cost. This cost is proportional to the reliability added to each maintenance. It affects the expenses, and it decreases the company capital. Consequently, the capital should be less important than without maintenance. Periodic maintenance often raises the reliability and allow producing more and longer. The sold of produces materials reduces the costs arising from maintenance. Thus, capital increases greatly (Table 5) with maintenance. The company is winning because even if it loses money by doing maintenance, it wins by changing less often product and by producing more products.

Table 5. Possession time and generated capital (without and with maintenance case)

	Time Use of system (Month)		Number of systems used on 180 months		Generated Capital (€)	
	Without	With	Without	With	Without	With
User 3	15	29	12	6,2	206 251	392 337

4. CONCLUSIONS

To meet the regeneration paradigm, companies must change their strategy. However, no tool allows knowing the potential impact of this paradigm on their strategy. This need is accentuated by the fact that regeneration means to create an ecosystem of companies. Therefore, this paper proposes a way to develop a regeneration management tool for an industrial

ecosystem. For this, the evolution of regeneration requirements (residual reliability and profitability) is modeled over time. These requirements come from many stakeholders such as nature, user companies, and decomposers. Combining all of these requirements is not easy and requires understanding the various interactions between them. However, the regeneration paradigm cannot be implemented without the support of companies. Therefore, we also propose to show profits that can be made while respecting the environment. For this, we run two scenarios to see which a new or used product is the most financially attractive for companies and to see the contribution of maintenance in this paradigm. In our future works, we will take into account all regeneration criteria and all decomposers to provide manufacturers a regeneration decision-making tool. In addition, our models must be implemented with real data to better reflect the business reality.

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