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Maintenance best way for meeting the challenge of regeneration

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Abstract: The circular economy is an economy that meets sustainable requirements, and that advocates a new paradigm, the paradigm of regeneration. This paradigm allows creating new businesses, new jobs and new skills all along about the product lifecycle. This is especially the case for maintenance and retirement processes. Indeed, these processes are the regeneration core. Those of retirements do not sum up to destructuring process but match also with repair, reuse and disassembly processes. As for maintenance, it becomes the cornerstone of all this. Through all its current skills, it allows managing and optimizing the regeneration by deciding when to stop a use and where studied items should go. Besides, maintenance must adapt to the regeneration. In other words, tools and methods used by maintenance can be able to maintain the regeneration potential of an item, and thus, create new jobs and experts. The purpose of this paper is to highlight the major challenges brought by the paradigm of regeneration to maintenance.

Keywords: Maintenance, maintenance services, maintenance management, sustainability, regeneration paradigm

1. INTRODUCTION

To resolve the problem of the climate change, the increase in the greenhouse gases and the consumption of goods, the exhaustion of natural resources, the accumulation of wastes, etc., the political powers orientate their strategy towards sustainable development. This development is defined as a “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (WCED, 1987). In this sense, several conferences and projects expand such as United Nations Conference on Sustainable Development (UNCSD), Rio+20 and COP21, and the Europe 2020 project.

Thus, the current economic model, the linear economy (take-make-jump), does not meet new requirements of sustainable development. It becomes obsolete. Therefore, we must change paradigm and turn towards, for example, the circular economy (make-use-return indefinitely). The circular economy considers that natural resources are limited and that waste does not exist (Foundation Ellen MacArthur, 2014). The idea of this economy is to create closed loops by reusing the manufacturing goods so that waste becomes resources. It is also called the “paradigm of regeneration”. The principle of the circular economy is based on several schools of thought:

- Biomimicry (Benyus, 2009) is the study of nature to design goods and to develop new technologies. For example, the form of eagle has inspired the high-speed train, and the skin of sharks has inspired the swimsuit;
- Industrial Ecology (Despeisse et al., 2012) is the study of material and energy flows through the

industrial system to add value to wastes produced by a firm. For this, a firm uses wastes produced by another firm as resources. Kalundborg area (Zhu and Ruth, 2014) is a good example;

- Regenerative Design (du Plessis, 2012) is the study of environment and communities of a place to design in harmony with them. The permaculture is an application of this concept;
- Cradle-to-Cradle (McDonough and Braungart, 2010) is the popular term for regenerative design, which uses a biomimicry approach to design a good. These authors use the term of nutrients to talk about resources. (Diez et al., 2015) have approached this notion.

These schools of thought are oriented design and consider a perfect exchange of wastes between different firms. The model regrouping all these concepts does not exist, but we can approach it.

Indeed, research areas such as maintenance turn towards the sustainable problematic with new concepts including the three sustainable pillars. They include:

- Green maintenance focuses on the elimination of all wastes produced and associated with maintenance, by practicing the pollution prevention, toxic use reduction and design for environment. (Ajukumar and Gandhi, 2013) propose an approach to evaluate it by basing on a multi-criteria decision-making and on green maintenance requirements (environmental compatibility, energy efficiency, and human health and safety risks);

- Maintenance-centered Circular Manufacturing (Takata, 2013) is based on the circular manufacturing but sees maintenance as a core activity in a system. In this vision, manufacturing, reuse and maintenance merge to create a cohesive flow forward/feedback loop and to increase the product longevity.

Our works are in the same logic as (Takata, 2013), but our point of view is directly inspired by nature. In this sense, the purpose of this paper is to highlight the major challenges brought by the paradigm of regeneration to maintenance. For this, section 2 develops the concept of regeneration in nature and the industrial world. Then, section 3 describes the industrial processes emerging from this concept and their impact on maintenance. Section 4 focuses on the regeneration influence on maintenance, and vice versa. Finally, section 5 concludes this paper.

2. PARADIGM OF REGENERATION

The biology literature defines “regenerate” as a process “to grow again”. The term of regeneration has used in two different contexts. The first is the regeneration of organic tissue. Indeed, we talk about this regeneration when, for example, the lizard’s tail grows back, or when your skin heals. Scientists have studied this phenomenon to create a self-healing rubber, metal and concrete. The second context corresponds to the trophic organization, namely, the food web. This organization is circular and reuse all that is produced by each entity. We are interested on this regeneration context and we apply it to the organization of the industrial world.

2.1 Trophic organization

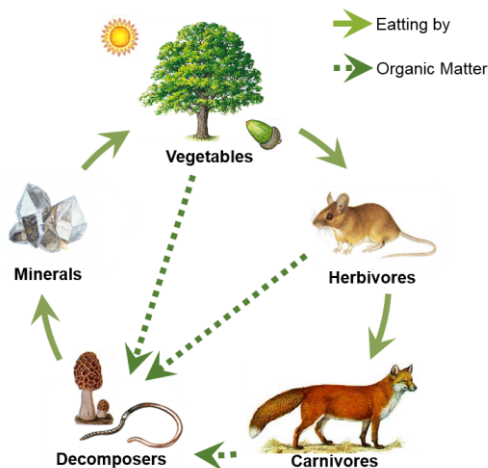


Fig. 1. Trophic organization

The concept of waste does not exist in nature. For it, all is food (Kormondy, 1969); each entity (living being) feeds another entity (Fig. 1). Indeed, vegetables eat solar energy and mineral salts. Herbivores eat vegetables and carnivores eat herbivores and other carnivores. Each entity produces organic matters that are eaten by decomposers (fungi, worms, bacteria). These decomposers produce mineral salts to feed vegetables, and the

cycle continues. To summarize, all resources produced by and in nature are regenerated, except solar energy.

The essential entities are decomposers, without them, nature would be a big rubbish dump and would not be circular. Therefore, to become circular the industrial world must add the notion of decomposer.

2.2 Towards a regeneration of industrial world

Contrary to the trophic organization, the industrial organization stays linear (Fig. 2). Indeed, primary industries extract natural resources and supply secondary industries. These industries transform natural resources in goods and supply human activities. These industries and activities produce wastes. However, no or very few industries (recycling process) exist to transform these wastes into resources. No recycled waste is very numerous and is landfilled.

Therefore, if we want to meet sustainable requirements in circular economy, we must be inspired by the trophic organization (Geng and Côté, 2002). We must add more processes, called “technical decomposers”, to transform unusable items to add value to them. They create new companies and new business.

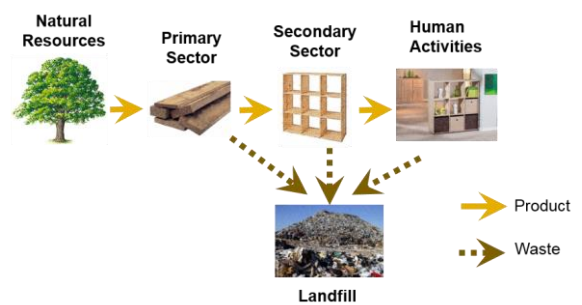


Fig. 2. Linear industrial organization

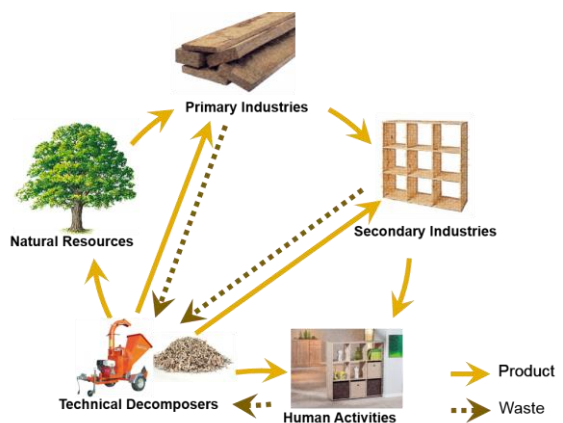


Fig. 3. Circular industrial organization

With the technical decomposers, industrial organization can become circular (Fig. 3). Moreover, contrary to natural decomposers, the technical decomposers can supply different industrial sectors, what give more possibility to regenerate an unusable item.

3. NEW FUNCTIONS OF RETIREMENT PROCESS

In the case of the regeneration paradigm, the functions of retirement process change and it becomes polyvalent (emergence of several sub-processes). From the Takata's works (Fig. 4), we propose to develop the emerging sub-processes that we call technical decomposers.

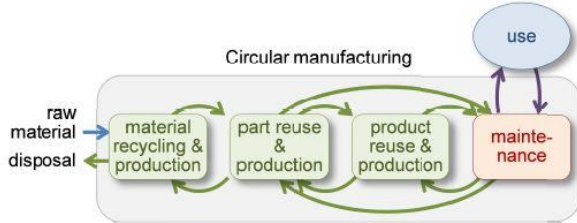


Fig. 4. "Concept of maintenance-centered circular manufacturing" (Takata, 2013)

In this part, we consider that all equipment, subassemblies and components must be regenerated.

3.1 Identification of technical decomposers

(Foundation Ellen MacArthur, 2014; Govindan et al., 2014) have identified four technical decomposers:

- Repair process: the repair is a physical action taken to restore the required function of a faulty item. This process makes a transformation of time, and preservation of item functionalities;
- Reuse process: the reuse is defined as an exhaustion of the items lifetime through multiple users or multiple products, to reduce the number of items needed to satisfy the requirements of a certain users groups for a certain period (Takata, 2013). This process makes a transformation of time and space, and preserves the items functionalities

- Remanufacturing process: the remanufacturing term is not clearly defined and includes many processes as disassembly, cleaning, control and reassembly (Barquet et al., 2013). In our works, we limit this concept as disassembly process. It makes a transformation of time, space and shape, and does not preserve the item functionalities. By contrast, the functionalities of its subassemblies are preserved.
- Recycling process: The recycling term includes the material and energy recovery. Making energy recovery does not allow regenerating an item indefinitely; there is loss of materials. We choose the term of destructuring to represent the material recovery by grinding. This process makes a transformation of time, space and shape, and does not preserve any item functionalities.

Finally, in this part, we consider the repair/adjustment, reuse, disassembly and destructuring processes as technical decomposers (Fig. 5).

3.2 Evolution in the technical decomposers

Depending on the incoming item type in a decomposer, possible transformations and outgoing items are not the same. Indeed, the point of view is very important. An equipment, a subassembly and a component will not have the same decomposers and transformations (Fig. 5 and Tab. 1).

Initials	Meaning	Initials	Meaning
E	Faulty Equipment	C	Faulty Component
Er	Repaired Equipment	C'	Component to be regenerated
SA	Faulty Subassembly	C*	Component necessary for repair
SA'	Subassembly to be regenerated	Cr	Repaired Component
SA*	Subassembly necessary for repair	SRM	Second Raw Material
SAr	Repaired Subassembly	RM	Raw Material

Tab. 1. Legend of Fig.5

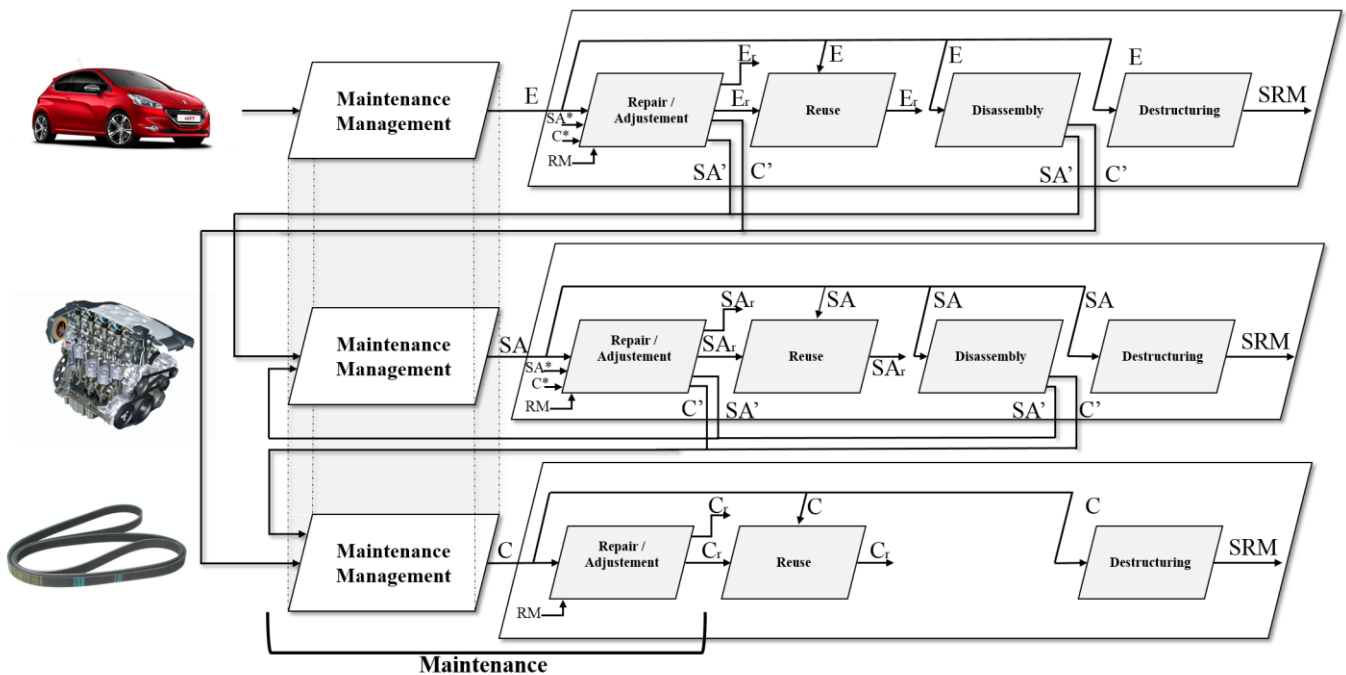


Fig. 5. Maintenance management and decomposition process

Firstly, we focus on the equipment. The equipment can be repaired, reused, disassembled or destructured:

- If it is repaired, then the repair process transforms a faulty equipment (E) in an equipment meeting operational requirements (Er). For this, the process needs subassemblies (SA*) and components (C*) to replace items to change. Therefore, it produces also subassemblies (SA') and components (C') to regenerate;
- If it is reused, then the reuse process can sell a faulty or repaired equipment;
- If it is disassembled, then the disassembly process transforms an equipment in subassemblies and/or components;
- If it is destructured, then the destructuring process transforms an equipment in a secondary raw material (SRM).

Next, we focus on the subassembly. Although technical decomposers are same as the equipment, the subassembly is considered as a spare part after repair and reuse processes.

Finally, we focus on the component. The component can be repaired, reused and destructured. A component cannot be disassembled because it is the lowest item in the parts list. So:

- If it is repaired, then the repair process transforms a faulty component (C) in a component meeting operational conditions (C'). For this, the process needs raw material (RW);
- If it is reused, then the reuse process can sell a faulty or repaired component;
- If it is destructured, then the destructuring process transforms a component in a secondary raw material.

Currently, during the operation phase, maintenance monitors an equipment, decides when and how to maintain it, and when to stop its use, and landfill it. In the regeneration paradigm, landfill is not a solution, so maintenance must choice among the technical decomposers.

3.3 Importance of maintenance in the decomposition

In Fig. 5, maintenance has two roles: decomposer and manager. Indeed, by definition, maintenance is able to repair an item and, in the same time, to manage it. We have seen above the repair decomposer, so in this section, we focus on the management process.

Here, maintenance is the first step of decomposition. If it estimates that an item must be regenerated, it stop its use, and orientates it towards a decomposer. As a result, maintenance must determine which decomposer is able to regenerate an item. This involves knowing each decomposer, their objectives, their actions, their productions, and their requirements.

Moreover, by knowing items outgoing of a decomposer, maintenance can optimize the regeneration and anticipate actions to take. For example, if a system is fixed and that subassemblies and components are changed, then maintenance knows that should also regenerate these items. On the other hand, that allows determining which future purchaser can buy the regenerated item, and by extension, identifying purchaser

requirements. These requirements affect directly decomposers processes and their actions, and by consequently, affect maintenance. Maintenance must consider these requirements, in addition to decomposers requirements. Thus, it can stop the use of an item when it respects again all requirements and increasing probabilities of sale.

Finally, through the regeneration paradigm, this process becomes one of the most important processes in the industry world. However, even if, maintenance is the cornerstone of the decomposition, it must adapt to meet the regeneration requirements.

4. MAINTENANCE AND REGENERATION

Maintenance and regeneration are closely related. Maintenance allows optimizing decomposition possibilities, and so, serves interests of the regeneration. Whereas, the regeneration allows creating new business skills and new jobs for maintenance.

4.1 Regeneration influence on maintenance

In (AFNOR, 2010), maintenance is “*the combination of all technical, administrative and management actions during the lifecycle of an item intended it in, or restore it to, a state in which it can perform the required function.*” With the paradigm of regeneration, this definition becomes “*the combination of ... the required function and a state in which it can be regenerated by at least a technical decomposer.*”

Thus, this new role raises the following research question: “How to preserve the potential of regeneration of an item?”

4.1.1 Regeneration Failures

In this new approach, new failures emerge, namely, regeneration failures. We define these new failures as the fact that an item cannot meet decomposer requirements, and consequently, remove regeneration possibilities.

These failures are difficult to manage because they are easily affected by technical failures. Indeed, if a technical failure occurs in an equipment, maintenance must be careful that its actions do not affect the potential of regeneration of the equipment. For example, a technician removes a faulty engine and replaces it by a new engine. This engine has the same properties as the original engine. However, the system capacities and properties are not the same as their origins, because the system is already deteriorated. Then, if the system operates based on the engine capacities, it is possible that it is unable meet the engine requirements. It could wear out faster or break. Consequently, the regeneration possibilities of the system and their components could be reduced, and the regeneration potential of the system would be negatively modified.

Thus, maintenance must manage two types of failures (technical and regeneration), and monitor that one type will not affect another (more particularly in the case of a technical failure). Consequently, it must put into question the current corrective action plan.

4.1.2 Monitoring and decision-making

To detect regeneration failures, maintenance must monitor new elements and new performances, or monitor elements by other means.

For example, to regenerate an equipment with the “disassembly” decomposer, maintenance must monitor interfaces, i.e., its subcomponents must always be separable. Indeed, if a component melts and merges with another component, then they cannot separate and regenerate by the disassembly decomposer. Consequently, merged components are considered as a single component.

Consider another example; a future purchaser accepts to buy a second-hand system if and only if the system is able to produce 40 pieces/hour. Therefore, if the current user wants to sell his system, he should not exceed this threshold. For this, the user must monitor production performances and stop the system use when the threshold is attained. Others requirements could have been added, as the energy consumption, the energy efficiency (Godichaud et al., 2012), the compatibility with another system, etc.

Moreover, current maintenance monitors items and decides when and how to maintain them, and when to stop their use and landfill them. In the regeneration paradigm, maintenance skills can be used to choice among decomposers. Indeed, if possibilities of retirement increase, then possibilities of “end-of-life” increase too. Maintenance must not only decide to repair or not an item but also decide to reuse, to disassemble or to destructure it. Consequently, required skills to maintain the potential of regeneration are very various; maintenance does not neglect any decomposers.

Finally, the role of monitoring and decision-making processes are especially complex. They must combine regeneration failures with technical failures; as a result, there is an increase of variables and retirement possibilities to manage. Furthermore, many requirements appears with the regeneration. These processes must be monitored in real time to meet requirements of sustainable development, decomposers and futures purchasers. Moreover, monitoring should also monitor different requirements depending on each possible decomposer.

Thus, the regeneration paradigm adds new business skills and jobs. Regeneration maintenance needs experts in regeneration monitoring and decision-making.

4.1.3 Anticipation

A solution to answer the preservation of regeneration problem is not waiting for the end-of-life of the equipment.

In that, for example, (Song et al., 2015) study the most critical component of a system to determine when to stop the exploitation of this system and remanufacturing it. In other words, the authors propose to make proactive remanufacturing. Whereas (Hu et al., 2015) have proposed a methodology to choice a remanufacturing process according to the system’s RUL. Another approach has used the capacity of maintenance process to predict a failure. (Iung and Levrat, 2014) propose to use the prognostic to study flows properties, and thus securing the respect of sustainability requirements. By anticipating a regeneration failure, we can regenerate an

equipment by another decomposer than the destructuring decomposer. The prediction can be made based on the decomposer selected by the user or based on available decomposers. For this, we can base on processes used by the PHM (Prognostics and Health Management) community, and adapt them to regeneration failures. Indeed, the prognostic is defined as a process that “*analyses the symptoms of faults to predict future condition and residual life within design parameters*” (AFNOR, 2004). With the regeneration view, the prognostic process must also analyze the regeneration requirements to predict when the use of an item must be stopped to meet decomposer requirements.

Thus, making prognostic will not be only limited to the calculation of a conventional RUL, but will also include the estimation of time before which a studied item cannot be regenerated by a decomposer. However, it is a complex estimation because this prognostic calls in different parameters that evolve with the decomposer. Requirements are not the same if the decomposer is the reuse or destructuring process.

Finally, the regeneration paradigm sets new objectives for maintenance. It becomes the regeneration coordinator and is even more omniscient than today. It also becomes a sector that creates jobs and business skills.

4.2 Maintenance influence on regeneration

To manage all this, we need a manager, and we propose maintenance as a regeneration manager, who meets the requirements of many stakeholders. Thus, the regeneration exists only if a market exists, i.e., a regenerated item must have the same properties than a new item. To maximize the resale possibilities, we must meet the purchaser requirements. Other regeneration actors are the technical decomposers. As already pointed out, they regenerate an unusable item to adding value to it. Consequently, an unusable item must meet the decomposer requirements. For example, by definition, the disassembly decomposer cannot regenerate only an item, which can be dismantled. Next, we consider biosphere in the stakeholders. This stakeholder is the basis of the regeneration. Indeed, the regeneration paradigm exists only to preserve the human life, which depends on the biosphere. Therefore, the biosphere must be also preserved. We do not neglect its requirements.

All these requirements can be functional, operational, interactional and constraining. One of the goals of maintenance is to maintain an item in operational conditions. In other words, maintenance is able to meet and to preserve functional and operational requirements. It monitors also interactions between some critical items. The regeneration requirements add and/or modify requirement repository, but as they are the same types of current requirements. Therefore, maintenance is able to manage these requirements.

On the other hand, maintenance uses methods to preserve an item in operational condition, as for example, Reliability Centered Maintenance, PHM and Total Productive Maintenance. Obviously, these methods can be used and adapted to meet the regeneration requirements. The research of PHM community can be also used to predict the time when

an item will not be able to regenerate by a decomposer, and when to stop its use to decompose it. Likewise, Computerized Maintenance Management System could be also adapted to help maintenance to manage at best regeneration.

Besides methods and tools used in maintenance, the Product Lifecycle Management (PLM) can help to improve the regeneration. This management allows managing all data relating to the design, production, support and retirement of products. In the case of the regeneration, PLM could be used to follow the different lives of a product, and the evolution of its regeneration requirements. For example, after each repairs, the data about the actions taken are saved. Then, when the user wants to sell his system, he sells in the same time the data about its use, its repairs, its consumption, etc. The purchaser will know all about his new acquisition. The same logic can be apply to the subassemblies and components removed during the maintenance operations.

Actually, maintenance wants to all about an equipment and their components: their RUL, their state, repairs made and their composition, etc. With these skills, it is able to monitor an item to regenerate it, to select the best decomposer for an item depending on this state. In other words, maintenance is the best candidate to maintain the potential of regeneration.

5. CONCLUSIONS

Nature is a good source of inspiration to move from linear economy to circular economy. Indeed, it allows highlighting missing elements to apply the principle of natural regeneration in the industrial world. In adding technical decomposers, the industrial regeneration becomes possible. This new concept creates new processes and new works, and more particularly, for decomposers. Decomposition processes transform wastes in resources and maintenance process becomes the manager of the regeneration paradigm. This process is the only process able to monitor, to diagnose, to predict and to provide a decision-making.

Finally, the paradigm of regeneration adds a new job to maintenance. This process does not only maintain an equipment in operational condition but must also maintain its potential for regeneration. Maintenance allows optimizing the regeneration of an item, and consequently, meeting sustainable requirements.

Our future work will focus on the regeneration requirements. In first, we must identify these requirements and determine their effects on requirements repository have to. Thus, we can determine and monitor the critical elements. We can regenerate them when they satisfy a maximum of stakeholder requirements depending on each decomposer. Next, we can determine an optimum point in terms of regeneration costs, between resale cost, decomposition cost, etc., and regeneration failures.

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