A value-oriented maintenance approach for product protection in EPR policies

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Abstract: EPR policies have the potential to be valuable and sustainable business opportunities. Operational leasing is an effective EPR implementation strategy, where the lessor maintains the product ownership, therefore controlling every phase of product life cycle. Hence the interest of protecting product's value across multiple use-cycles. In the case of items subject to wear and tear, such as mechanical components, the maintenance strategy is central to maintaining product's global value, protecting it from losses due to obsolescence and degradation. The recent systemability approach gave the opportunity to refine maintenance policies taking into account the operating environmental effects. However, degradation prediction models often take into account the manufacturer/lessor perspective, in a cost-effective approach, neglecting the service level requested by the user and the intrinsic characteristics of the leased product. Among these, the item's memory of the failure state is relevant. In this work, the authors propose to integrate, into the systemability paradigm, the user acceptance threshold and the memory effect of the fault state. Computational results demonstrate that the proposed approach may significantly vary the maintenance frequency and the product's use-cycle duration, towards protection of service value for the user and functional value for the manufacturer.

Keywords: product value; systemability; maintenance; service

1. Introduction: the global convenience of product value protection

Extended Producer Responsibility (EPR) is one of the key strategies to implement sustainability and circularity policies, shifting the environmental focus from processes to products' upstream and downstream lifecycle stages (Yamini & Samraj, 2015). In such arrangements, the producer/manufacturer must take care of the product end-of-life. Hence, the interest in maintaining the control during the operation phase. Returning end-of-life products bring with them many uncertainties (Mancusi, et al., 2023). Those regarding end-of-life conditions and recovery costs raise doubts on the product future value, therefore on the entrepreneurial convenience of sustainable practices. These should create value for all stakeholders of a closed-loop supply chain, *i.e.* business, customer and environment. What are the long-term benefits and value for producers and consumers environmentally responsible? What is a circular model able to balance the interests of stakeholders? Thurston *et al.*, (2007) demonstrated that leasing arrangements – where the manufacturer sells a service rather than a product – are the most valuable models able to "close the loop" while achieving global optimum for all involved agents (also considering a multi-attribute utility to globally satisfy customers in different segments, *i.e.*, technophiles, utilitarians and environmentalists). After all, in operating lease arrangements (Fishbein, et al., 2000), the product ownership is retained by the lessor (producer) during and after the lease term, thus allowing him/her to control the product during operation. Pialot *et al.* (2017) proposed the Upgradable Product-Service System paradigm *i.e.*, "Up-PSS", combining product upgradability with optimised maintenance. Up-PSS is conceived as a transforming value network over time, satisfying manufacturers (increasing revenues), customers (increasing service) and environment (reducing impact). Mancusi *et al.* (2024) introduced the Remanu-Leasing model as a solution to create global value (surplus) for product in multiple use-cycles loop. Here, the consumer's (CS) and the remanufacturer's (RS) surplus are expressed in economic value, and is noteworthy that both CS and RS depend on the cost and time of periodic maintenance and recovery at the end of each use-cycle (in a cumulative approach). Hence, the importance of defining the product functional degradation, determining the most suitable periodic maintenance strategy (by the lessor) and, in turn, product performance during the operating phase.

The centrality of maintenance in product value protection is evident. Several research works dealing with optimal configuration of leasing contracts have focused on maintenance issues, such as the optimal down time (Husniah, et al., 2020), or the costs of preventive and corrective maintenance depending on use (Iskandar, et al., 2018). Others have also taken into account the CO2 emissions due to maintenance and remanufacturing (Hajej, et al., 2019). Maintenance has the potential to protect leased durable products from intrinsic value losses. Among these, we mention the functional, environmental and market ones.

Functional Value (FV), is meant as the ability to satisfy consumer's functional needs and wants and, therefore, the utility derived from the perceived quality and expected performance (Delgado-Ballester & Fernandez S., 2015). Environmental Value (EV) is the value acquired by the environment from its non-polluted or pollution-free state (Babu, 2013). Life Cycle Assessment (LCA) models support EV protection, predicting environmental impact at each stage of product's life cycle (Ercan, 2013), thus allowing to identify the best (*i.e.*, less impactful) recovery time and strategy at the end-of-life stage. Market value (MV) can be interpreted as a price range, bounded by a minimum cost and a maximum cost that buyers are willing to pay and sellers are willing to accept (Kucharska-Stasiak, 2022). Protection of PV, EV and MV brings global benefits. The lessor (producer) derives economic value thanks to product life extension and cost optimization of maintenance and end-of-cycle recovery. The lessee (consumer) benefits in terms of service level and perceived quality/price ratio. Finaly, the environment's surplus can be found in reduced CO2 emissions thanks to avoided early or late maintenance, or disposal.

This work is aimed at supporting product value protection in EPR approaches, in leasing arrangements, by balancing the lessor's interest in optimal maintenance with lessee's demand for service level. The paper is organized follows. In section 2 factors reducing product value are discussed, with focus on preventive maintenance strategies as solutions. Section 3 presents the proposed approach for product value protection in multiple use-cycles, resulting from a hybrid cost-based and service-based preventive maintenance approach. Implications and future development are discussed in section 4.

2. A fluctuating product value. Between obsolescence, degradation and maintenance policies

In the previous section, three main product value losses have been mentioned, regarding functional, environmental and market value. Restricting the discussion to mechanical components, the root causes of such losses can be traced back to obsolescence and functional degradation.

2.1 Obsolescence

The concept of obsolescence refers to the condition of a system that becomes outdated or no longer competitive in the context of technological evolutions, market needs or changes in regulations (Romero Rojo, et al., 2010). Obsolescence, therefore, does not depend on the actual product performance, but rather on market trend and customer's demand. Mellal (2020) identified five types of obsolescence: *(i)* technological, when product technology lags behind innovation and consumers' demand; *(ii)* functional, in case of item's features are out of date; *(iii)* planned, when the manufacturer establishes in advance a short/medium term useful life; *(iv)* psychological, when the product is out of style; *(v)* optional, when the producer chooses not to implement technological improvements. Among those, technological obsolescence has been highlighted as the most relevant, as it determines the component replacement strategy (exhaustively summarized in Table 2 in Mellal's review). This brings the focus back to the maintenance policy, that is able to stem obsolescence.

2.2 Degradation

While obsolescence is an external and uncontrollable value reduction factor, functional degradation is an intrinsic value loss, related to its progressive performance reduction over time. That is due to *(i)* internal factors, related to intrinsic characteristics (Moreno & Gorur, 2003) such as materials quality, structural design, manufacturing process, mechanical wear, corrosion; *(ii)* external factors, deriving from environmental influences or usage (Lorvand, et al., 2020) such as operating environment, external stressors, improper maintenance, vibrations, contaminating agents, weathering. Functional degradation can be controlled through preventive or corrective maintenance.

2.3 Recent maintenance approaches

The concept of maintenance is inextricably linked to reliability (Rausand, 1998). Traditional definitions of systems' reliability are usually tied to the failure rate function (Pham, 2019). This last is typically obtained in a controlled test environment and determined with statistical predictions of parameter estimation in the field. However, the main assumption has been for years that operating environments and test environments are substantially equivalent. Pham *et al.* (2005), introduced the systemability paradigm to refine maintenance policies taking into account the operating environmental effects. This represents a milestone in systems' reliability, contributing to a more realistic prediction of degradation, maintenance and, therefore, value protection over multiple cycles of use.

Systemability Function (SF) is thus defined as the probability that a system will perform the intended function for a given period in a real environment characterized by variable, random or unpredictable operating conditions (Pham, 2005).

$$R_s(t) = \int_\eta e^{-\eta \int_0^t h(s)ds} dG(\eta) \qquad (1)$$

Equation (1) reports SF mathematical expression, where $h(s)$ is the failure rate function, η is a random variable representing the variability of the failure rate due to system's operating environment. η has a Gamma distribution $G(\eta)$ with shape parameter α and scale parameter β. Equation (2) expresses the probability density function

$$f_n(x) = \frac{\beta^\alpha x^{\alpha-1} e^{-\beta x}}{\Gamma(\alpha)} \quad for\ \alpha, \beta > 0\ and\ x \geq 0 \qquad (2)$$

Applying the Laplace transform to eq. (1), SF becomes:

$$R_s(t) = \left[\frac{\beta}{\beta + \int_0^t r(s)ds}\right]^\alpha \qquad (3)$$

According to the methodology presented by Persona *et al.* (2009), parameters α and β are obtained from an early data collection in system failure rate testing. Then SF parameters are calculated by least squares estimate. Such approach allows to compare the SF estimated value with the actual reliability observed in real environment, thus enabling to assess the system's performance in real environment operation. Sgarbossa *et al.* (2015) demonstrated that each subsequent failure is governed by a systemability intensity function $u_s(t)$:

$$u_s(t) = \frac{\alpha * \lambda * \gamma * t^{\gamma-1}}{\beta + \lambda * t^{\gamma}} \tag{4}$$

From this, the Unit Expected Cost (UEC) function has been derived, allowing to extend the systemability paradigm from non-repairable to repairable systems:

$$UEC_{\alpha\beta}(t_p) = \frac{C_p + C_f * \int_0^{t_p} u_s(t)dt}{t_p} = \frac{C_p + C_f * \left[\alpha * \ln\left(1 + \frac{\lambda}{\beta} t_p^{\gamma}\right)\right]}{t_p} \tag{5}$$

where C_p is the cost of component preventive replacement, C_f is the preventive maintenance cost, λ and γ are Weibull intensity and shape parameters (representing the probability distribution of early failure rate) and t_p is the planned replacement period (unknown).

Once the maintenance and replacement cost function are known, and correlated to the actual degradation level, the key choice to protect product value lies in the optimal time of maintenance. In systemability approach, optimal maintenance time is carried out by setting equal to zero the partial derivative of equation (4) with respect to time t. The optimal time period within maintenance has to be performed is obtained as per eq. (6). It depends on Weibull λ and γ parameters, and is proportional to scale parameter β of Gamma distribution. This remarks that maintenance policy cannot ignore actual operating (environmental) conditions.

$$t^* = \sqrt[\gamma]{\frac{\beta * (\gamma - 1)}{\lambda}} \tag{6}$$

The optimal time t^* thus replaces t_p in eq. (5), allowing to identify the optimal (cost-based) maintenance interval.

The main alternatives for maintenance are the Condition-Based Maintenance -CBM- and the Time-Based Maintenance -TBM. The former has been discussed by Husniah *et al.* (2021) in a leasing scenario, where the leased product deteriorates with age, usage and operating conditions, and ultimately fails when the cumulative degradation exceeds a critical level. They modeled degradation as a Gamma distribution where the effect of age, usage and operating condition has been represented by the shape parameter α. The CBM requires constant monitoring, periodic inspections and control of product condition, thus performing maintenance when degradation level exceeds a threshold. The major risk of CBM is serious damage or breakage of the product, with a drastic and irreversible drop in value. TBM, instead, involves periodic interventions, regardless of actual asset conditions, scheduled at regular intervals, based on a pre-established calendar rather than specific deterioration or failure signal. Although TBM has the potential to prevent value losses, it requires careful planning looking for a balance between the frequency of interventions and the actual need for maintenance. The use of condition monitoring systems and data analysis can help mitigate the risks of too early or too late interventions than the real needs. In case of too early maintenance, the customer would receive a better service, while the producer faces wasteful costs, resources and energy (also impacting the environment as CO2 emissions). In the latter case the customer suffers a drop in service, while the lessor, although delaying the cost of maintenance, risks irreversible damage to the product, nevertheless impacting more on the environment if recovery would require a greater effort.

TBM-related risks can be mitigated thanks to the cumulative analysis of the effects acting on the component during operation. Systemability curves change with the values of α and β parameters, characterizing η as follows:

$$\eta = \frac{\alpha}{\beta} \quad with\ \alpha, \beta > 0 \tag{7}$$

Sgarbossa *et al.* (2015) remarked the three different scenarios coming from the parameters ratio:

1) $\alpha > \beta \rightarrow \eta > 1$ "**hard** environment effects": the operating conditions cause fast degradation.
2) $\alpha < \beta \rightarrow \eta < 1$ "**soft** environment effects": the operating conditions cause slow degradation.
3) $\alpha = \beta \rightarrow \eta = 1$ "**medium** environment effects": the operating conditions are balanced with system's robustness.

The variability of environmental effects complicates the prediction of maintenance type and intensity. For example, during the first period a hard-effects scenario may occur (red curve), followed by two soft-effects periods as showed in Figure 1. Here is observed that the maintenance optimal time interval changes (according to UEC function).

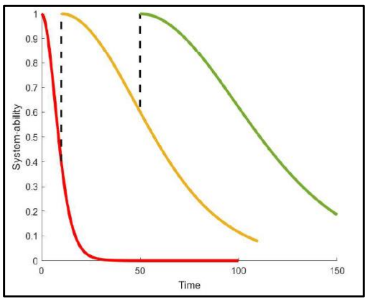

Figure 1: systemability in hard-soft-soft effects scenario

Although the type of stress can be predicted (or, in leasing contracts, fixed), thus managing to identify the (variable) cost-effective maintenance times, this formulation lacks consideration of the service level requested by the customer, *i.e.* the performance acceptance threshold (ultimately, the FV) of the component. Another limit is the assumption that maintenance is able to fully recover performance. It should be considered, instead, that the product may have a memory of the fault state, making 100% functional recovery impossible. In this case, not only the service level - on the consumer side - is compromised, but also the functional value of the product for the (re)manufacturer.

3. A value-oriented systemability-based approach

Degradation and maintenance forecast models mainly take into account the perspective of the manufacturer/lessor, claiming for minimum cost and, possibly, minimum environmental impact. In this section, we are proposing to refine the systemability-based models by integrating both the fault state memory and the minimum accepted service. This will contribute not only to protecting the product value thanks to a more effective maintenance prediction, but also to satisfying the customer in a service approach.

We are here introducing a binary variable, the System Failure Memory (SFM), representing the attitude of a component to maintain or remove the effect of the failure state after maintenance.

$$SFM = \begin{cases} 0 & (without\ memory) \\ 1 & (with\ memory) \end{cases} \tag{8}$$

SFM=0 represents a system able to go over the fault state after maintenance, with no losses on long-term operation.

SFM=1 implies that the system is unable to recover 100% efficiency after maintenance, due to long-term memory of the fault state.

The SFM-based maintenance approach shifts the focus from product's residual life to recoverable performance level. Each use-period between two subsequent maintenances must be considered independent from the others due to environmental effects, but retains the memory of the fault state with intensity dependent on the elapsed time. This condition can be modelled mathematically through the exponential smoothing forecasting method (Ostertagova & Ostertag, 2011), which assigns weights to an event decreasing with elapsed time. Therefore, it is possible to model recent fault states more intensive on item's memory than older ones. For each period t, the smoothed prediction can be expressed as:

$$S_{t+1} = \psi * \sum_{k=0}^{t-1} (1-\psi)^k * S_{t-k} \tag{9}$$

Where S_{t+1} is the forecast value of the variable S at time $(t+1)$, that is the weighted moving average of all past observations; ψ is the assigned weight between 0 and 1.

In order to evaluate the progressive degradation, due to SFM effect, we designed computations of 7 consecutive use-cycles (hard-hard-hard-medium-medium-medium-soft effect scenarios) interspersed with maintenances. Figure 2 reports on the right the case of progressive system's loss of performance due to the memory of the fault state after each maintenance.

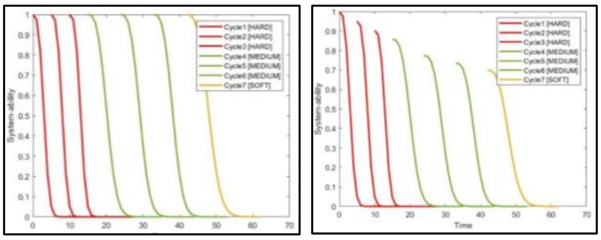

Figure 2: systemability in SFM=0 (left) and SFM=1 (right)

Although the maintenance intervals does not change for SFM=0 or SFM=1, it is evident that the maximum performance level to which the system can be brought back with the intervention will have an upper limit in the case of SFM=0. From this, the major implication is the need to define the minimum performance threshold required by the user, *i.e.* the minimum accepted service level (SL).

At a certain degradation level, it will no longer be possible to restore an acceptable performance (or SL) by minimal repairs, making it necessary to withdraw the product for an integral remanufacture process, then repurposing it in a subsequent life cycle.

Figure 3 shows what happens when SL changes, in SFM=1, in case of 7 cycles with hard-soft-soft-medium-medium-medium-soft envirnomental effects.

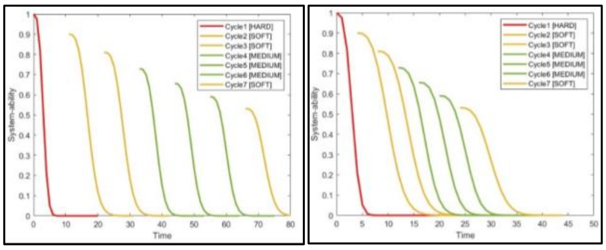

Figure 3: systemability in SFM=1 with SL=10% (left) and SFM=1 with SL=50% (right)

As SL increases (from 10% to 50% in the computation example), it is observed that maintenance frequency gets higher. Moreover, the useful field operation period before claim for remanufacturing is almost halved.

4. Implications and conclusions

Environmental and usage stressors affect product intrinsic properties, reducing its performance over time. In practice, we are talking about obsolescence and degradation, named as the main value reduction factors for mechanical components. In a leasing configuration, those losses affects both the lessor (causing product depreciation and value loss) and the lessee (due to reduced service level). However, an effective and targeted maintenance strategy is able to stem such negative effects, provided that the actual customer service level is considered.

Figure 4 illustrates, for a mechanical component, the progressive loss of value over time due to natural environmental degradation and usage stress. It highlights how the intrinsic degradation curve sets an upper limit for performance because of the memory effect of the fault state. On the vertical axis, representing product performance level, the customer's acceptance range is remarked, within which the service level is fixed. The horizontal axis shows that as the product deteriorates, the maintenance intervals become increasingly shorter. At a certain point, minimal repairs are no longer effective to restore the component to an acceptable performance level., thus complete remanufacturing becomes necessary.

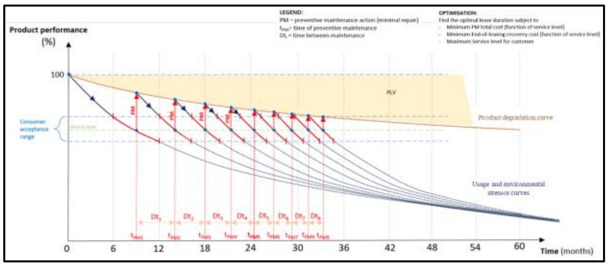

Figure 4: Conceptual framework

In this work, the authors tried to define a forecast approach to predict the optimal maintenance and remanufacturing time. Thanks to the systemability model it is possible to refine maintenance prediction models based on actual conditions of use. Starting from this point, the authors proposed to further refine the maintenance approach for mechanical components through two integrations. The first is the addition of the fault state memory effect, *i.e.* SFM, which introduces in systemability curves an upper limit after each maintenance. The second integration is the setting of a service level threshold, within the consumers' accepance range. Computational tests showed, in comparison to the previous method, an increase in maintenance frequency, and a reduction in use-cycle duration. Notable implications are: *(i)* the evaluation of maintenance costs must be done in a cumulative approach, in the use-cycle and not in the single intervention; *(ii)* the required service level is relevant for the leasing duration; *(iii)* the cumulative memory of the fault state determines the maximum use-cycle duration.

This work also lays the foundations for the evaluation of the environmental impact, in terms of CO2 emissions – in LCA studies-. Proactive remanufacturing should be designed on the basis of the useful life dictated by the fault memory.

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