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A conceptual framework for through-life services in industrial machinery

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Abstract

Moving towards solution-based approaches presents huge potentials for sustainable economic growth. However, this approach does not automatically lead to sustainability. Industrial solutions should be designed from a life cycle perspective, which requires the transition of industrial systems towards approaches focusing on the product's life-cycle optimization. This can be achieved through life-extension or recovery strategies. From a life-cycle viewpoint, the End-of-Life concept and disposal are replaced with restoration to extend the product lifespan and restore the material and energy. One of the main challenges in front of this circular approach is choosing the best through-life services. To address this need, this research articulates a conceptual framework to support the transition of the industrial solution towards the through-life service by translating life-extension service into an actionable pathway. In this context, the idea of services per life stage based on the chain of "Observation-Analysis-Acting" is proposed for industrial through-life services. An industrial use case from the ICP4Life project is conducted to validate the efficiency of the proposed framework.

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Keywords: Through-Life Services; Industrial Services; End-Of-Life Management.

1. Introduction

Industrial solutions should be designed from a life cycle perspective, which requires the transition of industrial systems towards approaches focusing on the product's life-cycle optimization [1][2]. Industries have already started their journey through sustainability by adopting approaches such as the improved design of the product and optimizing its lifespan as well as energy and material recovery [3].

In this matter, "considering decision factors across product and service activities" is crucial [4], which is complicated and general approaches like six sigma cannot be helpful in detail [5]. In doing so, solution providers need to achieve some important capability called "organizing for repeatable solutions" or solution-ready customization [6], as well as knowledge capturing and learning [7].

To address this need, this research articulates a conceptual framework to present the through-life services in a given

industrial context. In this context, the idea of services per life stage is proposed to fulfil the need for each phase. In doing so, the service life cycle is associated with a chain of service provision for maintenance, re-use, re-manufacturing, and recycling. A Scenario-Based Test is used for validation of its applicability.

This research can contribute to the through-life service literature by identifying and classifying the different types of services based on the circular economy.

In doing so, the remainder of this paper is organized as follows. Section 2 explains the theoretical background. Section 3 represents the proposed framework. Section 4 focuses on identifying and formulating the industrial case problem and validating the framework applicability on this industrial case. The discussion is drawn in Section 5.

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2. Theoretical background

A circular Economy (CE) is defined as “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling” [8].

From a Life-Cycle viewpoint, the Circular Economy replaces the EOL concept and disposal with restoration [9]. This approach considers that product restoration consists of iterative cycles to extend the product lifespan and restore the material and energy to reduce the environmental impact of industrial firms [10]. Circular approaches can be achieved by strategies such as low-carbon manufacturing and smart use of material during Beginning-Of-Life (BOL) [11], product life-extension and product restoration during Middle-Of-Life (MOL) and End-Of-Life (EOL) [4], useful application of material (recycling and recovery) during EOL [11].

During the BOL “Target-oriented Modularisation Method” and “Product Family Modularisation” are proposed to define the product architecture based on “specific goals” [12]. As an example, based on this approach, five levels of modularity for electrical devices are “add-on modularity (based on functions group), material modularity (based on materials), platform modularity (product configuration for individual specs), repair modularity (focusing on key components), mix & match modularity (flexible approach)” [13].

The MOL and EOL management is based on life-extension and restoration strategies. The product life extension can be in the form of “loop-extending” strategies such as optimization and maintaining services [14][15]. It extends the lifetime of the product without changing its ownership [16] or losing its quality [5]. Maintenance is connected to parts replacement as a basic reaction to minimize the failure risk or to put the system on work without a major change by replacing the “out-of-order parts” and recovering their functionality [5]. Maintenance might be corrective (in case of product failure), preventive (in advance to prevent product failure) or proactive (holistic approach from design to reduce failure)[17].

Besides maintenance, the upgrade is an accepted circular strategy to maximize the product life and performance or to deal with technological changes [18]. Product restoration is the industrial process in which the products at their EOL are “restored to useful life” [19]. It can be in the form of “loop-closing” or “longevity” strategies, focusing on closing the loop of material and energy [15]. During this process, the core passes through several remanufacturing steps, e.g. inspection, disassembly, part replacement/refurbishment, cleaning, and reassembly [19].

The MOL and EOL management needs a decision-making strategy based on analysing various information from the operation phase to predict the need and plan proactive maintenance (e.g. preventive, predictive, condition-based, and proactive) [20]. To maintain optimal performance, industries need to pass through a transition from the traditional ‘fail-and-fix’ to ‘predict-and-prevent’ e-maintenance-based strategies based on « observation, analysis, action » [21].

There are various methods to choose the best maintenance strategy based on machine health assessment. The most suitable maintenance strategy could be chosen employing methods such as FMECA (Failure Mode, Effects and Criticality Analysis) or Remaining Useful Life (RUL) [22][23]. In this context, the life cycle of an integrated solution can be considered as a chain of stages in which there is an action per life stage [24].

In this matter, the concept of “circular configuration” is proposed to use a wide range of through-life services to achieve the maximum from the circular strategies [25]. Inspection of the product will “generate the status report of the products and its components” to support the decision-making on the best circular configuration strategies [26].

As an example, advanced approaches in maintenance can directly (by using waste-to-energy processes) or indirectly (by the product’s performance optimization) decrease the energy consumption and CO2 footprint [20][11]. Based on the FairPhone3 Life-Cycle Assessment report, repairs and software supports can prolong the lifespan of smartphones from 3 years to 7 years, which drops 42% GWP per year [13]. However, another quantitative research showed that recycling, on its own, is not the ultimate solution for sustainability, and strategies such as dismantling, which is based on a modular design, are the best recycling scenarios with minimum CO2 emission and maximum energy recovery [3]. In this context, product design during the BOL, through-life services during the MOL, and energy recovery, recycling, and disposal during the EOL are inter-related core concepts in Circular Economy [27].

There is a mutual effect between life stages and actions like repair, renewal, reuse, etc. [24]. The EOL management strategy affects the product design process in which the product specifications will be refined to “optimize service intervals” [28]. As an example, the service-related activities for the EOL consider the required actions related to the materials flows which are possible to recover or to reuse in the same or other systems [29].

In this matter, it is necessary to consider some modifications in the physical product (design for upgradability) to enhance the lifespan of all components [30]. After the system installation or delivery, various product- or process-related services will be realized to optimize the useful life of the in-use product [31]. Connecting to the circular economy, the product life cycle is associated with a chain of service provision for maintenance, re-use, re-manufacturing and recycling [32].

The above-mentioned processes are knowledge-intensive to build or improve the strategic capabilities as well as to support the service processing through the system life stages [33]. The key knowledge processes (creation, integration, and transfer of knowledge), will be extended upwards and integrate the “task-specific capabilities” into the functional capabilities [34]. In doing so, real-time life cycle data capturing and knowledge discovered from the data and knowledge capitalization is continuously performed during the whole life cycle [35].

Based on the above literature review, circular economy, through-life services, and through-life knowledge capitalization are well addressed in the literature. However, they are not proposing an integrated framework considering the three subjects in an industrial context. The first novelty of this

framework is that it proposes a conceptual framework integrating these concepts through the system operation. The second one is that it proposes a flexible approach which is based on the operation-related events of the system. Finally, this framework is a data intensive approach which considers data analysis and knowledge capitalization as continuous activities at the same level of importance of other activities like maintenance.

3. Conceptual framework for through-life services

This section explains the descriptive framework for the through-life cycle service. The development process to provide the final solution follows through-life engineering. In this context, the idea of services per life cycle stage based on the chain of “Observe-Analysis-Act” is proposed for industrial services (Figure 1).

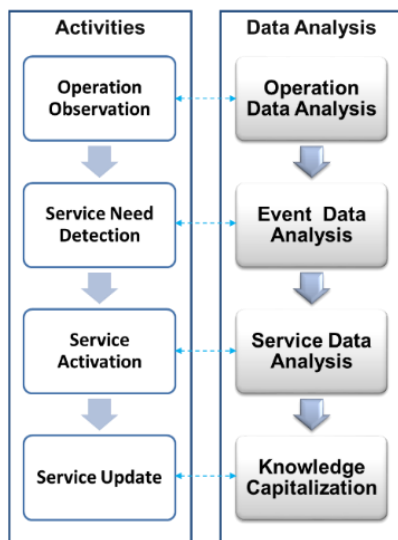


Figure 1. The general framework

The system life cycle is defined by connecting the chain of Life Stage-Events-Action-Process. In this point of view, each event during the life cycle triggers a new stage. The main phases of the above-mentioned approach are:

1. Operation observation: The life stages of the integrated solution are detailed as system design, realization, operation and “operational services” phases. After system design, system realization is followed by system operation. In the end, the system evolution might be realized by upgrading or replacing the system.
2. Service needs detection: Events are the operation or collaboration related changes that happen during the life cycle. Each event during the life cycle triggers a new stage. The operation related events are any failure in the product, technology obsolescence or infrastructure out of capability. These events could occur as an incidence or according to the life stages. Based on the information from the system’s operation observation, a primary analysis is performed to identify the required service in general. This analysis enables the service provider to diagnose

any failure, need for optimization or end of life of the system, product, or components. Based on this analysis, the service provider can verify whether the product must be disposed or not. They can then decide on general aspects of the service such as the global service strategy (restoration or life-extension).

3. Service activation: Actions are the provider response to events. These actions are based on the contract and the nature of the event. Business processes will fulfil actions. As an example, the service-related data for end-of-life consider the required actions related to the materials flows which are possible to recover or to reuse in the same or other systems.
4. Service update: Focusing on the knowledge capitalization, the system and service information will be updated in a knowledge repository that supports the through-life services.

The circular configuration supports the decision-making on choosing the best services to extend the lifespan of the product (product life-extension) or give it a second life (product restoration) at the product- or component level. This circular configuration is a combination of service strategies for rationalizing material use and value creation at the product- or component level. In doing so, the company needs to choose the best EOL management service (Figure 2).

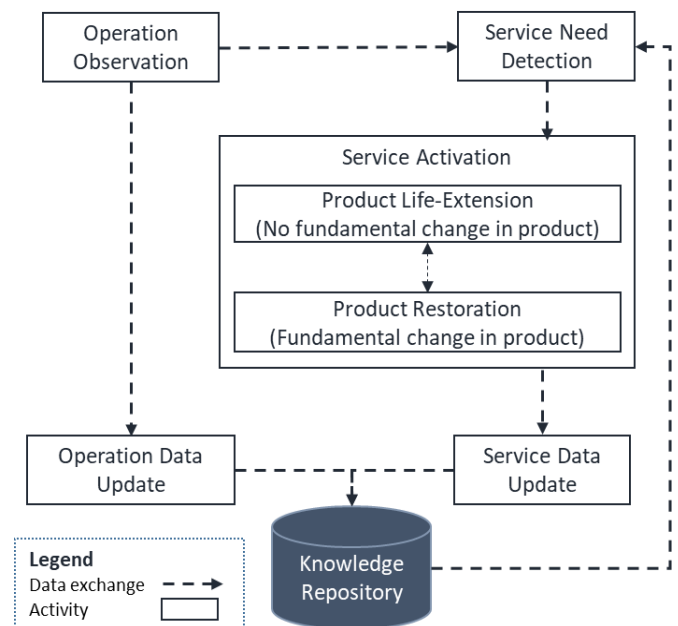


Figure 2. The general framework for through-life services

It is crucial to detect the nature of the problem or the barriers to performance optimization. In doing so, from the primary analysis, the service scenarios are defined in which it is clarified which restoration option is needed (maintenance, product disposal, remanufacturing, refurbishing, or recycling). In the end, if the product is not disposed, it would be reassembled. Redelivery and/or reinstallation are the final steps to put the system back in operation for the same or different customer. The specifications of the customized PSS will be saved to keep track of the product modifications. In case the

product can be restored by recycling, remanufacturing or refurbishing, there is a need to choose the best life extension service for each module or component.

In doing so, using a matrix containing three categories of information is necessary.

1. The detailed information on the product by creating the product tree (from main modules to components): The product information analysis gives details such as the age, the type, the structure, the working condition, etc.
2. The operational status of the product and service: Analysis of the failure, the status of the product or service life stage, or the optimization plan as well as the production line performance optimization that needs some improvements in some machines is crucial. In doing so, connecting the product information from the previous step with the details of failure or status is useful.
3. The best life-extension services: Clarifying the required life-extension services (component disposal, cannibalization, maintenance/repair, upgrade, replace, clean, reuse) for each component with different status or failure.

In the end, the same as all industrial projects, the machine will be reassembled, tested and reinstalled/redistribute. In case the chosen strategy is the 'product restoration', a full reassembly of the previously disassembled product would be necessary. Redelivery or reinstallation is the final steps to put the system back in operation for the same or different customer.

4. The industrial application

The proposed framework has been validated using in a network of industrial partners (machinery, manufacturer, and energy provider) creating an innovative customized solution. Each partner provides a customized service according to their core competencies (machine health and performance as well as energy management service). The integrated service system network is enabled through a collaborative platform supported by a common knowledge repository.

The leading actor in this industrial use case is a manufacturer of industrial machines, wishing to upgrade the existing machines to provide through-life services as "Machine Performance Optimization (MPO)" and "Machine Health Monitoring (MHM)" service, as well as collaborating with an energy provider partner for two more services as "Power Interruption Planning (PIP)" and "Energy Consumption Management (ECM)" (Figure 3).

The MHM service aims at minimizing the machine breakdown times by observing and recording the machine vibration pattern through its lifetime and use it to detect any variation from normal behavior. The general scenario is a chain of steps as the machine's operation routine, monitoring vibration amplitude, sending related notifications, saving vibration patterns and predicting maintenance need. During the above-mentioned service system, continues exchange between the analytical software and the project knowledge repository happens to predict deviations, maintenance and power interruption need and forecasting energy need as well as to

create/update the solution ready packages. In this matter, saving these provided packages to be reused in providing a new service is the final step The MHM service is the basis of predictive maintenance.

In this case, the machine health monitoring service is the basis of predictive maintenance and highly relies on vibration monitoring. Involving the sensors in the PSS lifecycle eases the monitoring and predicting services like maintenance. To fulfil this service, vibration sensors are integrated with the machine to monitor its vibration during operation. The health monitoring application will analyze data from this sensor. When the vibration amplitude shows a deviation from acceptable acceleration and frequency during its normal operation, an alarm notification will be sent to the equipment user. The vibration pattern (the machine behavior) is saved and used as a reference for vibration deviation detection. Based on this, the maintenance need is predicted. Next step, this data will be used for Machine Performance Optimization (MPO).

The energy provider monitors the machine during its routine operation to provide two different services as Power Interruption Planning (PIP) and Energy Consumption Management (ECM). These two services are linked to MHM and MPO. The PIP service supports the maintenance in the MHM service. After predicting the maintenance need, the manufacturer needs to plan the maintenance (service operation). In doing so, power interruption is planned based on the maintenance plan. Making the power restoration and starting the machine operation routine is the final step.

In parallel, the ECM service scenario is as follow. The machine is in its routine operation. The embedded process sensors and measurement devices are added to the machine. These sensors detect any deviation from normal energy usage as well as energy picks. The system sends related notifications for the manufacturer to shift the energy consumption or realize any necessary maintenance. Based on the energy consumption pattern, the system forecast the energy need and updates the customer energy consumption profile.

The above mentioned through-life services are interconnected. They are all based on the operation observation, service need detection, service activation, and service update. While the proposed framework in this work is global and useable in different contexts, choosing the modules from the model depends on the scenario of use. As an example, for the life cycle of the MHM service, the event that triggers the action is either a break down in a component of the machine or a prediction of its end of life. In energy management, on the other hand, the event to trigger the action is the received data from the energy usage which comes from the monitoring system.

Moreover, the definition of service is different in each of the above-mentioned scenarios. For the Machine Performance Optimization service and the Machine Health Monitoring service, the predictive maintenance to extend the life-span of the machine is the main objective. While, the Power Interruption Planning is not directly providing any service and is considered as a support service to realize the maintenance. The Energy Consumption Management is focusing on a combination of proactive maintenance and operation modification.

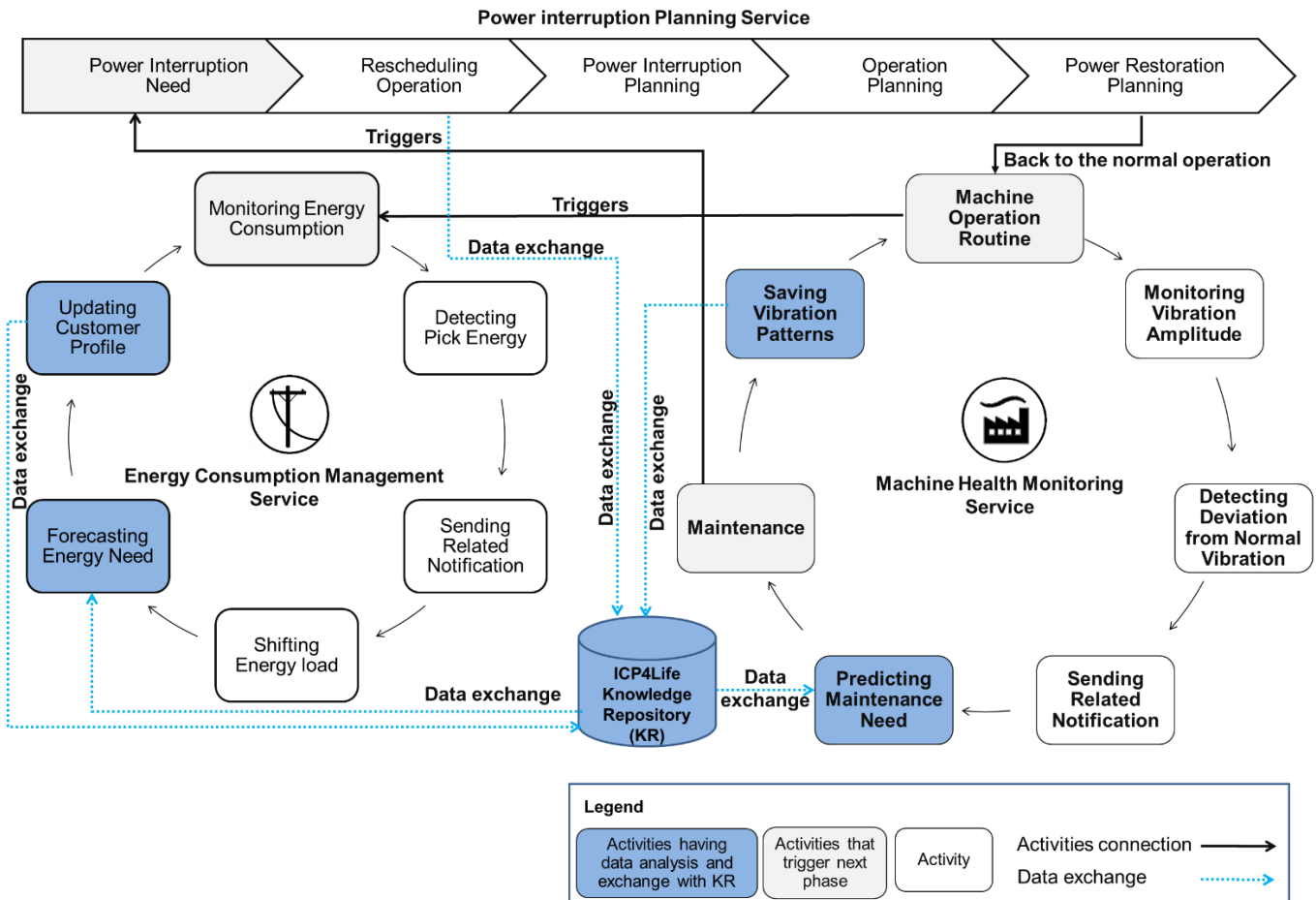


Figure 3. Integrated service network

4. Conclusion and perspectives

This research aimed at contributing to the concept of through-life services. This paper proposed a conceptual model to apply a circular economy and life cycle approach in the context of industrial services networks. The proposed framework contains crucial steps for knowledge capitalization integrated into the global development process. This approach integrates key enablers to create value in the offer along with its life cycle as well as continuous improvement of capabilities.

Intentions for future work concentrate on extending the framework to define actions per life stages. The through-life service in this work is mainly focusing on industrial machinery services. Detailing actions based on interconnected through-life services within an industrial cluster remains as a motivation to develop the model. In doing so, interfaces between systems and services are a promising subject.

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