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Value-based Smart Retrofitting of Maintenance in the Hydropower Plants of Celsia

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Abstract: Smart Retrofitting in maintenance indicates the development of maintenance services through the retrofitting of legacy devices with the functionalities of data collection, data communication and data processing. Many companies nowadays desire to retrofit their assets through the implementation of Prognostics and Health Management (PHM) services to assist in better predicting their future state and making timely and sound decisions. In this context, this work presents the PHM center developed by the company Celsia in the Alto Anchicayá hydropower plant and discusses the available approaches for estimating the value brought by PHM investments. Even if different works can be found in the literature with this purpose, only the economic feasibility of PHM implementations is generally considered. Whereas, in value-based decision-making different dimensions are embraced and not only the performance and cost ones. Therefore, the need of a value model to support decision-making concerning PHM implementations is presented and the potential of System Dynamics for this purpose is discussed.

Keywords: Asset Management, Strategic Maintenance, Smart Retrofitting, Prognostics and Health Management, Predictive Maintenance, Hydropower Plant, Value-based Decision-Making, Decision-Making, System Dynamics, Value Model

1. INTRODUCTION

Due to the digital transformation of industrial plants boosted by industry 4.0, *Prognostics and Health Management* (PHM, also known as Predictive Maintenance) has emerged and is defined as a condition-driven preventive maintenance program. According to (Lee et al., 2017), three types of end results of a PHM approach are often distinguished: i) detection: used as a safety warning or last resort; ii) diagnosis: fault state determination and short-term (failure) behaviour forecast; iii) prognosis: long-term (failure) behaviour prediction.

Hydropower is one of the renewable energy sources with the highest conversion efficiency. Hydropower plants (HPPs) produces electricity from water potential energy by means of a hydro turbine that drives a generator. Typical average operations and maintenance costs for HPPs represents 2% of the investment cost (Taylor, 2010). Therefore, HPPs are often the cheapest means of generating electricity. Furthermore, HPPs are characterized with a very long lifespan.

Maintenance of HPPs is fundamental for their efficient operation and long life. Lack of effective maintenance processes can result in major losses such as electricity generation and revenues, whereas poor maintenance practices can also affect employees and public safety.

Online monitoring of HPPs is important for granting an uninterrupted generation. Monitoring of silt, vibration, discharge, level, energy generation, and tandem operation of HPPs to know the real-time condition of the plants is essential. Better monitoring and control strategies based on PHM policies can minimize unwanted breakdowns and improve the performance (Kumar & Saini, 2022).

Typically, two motivations can be discerned for implementing PHM policies (Tiddens et al., 2018): i) *top-down approach*: industrial practitioners look for the best maintenance policy for their high-impact assets, and PHM appears to be the most suitable one; ii) *bottom-up approach*: opportunities arise that make the application of PHM feasible. In the first case, the decision concerning the PHM implementation is driven from a strategic point of view, whereas in the second PHM is implemented and then its added value is quantified.

Furthermore, the implementation of PHM programs may require companies to either replace or upgrade their existing legacy devices to get access to industry 4.0 technologies. The second approach is defined as *Smart Retrofitting* (Sanchez-Londono et al., 2022): the development of maintenance services through the retrofitting of legacy devices with the functionalities of data collection, data communication and data processing.

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Celsia is a Colombian company that owns 25 plants in between hydro, thermal, and wind power generation in Colombia, Panamá, and Costa Rica. The company has an installed capacity of 1788 MW and in 2021 generated more than 5670 GWh. However, two factors complicate its operation and force the company to look for innovative solutions: i) the growing need of renewable energy is pushing regulators to demand more complex and strict requirements; ii) most of the HPPs of Celsia has more than 40 years of operation and are facing a loss of performance and reliability due to the aging of the assets. In response to these issues, Celsia started looking for technological solutions for: i) improving its operation because of better maintenance; ii) taking sound decisions concerning the progressive renewal of its assets.

In line with a smart retrofitting bottom-up PHM approach, in 2019 Celsia won a tax relief grant of the Colombian government for the development of a PHM center in the Alto Anchicayá HPP. The proposed center is called *Centro de Diagnóstico Avanzado en Generación* (CDAG, advanced diagnostic center for hydropower generation) and its hardware implementation is expected to finalize in December 2022. From 2023, the company will start operating CDAG and the objective will be to estimate the potential value brought by this center to evaluate the scalability of the technology to the other 18 HPPs that Celsia operates in Colombia.

Given the above, this paper presents the implemented CDAG center and the strategy that will be investigated to estimate the generated value. The paper is structured as follows: section 2 illustrates the context of the CDAG project, and section 3 the implemented CDAG PHM center. Section 4 depicts the need of a decision-making model for estimating the added value brought by CDAG, and section 5 presents the conclusions and sets the directions for future work.

2. CONTEXT OF THE CDAG PROJECT

In this section, the socio-technical context of the Alto Anchicayá HPP is illustrated (sec. 2.1), along with the tax relief grant that allowed the implementation of CDAG (sec. 2.2).

2.1 Alto Anchicayá hydropower plant

The Alto Anchicayá HPP (Fig. 1) began to operate in July 1974 and is located in the department of Valle del Cauca, Colombia. It counts with an installed capacity of 355 MW, distributed in 3 generation units with vertical Francis turbines: 2 units of 120 MW and 1 unit of 115 MW. Its reservoir has a total volume of 45 Mm3 and a head of 440m.

This HPP is part of the Farallones of the Cali National Natural Park (known in Spanish as PNNFC). The PNNFC was established in July 1968 and has an area of 196,364.9 hectares. This region is rich in biodiversity and its flora and fauna are protected by the Colombian Ministry of the Environment and Sustainable Development. The PNNFC's conservation objectives include not only the protection of its ecosystems, water resources and cliffs but also the cultural preservation of the ethnic communities that live in the national park. For this reason, some key stakeholders of the HPP are the environmental institutions that supervise the PNNFC such as the National Environmental Licensing Authority and the National Natural Parks of Colombia.

The operation of the Alto Anchicayá HPP is carried out in accordance with the environmental and social legislation established by the government and the local authorities. However, this situation is complicated by the presence of illegal actors associated with paramilitary forces that cultivate illicit crops within the national park.

It can be noticed that the context of the HPP is quite complex and heterogeneous. Therefore, the harmonization of the conflicting stakeholder requirements and expectations represent a challenge and must be considered within the decision-making process of the plant.

Fig. 1. Reservoir of the Alto Anchicayá HPP.

2.2 Tax relief grant

In response to the aging of its assets and the regulators demand for more complex and strict requirements concerning the energy generation, Celsia decided to start a pilot project in the Alto Anchicayá HPP to explore the potential of smart retrofitting in facing these challenges. The project was founded through the grant 839-2019[1] offered by the Colombian Ministry of Science, Technology and Innovation. This grant had the objective to boost the investment of Colombian enterprises in science, technology and innovation by providing tax benefits directly proportional to the investment. Celsia won the grant through a project that proposes the development of a PHM center able to improve the decision-making concerning the maintenance and the renewal of its assets based on the information and knowledge resulted from the processing of data acquired in the plant. The project is broken-down in two phases:

1. *2020-2022*: functional design of the center and implementation of the data acquisition, transmission and storing functionalities.

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[1] https://minciencias.gov.co/convocatorias/innovacion/convocatoria-para-el-registro-proyectos-que-aspiran-obtener-beneficios-1

2. *2023-2024*: data conversion into information through diagnostics and prognostics algorithms for supporting the decision-making process, and estimation of the potential value brought by the center.

3. CDAG PHM CENTER

This section describes the results of the first phase of the project (i.e. 2020-2022). The CDAG functional architecture is illustrated in section 3.1 and its implementation in section 3.2.

3.1 Functional architecture

The functional architecture of CDAG is depicted in Fig. 2. CDAG is able to monitor and acquire: i) data concerning the quality of the generated energy; ii) process variables; iii) condition variables. Most of the data are automatically acquired with sensors. However, measurements manually performed during inspections or based on human senses can also be input to the system. Next, the monitored and acquired variables are illustrated.

Quality of the generated energy

- Primary Frequency Regulation (PFR): monitoring of the active power signal produced by each generation unit.
- Electrical Variables (EV): monitoring of the voltage (± 120 VAC) and current (± 5AAC) variables of the generation units.

Process variables

- Online Efficiency (OE): monitoring of the generation efficiency through the acquisition of the discharge and the generated power signals.
- Reservoir Signals (RS): monitoring of the main variables associated with the status of the dams; e.g. seismological variables, displacements, internal flows, runoff water, levels, gauging, etc.
- Cooling System (CS): monitoring of the process variables of the cooling liquid utilized for the generator and the transformer radiators.

Condition variables

- Vibration (VIB): monitoring of the vibration signals in different elements of the generation units.
- Oscilloscope Disturbances (OD): monitoring of the oscillographs and the protection IEDs (Intelligent Electronic Devices).
- Temperature (TEMP): monitoring of the temperature through the use of infrared thermal images.

After the acquisition, data are stored and then converted into information. Finally, information is transmitted to four modules that support the decision-making process. Next, the services defined for the decision-support system are presented.

Decision-support system

- Remote Monitoring: remote access to all the services of the CDAG center.
- Asset Management: utilization of the information generated from the processing of the plant data to take sound decisions concerning the maintenance policies and the renewal of the assets.
- Digital Twin: modelling of the critical assets of the plant to optimize their operation.
- Augmented Reality: utilization of this technology to train operators and to provide remote support to the technical teams working in the plant.

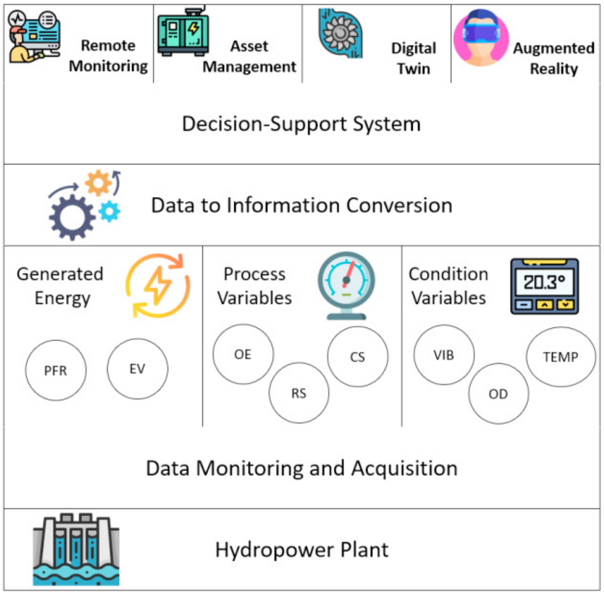

Fig. 2. Functional architecture of the CDAG PHM center.

3.2 Technological implementation

In this section, the deployment of the CDAG functional architecture is illustrated. CDAG consists of different hardware modules and software units that are depicted in Figure 3. In the figure, the CDAG implementation is presented in accordance with the IoT reference model of the International Telecommunication Union (ITU, 2012). Next, each layer and the associated capabilities are briefly resumed.

Device layer: responsible for the data acquisition and transmission.

- Device capabilities: National Instruments hardware for the data acquisition, synchronization and edge processing. It offers high response times and low latency, as well as native hardware synchronization via the Time-Sensitive Network (TSN) standard.
- Gateway capabilities: acquired data are transmitted to a CISCO IE4000 switch granting the synchronization via TSN standard.

Network layer: provides relevant control functions of network connectivity, such as the functions of access and transport resource control through the CISCO 2690 switch.

Service support and Application support layer: consists of the following two capability groups:

- Generic support capabilities: acquired data are stored in Dell servers.
- Specific support capabilities: data to information conversion through the implementation of detection,

diagnostics and prognostics algorithms in the M&D software. Then, the obtained information is synthesized and transmitted to the application layer through the PI OSIsoft software.

Application layer: ptc software is utilized for the remote control, the augmented reality and the generation of reports. A module of PI OSIsoft is utilized for further synthesizing the information required from the augmented reality model.

Security capabilities: management for authorization, authentication, security auditing through the Ruggedcom RX device, and demilitarized zone (DMZ) creation.

Management capabilities: traffic and congestion management, such as the detection of network overflow conditions. The M&D server temporally stores raw data that are then synthesizes into the PI OSIsoft data Archive. This latter can be remotely access through the PI OSIsoft interface Nodes.

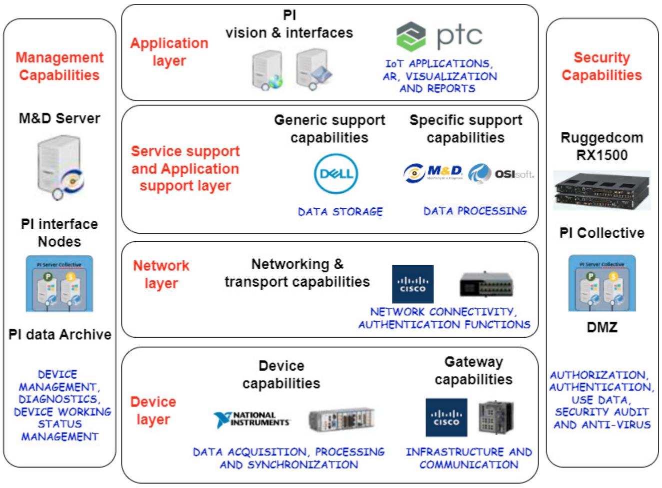

Fig. 3. CDAG hardware implementation. PI OSIsoft is simply defined as PI for the sake of simplicity.

4. VALUE-BASED DECISION-MAKING

Considering that in the second phase of the project (i.e. 2023-2024) the potential value brought by the CDAG center must be estimated, a literature review has been implemented to identify a viable approach for this purpose. This section presents the results of this analysis. In particular, it demonstrates the need of a decision-making model for quantifying the added value of PHM implementations and illustrates the strategy that will be investigated in future works. In section 4.1, a state-of the-art analysis concerning the economic feasibility of PHM policies is presented. Section 4.2 depicts the principle of value and the methods that have been proposed for its quantification, and section 4.3 the potential that System Dynamics may have for this purpose.

4.1 Economic feasibility of PHM policies

The purpose of studying the economic feasibility of PHM policies is to assess where PHM would provide the greatest benefit in terms of performance and cost. Since many maintenance techniques that enable PHM are costly to develop, it would not be cost-efficient to apply them on all the assets. It is estimated that almost 30% of industrial assets do not benefit from applying techniques that enable PHM policies (Hashemian & Bean, 2011). Therefore, PHM should only be applied where it is suitable and not as an overall policy (Moubray, 2001).

Different works can be found in the literature concerning the study of the economic feasibility of PHM policies. Al-Najjar (2012) proposes a methodology for establishing and running cost-effective PHM policies. Nevertheless, author indicates that the economic impact of the PHM implementation must be estimated without providing a tool for this purpose.

Few works utilize the Monte Carlo simulation based on the Reliability Block Diagram model. Tiddens et al., (2017) develop a hybrid business case approach that combines non-financial (strategic multi-criteria analysis) and financial elements (using Monte Carlo simulation) for comparing the investment in PHM against both fixed-interval preventive maintenance and corrective maintenance. Roda et al. (2019) propose the use of Monte Carlo simulation to evaluate different implementation scenarios of maintenance policies and utilize the Total Cost of Ownership criterion for the selection of the most promising one.

Arena et al. (2022) develop a decision support system based on decision trees that guides the decision-making process of PHM implementations. The model allows the study of different scenarios to identify the conditions under which a PHM policy is economically profitable compared to corrective maintenance.

It can be noticed that the presented works only consider the economic feasibility of the PHM policy. Value is the key principle of asset management and includes all the dimensions that are necessary to achieve the organizational objectives. In value-based decision-making different dimensions are embraced and not only the performance and cost ones. Therefore, a value-based decision-making model would be desirable to drive the implementation of PHM policies.

4.2 Value and value quantification techniques

Value is obtained by acquiring assets that allow an organization to fulfil its strategic objectives (El-Akruti et al., 2013), and ensuring that the assets keep fulfilling those objectives throughout their life cycle. Each organisation has to determine what constitutes value in relation to achieving its organisational objectives. These objectives have to consider the needs and expectations of the stakeholders such as investors, customers, regulators, employees and local communities. This requires organisations to include both tangible and intangible elements of value in their decision-making.

Two techniques have been proposed for value-based decision-making (The IAM, 2014):

- *Total Cost of Ownership* (TCO): the analysis of costs implications for an asset or asset system over the organisation's period of responsibility. If a required asset performance is met, then the lowest life cycle cost corresponds to the best value way of delivering this requirement for the organisation.

- *Value Optimisation* (VO): considers the value of the asset system in addition to the asset costs. It aims to deliver the best ratio of benefits (in terms of delivering organisational objectives) and life cycle costs – in other words, the best value-for-money.

Although individual assets can contribute value to an organisation, it is usually when they are connected together as an asset system, or a larger entity, that they generate value for an organization. For this reason, TCO is preferable for the decision-making concerning individual assets, while VO for asset systems. In a smart retrofitting bottom-up PHM approach, it is fundamental to quantify the added value brought to the organization by the application of this policy to assets and asset systems. Therefore, VO should be applied in this decision-making process.

VO is not trivial since value contains several dimensions. The most known representation of the dimensions of value is the Shamrock diagram developed within the European EU1488 MACRO Project; see Fig. 4. This diagram shows how typical stakeholder interests (external ring) can be represented in just five 'universal toolkit' methods (inner ring) for quantifying the scales of their achievement (Woodhouse, 2019).

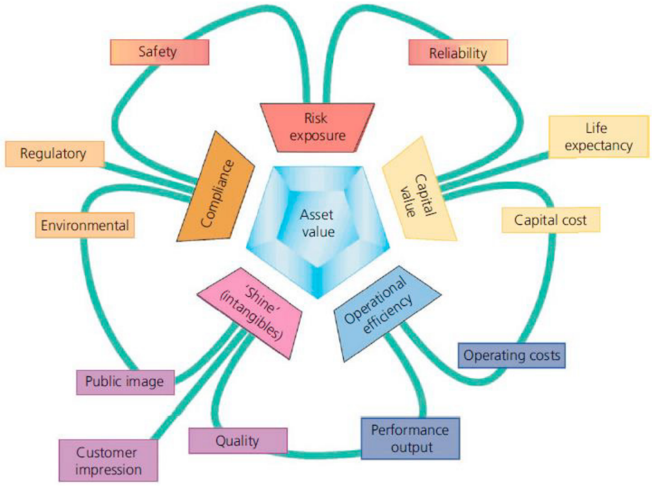

Fig. 4. *Shamrock diagram for value quantification.*

In this context, a value model should be utilized. A *value model* refers to a model that can measure the effects of any decision over value, supporting decision-making concerning the assets through their whole life cycle (Crespo et al., 2020). However, to the best of authors knowledge no work has been done for integrating the different dimensions of value in the development of a value model for the decision-making concerning the implementation of PHM policies. An intrinsic challenge of this model is that the dimensions of value are both tangible and intangible. Consequently, intangible dimensions are generally estimated with qualitative or semiquantitative methods, while tangible dimensions with semiquantitative or quantitative methods. Therefore, the value model should be able to integrate the dimensions of value considering their different quantification methods.

4.3 System Dynamics for value-based decision-making

System Dynamics (*SD*) is a widespread systemic modelling and computer simulation technique for improving decision-making in complex systems (Forrester, 1961; Sterman, 2000). Following dynamical systems theory, SD employs differential equations for building high-level models of systems driven by both physical elements and human actions such as social and organizational systems.

SD has been used for supporting operations management, especially for supply chain planning and management, project management, and new product development, innovation, and diffusion (Groessler, 2020). However, the utilization of SD to drive maintenance decisions from a strategic point of view is not common, even if not new. For instance, Sterman (2000) presents a simplified version of the SD model developed in the company Du Pont in the 1990s. The model was built for: i) explaining why a culture of reactive maintenance induced by cost pressure generated employees working overtime, excessive spare parts inventories, low availability and high maintenance costs; ii) designing high leverage policies to escape from the reactive regime. This case study demonstrated how SD can be adopted for the *strategic development of maintenance*. In fact, the model not only supported the decision-making process but also provided insights concerning implementation aspects. For instance, it represented the worse-before-better behavior that the company had to face at the beginning of the implementation of proactive maintenance policies due to the need to bear the cost of both the repair work and the additional planned maintenance effort.

SD has also been utilized to select *maintenance policies*. In (Gary et al., 2018), a SD model is proposed for the study of the dynamic behaviors of maintenance performance and costs. The model has the objective to support the long-term, strategic development of maintenance in contrast with the economical short-termism framework through which maintenance is generally managed. The purpose of using SD is to support the investigations of maintenance policies that consider: i) the causal relationships between strategic initiatives and performance results; ii) the consequences of time delays of different maintenance actions.

Concerning the Celsia case study, SD has also been proposed as a tool for studying the *economic feasibility of PHM policies*. Meng et al. (2022) illustrate an integrated method for the economic evaluation of PHM policies by considering the incremental costs and benefits associated with their deployment. A cost-benefit analysis model is established by using SD to make decisions about cost-effectiveness. Then, an enterprise-government evolutionary game model is developed to optimize the cost investment strategy for the PHM policies.

It can be noticed that the presented works utilize SD to evaluate the economic feasibility of the maintenance policies instead of estimating the added value brought to the enterprise. Furthermore, additional factors that may hinder the implementation of PHM are not considered; e.g. lack of system and domain knowledge, lack of trust in the monitoring systems, organization not ready to implement the technology, etc. As illustrated in section 4.2, value is characterized with different dimensions that must be integrated for its quantification. Due to its ability to model complex systems, SD is a promising tool to support value-based decision-making. SD models integrate tangible and intangible elements in virtual environments representing diverse interests, goals and decisions driven by a multiplicity of stakeholders acting under changing environmental conditions (Olaya, 2015). Hence, in the next steps of this project a *SD value model* will be developed for supporting planning and improved decision-making targeting the added value brought by CDAG.

5. CONCLUSIONS

In response to the aging of its assets and the regulators demand for more complex and strict requirements concerning the energy generation, Celsia started a smart retrofitting pilot project to build a PHM center defined as CDAG. The center has the objective to: i) improve the operation of the studied HPP because of better maintenance; ii) take sound decisions concerning the progressive renewal of the plant assets.

In this work, the CDAG PHM center has been illustrated, along with the need of a value model to estimate the added value brought by CDAG. Next, future works are identified:

- *Value model:* a model based on SD will be built by integrating the different dimensions of value.
- *Data to information conversion:* diagnostics and prognostics algorithms will be developed for supporting the decision-making process.
- *Services*: the decision-support system will be designed through the services of remote monitoring, asset management, digital twin and augmented reality.

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