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The requirements of a value model for the strategic implementation of predictive maintenance

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Abstract:
Predictive Maintenance (PdM) in industrial plants aims not only to reduce the failure rates of assets, but also to increment their useful life. However, additional costs must be faced when adopting such a policy, and granting that it will have a positive impact in the long term is not a trivial issue. The implementation of PdM should then be justified from a strategic perspective. Efforts have been made to develop models that provide guidance for the strategic implementation of PdM policies. However, these models generally consider only the economic feasibility of the policy, and not the contribution to value for the organization. Asset Management provides relevant principles for approaching this decision-making activity while following a value-based approach. This work aims to investigate the extent to which value-based decision-making has been implemented to drive the strategic implementation of PdM. The work concludes with the requirements that should be fulfilled by a value model to guide decision-making concerning PdM implementations.

Keywords: Industry 4.0, predictive maintenance, value, asset management, decision-making, industrial digitalization.

1. INTRODUCTION

Industry 4.0 has kick-started the integration of information and communication technologies (ICT) into manufacturing for the last decade, under the premise of improving the efficiency and competency of enterprises (Xu et al., 2018). This integration has led to enhanced decision-making capabilities, such as those in Predictive Maintenance (PdM). PdM allows for maintenance decisions to be made based on the current and predicted condition of the assets in an organization (Bokrantz et al., 2020).

However, the capabilities of PdM do not come for free, as PdM has technical requirements that must be fulfilled for its implementation. Assets must be upgraded or replaced to have sufficient data collection, transmission, and processing capabilities for an organization to enable PdM services (Sanchez-Londono et al., 2022). Implementing PdM policies will always carry certain costs, with economic limitations sometimes being a challenge in implementing PdM (Jaspert et al., 2021). Decisions to implement PdM should then be properly motivated.

One of two motivations typically drives the implementation of PdM (Tiddens et al., 2018). In a *top-down* approach, practitioners follow a strategic perspective to find the best maintenance policy for their systems, and PdM results as the most suitable approach. Instead, in a *bottom-up* approach, certain assets are upgraded with PdM capabilities due to an arising opportunity; i.e., there is no previous analysis of the value these upgrades can bring. If a strategic orientation is followed, organizations should justify the decision to implement PdM policies, rather than first implementing PdM and then trying to realize value. This decision can be supported by asset management.

Asset management refers to the coordinated activity of an organization to realize value from its assets (ISO, 2014). It aims to take into consideration the objectives of an organization, its operating context, and the needs of all stakeholders towards realizing value from assets through their whole life-cycle (Crespo et al., 2020). This makes value-based asset management a powerful approach to support decisions that lead to value realization. As such, an important opportunity can be found in exploiting asset management towards designing a value model to guide decision-making concerning the implementation of PdM.

This article aims to deliver a vision of the requirements that such a value model would need to fulfill. To this end, a discussion of existing strategic decision-making models for guiding the implementation of PdM is presented in Section 2. Section 3 then presents a literature review of value-based decision-making methods. A discussion of the requirements for a value model that guides the decision-making concerning PdM implementations is found in Section 4, followed by a foreword and conclusions in Section 5.

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2. PDM DECISION-MAKING

Different models that support PdM decisions can be found in the literature. Nevertheless, models that provide strategic guidance for implementing PdM are uncommon. This section discusses some of these strategic decision-making models for the implementation of PdM, with an emphasis on their alignment with value-based decision-making.

A model that provides strategic guidance in PdM towards reducing the Total Cost of Ownership (TCO) is provided by Roda et al. (2019). Their model first estimates the system-level performance that will arise from a production context that implements PdM (measured as the Overall Throughput Effectiveness, or OTE). The model then calculates the resulting TCO for each asset.

Another model that supports PdM implementation decisions is presented in Arena et al. (2022). They propose an approach based on FMECA and machine learning that supports the selection of a PdM or non-PdM maintenance policy for each asset. Their model returns as its output the economic value that would result from implementing and not implementing PdM in assets, obtained by considering both costs and failure-related uncertainty.

A third model is found in Kirubakaran and Ilangkumaran (2016). Here, the authors use multi criteria decision-making (MCDM) to choose among various maintenance policies (PdM included) by considering four criteria: safety, cost, added value, and feasibility. While the previous models operate on quantitative inputs, this model depends on scores given by the decision-makers. These scores are calculated through an Analytical Hierarchy Process (AHP).

A final model is worth examining. Tiddens et al. (2017) use multi-criteria analysis and Monte Carlo simulations to evaluate potential investments in PdM, from both a non-financial and financial perspective. In the non-financial evaluation, the authors consider the impact of PdM towards the objectives of the organization, specifically: innovation, maintenance (i.e., ensuring a high life expectancy for assets), operational effectiveness, and fulfillment of the needs of customers and society. Much like Kirubakaran and Ilangkumaran (2016), these authors rely on scores given by the decision-makers to quantify non-financial indicators.

The presented works aim to support decision-making for the implementation of PdM. However, some of these models focus on economic value, while others that try to have non-economic considerations do not agree on which these considerations should be. It then becomes relevant to identify the requirements of value-based decision-making that should be considered when designing a value model for the implementation of PdM.

3. VALUE-BASED DECISION-MAKING

Value has been defined as the "benefits from use, ownership or custodianship of assets"(ISO, 2014), going beyond measuring economic performance and moving towards measuring stakeholder satisfaction (Crespo et al., 2020). The ISO5500x series of standards place the concept of "value" in the center of asset management (ISO, 2014), making the implementation of value-based decision-making relevant to this discipline.

Value models can be used for this purpose. A *value model* refers to a model that can measure the effect of any decision over value, supporting asset-related decision-making through the whole asset life-cycle (Crespo et al., 2020). Such models are characterized by their alignment with the value drivers of the organization where they are implemented. These value drivers usually include economic performance, but also consider environmental impact, customer satisfaction, and other dimensions of value (Roda et al., 2016). This section focuses on the study of value through a scoping review of literature.

It was decided to not limit the scope of the review to asset management or PdM. Instead, any work that deals with value-based decision-making was considered. This way, knowledge could be found from other domains that can then be applied to a PdM and asset management context.

Methodology

The steps adopted for this review are: defining research questions, identifying potentially relevant works, selecting works, charting data, and reporting results (Arksey and O'Malley, 2005). The research questions selected for this literature review were:

- RQ1: How is value *defined* in value-based decision-making?
- RQ2: How is value *quantified* in value-based decision-making?

After selecting the research questions, a group of keywords was chosen for a search in the Scopus search engine. This set of keywords is organized in a keyword matrix, which consists of thematic groups of keywords connected with AND/OR operators in a way that all the results include at least one keyword from each group (Jaspert et al., 2021). The resulting matrix is presented in Figure 1.

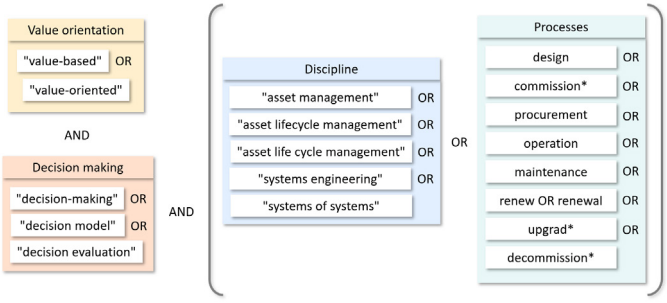

Fig. 1. Keyword groups in the keyword matrix.

The keyword matrix was built to find papers that discuss value-based decision-making with an asset management orientation. The first thematic group ensures an inclination towards value-based methods, and a second group is made for synonyms of decision making. The third and fourth groups exist to encourage an asset management orientation without limiting the search to asset management works. These groups consist of asset management keywords and a list of processes that are commonly managed in asset management. This approach allows the search to also find works from fields outside asset management.

The methodology for this review follows PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) (Liberati et al., 2009) to filter the documents that are the most relevant to value-based decision-making. 655 works were found in the initial Scopus search, and these were narrowed through PRISMA to 16 papers. This subset was selected considering both thematic relevance (the works must discuss value-based decision-making) and citation frequency (only papers with at least 5 citations and/or which were published since 2020 were considered). 10 of these papers were related to asset-intensive industrial sectors, meaning they involve asset management, and 6 were not. This was considered to be an acceptable balance between asset management literature and more general value-based decision-making literature.

Research Question 1: Definition of Value

Value is defined as the "benefits from use, ownership, or custodianship of assets" (ISO, 2014). However, a single definition cannot be found because value depends on the purpose of the organization, the nature of its assets, its objectives, and the requirements and expectations of its stakeholders (Crespo et al., 2020). Rather than finding a unified definition of value, RQ1 aims to a) verify if the literature shares the vision of value presented by the ISO standards, and b) identify what dimensions of value are commonly considered.

Some papers do not attempt to describe what value is, but instead treat it as a concept that the reader should already be familiar with. Other works mention what value is but do not provide a formal definition. Only two papers (Roda et al., 2016; Trindade et al., 2019) present a formal definition of value by citing the ISO5500x series of standards.

Some of the most common remarks on value are related to stakeholders. Value refers to perceived *stakeholder satisfaction* (Roda et al., 2016; Trindade et al., 2019; Isaksson et al., 2015; Vom Brocke et al., 2010; Brathwaite and Saleh, 2009; Sinkkonen et al., 2016; Kannan et al., 2016), and in some sectors, to the satisfaction of the specific "customer" stakeholder (Kothari and Lackner, 2006; Henshall and Schuller, 2013; Husereau et al., 2016). It is also often said that value will vary from one stakeholder to another, making it *stakeholder specific* (Roda et al., 2016; Vom Brocke et al., 2010; Brathwaite and Saleh, 2009; Henshall and Schuller, 2013; Pan et al., 2012; Topcu and Mesmer, 2018). Other papers observe that value is realized by providing assets that allow an organization to fulfill its *strategic intent*, and thus, the definition of value depends on the strategic objectives of the organization (Roda et al., 2016; Vom Brocke et al., 2010). These views are all in line with the ISO5500x series of standards.

As mentioned in (Pan et al., 2012; Tsang et al., 1999), value is multi-dimensional. As a result, various aspects must be measured to exploit value-based decision-making.

The *economic* dimension is by far the most common one in the analyzed papers; see Figure 2. Works that consider economics usually rely on indices such as the Net Present Value (NPV) (Isaksson et al., 2015; Brathwaite and Saleh, 2009; Sinkkonen et al., 2016) or other measures of profit (Vom Brocke et al., 2010; Kannan et al., 2016; Topcu and Mesmer, 2018). A common trend is that authors pursue measurements of economic value beyond costs (Brathwaite and Saleh, 2009; Pan et al., 2012). For them, it becomes relevant to consider both economic losses (i.e., costs) and gains (i.e., performance) (Tsang et al., 1999).

The second most common dimension is *risk* (Trindade et al., 2019; Brathwaite and Saleh, 2009; Kannan et al., 2016; Topcu and Mesmer, 2018). As described by Crespo et al. (2020), a risk orientation is one of the principles of asset management: decisions makers must be empowered with the tools for predictive decision-making. The quantification of risk is realized either by integrating uncertainty into the calculation of economic value (Kannan et al., 2016; Topcu and Mesmer, 2018) or through a separate index that represents risk (Brathwaite and Saleh, 2009).

A third dimension that is considered in the literature is *sustainability*. Various papers consider the need to involve this dimension in value-based decision-making, whether as a set of separate dimensions (economic, social, environmental) (Delai and Takahashi, 2011; Gade et al., 2018) or as a single "sustainability" dimension (Pan et al., 2012). A point of interest is found in Delai and Takahashi (2011), who mention that there is some maturity in the consideration of environmental sustainability in organizations, but social sustainability is still not widely considered.

Pan et al. (2012) mention other dimensions that are relevant to the realization of value. These include time requirements, quality, health and safety risks, and regulatory acceptance.

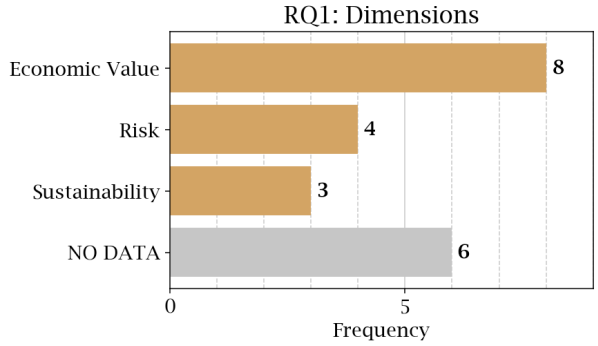

Fig. 2. Dimensions of value in the selected papers. Each paper can include multiple categories, and some papers (indicated as NO DATA) did not attempt to specify what dimensions are considered in value realization.

Research Question 2: Quantification of Value

While RQ1 attempted to approach value from a conceptual perspective, RQ2 asks how it is *measured*. If value is to be used in value-based decision-making, it must be quantified. This need is particularly relevant to the construction of a value model, as "the quantification of value delivered by assets" is the output of this model and is necessary for value-based decision-making in asset management (Roda et al., 2016). Some authors decided to calculate a profit metric such as NPV or other single measures of profit as mentioned earlier. Nonetheless, a more thorough analysis is required to answer RQ2. RQ2 aims to a) find what

common attributes exist in value-based decision-making, and b) identify what methods are used to quantify value.

In the analyzed literature, authors frequently mentioned the need for quantification models to be *adaptable to the organizational context*: methods to quantify value must consider a) the strategic intent of the organization and its objectives, b) the importance that each stakeholder gives to each dimension of value, and c) the compliance with regulatory requirements (Sinkkonen et al., 2016; Pan et al., 2012; Tsang et al., 1999; Gade et al., 2018; Mendes et al., 2018). This means that the same model to quantify value will assess value differently in different organizations with different stakeholders. It is also expressed that some stakeholders might be more relevant than others in decision-making, and this weighing of stakeholder importance must be considered when quantifying value (Kothari and Lackner, 2006; Henshall and Schuller, 2013; Husereau et al., 2016; Topcu and Mesmer, 2018).

Another attribute that was discussed by some authors is the *multiplicity of indicators*: whether a single indicator of value is sufficient, or if multiple indicators that represent the multi-dimensional nature of value are desirable. In the cases where one indicator was used, the form of this indicator was varied. For some, the measurement of value comes from profit-based indicators like the Return on Investment (ROI) (Vom Brocke et al., 2010) or a custom indicator that combines total costs and revenue (Kannan et al., 2016). Other works used more abstract measures that give weights to multiple indicators that affect value (Isaksson et al., 2015), (Pan et al., 2012), (Gade et al., 2018), (Mendes et al., 2018). In the case of works that opt for a multi-indicator approach, authors decided to keep indicators for different criteria separate for more transparent decision-making (Brathwaite and Saleh, 2009), (Henshall and Schuller, 2013) while leaving the weighing of the importance of each indicator to the decision-makers. Other authors arrive at a singular value indicator, but calculate this value separately for each stakeholder (Topcu and Mesmer, 2018).

Multiple methods were used in the analyzed literature to quantify either one or various measures of value, as shown in Figure 3. These methods include *measurement systems*, where a set of interrelated indicators with a tree-like structure converge into either one or various indicators of value. Such measurement systems are used to calculate indicators for the different dimensions. They also include *weighted aggregation*, where indicators in a list are assigned a specific weight and then aggregated (in this case by addition) returning a final index of value (Pan et al., 2012; Gade et al., 2018; Mendes et al., 2018). These methods always resulted in a single index that represents value. *Stochastic models* were also used as quantification methods. In one instance, a "response surface model" was used to create a mapping between product design variables and generated value (Isaksson et al., 2015). In other instances, stochastic models were used to consider uncertainty and risk. Both Brathwaite and Saleh (2009) and Topcu and Mesmer (2018) utilize Monte Carlo simulations to model the uncertainty of the output value for any given scenario. In these cases, the calculation of value within the Monte Carlo simulation was made through a measurement system.

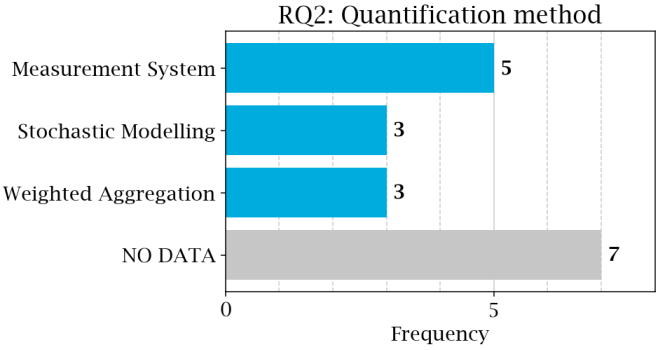

Fig. 3. Methods of quantifying value. Each paper can include multiple categories; some papers (indicated as NO DATA) did not specify a quantification method.

4. TOWARDS A VALUE MODEL FOR THE IMPLEMENTATION OF PDM

The characteristics of value models for supporting decision-making were illustrated through the literature review in the previous section, presenting the properties of both value and value quantification that exist in such models. Following this value-based perspective in decision-making is advantageous, as value realization aims to achieve the objectives of an organization (ISO, 2014). However, as it was illustrated in Section 2, there do not appear to be decision-making models for the implementation of PdM that completely follow a value-based approach. The remainder of this work then presents a landscape of how value might be integrated into PdM decision-making.

Having specified how decisions at the asset level can impact the value realization of an organization, this subsection presents requirements for a value model to guide the decision-making concerning the implementation of PdM.

Specific to the organization Measurements of value in an organization should consider a) the strategic intent and the objectives of the organization, b) the needs and expectations of the various stakeholders, and c) the compliance with regulatory and statutory requirements. This means that a single model that applies to multiple organizations is not possible, since the objectives and stakeholders of each organization will be different. Instead, a flexible model *template* or a model-making *methodology* might be designed. Such a template or methodology could be adapted to different contexts and stakeholder needs. Consider, for instance, two organizations with differing perspectives on asset failure. One organization might want to prioritize the *prevention* of failure, while another could give importance to *responding efficiently* to failures that do occur. A third organization might not even have a preference between these perspectives, but instead prioritize asset uptime regardless of the means required to achieve it. In any scenario, both asset reliability and maintainability would be relevant, but their importance in the quantification of value would have to be different. As a second example, consider two organizations that have differing perspectives on sustainability. They might consider the reduction of emissions and waste as an organizational goal, but one organization might still prioritize economic value - while the other might be willing to slightly reduce their

economic gains if this results in a positive environmental impact. Such differences must be accounted for in the measurement of value.

Multi-dimensional Each organization has multiple objectives and several stakeholders. Supposing that the maximization of economic value will both satisfy all stakeholders and fulfill all organizational objectives is not realistic. It is necessary for value to be measured in dimensions other than immediate economic feasibility. These dimensions might include risk management, sustainability, health and safety, and regulatory/statutory acceptance. A framework that attempts to list all such relevant value dimensions might be found, for example, in the Shamrock diagram of asset value (Woodhouse, 2019).

Semi-quantitative The principle of value models lies in estimating the value that can be realized from a given scenario. This allows for the value realization of multiple scenarios to be assessed, which in turn leads to value-based decision-making. As a result, all the dimensions of value in a model (even those with a more qualitative nature, like health and safety) need to be translated into quantitative or semi-quantitative measures that will allow for the comparison of multiple scenarios. Some alternatives found in the literature include measurement systems and weighted aggregation, which can transform qualitative information into semi-quantitative numerical indicators.

Aligned with asset management principles Guidelines for decision-making that concerns assets already exist in the form of *asset management principles* (Roda and Macchi, 2018). The implementation of PdM is an asset-centric decision, so it is important to follow asset management principles. These consist in the assessment and realization of value through the *whole lifecycle*, the optimization of value at the *system level*, a consideration of the *risk* associated with all decisions, and the need of a proper understanding and management of the information related to assets – i.e., an *asset-centric* orientation.

Following the results of this work, the consideration and implementation of these four requirements (i.e. specific to the organization, multi-dimensional, semi-quantitative, and aligned with asset management principles) will be sufficient for a decision-making model for the implementation of PdM to be considered *value-based*.

Limitations

This study has some potential limitations. The pool of analyzed works was limited in number; this can be attributed to the requirement of having a value orientation. This apparent shortage of research that deals with a value orientation of asset management is consistent with previous research found in (Polenghi et al., 2022). However, the number of analyzed papers means that numerical results (e.g., 31% of papers discussed a *measurement system*) might be skewed. Instead, this work focuses on discussing the *overall trends* found in the papers, rather than the perceived differences of frequency among said trends.

5. CONCLUSIONS

This work aims to deliver a vision of the requirements that need to be followed to design a PdM-focused *value model* to guide decision-making concerning PdM implementations. To this end, it first presents a discussion of existing strategic decision-making models that guide the implementation of PdM. It then provides a review of the literature on value-based decision methods. After following this discussion and review respectively, it is possible to arrive to certain conclusions.

First, it was found that existing models for the strategic implementation of PdM mostly focus on realizing economic value, without considering all the requirements of value-based decision-making. Second, it was confirmed that the definition of value in value-based decision-making literature closely adheres to the ISO standards of asset management; i.e., value is specific to each organization (it depends on the different stakeholders, organizational objectives, and regulatory requirements of each organization), and it is multi-dimensional. Third, important attributes and methods of value quantification were found. These include being adaptable to specific stakeholders, and representing multiple dimensions of value in a quantitative manner. The results in this work lead to a definition of four *requirements* that should be followed towards the creation of a value-based decision-making model for the implementation of PdM. These requirements are being *specific to the organization*, *multi-dimensional*, *semi-quantitative*, and *aligned with asset management principles*.

By following these requirements, it will be possible to create a model that supports value realization through PdM implementation decisions, following a strategic top-down approach that considers the needs of all stakeholders in an organization. A singular model that is applicable to any organization is not possible. With this consideration in mind, three main paths for potential research arise:

- This work presents the most common value dimensions in general value-based decision-making; therefore, for research to continue in a specific domain (e.g., manufacturing), the dimensions that are most relevant to that domain should be found.
- A framework or methodology to strategically guide the implementation of PdM solutions could be constructed. Such a methodology would not be tied to a specific context, but instead provide guidelines towards creating a model that is useful for a specific organization.
- A case study could take place to validate the proposed framework or methodology. Here, a value model that guides decision-making concerning PdM implementations would be built. Being a specific value model, it would need to focus on a specific context, with specific organizational objectives, stakeholders, and regulatory constraints.

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