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# An Analysis of Physical Asset Management Core Practices and Their Influence on Operational Performance

**Damjan Maletič [1,*], Matjaž Maletič [1], Basim Al-Najjar [2] and Boštjan Gomišček [3,*]**

1 Faculty of Organizational Sciences, University of Maribor, Kidričeva 55a, 4000 Kranj, Slovenia; matjaz.maletic@um.si
2 Department of Mechanical Engineering, Faculty of Technology, Linnaeus University, Building M, 351-95 Växjö, Sweden; basim.al-najjar@lnu.se
3 Faculty of Business, University of Wollongong in Dubai, Knowledge Park, Block 15, P. O. Box 20183, Dubai, UAE
* Correspondence: damjan.maletic@um.si (D.M.); BostjanGomiscek@uowdubai.ac.ae (B.G.)

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**Abstract:** The commitment of organisations to physical assets management (PAM) has recently received considerable attention in theory and practice. Indeed, PAM plays a key role in asset-intensive organizations and is also considered as a principal actor within Industry 4.0. Therefore, this paper aims to examine the PAM core practices and the performance implications of integrating these practices into business, in particular by assessing their impact on operational performance. Survey data were collected from managers in 138 international and local organisations. The data was analysed using Partial Least Squares Path Modeling (PLS-PM). The study validates the second-order construct consisting of PAM latent variables, namely Strategy and Planning, Risk management, Lifecycle Delivery, Asset Information, and Asset Review. The results have shown that PAM core practices directly influence operational performance. This paper is a response to recent calls for empirical studies on the organisational approaches that can increase the success of organisations.

**Keywords:** physical asset management; operational performance; ISO 55001; PLS-PM

## 1. Introduction

Physical asset management (PAM) has recently been considered as one of the most important sources of competitive advantage [1–3]. The relationship between PAM practices and organisational performance is an important issue, as researchers [3,4] have argued that the ultimate goal of PAM is to realize the value of an organisation's assets. Further, Alsyouf et al. 2018 [3] claim that use of an asset management system (AMS) helps organisations to improve financial performance, decision-making processes, risk management, services and results, social responsibility, as well as reputation and organisational sustainability. PAM is multidisciplinary and involves cross-functional processes, people and technologies within the organisation [5]. As shown in previous studies, PAM is related to a systematic and coordinated effort (in terms of strategic, operational, maintenance and technical processes) to realize the value of an asset or portfolio of assets in a sustainable manner throughout its life cycle, while considering risks [6]. Physical assets, also known as engineering assets, are important for creating tangible value for an organisation in a wide range of industrial environments such as manufacturing, electricity supply, water supply, construction, mining, transportation services and various other sectors [7,8]. Although our study focuses on physical assets, it should be noted that asset management (AM) considers any type of asset that has an actual or potential value for the company. It should therefore be noted that the practise of

AM has broadened in scope and complexity. This is particularly true when considering the change from PAS 55 to ISO 55001, which covers any type of asset that has an actual or potential value to the enterprise. The development of PAM has been framed by the need for an integrated and holistic approach to PAM [2,9], a need to optimize the value of assets throughout their life cycle, in particular through the development and implementation of an AMS (e.g., [10]), the necessity to recognize the business value (i.e., financial payoff) [4], a need to reduce business risk and by the expectation to reduce the whole-life costs of assets [11,12]. However, from an Industry 4.0 perspective, asset management has gained considerable attention, particularly through the integrated and holistic approach to physical asset management [13,14]. The advent of industrial digitalization and the Industry 4.0 revolution offers industrial companies opportunities to holistically manage the costs, risks and performance of assets [15]. To this end, they can use advanced technologies such as predictive analytics, artificial intelligence and digital twins as a means of monitoring and predicting the performance of assets and processes [16]. As argued by Kans and Gallar [15], the whole AMS could be supported by these new technologies.

The early stages of empirical research in PAM were almost exclusively limited to attempts to delineate the relevant constructs and frameworks. For example, several initiatives were developed to contribute to the knowledge base in the emerging discipline of asset management [17–19]. Furthermore, in 2014, the International Standards Organization (ISO) launched a new series of international standards called ISO 55000 [10]. The latter has reinforced the importance of establishing an AMS to formally adopt processes that support and clearly demonstrate the achievement of the objective of asset management, namely the realization of value from assets [5].

Although recent studies have examined the performance of PAM [2,4], few have empirically investigated the impact of PAM practices on performance outcomes. Therefore, while there is evidence of a growing body of research on asset management issues over the past decade, to the best of the authors' knowledge, there is as yet no empirical research that addresses the specific issue of PAM practices and their link to operational performance. As such, the question remains unanswered as to what the core PAM practices are and to what extent PAM conceived as a second-order construct influences operational performance.

Recent research findings and reviews in the field of PAM [20] are taken into account and serve as a basis for building the proposed research model. Previous studies in this context contribute from different perspectives to understanding the role of PAM in enhancing operational performance. Many proponents of PAM [9] argue that mastering assets is a necessary and important investment and should be understood as a driver of business performance.

The paper is structured as follows. The outcomes and impacts of PAM with respect to earlier findings are described in Section 2. Section 3 describes the research process and methodology. An analysis of the PAM dimension (core practices) appears in Section 4; and the research findings are interpreted and discussed in Section 5. The development and validation of the research model is important for researchers and practitioners as it provides a summary of relevant issues that need to be considered particularly carefully during PAM implementation.

## 2. Background Literature and Hypothesis Development

In recent years, great efforts have been made to identify new competitive factors and issues that are important for excellence in asset intensive environments [21]. The latter can be supported by various theories. For example, the resource-based view (RBV) assumes that companies achieve competitive advantages by using their various resource bundles [22]. Earlier studies on PAM [23] emphasise that the development of resources and capabilities is of great importance in the process of gaining competitive advantages. Skinner [24] was the first to observe that companies could do more than just produce and ship products. He defined production goals as cost, quality, flexibility and delivery, which are now well-established priorities of competitive performance. El-Akruti et al. [25], for example, argued that the impact of inadequate or missing elements of the AMS framework could lead to negative effects on costs, productivity and quality and ultimately on business results. More recent research [3,4] also emphasised that AMS should follow formal guidelines (i.e., ISO 55001:2014), which is in line with institutional theory [26]. On the other hand, the stakeholder theory is based on the assumption that companies can only be considered successful if they provide added value to the majority of their stakeholders [27]. The summarized literature supporting the identification of PAM's core themes (study subjects) is presented in Table A1.

Operational performance has been widely recognized by researchers as a key source of competitive advantage [28]. In particular, operational performance refers to the organization's ability to reduce operating costs, meet order cycle time, improve raw material utilization efficiency and meet delivery capacity [29]. Although some of the literature refers to the link between various aspects of PAM and operational performance dimensions [9,30,31], the literature review revealed a lack of a holistic approach towards PAM and its link to operational performance. Accordingly, an empirical investigation of the relationship between PAM and operational performance is required. Despite a clear gap in empirical research on PAM practices and operational performance, the importance of PAM practices in relation to performance can thus be established. Effective PAM ensures the proper management of assets throughout their life cycle [9]. The latter is also consistent with ISO 55001, which points out that effective asset management is essential to create value by managing risks and opportunities in order to achieve the desired balance between cost, risk and performance. As found by the authors of [3], ISO 55001 AMS is linked to organisational performance, thus supporting the argument that commitment and engagement in AM ultimately lead to improved performance outcomes.

Komonen et al. [32] posit that PAM should be part of strategic management. They emphasised that AM strategy reflects the vision, values and mission of the company as well as the business objectives defined by stakeholders and incorporates information from strategic analyses and scenarios. Therefore, from a strategic perspective, organisations need to develop sources of competitive advantage throughout the development and management of the organisation's key assets. To build an effective AMS, an asset management policy, objectives and a strategic asset management plan (SAMP) are critical [10]. Another essential aspect is the availability and quality of information that is critical to all aspects of the AMS [33], as it can effectively support systematic decision making at all levels of the organisation [32]. Recently, due to advances in technology, interest in discussing information relevant to PAM has increased [34]. The efficient handling of existing and emerging risks is another relevant topic that is well discussed within the AM knowledge base [35–37]. Similarly, in recent years great attention has been paid to the assessment of asset performance [38]. The latter is also an important part of AMS, as it is crucial to define appropriate financial and non-financial measures to assess performance against organisational objectives [33]. Although there is certain agreement on what constitutes PAM practices [25], the challenge remains to provide rigorous validation of the PAM framework and evidence regarding the performance implication of PAM practices [39]. According to the previous theoretical underpinnings, each of the core constructs of PAM should bear a positive association with the organisation's performance [4,9,39]. As such, the literature suggests that PAM (particularly AMS in accordance with ISO 55001) can lead to improved financial performance, risk management, improved services and outcomes, and enhanced ability to demonstrate corporate and social responsibility [3,39].

Due to the current challenges and opportunities in industrial environments, more and more companies are directing their attention towards PAM [6]. Hence, PAM can be seen as an essential prerequisite for achieving world-class performance in any manufacturing facility [40]. Failure to do so can have serious health, safety and environmental (HSE) and financial consequences [41]. In many cases, profitability is increased by improving availability and preventing accidents (avoiding production stoppages and the loss of human or capital resources) [42]. In addition, ineffective asset and maintenance management could be attributable to issues such as lost profits due to lack of production during planned and unplanned stoppages, loss of customers, damage to reputation and consequently loss of market share due to maintenance-related factors leading to delivery delays and poor quality [43]. On the other hand, it has been argued that early phases such as the design of an asset also have a direct impact on its productivity. The latter concerns the minimization of disruptions such as unplanned outages [44]. Performance benefits can therefore be reflected in the form of added value and value retention in each life cycle phase and throughout the asset's life [40] and in the achievement of factors such as quality, cycle time, employee skills and productivity [45]. These holistic views of AM emphasize the importance of PAM rather than just asset maintenance [1]. However, maintenance plays a key role in PAM and is also a principal actor within Industry 4.0 [15,46] and a contributor to operational performance [47,48].

In light of the above discussion, there are theoretical arguments and support to link PAM, in particular, AM policy and strategy [21], life-cycle perspective [9], asset risk management [35,37,49], asset performance monitoring [50] and asset-related information management [13,51], to performance outcomes. Therefore, the PAM practices discussed above are crucial to the establishment of an efficient AMS, which can be an effective tool for organisations to improve both their operational performance and business efficiency. The study proposes the following hypothesis to support the above proposition:

**Hypothesis 1.** *Physical asset management core practices are positively and significantly related to operational performance.*

## 3. Research Methodology

This section describes important aspects of the study's research methodology. Accordingly, this section outlines the research design as a blueprint for sample and data collection, measurement and data analysis. Given the research objective, it was considered appropriate to adopt empirical research. In fact, empirical research allows the researcher to focus on the particular phenomena studied and to verify the validity of the proposed model [52]. Moreover, this approach provided an effective means for studying specific casual relationships between the PAM core practices and operational performance. Indeed, the aim of empirical research is to focus on the rigor, the reproducibility of the study, the reliability of the observation and the generalisability of the results [53].

The PAM, grounded in the operational performance perspective, provides the frame of reference of the present study, which focuses on the verification and validation of the underlying dimensions of PAM. In particular, this study responds to the need for theoretically grounded and empirically based models [4,23,39] that capture PAM core practices and their link to operational performance. Our research approach consists of several steps, namely literature review, definition of the research problem, hypothesis development, research design and survey implementation [54]. In particular, the following research activities were carried out: First, desk research was conducted; the findings from the literature review were used to specify the theoretical domains of the constructs. Accordingly, the research problem, the research purpose and the hypothesis were formulated, the conceptual framework that specifies the most important constructs studied (i.e., PAM core practices) was constructed, and insight was gained into the most important relationships between the constructs. Second, after developing the conceptual framework, the survey was constructed. For this purpose, relevant existing measures from the literature were selected [4,17,18,39,55,56]. The empirical research served to deepen the understanding of causal mechanisms between the constructs. Given the sampling strategy, asset-intensive industries were considered the most appropriate for this study to represent the population frame. Simple random sampling was used for data collection purposes [53]. Third, this paper applies Partial Least Squares Path Modeling (PLS-PM), which captures a rapidly increasing use in different management and business disciplines [57]. Finally, the results are discussed in terms of their contribution to the literature and possible future research avenues (see Section 5).

### 3.1. Sample and Data Collection

A questionnaire was developed to examine the impact of PAM core practices on operational performance. The data was collected through an on-line survey using the 1ka web survey platform (https://www.1ka.si/d/en). An online questionnaire was developed and distributed to organisations in six countries. During the design and implementation of the survey, the recommendations of the authors of [58] were followed. By considering criteria for survey design (layout, criteria for the arrangement of questions, questionnaire length, etc.) and implementation (personalized correspondence, principles for the design of an invitation letter), an intention was given to reduce possible sources of bias (e.g., item ambiguity, scale length, artifactual covariance between predictor and criterion variables, etc.) [58,59]. The survey was conducted as part of a research project involving six partner universities. The nominated researcher of each participating university was recruited as a contact person for this survey. In each country, the questionnaire was addressed to a manager who has primary responsibility for the operations management and who is competent in the organisation's PAM practices and in the assessment of performance outcomes. The organisations were selected via national business registers and e-mail addresses from the contact databases of the participating universities. Each survey coordinator had to ensure that a list of population members to be surveyed (sampling frame) was both up-to-date and obtained from a reliable source (business register mentioned above, etc.). Target organisations were randomly selected from databases of listed companies. A total of 138 managers responded to the survey, resulting in a response rate of 13%. The profile of the respondents is provided in Table 1. The questionnaire was answered by organisations based in Slovenia (31.9% of all respondents), Poland (34.1%), Greece (16.7%), Sweden (6.5%), Turkey (5.7%) and Slovakia (5.1%). The organisations surveyed covered all the industrial sectors surveyed. The majority (39.3%) of the organisations were classified as manufacturing industries according to the standard industrial classification, while other industries were spread across several industrial sectors (e.g., mining, retail trade services). The size of the organisations was categorized according to the guidelines of the Statistical Office of the Republic of Slovenia. The size of the organisation was described by the number of employees, which reached the following proportions of the total number of respondents: 51–250 employees = 31.3%, 251–500 employees = 21.7%, 50 or less employees = 17.4%, five or less employees = 12.2% and organisations with more than 500 employees = 12.2%.

**Table 1.** Profile of the respondents in our sample.

| Sample Distribution | | Fraction of Responses (in %) |
|---|---|---|
| Country of origin | Slovenia | 31.9 |
| | Poland | 34.1 |
| | Greece | 16.7 |
| | Sweden | 6.5 |
| | Turkey | 5.7 |
| | Slovakia | 5.1 |
| Organisation profile (No. of employees) | 0–5 | 12.2 |
| | 6–50 | 17.4 |
| | 51–250 | 31.3 |
| | 251–500 | 21.7 |
| | Over 500 | 12.2 |
| | Data not available | 5.2 |
| Industry type | Manufacturing | 39.3 |
| | Wholesale and Retail Trade, Repair of Motor Vehicles and Motorcycles | 16.2 |
| | Construction | 6.8 |
| | Mining and Quarrying | 6 |
| | Electricity, Gas, Steam, and Air Conditioning Supply | 2.6 |
| | Agriculture, Forestry, and Fishing | 1.7 |
| | Water Supply, Sewerage, Waste Management, and Remediation Activities | 0.9 |
| | Other | 26.5 |
| | Total | 100 (N = 138) |

### 3.2. Measures

The literature review provides the basis for the survey design. Survey items were adapted from the existing literature with appropriate amendments for the PAM context. Referring to PAM core practices, a set of 29 items was compiled (see Table A2). Self-reports of the studied variables (e.g., perceived PAM core practices and perceived operational performance) were chosen for this survey. Accordingly, respondents were asked to rate each item on a five-point Likert scale, ranging from strongly agree (i.e., 5) to strongly disagree (i.e., 1) with the various statements that measure the core PAM practices. In addition, an operational performance measurement scale (seven items) was used to measure the perception of the extent to which business results were achieved. The measures of PAM core practices and operational performance were taken from previous studies [4,18,55]. Key sources that were used for operationalisation of study constructs are summarized in Table 2. In addition, the measurement scales for environmental uncertainty and competitiveness [55,60,61] were used as potential instrumental variables (see Section 3.4). The questionnaire was reviewed by 7 academics and pilot-tested by an industry expert from a food manufacturing company based in Greece. All study scales were translated into local languages prior to their application. The items of the questionnaire were adjusted until a panel of experts agreed that the two versions (local version and English version) were comparable. The final version of the questionnaire consisted of three parts. The first part contained questions on company profiles. The second part contained statements on the degree of implementation of the PAM core practices. Finally, the third part dealt with the degree to which results were achieved in terms of operational performance.

**Table 2.** Study constructs and their corresponding key sources.

| Construct/Variable | Key Sources |
|---|---|
| Strategy and Planning | [4,17,18,25,32,55,62] |
| Risk Management | [4,5,17,18,37,55] |
| Lifecycle Delivery | [4,9,17,18,32,55,62] |
| Asset Information | [4,17,18,55,62] |
| Asset Review | [4,17,18,55,62] |
| Operational Performance | [31,56,63] |

### 3.3. Data Analysis

To test the research model and the proposed hypothesis, this study applies Partial Least Squares Path Modeling (PLS-PM), a variance-based structural equation modeling technique (SEM) [64]. The PLS-PM R-package was used to analyse the data and a two-step analysis approach was chosen. Therefore, two models were considered in the PLS analysis [65]: the measurement model (i.e., the outer model) and the structural model (i.e., the inner model). The composite reliability (CR), Cronbach's alpha (α) and Dijkstra–Henseler's rho (rho_A) were used in the measurement of construct reliability. It is important to note that CR, α and rho_A should be above the common standards of 0.7 [66]. Furthermore, convergent validity (average variance extracted—AVE) and discriminant validity (Fornell–Larcker criterion, cross-loading, Heterotrait monotrait—HTMT criterion) were assessed [67]. The results of discriminant validity indices together with the corresponding thresholds are presented in Section 4.

To model a second-order PAM construct, the molar model approach was used, which suggests that a higher order construct is considered to be composed of lower order latent variables. A two-step approach was used to model a second-order construct [65]. The first step involves calculating scores for the lower order constructs. Following the second step, the lower order latent scores are then used as indicators for the higher order construct in a PLS path model. In the first step, a Principal Component Analysis (PCA) was applied to obtain scores for the first-order latent variables. The calculated principal components are then used as indicators for PAM core practices (LV6) in the second step of the two-step approach.

The PLS-PM was selected mainly because this technique seems best suited to handle a composite measurement model [68] and to test a theoretical framework from a prediction perspective [69]. In addition, arguments from previous studies suggest that the PLS-PM technique is particularly suitable under conditions with small sample sizes [70].

### *3.4. Common Method Variance and Endogeneity Assessment*

Taking into account that data for both independent and dependent variables were collected at the same time, the common method variance could be a potential source of bias [59]. In this context, the Harman's single-factor test using exploratory factor analysis (unrotated principal factor analysis) was performed for all measured variables. The results showed that the total variance for a single factor was less than 50% (i.e., 38.2%), consistent with the arguments that common method variance in our data set should not be a significant problem.

The Durbin–Wu–Hausman specification test is used to assess the existence of an endogeneity problem in our data set. The challenge in estimating endogeneity is to choose instrumental variables that are independent of errors and correlated with endogenous explanatory variables [71]. It is possible that instrumental variables can also be identified outside the model under investigation [72]. Contingency factors (i.e., environmental uncertainty and competitiveness) were used as potential instrumental variables. The validity of the instrumental variables is judged by: (i) the Sargan–Hansen test of overidentifying restrictions (0.780, p-value 0.377); (ii) Hansen's J statistics (3.347, p-value 0.070). The above tests demonstrate the absence of significant endogeneity problems in our data set.

## 4. Results

### *4.1. Measurement Model Assessment*

To assess the validity and reliability of the measurement model, several indices were used, namely: loadings, cross-loadings, communalities, Cronbach's alpha, Dijkstra–Henseler's rho (rho_A), composite reliability (CR) and eigenvalues. The results of the evaluation of the measurement model are summarized in Table 3. In this study, the confirmations recommended in previous studies [65,66,69] were followed, with Cronbach's alpha ($\alpha$), rho_A and CR being 0.70 or higher for each construct. These indices were used to test the block unidimensionality. In addition, eigenvalues were taken into account when assessing the unidimensionality. The block is considered unidimensional if the first eigenvalue is greater than 1. It appears that all blocks of interest meet this criterion [65].

**Table 3.** Summary of the results regarding the measurement model.

| | Mode | Cronbach's Alpha | rho_A | CR | eig.1st | eig.2nd |
|---|---|---|---|---|---|---|
| Strategy and Planning (LV1) | A | 0.869 | 0.874 | 0.907 | 3.31 | 0.783 |
| Risk management (LV2) | A | 0.926 | 0.929 | 0.941 | 4.86 | 0.537 |
| Lifecycle Delivery (LV3) | A | 0.855 | 0.860 | 0.892 | 3.48 | 0.664 |
| Asset Information (LV4) | A | 0.826 | 0.835 | 0.878 | 2.96 | 0.657 |
| Asset Review (LV5) | A | 0.891 | 0.895 | 0.917 | 3.91 | 0.663 |
| PAM core practices (LV6) | A | 0.902 | 0.751 | 0.927 | 3.60 | 0.550 |
| Operational Performance (LV7) | A | 0.826 | 0.830 | 0.868 | 3.25 | 0.934 |

Note. A—reflective mode. eig.1st and eig.2nd—Eigenvalues of the indicators' correlation matrix. Rho_A—The most important reliability measure for PLS [66]. CR—composite reliability.

Furthermore, average variance extracted (AVE), which measures the amount of variance that a latent variable captures from its indicators, in relation to the amount of variance due to measurement errors [53], was used to evaluate convergent validity (Table 4). It appears that AVE mostly exceeded the acceptable thresholds of 0.5 [73].

**Table 4.** Average Variance Extracted (AVE), square root of AVE (in bold) and inter-construct correlations.

| Constr. | AVE | LV1 | LV2 | LV3 | LV4 | LV5 | LV6 | LV7 |
|---|---|---|---|---|---|---|---|---|
| LV1 | 0.663 | **0.814** | | | | | | |
| LV2 | 0.694 | 0.756 | **0.833** | | | | | |
| LV3 | 0.580 | 0.604 | 0.687 | **0.762** | | | | |
| LV4 | 0.592 | 0.589 | 0.586 | 0.605 | **0.769** | | | |
| LV5 | 0.651 | 0.646 | 0.627 | 0.650 | 0.761 | **0.807** | | |
| LV6 | 0.719 | 0.629 | 0.685 | 0.656 | 0.616 | 0.648 | **0.848** | |
| LV7 | 0.524 | 0.299 | 0.299 | 0.358 | 0.404 | 0.439 | 0.381 | **0.724** |

Note. AVE—Average Variance Extracted. Square root of the AVE (on the diagonal).

To assess the discriminant validity, the loading for each measurement item and cross-loading needed to be checked. The results show that the items load on their respective variables; therefore, the assumption of discriminant validity was fulfilled [74]. The results of the evaluation of the outer model (loadings, weights and communalities) for all constructs are presented in Table A2. In addition, tests such as the Fornell and Larcker criteria [73] and the HTMT criterion [75] were used to determine discriminant validity.

Table 4 shows that the inter-construct correlations in the model do not exceed the square root of the AVE, thus supporting the discriminant validity as proposed by the Fornell–Larcker criteria [73].

Furthermore, Table 5 indicates the discriminatory validity by HTMT ratio criteria. Henseler, Ringle and Sarstedt [75] suggested different thresholds of 0.90 [76] and 0.85 [77] for HTMT to determine discriminatory validity. It is suggested that $HTMT_{0.90}$ is an appropriate threshold value for structural models with constructs that are conceptually very similar [69]. Accordingly, the HTMT criterion of 0.90 was adopted in this study and discriminant validity was established because the HTMT ratio is below the critical value of 0.90.

**Table 5.** HTMT for discriminant validity.

| Constr. | LV1 | LV2 | LV3 | LV4 | LV5 | LV6 | LV7 |
|---|---|---|---|---|---|---|---|
| LV1 | - | | | | | | |
| LV2 | 0.832 | - | | | | | |
| LV3 | 0.700 | 0.767 | - | | | | |
| LV4 | 0.682 | 0.667 | 0.721 | - | | | |
| LV5 | 0.730 | 0.689 | 0.748 | 0.889 | - | | |
| LV6 | 0.830 | 0.863 | 0.889 | 0.857 | 0.863 | - | |
| LV7 | 0.328 | 0.315 | 0.400 | 0.454 | 0.487 | 0.496 | - |

Note. HTMT < 0.85 (Kline, 2011) [77], HTMT < 0.90 (Gold et al. 2001) [76].

In view of the above analysis, it can be argued that the constructs and the corresponding measures are valid and reliable.

### *4.2. Assessment of Structural Model*

Prior to evaluating the structural model, researchers have to ensure that there are no collinearity issues in the inner model. The values of the Variance Inflation Factors (VIF) for each construct in the inner model are well below the threshold value of five [67], thus implying that there are no significant collinearity issues.

In addition, the coefficient of determination $R^2$ is calculated for each endogenous latent variable (Figure 1). This coefficient determines the model's predictive capability and must be greater than 0.1 [78]. In addition, the Goodness-of-Fit (GoF) index could be calculated on the basis of the geometric mean of the average communality index and the average $R^2$ value [79]. The estimated GoF for our model is 0.61.

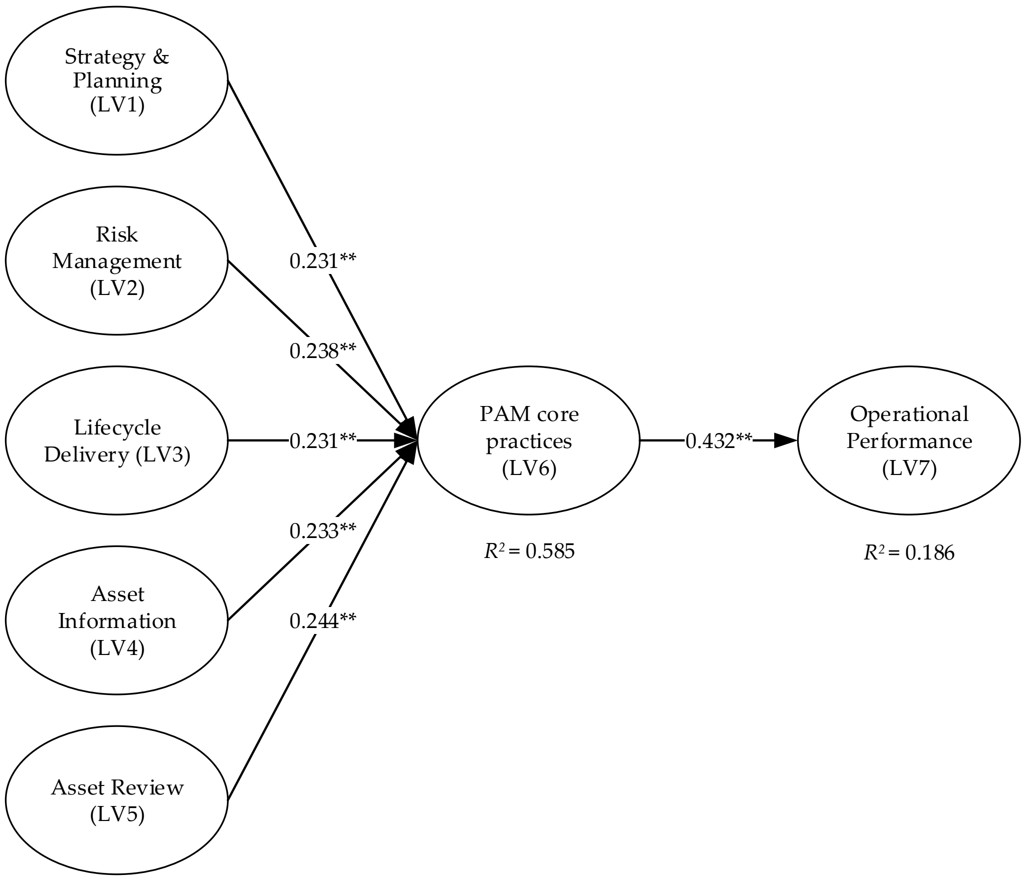


**Figure 1.** Structural (inner) model with path coefficients (Notes. ** statistically significant at the 0.01 level).

The next step in the PLS-PM analysis is the estimation of the specified structural equations. It should be noted that PLS-PM does not make any assumptions about the data distribution. Against this background, bootstrapping was also used as a non-parametric approach to estimate the precision of the PLS parameter estimates (Table 7). Table 6 and Figure 1 illustrate the path coefficients for the investigated research model, namely direct and indirect effects. The use of PAM as a second-order hierarchical construct confirms that the five layers of PAM significantly support the construct to capture the direct effect on operational performance (0.432, t = 5.58).

**Table 6.** Path coefficients.

| Path | Direct | Indirect | Total | t |
|---|---|---|---|---|
| LV1→LV6 | 0.231 | 0.0000 | 0.2308 | 2.23e + 02 ** |
| LV1→LV7 | 0.000 | 0.0996 | 0.0996 | |
| LV2→LV6 | 0.238 | 0.0000 | 0.2376 | 2.17e + 02 ** |
| LV2→LV7 | 0.000 | 0.1026 | 0.1026 | |
| LV3→LV6 | 0.231 | 0.0000 | 0.2313 | 2.39e + 02 ** |
| LV3→LV7 | 0.000 | 0.0999 | 0.0999 | |
| LV4→LV6 | 0.233 | 0.0000 | 0.2334 | 2.25e + 02 ** |
| LV4→LV7 | 0.000 | 0.1008 | 0.1008 | |
| LV5→LV6 | 0.244 | 0.0000 | 0.2435 | 2.17e + 02 ** |
| LV5→LV7 | 0.000 | 0.1051 | 0.1051 | |
| LV6→LV7 | 0.432 | 0.0000 | 0.4317 | 5.58e + 00 ** |

(Notes. ** statistically significant at the 0.01 level).

By amplifying the results of the structural model, a non-parametric bootstrap procedure could be given to estimate the accuracy of the PLS parameter estimates [65]. Therefore, a bootstrapping with 10,000 resamples was used to validate the structural model [80]. The results of the bootstrap validation of the structural model are shown in Table 7. As shown in Table 6, the original parameters of the path coefficients, the mean values of the parameters obtained from the 10,000 replications, the deviation of these estimates (i.e., standard errors), and the lower and upper percentile of the 95% bootstrap confidence interval are presented.

**Table 7.** Results of bootstrap validation of the structural model.

| Path | Original Path | Mean Boot | Std. Error | perc.025 | perc.975 | t-Statistic | *P* Values *** | Path coef. Sign. |
|---|---|---|---|---|---|---|---|---|
| LV1→LV6 | 0.231 | 0.230 | 0.00859 | 0.184 | 0.215 | 26.892 | 0.000 | Yes |
| LV2→LV6 | 0.238 | 0.238 | 0.00865 | 0.276 | 0.222 | 27.514 | 0.000 | Yes |
| LV3→LV6 | 0.231 | 0.231 | 0.00782 | 0.193 | 0.217 | 29.540 | 0.000 | Yes |
| LV4→LV6 | 0.233 | 0.233 | 0.00861 | 0.163 | 0.218 | 27.062 | 0.000 | Yes |
| LV5→LV6 | 0.244 | 0.244 | 0.00943 | 0.234 | 0.227 | 25.875 | 0.000 | Yes |
| LV6→LV7 | 0.432 | 0.448 | 0.05738 | 0.334 | 0.556 | 7.529 | 0.000 | Yes |

Notes. *** t > t (0.001; 9999); one-tailed test t (0.001; 9999) = 3.091.

As shown in Table 7, all interval coefficients (i.e., bootstrap estimates) are significantly different from zero at a significance level of 0.1%. It could therefore be argued that the results of bootstrap validation support the results of the structural model. In addition, the values of the t-statistics in Table 6 are calculated as the original path divided by the standard error from the bootstrap [64]. The significance of the path coefficients is examined based on the value of t-statistics and corresponding critical values of $t_{0.001}$.

## 5. Discussion and Conclusions

Research on PAM is burgeoning, yet our understanding of the consequences of PAM activities remains rather unclear. Despite the growing amount of literature in PAM, the empirical evidence supporting the PAM operationalization and the relationship between PAM and performance outcomes is surprisingly sparse. Therefore, this paper develops and presents a conceptual framework that links the PAM and operational performance. Our study contributes to the exploration of the underlying PAM mechanisms and complements the few studies that focus on the role of PAM in enhancing operational performance. In particular, the paper contributes to the literature by validating the framework using the PLS-PM methodology. The latent factors of PAM identified in the current study, i.e., the core PAM practices as reflected in LV1 to LV5, are compatible with the emerging frameworks (e.g., the asset management landscape published by the authors of [18] and standards (i.e., [10]) that strongly emphasize the integrated view of developing and maintaining asset management systems. More specifically, the identified PAM factors contribute to the efforts devoted to developing a knowledge base in asset management.

A hierarchical, second-order factor model was used to represent the construct of PAM. There are two main reasons for developing a second-order model, namely theoretical and empirical perspectives. First, the underlying theory [20,81] suggests that the components of PAM, such as strategy and planning, and risk and review, must be implemented in a holistic and not incoherent manner in order to be effective in achieving the desired results. A similar methodological approach is found, for example, in the modeling of Total Quality Management (TQM) as a second-order construct [82]. To support the empirical reasoning, it has been shown earlier that the PAM elements are strongly correlated, which supports the synergy between the elements [4]. Therefore, our study provides further confirmation of the validity of PAM as one set of integrated practices. Such integration appeals to the need to implement PAM practices as a whole across an organisation and not in a piecemeal manner, especially in terms of continuous improvement and ongoing value creation [5]. The results presented an $R^2 = 0.186$ for Operational performance (LV7), suggesting that 18.6 % of the variance in Operational Performance (LV7) is explained by its predictor construct (i.e., PAM core practices). The second order construct satisfactorily meets all acceptable criteria (Alpha = 0.902, rho_A = 0.751, CR = 0.927, AVE = 0.719) and acceptably represents the path coefficients of the first-order constructs of Strategy and Planning (LV1) (β = 0.231), Risk management (LV2) (β = 0.238), Lifecycle Delivery (LV3) (β = 0.231), Asset Information (LV4) (β = 0.233), and Asset Review (LV5) (β = 0.244). Using the bootstrapping method, the significance values were evaluated and are presented in Table 7. As shown by the results, the coefficients of the first order variables and the respective construct (i.e., PAM core practices) range from 0.231 to 0.244, exceeding the level of 0.1, and the *p* levels, less than 0.05, are significant, which shows the nomological validity of the construct [83]. This evidence supports the use of PAM as a second-order construct to represent all five elements of the PAM core practices.

The results of this study identify the key mechanisms that enable asset management and suggest that key PAM decisions and activities are supported by asset information, life cycle delivery, risk management, and performance evaluation and improvement (i.e., asset review). The results obtained by applying PLS path modeling reveal that PAM core practices have a statistically significant direct impact on operational performance (β = 0.432 **, t = 5.58). This result confirms the studies aimed at providing empirical evidence for the operationalization of PAM [62,84] and evidence for the performance outcomes of PAM [4,9,30]. Accordingly, the results of our empirical study illustrate the relative importance and interaction of core PAM practices and operational performance. Hence, our findings demonstrate the growing importance of PAM by providing evidence that organisations could benefit from focusing their efforts on PAM [19]. Further, AM improves the sustainability of an organisation by effectively managing expenditures and activities to achieve both short and long-term intended impacts, including the sustainability of operations and performance [85]. This concurs with theoretical arguments in the literature suggesting that PAM deployment should trigger benefits in terms of sustainability performance [4,86]. More longitudinal research is clearly needed to further clarify PAM's causal role. Although the present study is not directly related to the investigation of the ISO 55001 implications, the research results seem to complement those of [3]. They furthered the theoretical authenticity of PAM by examining and confirming the positive impact of ISO 55001 on the performance of organisations. By using and validating the PAM framework, our study deepens the understanding of the underlying PAM practices associated with performance outcomes. By finding support for this notion, our study provides new insights into what specific PAM core practices are required in organisations to develop, implement, coordinate, assess and improve the AMS. In light of the results of this study, it is clear that the sample organisations have adequate experience in PAM (as demonstrated by the introduction of PAM practices), although the diffusion of ISO 55001 certification, which is considered to be one of the important frameworks for setting up the AMS, is not yet at the desirable level. In general, previous studies and PAM survey reports indicate that organisations are determined to continue along the asset management journey, particularly in the face of strong competition, customer demands as well as potential economic downturn.

In the concluding remarks, it could be stressed that from an academic perspective, this paper extends the current state of knowledge in identifying and validating PAM's underlying factors and their relationship to operational performance. Furthermore, the application of the PAM model will provide a basis for putting the achievement of performance outcomes into a new context.

### *5.1. Managerial Implications*

The results of this study also provide practical implications for organisations wishing to develop or maintain a high level of excellence in PAM. The results of this study are relevant for both top management and those responsible for various functional areas such as asset management, maintenance, operations, quality, human resources and finance, particularly in the sense that it gives them an insight into the potential of the PAM practices. Several major contributions can be highlighted in this section as follows. Firstly, our findings offer an optimistic message to managers of organisations that are applying PAM practices as they can have a positive impact on operational performance. Organisations seeking improvement of PAM would achieve better results if they pursued a holistic and long-term asset management strategy to ensure operational excellence [19]. In particular, managers can use our PAM framework as a tool to assess their asset management maturity and as a guide for developing an AMS by considering how to improve their organisation's performance. In addition, managers can use our framework to diagnose their PAM status and develop appropriate action plans. It is further advised to adopt a Strategic Asset Management Plan (SAMP) to develop a high-level and long-term action plan. Furthermore, the empirical validation of our model suggests that managers should consider a systemic approach to implementing a PAM initiative. Such analysis allows managers to identify those PAM actions that will improve their competitive position by taking into account an integrative perspective on the interplay between PAM core practices.

### *5.2. Limitations and Future Research*

As with all other empirical studies, caution should be taken into account when interpreting the results and implications of this study due to possible limitations. First, our study uses perceptual data to measure PAM core practices and operational performance, and it is worth acknowledging the possibility that these data do not provide a completely accurate view of reality. Against this background, future studies could integrate multiple sources of information to minimize the potential bias in the response. Second, even though the study has invested considerable effort and time into developing PAM measures and the PLS-PM analyses meet most of the acceptable criteria, there is still room for improvement of the model. Accordingly, additional measures could be considered and control variables could be included in the study. For example, Industry 4.0 adoption could be utilized as a moderator of the impact of PAM on operational performance. Regarding the identification of possible instrumental variables, it should be noted that the selection of these variables in our study may not exactly match the necessary assumptions about these variables. Thirdly, a qualitative study based on interviews at different levels such as the strategic level, the tactical level and the operational level could be considered in order to gain deeper insights into the PAM approach of the organisations. Fourthly, despite the important implications that can be derived from this study, further research that would validate the usefulness and applicability of the PAM concept would be of great importance. Finally, a limitation in this study was also the concentration on organisations that are predominantly active in the manufacturing sector; however, this sector was specifically selected because the manufacturing sector is commonly acknowledged as an asset-intensive industry. Larger sample sizes and more specific research settings (e.g., by focusing on a particular industry or size of organisation) would definitely enrich the study.

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## Appendix A

**Table A1.** Literature summary.

| Reference | Methodology | Main AM Topics Studied |
|---|---|---|
| Amadi-Echendu et al. (2010) [1] | Literature review/Conceptual paper | A detailed characterization of the basic concepts of Engineering Asset Management (EAM) on the following topics is presented and discussed: Life Cycle Asset Assessment, AM Strategy, Risk Measurement, Safety and Environment and Human Factors. |
| Al Marzooqi, Hussain, and Ahmad (2019) [2] | Empirical study | The Analytic Hierarchy Process (AHP) is used to select and prioritize the most appropriate factors for PAM performance. |
| Alsyouf, Alsuwaidi, Hamdan, and Shamsuzzaman (2018) [3] | Empirical study | AM Key Performance Indicators (KPIs) and their impact on the organisational performance are examined. The study is based on ISO 55001 certified organisations. |
| Maletič, Maletič, Al-Najjar, and Gomišček (2018) [4] | Empirical study | PAM framework (consisting of four sub-constructs, namely PAM Policy and Strategy, Physical Asset Risk Management, Physical Asset Lifecycle Management, and Physical Asset Performance Assessment) is developed. The study examined the impact of PAM practices on sustainability performance. |
| Trindade, Almeida, Finger, and Ferreira (2019) [5] | Literature review/Conceptual paper | A formal and systematized value-based opportunity management process for asset intensive organizations is developed. |
| Schuman and Brent (2005) [9] | Case study | Asset life cycle management (ALCM) model for assets in the process industry is proposed and discussed. |
| de la Fuente et al. (2018) [14] | Literature review | The importance of new and advanced techniques to support decision-making in various business processes for maintenance and asset management is highlighted. In addition, a management framework with a clear process map and the corresponding IT supporting systems are proposed. |
| EFNMS-EAMC (2012) [17] | Report | Report based on EFNMS PAM survey. Main studied topics: Organisation and Decision-Making in the area of AM, Asset Knowledge Management, Policy and Strategy, Whole Life Costing (WLC) justification and Risk Analysis, Asset Lifecycle Management, AM Review and Improvement. |
| GFMAM (2014) [18] | Report | The report covers the key AM subjects, namely Strategy and Planning, AM Decision-Making, Lifecycle Delivery, Asset Information, Organization and People, and Risk and Review. |
| Gavrikova, Volkova, and Burda (2020) [23] | Literature review | A systematic review of the existing research through the analysis of over 700 articles devoted to asset management with a focus on strategic aspects is performed. |

**Table A1.** *Cont.*

| Reference | Methodology | Main AM Topics Studied |
|---|---|---|
| El-Akruti, Dwight, and Zhang (2013) [25] | Case study | AM model is developed and discussed (this includes identifying the strategy event, defining the asset solution and its provision, determining the asset performance and outcomes related to the strategy). Two case studies involving AM have been analyzed using a proposed model. |
| Komonen, Kortelainen, and Räikkönen (2012) [32] | Literature review/Conceptual paper | The main factors of industrial AM are outlined and discussed, namely physical asset creation and improvements (investments), use of assets and maintenance of assets. |
| Komljenovic, Gaha, Abdul-Nour, Langheit, and Bourgeois (2016) [37] | Case study | The high level Risk-Informed Decision-Making framework in AM that integrates risks extreme and rare events as part of an overall risk assessment and management activity is developed and evaluated based on two case studies. |
| Ratnayake and Markeset (2012) [41] | Literature review/Conceptual paper | In this paper, Asset Integrity Management (AIM) is cascaded down to design, operational and technical integrity management. Furthermore, the performance of physical assets (PA) is discussed in terms of financial, societal and environmental dimensions that deliver sustainability value to the assets' owner. |
| Emmanouilidis and Komonen (2013) [62] | Empirical study | Study is based on the EFNMS PAM framework. Main studied topics: lifecycle phase of surveyed industry, investment decision criteria, financial responsibility for AM, risk-based maintenance requirements, business risk management. |

## Appendix B

**Table A2.** Questionnaire items and outer model assessment statistics for PAM and operational performance.

| Variable | Weight | Loading | Communality | Redundancy |
|---|---|---|---|---|
| **Strategy and Planning (LV1)** | | | | |
| We apply asset management policy | 0.191 | 0.628 | 0.394 | 0.0000 |
| We develop asset management objectives | 0.255 | 0.848 | 0.720 | 0.0000 |
| We execute asset management strategy | 0.250 | 0.876 | 0.767 | 0.0000 |
| We undertake analyses of asset management policy to determine future production capacity | 0.260 | 0.851 | 0.724 | 0.0000 |
| We create strategic asset management plans including costs estimation | 0.265 | 0.842 | 0.709 | 0.0000 |
| **Risk Management (LV2)** | | | | |
| We continuously perform risk assessment of company's strategic objectives | 0.182 | 0.801 | 0.642 | 0.0000 |
| Risk management is an integrated part of asset management strategy | 0.174 | 0.845 | 0.715 | 0.0000 |
| We perform risk assessment in order to minimize business losses | 0.183 | 0.872 | 0.760 | 0.0000 |
| We embed risk into all activities which could affect assets performance | 0.157 | 0.842 | 0.710 | 0.0000 |
| We analyse equipment failure causes and effects to address risk | 0.173 | 0.820 | 0.672 | 0.0000 |
| We analyse operation, production, quality and logistic process and address risk | 0.167 | 0.828 | 0.686 | 0.0000 |
| We analyse IT-system, business system, human resources, competence, etc. and address risk | 0.163 | 0.821 | 0.674 | 0.0000 |
| **Lifecycle Delivery (LV3)** | | | | |
| We evaluate capital expenditure requirements considering whole life costs of ownership | 0.197 | 0.697 | 0.485 | 0.0000 |
| We assure quality of our assets during the whole life cycle phases | 0.214 | 0.785 | 0.575 | 0.0000 |
| We assure execution of maintenance processes within all assets' life cycle phases | 0.247 | 0.813 | 0.661 | 0.0000 |
| We continuously rationalise our assets to reduce production cost | 0.198 | 0.729 | 0.531 | 0.0000 |
| We continuously modernise our assets in accordance with our renewing/revision plans | 0.216 | 0.800 | 0.640 | 0.0000 |
| We execute disposal of assets in accordance with the asset management plan | 0.238 | 0.768 | 0.590 | 0.0000 |
| **Asset Information (LV4)** | | | | |
| We exploit information systems to support asset management activities (ERP, CMMS, AMS, or similar ones) | 0.223 | 0.687 | 0.471 | 0.0000 |
| Company collects and analyses data related to asset management activities | 0.260 | 0.770 | 0.594 | 0.0000 |
| We exploit asset history to enhance asset knowledge | 0.269 | 0.787 | 0.620 | 0.0000 |
| We undertake benchmarking to support asset management activities | 0.288 | 0.851 | 0.724 | 0.0000 |
| We search for external sources (e.g., partners, customers, research institutions) in order to obtain the newest knowledge and expertise | 0.256 | 0.741 | 0.550 | 0.0000 |
| **Asset Review (LV5)** | | | | |
| We monitor organisation's asset management performance | 0.176 | 0.650 | 0.423 | 0.0000 |
| We monitor condition of critical assets | 0.219 | 0.826 | 0.682 | 0.0000 |
| We regularly review overall efficiency of asset management activities | 0.210 | 0.831 | 0.691 | 0.0000 |
| We regularly review overall effectiveness of asset management activities | 0.213 | 0.874 | 0.764 | 0.0000 |
| We monitor key performance indicators (KPIs) to verify the achievement of organisation's asset management goals | 0.216 | 0.829 | 0.688 | 0.0000 |
| We proactively pursue continuous improvement of asset management activities | 0.203 | 0.813 | 0.661 | 0.0000 |

**Table A2.** *Cont.*

| Variable | Weight | Loading | Communality | Redundancy |
|---|---|---|---|---|
| **PAM core practices (LV6)** | | | | |
| Strategy and Planning | 0.233 | 0.843 | 0.711 | 0.7107 |
| Risk Management | 0.236 | 0.857 | 0.735 | 0.7348 |
| Lifecycle Delivery | 0.231 | 0.832 | 0.692 | 0.6920 |
| Asset Information | 0.234 | 0.836 | 0.699 | 0.6986 |
| Asset Review | 0.244 | 0.871 | 0.759 | 0.7587 |
| **Operational Performance (LV7)** | | | | |
| Unit cost of manufacturing has decreased during the last 3 years | 0.356 | 0.678 | 0.459 | 0.0856 |
| Cost of poor quality has decreased during the last 3 years | 0.165 | 0.717 | 0.514 | 0.0958 |
| Percentage of internal scrap and rework has decreased during the last 3 years | 0.273 | 0.795 | 0.632 | 0.1178 |
| On-time delivery performance has improved during the last 3 years | 0.198 | 0.723 | 0.523 | 0.0974 |
| Average lead time (from order to delivery) has improved during the last 3 years | 0.167 | 0.671 | 0.450 | 0.0839 |
| Flexibility to change product mix has improved during the last 3 years | 0.224 | 0.653 | 0.567 | 0.1057 |

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