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METHODS EVALUATING THE IMPACT OF STRUCTURAL HEALTH MONITORING ON AIRCRAFT LIFECYCLE COSTS

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Abstract

Today, 30 years after the introduction of the first aviation industry standard specifically dedicated to health management, modern aircraft are equipped with a variety of prognostics and health management applications. It is envisioned that structural health monitoring (SHM), as the next evolutionary step in aircraft health management, enables the achievement of zero downtime due to unscheduled maintenance events. Besides the avoidance of unscheduled maintenance, various other applications of SHM are discussed in literature, ranging from operational process improvements to new aircraft structure design philosophies. Due to potential cost savings, aircraft operators and manufacturers inherently take a strong interest in a detailed evaluation of the impact of SHM on operational processes and thus lifecycle costs (LCC). For the lack of compelling and credible business cases, the introduction of such technologies is inhibited in practice. In order to illustrate financial benefits, various methods evaluating the impact of SHM on aircraft LCC and operational processes have been proposed. While they offer extensive insight within their scope of research, their ability to consider interdisciplinary implications is intrinsically limited. By presenting a literature review of current evaluation methodologies, the work in hand seeks to answer the following principal research questions: Q1: What type of SHM-applications are being analyzed? Q2: What are the main challenges when analyzing the cost and benefit of SHM? Q3: What methodologies are employed to analyze the cost and benefit of SHM? To this end, an attempt is made to characterize and evaluate these methods with respect to their capabilities of correctly representing health monitoring characteristics, operational and organizational processes as well as influenced LCC. It is found that SHM constitutes a complex impact on aircraft and organizations while current studies primarily focus on individual aspects lacking the ability to identify benefits outside their scope of investigation. Depending on the employed methodology, the identified influence of SHM on aircraft lifecycle cost varies between studies and is inconsistent.

Nomenclature

AIT = Assembly, Integration & Test
AMC = Acceptable Means of Compliance
DLR = Deutsches Zentrum für Luft- und Raumfahrt
EASA = European Aviation Safety Agency
FAA = Federal Aviation Administration
GM = Guidance Material
IVHM = Integrated Vehicle Health Management
LCC = Lifecycle Cost
LRU = Line-Replaceable Unit
MPD = Maintenance Planning Document
MRO = Maintenance, Repair and Overhaul
MSG-3 = Maintenance Steering Group - Revision 3
NDT = Non-Destructive Testing
ROC = Receiver Operator Characteristic
SHM = Structural Health Monitoring

1. INTRODUCTION

In order to raise profits, airlines inherently take a strong interest in decreasing their direct operating cost [1]. Being responsible for 10-20 percent of the direct operating cost, maintenance is the biggest cost driver for airlines after fuel [2]. Various strategies are being employed to control and bring down costs, e.g. airlines traditionally pool different tasks into major checks to minimize the overall time an aircraft spends in maintenance and to avoid unnecessary additional shop visits [3]. The optimal inspection frequency can be formulated as a constrained minimization problem with inspection frequency and inspection quality being the primary influencing factors to minimize a pre-defined cost function [4]. Knowing a systems failure behaviour over time can significantly improve the results of the minimization problem. The desire to collect information about system malfunctions gave rise to System Health Management. System Health Management is defined as the capability of a system to preserve its ability to function as intended and emerged in aerospace applications in the 1950s with system engineering [5]. Later, this development led to built in test equipment (go or no-go testing and push-to-test) in the 1980s and condition-based maintenance in the 1990s [5]. Today, aircraft engines already provide airlines with diagnostic, prognostic and analytical capabilities in order to optimize their maintenance scheduling and to avoid an increased fuel burn through worn out parts [6]. Accordingly, Airbus estimates that by 2025 no aircraft will be on the ground because of technical faults and Integrated Vehicle Health Management (IVHM) comprising the continuous monitoring of all safety relevant aircraft components is seen as a key to achieve this goal [7]. Even though monitoring and prediction capabilities of aircraft engines already enable their integration into the business intelligence of organizations, structural components are not monitored in an operational environment, though proposed over four decades ago [6, 8, 9]. While a variety of technological solutions for structural health monitoring (SHM) in aviation has been proposed and validated, their usage in practice is very limited due to the lack of a profound business case [10]. In order to formulate a compelling business case, a variety of methods evaluating the financial impact of SHM

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has been proposed in literature. The pape specifically aims at analyzing, synthesizing and a structured analysis of current literature or evaluations of SHM for the use in aircraft. In orde a meticulous though not exhaustive literature re three phased approach described by Tranfie employed [11]. The presented work is thus st following: Chapter 2 provides background info SHM, the governing legal framework, Lifecycle models, operational aspects about maintenance overhaul and SHM sensor technology. Chapte the key research questions Q1 to Q3 for th research and chapter 4 introduces the methodology to conduct the literature review. presents results and findings while chapter 6 f concluding remarks to the presented work.

2. A NORMATIV PERSPECTIVE ON TH BACKGROUND OF SHM

The technological, organizational and financial impact of SHM is complex. The following chapter provides background information on suggested SHM applications, relevant parts of the legal framework governing SHM, an overview of lifecycle models, operational aspects of Maintenance, Repair and Overhaul (MRO) and principles in sensor technologies.

2.1. Possibilities of SHM

A multitude of potential applications for SHM has been suggested over the entire aircraft lifecycle. The continuous monitoring of structural components allows improved designs enabling lighter structures or the application of new materials while holding the current level of safety [12]. Further, it is proposed that SHM can decrease repair and scheduling cost, increase inspection intervals and reduce inspection time by monitoring the operational characteristics and detecting damages [13]. Additionally, it is anticipated that the reduction in uncertainties about the state of structural components can increase their remaining useful life [13, 14].

2.2. Legal Framework Governing SHM

Due to its influence on aircraft safety, various legal and regulatory frameworks are governing SHM. Primary legal sources are the Acceptable Means of Compliance (AMC) and Guidance Material (GM) by the European Aviation Safety Agency (EASA) and Title 14 of the federal code of regulations provided by the Federal Aviation Authority.[*] Depending on the functionality of the SHM application, relevant regulations for initial airworthiness as well as continued airworthiness have to be applied. The implementation of SHM is also supported by ARINC 604 “Guidance for Design and Use of Built-In Test Equipment” and ARP6461 “Guidelines for Implementation of SHM on Fixed Wing Aircraft” [15, 16]. Since the 2011.1 Rev 9 update of the maintenance steering group revision 3 (MSG-3) logic, a process exists to integrate SHM in the maintenance planning document (MPD) for inspections and functional checks [17]. According to the MSG-3 logic, SHM-systems can be classified by their operational mode in scheduled SHM and unscheduled SHM and by their technology type in damage monitoring and operation monitoring, as depicted in Figure 1 [18].

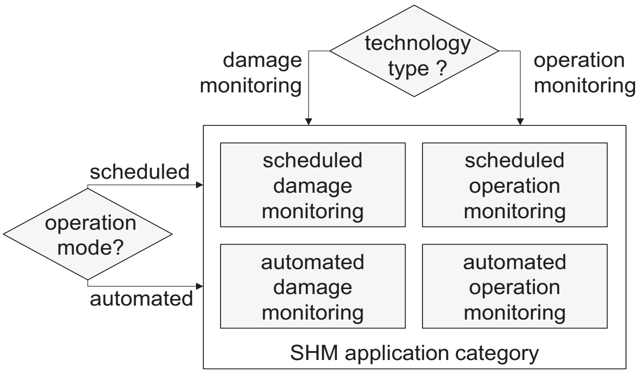

Figure 1: SHM Classification Matrix [18]

2.3. LCC Models

Similar to product cost estimation techniques, LCC models can be separated in qualitative and quantitative techniques, as shown in Figure 2 [19]. While intuitive techniques employ the past experience, analogical cost estimation techniques rely on similarity criteria based on historical data [19]. Parametric models on the other hand, are derived using statistical methodologies and by expressing costs as a function of its constituent variables [19]. The analytical approach relies on the decomposition of the estimated object into elementary units, operations and activities and expresses the cost as a summation of all these components [19].

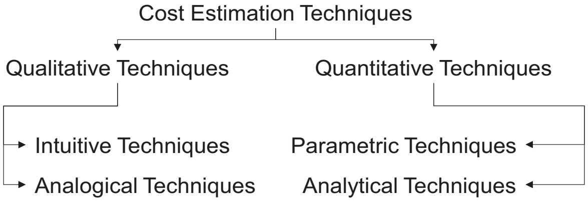

Figure 2: Cost estimation techniques [19]

2.4. Operational aspects of MRO

The main goal of MRO from an operators point of view is to provide a fully serviceable aircraft at minimum cost and optimum quality [20]. Even though the legislation does not provide any regulations as to how a maintenance organization has to be organized, MRO organizations are highly similar in practice [3]. Aircraft maintenance can typically be separated into line maintenance, covering smaller scheduled and unscheduled events, and base maintenance, typically covering letter checks from C-check upwards, modifications, implementation of airworthiness directives and structural inspections [3]. Finding the optimal tradeoff between operational utilization and maintenance of aircraft has already been formulated in the aircraft rotation problem [21, 22]. IVHM can aid in solving the aircraft rotation problem by providing further diagnostic and prognostic techniques and thus reducing inspection intervals and unscheduled maintenance events [5].

2.5. SHM Sensor Technology

A variety of SHM concepts has been presented in literature ranging from technologies relying on monitoring a damage dependent physical phenomenon to concepts based on

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[*] In regions outside of the legislative scope of the FAA and EASA, the local civil aviation authority is responsible for providing legal guidelines.

operational monitoring. The difference between the two concepts is illustrated in Figure 3. Regardless of the applied monitoring concept, the performance characteristics of an SHM system can be included into a cost benefit analysis by considering its physical properties (e.g. weight) and its Receiver Operator Characteristic curve (ROC-curve) [23]. The ROC-curve represents the relation between a systems probability of detection and probability of false alarms [24].

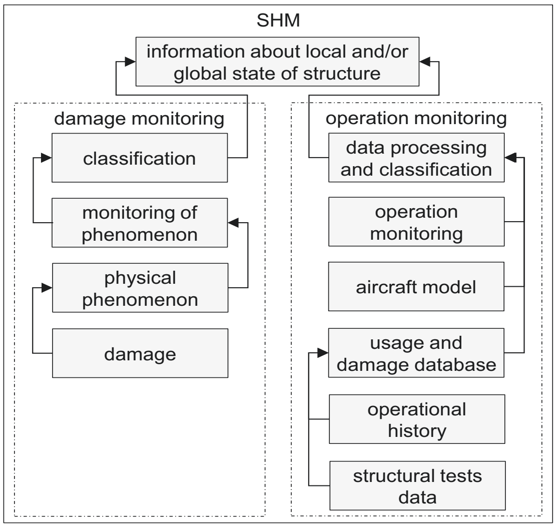

Figure 3: Difference between SHM based on damage monitoring and operation monitoring

3. PRINCIPAL RESEARCH QUESTIONS

The lack of a solid business case has been identified as the main reason why SHM still remains out of service [25]. Even though numerous studies have been presented finding a highly beneficial impact of SHM in terms of cost, various studies find the exact opposite [26, 27]. It is proposed that these contradicting results can in part be explained by the varying focus and applied methodologies used to determine the financial impact of SHM on LCC. First, the question about the main challenges when analyzing the cost and benefits of SHM is drawn up. Second, the question about the class of investigated applications is presented and third, the question about the type of methodologies applied to investigate the cost benefit of SHM is introduced.

3.1. Type of investigated SHM applications– Research Question Q1

A multitude of potential SHM applications in aircraft have been suggested while only a fraction have been investigated with regard to their potential financial benefits. The first primary research question aims at identifying the class of SHM applications investigated in current cost-benefit analysis.

3.2. Challenges in Evaluating the Financial Impact of SHM – Research Question Q2

Even though multiple promising SHM applications have been suggested in literature and are evaluated in field tests, their financial impact on organizations still remains unclear. This is in part attributed to challenges emerging when defining model boundaries, the level of regarded detail and the employed data. Since SHM only provides the means of generating additional information about the state of components, the manner of how the information is used depends on the purpose of the application. Therefore, the financial benefit is not solely driven by the technology but also the organizational circumstances in which it is applied. One aim of this literature review is to provide insight on how previous studies mitigate the challenges when evaluating the impact of SHM. The main challenges as described in Figure 4 can be summarized as following:

- Sufficiently setting the system and model boundaries according to the purpose of the study
- Regarding the technological performance of the sensor system and its inability to provide absolute information
- Correctly considering operative behaviour depending on the analyzed application
- Representing the required level of detail within the LCC model

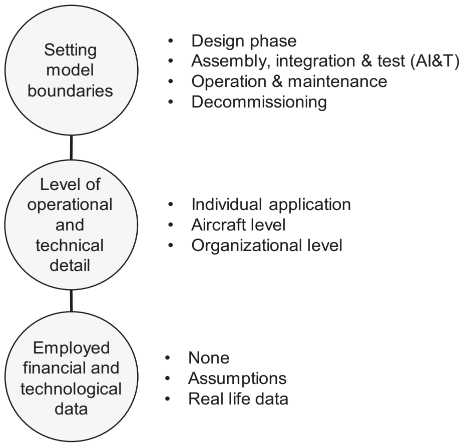

Figure 4: Challenges in evaluating the impact of SHM on aircraft lifecycle cost

3.3. Methodologies Evaluating the Financial Impact of SHM – related to Q3

When conducting a cost benefit analysis for SHM, different methodologies can be applied depending on the investigated application and target audience. The applied methodologies can be distinguished by their cost-estimation technique and their regarded model inputs as depicted in Figure 5. The considered in- and outputs depend on the investigated application and vary.

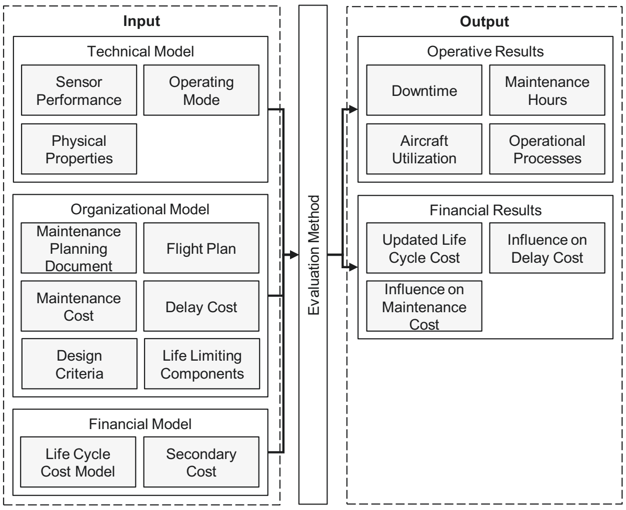

Figure 5: Generalized model in- and outputs when determining the financial impact of SHM

With regard to the literature research, it is proposed to group the employed methodological approaches into four categories as depicted in Figure 6:

1. Holistic approaches: Considering sensor performance, lifecycle cost and organizational processes equally
2. Sensor centric approaches: Applied methodologies primarily considering sensor functionality, sensor performance and sensor maintenance requirements.
3. Process centric approaches: Applied methodologies primarily analyzing the influence on processes and organizations as a result of SHM
4. Life cycle cost modelling centric approaches: Applied methodologies primarily focusing on financial positions that are influenced by SHM.

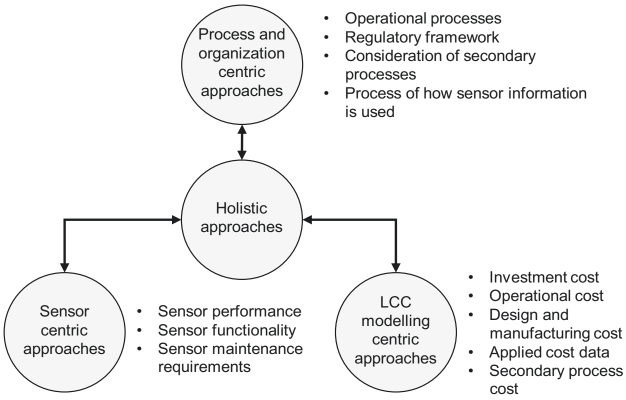

Figure 6: Different categories of methodological approaches evaluating the financial impact of SHM

4. RESEARCH METHODOLOGY

The lack of promising business cases has already been identified as the main obstacle in introducing SHM into commercial service [28]. Consequently, a variety of methods has been suggested to evaluate the financial impact of SHM on aircraft LCC to establish the foundation of a business case analysis. The work at hand aims at providing a comprehensive review of these methods. The following chapter describes the three phased methodology suggested by Tranfield et al. utilized to conduct the literature review [11].

- Phase 1: Planning the review process: Identification of need and aim for the literature review (chapter 1), preparation of a proposal for a review (chapter 3) and development of a review protocol (chapter 4)
- Phase 2: Conducting the review process: Identification, selection, quality assessment and data extracting of relevant studies (chapter 4).
- Phase 3: Results and findings: Reporting of findings in order to answer the main research questions (chapter 5).

4.1. Phase 1 – Planning the review process

The first step of defining the need for a structured literature review is provided in the introduction as well as in sections 3.2 to 3.3. In the second step, relevant literature is identified by querying the Scopus database containing over 22.500 titles covering SHM, with the following keyword:

- (ALL (("financial impact" OR "Cost-benefit analysis") AND "Condition-based Maintenance" AND (aircraft OR aviation))) OR
- (ALL ("Structural Health Monitoring" AND aircraft AND financial W/15 impact)) OR
- (ALL ((aviation OR aircraft) AND "Structural Health Monitoring" AND ("Cost-Benefit Analysis" OR "Cost Benefit Analysis" OR "Economic analysis" OR "business case analysis" OR "financial impact analysis"))) OR
- (ALL (("Integrated vehicle health management" OR "IVHM") AND (aviation OR aircraft) AND ("structural health monitoring" OR SHM) AND ("Cost-Benefit Analysis" OR "Cost Benefit Analysis" OR "Economic analysis" OR "business case analysis")))

The third step includes the research protocol which is comprised of several conditions as to how the literature for this review is selected, considering the approach for quality assurance suggested by David & Han 2004 [29]:

- Condition 1: Only articles published in English between 2000 and 2018 from the following subject areas have been selected for this review: Engineering, Computer Science, Materials Science, Mathematics, Business, Management and Accounting as well as Physics and Astronomy.
- Condition 2: In order to focus on enhancing quality control, only articles published in peer-review journals have been considered.
- Condition 3: Articles have to include the phrases “structural health monitoring” and either “cost-benefit analysis” or “economic analysis” or “business case analysis” in either title, abstract or keywords.
- Condition 4: Only articles in the context of aviation are considered in the review
- Condition 5: Due to the focus of the literature review, articles exclusively covering rotorcraft without considering fixed-wing aircraft are excluded from the review.
- Condition 6: Only articles that cover SHM as their primary focus are considered in order to neglect publications where SHM appeared only as a reference.

4.2. Phase 2 – Conducting the review process

Searching the Scopus database for the keywords presented in 4.1 yielded a total of 195 results in July 2018 and 178 considering duplicates. Applying the conditions 1 to 6 described in 4.1 further reduces the results to 46 articles with an h-index of 7. Subsequently, an in depth qualitative review of the identified articles has been conducted in order to gain insight on the following subjects:

- *Research landscape*: General information about the selected literature including meta data and background information are presented.
- *Investigated applications*: SHM applications investigated within the scope of this literature review are summarized and the limits to individual studies are pointed out.
- *Challenges in evaluating the impact of SHM*: insight on how previous studies mitigate the challenges when evaluating the impact of SHM.
- *Types of employed methodologies*: Four categories of methodologies to assess the impact of SHM on aircraft LCC are presented. The metrics applied to evaluate and categorize the reviewed methodologies is described in Appendix A.1.

5. RESULTS AND FINDINGS

The following chapter presents the results and findings of the literature research. Section 5.1 summarizes general findings of the reviewed literature. Section 5.2 includes the analyzed SHM applications and section 5.3 outlines how reviewed studies mitigate the challenges in evaluating SHM. Finally, section 5.4 presents the employed methodologies in evaluating the impact of SHM on aircraft LCC.

5.1. Summary of reviewed literature

The following sections provide meta data about the reviewed literature and general insight on the evaluated methodologies and tools.

5.1.1. Meta data of surveyed literature

Figure 7 illustrates the publications by year and Figure 9 shows their geo-spatial coverage. Figure 10 contains the affiliation of authors and Figure 8 the type of publication.

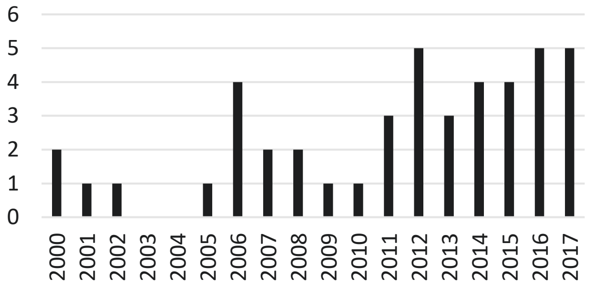

Figure 7: Number of published articles by year until 2017

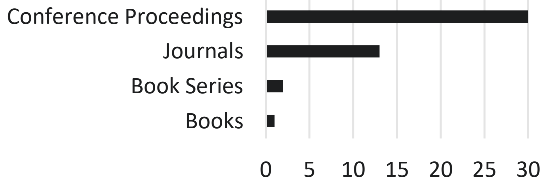

Figure 8: Type of publication

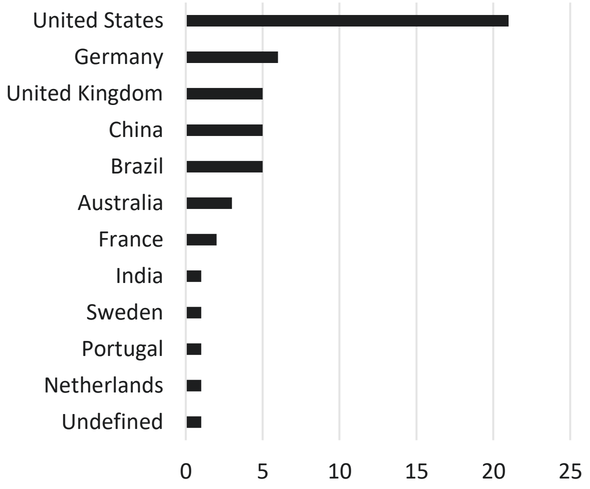

Figure 9: Geo-spatial coverage of the literature by publishing country

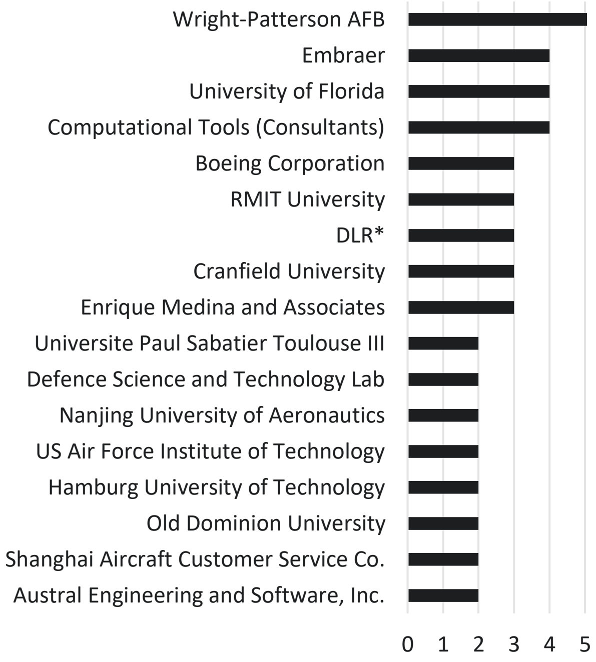

Figure 10: Institutions with more than two contributions included in the literature review

5.1.2. Research landscape

Of the 46 reviewed articles, 18 are solely descriptive (39 percent), 6 employ analytical cost estimation techniques (13 percent), 21 employ parametric cost estimation techniques (46 percent) and one uses an intuitive cost estimation technique (2 percent), summarized in Figure 11.

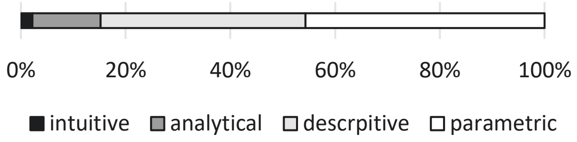

Figure 11: Employed cost estimation techniques

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* German Aerospace Center

The numerical methodologies rely on the commercially available software Arena and Matlab as well as the proprietary software tool "risk-based design and maintenance system" (RBDMS) by Boeing and the self developed tool VirtualNDE. Further Lockheed Martin developed the "JSF prognostic tool" for the joint strike fighter program. 21 (46 percent) of the analyzed studies cover SHM within the context of an integrated health monitoring system and 25 (54 percent) articles are primarily analyzing SHM. With 24 articles (52 percent), the majority has a background in civil aviation, 15 (33 percent) are not specifying their background and 7 (15 percent) have a military background, as depicted in Figure 12. Further, the review literature was comprised of 16 case studies (35 percent) and 30 generic studies (65 percent).

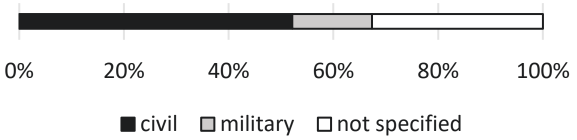

Figure 12: Background of reviewed literature

5.2. Types of evaluated SHM applications

The majority of the reviewed literature covers maintenance with 38 articles (83 percent), 4 articles (9 percent) contain general suggestions about SHM, 2 articles (4 percent) cover improved safety and 2 articles (4 percent) cover improved information about the system. In accordance, 40 (87 percent) articles cover the aircraft in the operational phase while only 6 (13 percent) focus on additional lifecycle phases. Even though the vast majority of methodologies analyzing SHM during the operational phase of an aircraft, only 21 (46 percent) consider operative behaviour in their analysis. Figure 13 illustrates the investigated SHM applications.

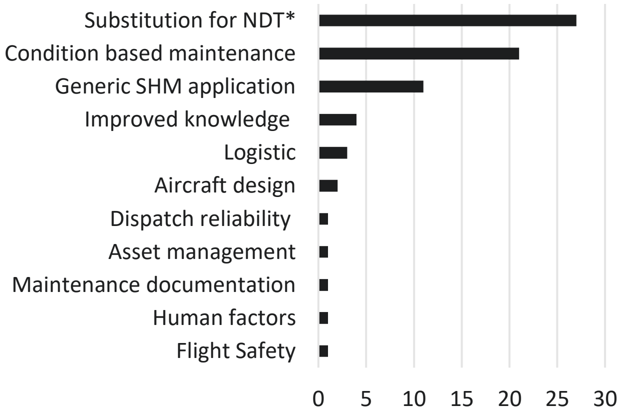

Figure 13: Analyzed SHM application by category (multiple assignments allowed)

5.2.1. SHM as substitution for non-destructive testing

Different strategies and applications to integrate SHM as a substitution for NDT have been suggested. Murphey et al. 2000, Aldrin et al. 2006, Medina et al. 2006, Fitzwater et al. 2011 and Pattabhiraman et al. 2011 suggest dropping selected maintenance tasks by using SHM. Malere et al. 2013 suggest SHM to avoid unscheduled removals and automate the documentation of the evaluation process. Torng et al. 2013 point out the effects SHM sensor degradation can have on the lifecycle cost while Albinali et al. 2014 study the relation between crack growth in structures. Additionally, they investigate the probability of detection of SHM equipment on the resulting false alarm rate and its influence on lifecycle cost.

5.2.2. Condition based and prognostic maintenance using SHM

Repeatedly gathered information about the structural health can be used to predict failures and thus enable prognostic maintenance to mitigate unscheduled events. Pattabhiraman et al. 2012 and Chen et al. 2014 compare the influence of scheduled, prognostic and condition based maintenance enabled by SHM. Besides describing a multitude of benefits connected to SHM, such as improved dispatch reliability, reduction of scheduled maintenance task cost, reduction of secondary damages and reduction of maintenance induced failures, Leão et al. 2008 point out the reduced no-fault-found rate by using prognostic SHM solutions.

5.2.3. Improved logistics as result of SHM

The capability of SHM to provide information about the state of structural components during regular operation before the aircraft enters maintenance, offers additional time and information to the logistical function of the organization and thus enables optimizations within the supply chain. Vandawaker 2017, Cai et al. 2017 and Malere et al. 2013 analyze the influence of SHM on the supply chain and inventories of maintenance organization.

5.2.4. Enhanced information

With an increasing degree of automated processes and products in organizations, digital available information becomes key in generating value [30]. Leão et al. 2008, Feldmann et al. 2009, Li et al. 2016 and Cai et al. 2017 note that SHM is not an isolated system but integrates into various functions of aircraft and airlines.

5.2.5. Validating aircraft design

Leão et al. 2008 and Lloyd 2008 point out the benefits of utilizing SHM to validate dimensioning criteria used during the design phase of the aircraft. Additionally, SHM can aid in complying with failure probability requirements when optimizing lightweight structures.

5.2.6. Further benefits of SHM

In addition to the aforementioned benefits, SHM can yield a variety of additional benefits. Fitzwater et al. 2011 mention a possible increase in dispatch reliability and thus combat readiness of military aircraft. Benefits are also expected by improving asset management through a more detailed understanding of the health state and the automation of maintenance reporting processes as pointed out by Leão, et al. 2008 and Malere et al. 2013. Duarte et al. 2016 and Aldrin et al. 2007 prompt the possibility of increased flight safety and reduced opportunities for human error when automating the NDT process with SHM.

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* NDT = Non-Destructive Testing

5.3. Challenges in evaluating the financial impact of SHM

The integration of SHM into aircraft requires a rigorous scrutiny of the systems technological properties and desired application. Therefore, methods evaluating the LCC impact have to consider the scope of their investigation, regard the technological performance of the investigated sensor systems and mind operating and maintenance behaviour of the system as outlined in 3.2.

5.3.1. Definition of scope and level of model detail

A multitude of potential SHM applications has been suggested in literature for different purposes over the entire lifecycle of an aircraft. Consequently, the published studies vary in scope and assumed model boundaries. Methodologies evaluated within the literature research regard the impact of SHM only to a varying extent. Relating to their considered scope, they are categorized in Figure 14 using the following definitions.

- Application specific boundary conditions include the consideration of technological coherences and requirements resulting from the individual SHM system.
- Additionally, aircraft specific boundary conditions consider boundary conditions stemming from the integration of the system into an aircraft such as increased fuel burn through additional weight or legal requirements.
- Additionally, organizational and operational specific requirements consider scheduling and support processes necessary to operate the aircraft, such as maintenance, logistics and supply.
- Studies disregarding boundary conditions or not fitting any of the descriptions above are categorized as unassignable.

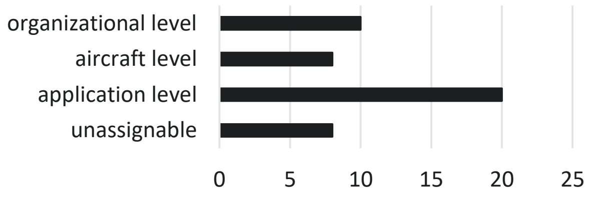

Figure 14: Considered hierarchical level of reviewed literature

Furthermore, Figure 15 illustrates the lifecycle phases, considered in the evaluated studies.

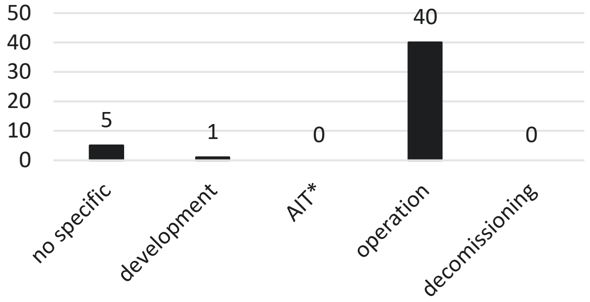

Figure 15: Lifecycle phase considered by reviewed literature*

5.3.2. Selection of research approach

Besides defining the scope and level of detail, an appropriate research approach has to be selected to evaluate the financial impact of SHM. Figure 16 illustrates the cost-estimation techniques employed by the reviewed methodologies. Analytical methods are only applied when considering individual applications or aircraft, whereas studies considering organizational issues are not utilizing analytical cost-estimation techniques. With an expanding scope of research, the cost estimation techniques shift from quantitative to descriptive.

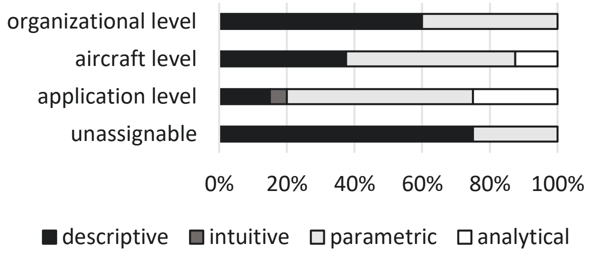

Figure 16: Cost estimation techniques of reviewed literature by hierarchical level

As described in chapter 1 and chapter 2, SHM can also be considered as subsystem of an IVHM system. Figure 17 illustrates the context in which SHM has been evaluated within the reviewed literature.

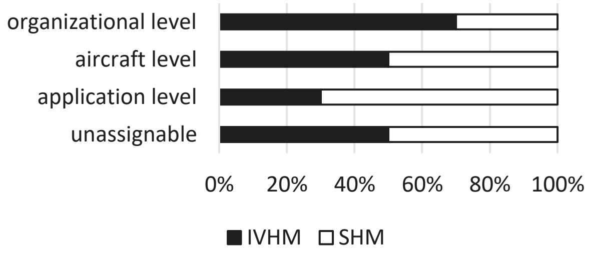

Figure 17: Context of investigated SHM system

Figure 18 illustrates the focus of the reviewed literature divided in case study and generic approaches.

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* AIT = Assembly, Integration & Test

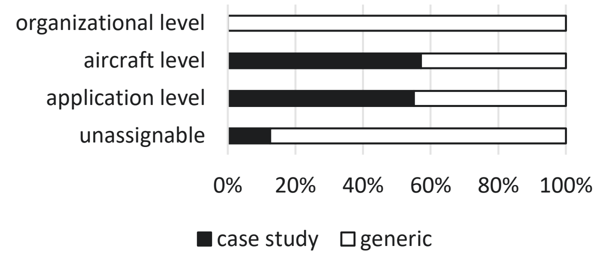

Figure 18: Study approach of reviewed literature

As constituted in Figure 15 the majority of methodologies proposed to evaluate the impact of SHM on LCC focuses on the operative phase of an aircraft. Hence, Figure 19 illustrates the consideration for operative processes and behaviour of applications, aircraft and organizations within the proposed methodology.

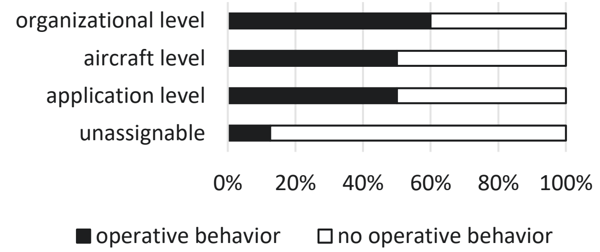

Figure 19: Consideration for operative behaviour in reviewed literature

Employing the scoring method described in Appendix A.1, each reviewed article received a score depending on the considered detail for technological functionalities of the SHM system. Figure 20 illustrates the results grouped by considered hierarchical level. Methodologies possessing a wider scope are not necessarily employing less scrutiny to technological considerations.

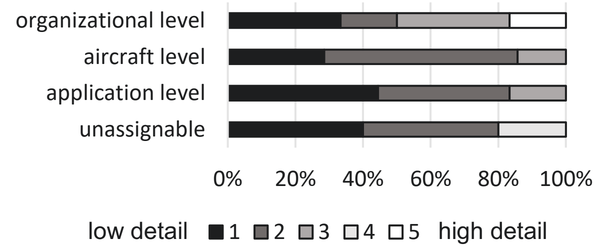

Figure 20: Level of technological consideration of reviewed literature

5.3.3. Utilized data

As illustrated in Figure 5, the economic evaluation of SHM relies primarily on three inputs: sensor performance and properties, information about the environment (e.g. operative behaviour of the aircraft) and cost data. The following section summarizes the consideration for required inputs of the reviewed literature. Figure 21 illustrates information used by the reviewed methodologies to consider technological implications of the SHM system.

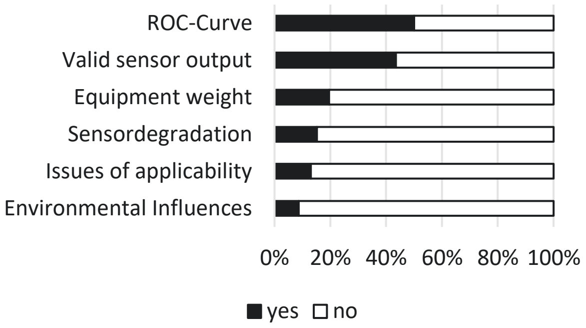

Figure 21: Consideration for technological influences

Depending on the focus of the reviewed methodology, application specific background information has to be considered. Three categories have been investigated as a proxy for the organizational environment, depicted in Figure 22. “General assumptions” reflect application specific environment information, e.g. schedule constraints when considering operative behaviour or manufacturing requirements when using SHM to influence the design process. “Support processes” include information about organizational functions only remotely influenced by SHM, e.g. logistics when using SHM as NDT substitution in MRO. The category “SHM requirements” represents the considered organizational boundaries that influence the usage of investigated SHM systems.

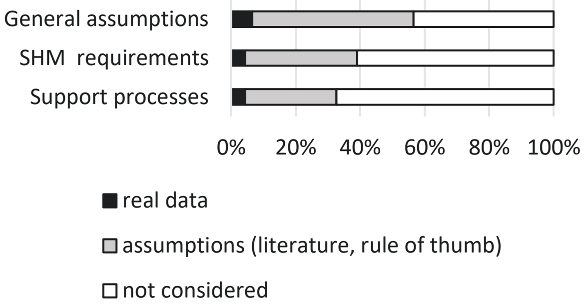

Figure 22: Consideration for processes and organizational environment

Additionally, the methodologies evaluating the impact of SHM on LCC have to include financial data to estimate potential savings and losses. Figure 23 illustrates how aircraft structures and SHM sensors are being considered in terms of cost in the reviewed literature.

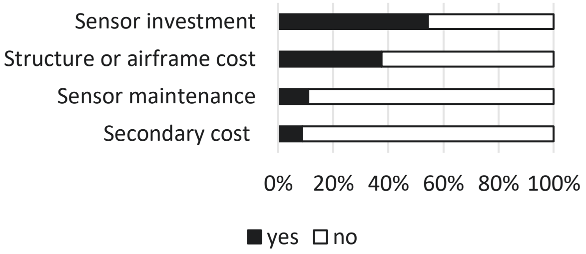

Figure 23: Types of cost considered for SHM equipment and aircraft structure

5.4. Methodologies evaluating the financial impact of SHM

The following section describes the methodologies put forward in the reviewed literature to evaluate the impact of SHM on aircraft LCC. Based on a qualitative assessment of the reviewed literature, the suggested evaluation approaches are clustered into four groups. The resulting categories are presented in 5.4.1, with their content subsequently described in 5.4.2 to 5.4.5.

5.4.1. Categorization of methodologies

The literature selected for the review has been evaluated utilizing the approach described in Appendix A.1. Consequently, each reviewed publication received a score in the dimensions technology, processes and organization as well as cost. The scores have been normed to the highest achievable score. It is recognized that the resulting scores depend on the choice of evaluation metrics and their individual weighting. Subsequently, the investigated methodologies have been grouped into four categories using k-means clustering [31]. Figure 27 in Appendix A.3 displays the resulting groups of methodologies. Figure 26 in Appendix 0 illustrates the total within cluster sum of squares depending on the number of categories set for clustering. Choosing more than four clusters only marginally improves the accuracy while four categories can be explained by the evaluation approaches identified in literature. The centers of the identified clusters on the introduced three-dimensional scale are summarized in Table 1.

Table 1: Center of calculated clusters on normalized scale

Methodology	Technological dimension	Procedural dimension	Lifecycle cost dimension
Process and organization oriented	0.07	0.29	0.03
cost oriented	0.33	0.16	0.26
Technology oriented	0.61	0.47	0.06
Holistic	0.33	0.49	0.42

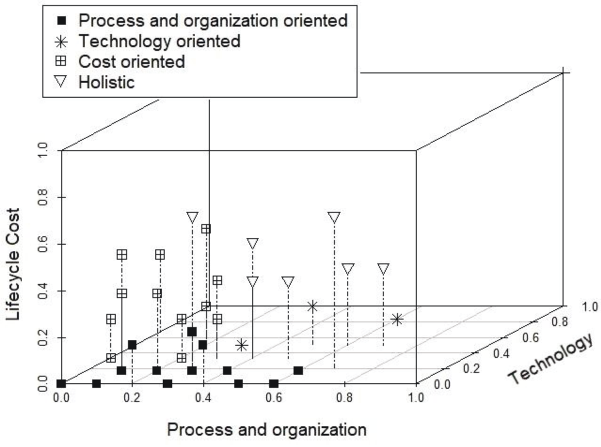

Figure 24: Clustering of methodologies according to their focus

5.4.2. Process and organization oriented methodologies

Process and organization oriented methodologies predominantly consider legal and procedural requirements when introducing SHM into aircraft systems. 18 methodologies investigated fall under the category "process and organization" oriented with 13 of them following an entirely descriptive and 5 a parametric cost-estimating approach. Lloyed [32] and Dos Santos [33] summarize general legal and procedural requirements for the introduction of SHM while Mukkamalla et al. [34] additionally identify relevant user groups for such a system. Duarte et al. [35] mention the effects SHM can have in the scope of failure analysis and its contribution to flight safety. Jata et al. [36] describe the issues and challenges of transitioning to the usage of SHM and Sebastian et al. [37] derive an IVHM system including SHM from relevant SHM requirements. Cai et al. [38] consider the influence SHM can have on stock keeping in maintenance and logistics. Dhanisetty et al. [39] propose a decision support tool that employs a relative survivability-cost ratio in order to determine repair levels for composite structures, while Thyagarajan & Gollnick [40] integrate proportional hazard modeling into the repair decision support model. Dos Santos [41] describes the relevant processes Embraer deems relevant for the introduction of SHM while Rulli et al. [42] identify possible application scenarios considering different SHM technologies for Embraer. Kapoor et al. [43] and Hongsheng et al. [44] describe and evaluate the introduction of condition based and predictive health monitoring applications into selected maintenance processes. The quantifiable findings within the process and organization oriented methodologies vary. Dos Santos [41] estimates potential savings of 120 to 250 hours every 12,000 FC for substituting the internal visual inspections of the rear passenger and service door cutout structures with SHM for E-Jet family aircraft. Based on the analysis of a maintenance planning document, Kapoor et al. [43] identify critical process blocks hard to reach for manual inspection within the D-check and estimate that SHM can potentially save up to 9.4 hours in maintenance. Additionally they identified potential drop out candidates that can save up to 276 hours of maintenance over the aircraft lifetime.

5.4.3. Technology oriented methodologies

As presented in Table 1, technology oriented methodologies focus on the technological coherences of SHM when evaluating the impact on LCC. Within the scope of this literature research three articles contain a primarily technology oriented methodology. Keller et al. [45] introduce a sequential prognostic cost-benefit analysis process that includes the identification of wear mechanism and degradation modes of materials. Even though they focus on IVHM, the proprietary tool developed is capable of incorporating SHM systems. Vandawaker et al. [46] analyzes "the impact of prediction accuracy uncertainty in remaining useful life prognostics" though not considering lifecycle cost in the first approach. Amongst other aspects of SHM, Lloyd [47] draw up technical issues including system performance, reliability, environmental performance, data management and performance verification. Studies presented within this category are not quantifying the benefit of SHM in terms of LCC.

5.4.4. Cost oriented methodologies

Within this literature review, 15 articles fall into the category of cost-oriented methodologies. Esperon-Miguez et al. [48] suggest to employ modern portfolio theory – introduced by Markowitz – to optimize the combination of different SHM systems [49]. Aldrin et al. [50] compare the influence of human factors on SHM and NDT systems. Fitzwater et al. [51] find that SHM can decrease the maintenance cost of a F-15 bulkhead by 52 percent. Chen et al. [52, 53] find that maintenance strategies based on SHM can influence the maintenance cost between - 34 percent and + 150 percent of its original value. For a case by case analysis of SHM, Halbert et al. [54] find an increase in application specific lifecycle cost of up to 87 percent. Therefor they propose to investigate additional secondary effects of SHM such as improved logistics. When substituting selected maintenance tasks within the fuselage of an commercial aircraft, Dong & Kim [26] estimate that the cost caused by additional weight of the SHM system exceed the benefits by a factor of 5. Chen et al. [55] estimate the cost benefit of different condition based maintenance strategies enabled by SHM for a composite wing to 33 percent.

5.4.5. Holistic methodologies

Holistic methods equally regard technological, procedural and organizational as well as financial considerations. Feldman et al. [56] investigated prognostic and health monitoring technologies and find that they are likely to be used to monitor dissimilar Line-Replaceable Units (LRU). Pattabhiraman et al. [57, 58] propose cost savings of USD 8 million over the entire lifecycle of an A320 type aircraft by using SHM without regarding secondary processes like logistics. Sun et al. [59] quantify SHM benefits with regard to safety levels and find a 42 percent decrease in maintenance cost for S-SHM with an acceptable safety level and a decrease of 30 percent in maintenance cost without an impact on the aircraft safety level. Hölzel et al. [27, 60, 61] investigate the impact of SHM using the Aircraft Technology and Operations Benchmark System (AirTOBS). AirTOBS includes a flight and maintenance schedule builder allowing the investigation of the impact SHM technologies have on aircraft operating behaviour and thus cost. Hölzel et al. find that overall maintenance cost stay constant while delay cost decrease by 60 percent. Their findings indicate that the strongest cost influence stems from the probability of detection a system offers. Additionally, Vandawaker et al. [62] raise the issue of secondary benefits enabled by SHM, e.g. improved stock keeping of spare parts.

5.4.6. Summary of quantitative findings

Within the reviewed literature a variety of potential SHM applications are reviewed. However, the investigated financial impact is inconsistent. This is in part due to the investigated application itself but also the challenges associated with the financial evaluation of SHM as described in section 3.2 and section 5.3. To this end, Figure 25 compiles the quantitative findings of the reviewed literature, assuming maintenance costs of USD 610 per flight hour, average labor costs of USD 75 per hour and total maintenance cost of USD 55 million for an A320 type aircraft over its entire lifecycle.

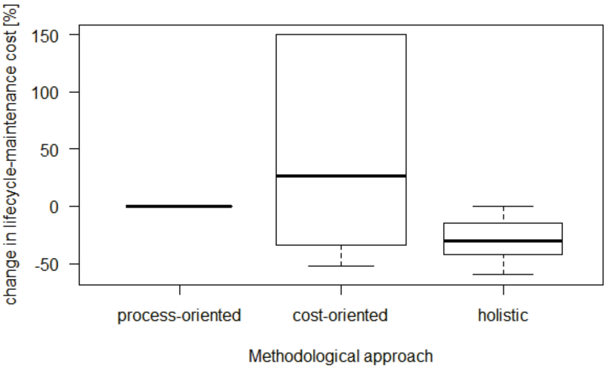

Figure 25: Compilation of quantitative findings within the reviewed methodologies by category (n=15)*

6. CONCLUSION

The aim of the presented literature review is the compilation of methodologies evaluating the impact of SHM on LCC. It is proposed that the validity of current studies is intrinsically limited due to primary three reasons.

- The impact of information provided by SHM is not limited in time and location but rather constitutes a complex impact on entire organizations.
- Current studies primarily focus on individual aspects of SHM and thus lack the ability to include costs and benefits outside their scope of investigation.
- The utilized cost estimation techniques employed in literature vary between individual studies and impede the comparability of results. The consolidation of findings covering individual aspects of SHM is therefore restrained.

Using a qualitative evaluation of the reviewed literature, the existence of different methodological categories evaluating the financial impact of SHM are identified. It is found that the results of evaluated studies quantifying the financial impact of SHM diverge. Studies evaluating SHM as substitution of current technologies conclude that the primary benefits lay outside their scope of research. However, cost savings resulting from SHM are found in applications that rely on multiple sources of information and are heavily influenced by uncertainty, e.g. dispatch reliability, flight and maintenance scheduling as well as structural design processes. By summarizing the analyzed SHM-applications, identifying SHM evaluation methodologies and considering their challenges in the reviewed literature, it is shown that the validity of studies covering only individual aspects of SHM is intrinsically limited. It is noted that the outcome of the presented review depends primarily on the selection of reviewed literature. Including only peer-reviewed publications in the English language poses the risk of neglecting relevant insights and findings. Further, the introduced categorization of publications significantly depend on the described classification procedure. Even though the choice of evaluated categories is subjective, general findings of the presented literature review remain valid.

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[*] Outlier at +500% in cost oriented methodologies neglected

7. ACKNOWLEDGMENTS

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A. APPENDIX

A.1. Qualitative scoring method

The following section describes the approach to score the reviewed literature within the three considered dimensions. Before evaluating the first article, the strictly binary scoring system, as summarized in Table 2 to Table 4 is set. The score for a single dimension is represented by the unweighted sum of scores in this dimension. The resulting score was normed to the highest achievable score.

Table 2: Scoring system technological dimension

Category		Score
Equipment weight	yes	1
	no	0
ROC-curve	yes	1
	no	0
Degradation over time	yes	1
	no	0
Environmental Influences	yes	1
	no	0
Consideration of material	yes	1
	no	0
Validity of sensor signals	yes	1
	no	0

Table 3: Scoring system procedural and organization dimension

Category		Score
Scope	No processes	0
	Generic assumptions	1
	Real processes	2
Input data	Non	0
	Generic assumptions	1
	Real data	2
Description of process and organization	Non	0
	Qualitative	1
	Quantitative	2
Secondary processes	Non	0
	Qualitative	1
	Quantitative	2
Legal framework	Yes	1
	no	0

Table 4: Scoring system cost dimension

Category		Score
Sensor investment	yes	1
	no	0
Sensor maintenance	yes	1
	no	0
Structure specific cost	non	0
	Assumptions	1
	Real data	2
Secondary cost (e.g. fuel)	Non	0
	Assumptions	1
	Real data	2

A.2. K-means clustering

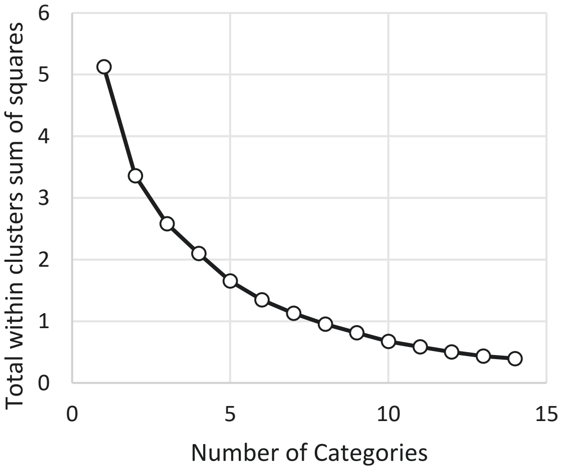

Figure 26: Total within clusters sum of squares over number of categories for k-means clustering

Figure 26 illustrates the total within clusters sum of squares depending on the set amount of clusters. Smaller sums represent denser clusters.

A.3. Reviewed literature

Table 5: Reviewed literature

Token	Publication
Muk00	R. Mukkamala, „Distributed scalable architectures for health monitoring of aerospace structures“, *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, Jg. 2, 2000
Mur00	D. A. Murphy, T. E. Munns und R. M. Kent, „Operational and cost benefit considerations associated with sensor-based structural health monitoring“, *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, Jg. 2, 2000
Kel01	K. Keller *et al., Hg., A process and tool for determining the cost/benefit of prognostic applications*. IEEE: IEEE, 2001
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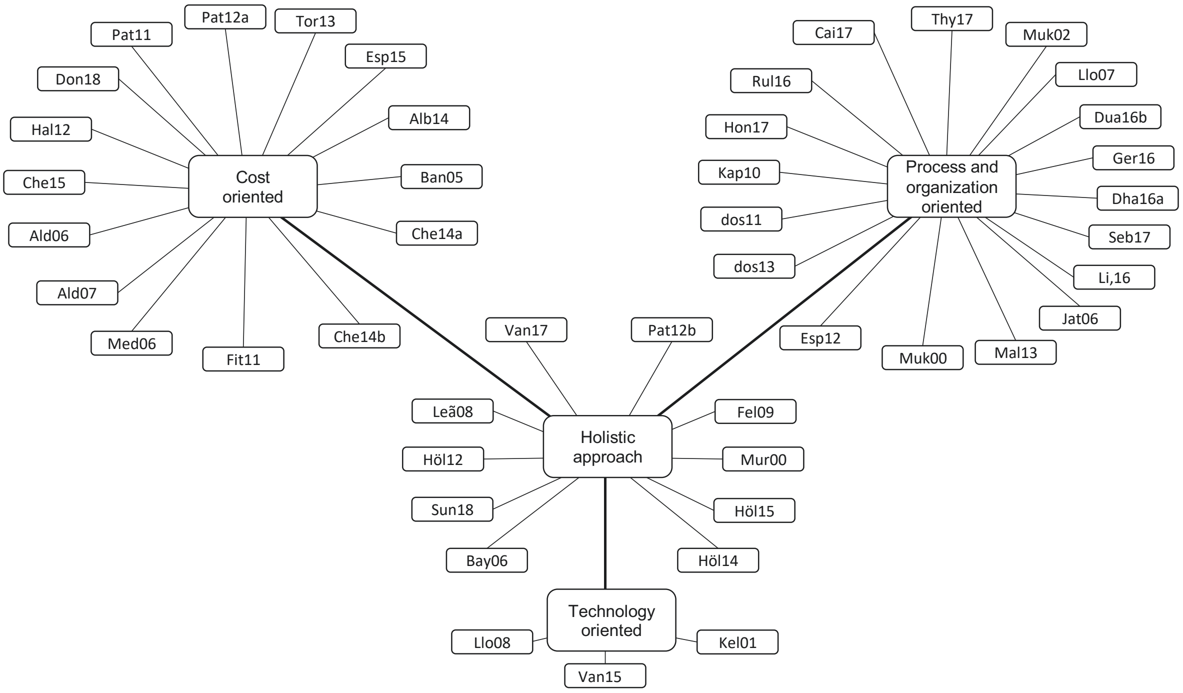

Figure 27: Categorization of reviewed literature