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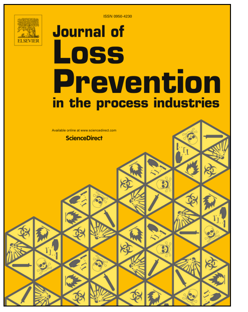

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Life extension decision making of safety critical systems: An overview

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Abstract

In recent years, the concept of "asset life extension" has become increasingly important to safety critical industries including nuclear power, offshore oil and gas, petrochemical, renewable energy, rail transport, aviation, shipping, electricity distribution and transmission, etc. Extending the service life of industrial assets can offer a broad range of economic, technical, social and environmental benefits as compared to other end-of-life management strategies such as decommissioning and replacement of equipment. The aim of this paper is to present a comprehensive literature review and classification framework for academic research and industrial practices related to life extension of safety critical systems and installations. To achieve this, a systematic review is performed on the current state-of-the-art and new developments in the field of asset life extension in various industries. Major sources from which the literature can be gathered are identified and some assessment criteria are defined to categorize the selected publications. A classification framework is then proposed to support life extension decision making process with respect to the type of asset and industry sectors where the concept of life extension has been of interest, condition assessment techniques used for qualification of assets for life extension, life prediction models, life extension strategies, etc. The current key issues in relation to the subject are outlined and the strengths and weaknesses of existing life extension decision-making tools are highlighted. This review contains an exhaustive list of scientific references on the topic, including articles published in journals, industry magazines, books and conference proceedings, university dissertations, technical reports and government documents. The proposed literature classification and analysis can help asset owners, asset managers, service providers, stakeholders, public policy-makers, environment protection authorities, and regulatory bodies gain valuable insights on asset life extension decision-making procedures and methodologies.

Keywords

Asset life extension, Safety critical system, Remaining useful life, Condition assessment, Maintenance.

1. Introduction

Extending the service life of safety-related systems and structures has recently attracted much attention across a broad spectrum of capital-intensive industries such as nuclear, offshore energy, manufacturing, shipping, etc. The safety critical elements (SCEs) are traditionally designed for a specific life span and when the end of their useful life approaches, the stakeholders must decide whether to extend the operating life of existing components or to decommission and replace them with new ones.

Life extension as an alternative to conventional end-of-life management strategies (such as decommissioning and replacement of equipment) is gaining popularity in the last years. The decision to extend the service life of safety critical assets is motivated by the benefits to be achieved from continuing the operation of assets beyond original design life. The prolongation of the life of industrial assets (e.g. the wind turbines installed during 1990s, the nuclear power plants built three decades ago, the offshore oil and gas platforms commissioned in the 1980s) can provide significant added-value benefits to asset owners, asset managers, service providers, stakeholders, health and safety executives, public policy-makers, environment protection authorities, regulatory bodies, etc. As shown in Figure 1, the benefits associated with life extension of SCEs include a broad range of economic, technical, social and environmental effects.

“Fig. (No. 1)”

Figure 1. Benefits associated with life extension of safety critical systems.

One of the major economic benefits of life extension is reduction in capital expenditures (CAPEX) and on-going operational expenditures (OPEX) throughout the life of the asset. According to [1], the investment needed to safely extend the life of components mainly includes cost of structural modifications which is often much less than cost of replacement with a new system. Tveit *et al.* [2] showed that life extension interventions can also reduce assets downtime in long-run and, thereby, result in improved overall equipment effectiveness (OEE) and increased revenue streams. In addition to the economic advantages, some technical benefits such as improved fault detection and monitoring capabilities and restoration of ageing equipment to an acceptable operating condition can be offered by life extension programs.

The safety critical industries have employed a large number of workers at different phases of assets lifecycle, from design, construction and commissioning through to operations and maintenance. Decommissioning of legacy infrastructures as the only end-of-service-life option may result in loss of jobs and eventually negative social impacts. Therefore, life extension can be seen as an employment potential which not only secures the existing jobs but also will create new ones. Life extension can also ensure a sustainable approach to protecting and maintaining the natural environment. Regulators in most jurisdictions around the world are planning to implement strict environmental policies regarding the decommissioning and disposal of SCEs. Life extension of operating assets (as a substitution for decommissioning) can reduce toxic substances emission (e.g., CO_2, SO_2 and NO_x). For further information on the benefits associated with life extension of equipment, the readers can refer to [3].

In order to achieve the above-mentioned benefits, it is crucial for decision makers (asset managers, investors or regulators) to have a holistic view on the current processes and issues involved in undertaking a life extension program. Life extension processes include: definition of premises for the life extension program, assessment of asset condition, estimation of remaining useful life (RUL), evaluation of different strategies for life extension, obtaining regulatory approval, and implementation of the program ([4]). Ignoring any one of these processes may result in revocation of the operator's license for extended operation, suspension of the original licence, fines and reputational damage to industry.

To date, a significant number of research and technological development studies have been conducted on life extension of safety critical systems and installations within various industries, including nuclear power, oil and gas, petrochemical, renewable energy, rail transport, aviation, shipping, electricity distribution and transmission, etc. In this paper, we perform a systematic review of the published academic research and industry practices concerning life extension of SCEs. An exhaustive list of scientific references on the topic is identified, including articles published in journals, proceedings from conferences and symposia, government research reports, industry magazines and reports, and university dissertations. A classification framework is then proposed to support life extension decision making process with respect to the type of asset and industry sectors where the subject has been of interest, condition assessment techniques used for qualification of assets for life extension, life prediction models, life extension strategies, etc. The key issues in each category are outlined and the strengths and weaknesses of existing life extension decision-making tools are discussed. The proposed literature classification and analysis can help both researchers and practitioners gain the most current scientific knowledge and the best practices available in the field of asset life extension.

The structure of this paper is as follows. In Section 2, the review methodology and the classification framework applied to this study are presented. Section 3 gives the results of the classification process and discusses the key issues in relation to the subject. Section 4 provides future directions for researchers and practitioners, and finally, the concluding remarks are given in Section 5.

2. Review process

2.1 Review methodology

The review methodology aims to identify, classify and analyse all the available publications and industrial reports, guidelines and recommended practices relating to life extension of safety critical systems and installations. For this purpose, a systematic review is conduced to identify literature on the subject area. A number of relevant indexing databases such as Scopus, Web of Science, OnePetro, Knovel and IEEE Xplore were selected and searched to provide a comprehensive bibliography on the life extension subject. Scopus and Web of Science databases were chosen due to their broad coverage of scientific peer-reviewed journal articles. OnePetrol contains lots of conference publications and technical reports in the context of energy industry. The rationale behind choosing IEEE Xplore is that IEEE's publications include numerous case studies on life extension in various industries such as nuclear power, electrical/electronics, transport, etc. Some other online resources such as Knovel and Google scholar were also used to search for the literature. In order to search standards and regulations from a wide range of developers including the organizations accredited by the American National Standards Institute (ANSI), British Standards Institution (BSI), other private-sector standard setting bodies, government agencies and international organizations, some search engines such as NSSN (https://www.nssn.org), IHS (https://global.ihs.com) were used.

The search of the literature on the subject covered a broad range of industry sectors, but this was further narrowed down to ten safety critical industries, namely: electrical/electronics, oil and gas, transportation, nuclear power, renewable energy, automotive, software, maritime, defence, and petrochemical. The keyword search resulted in a total of 365 publications from the year 1986 to the end of the year 2015 (a 30 years period). Among the identified publications, 140 works were excluded because of irrelevant subject areas. After reviewing titles, abstracts and content and removing duplicate studies, a total of 97 publications from the year 1988 to the end of year 2015 were chosen and then analysed and classified in a systematic and comprehensive manner. The search strategy applied to identify relevant literature for this review is shown in Figure 2.

"Fig. (No. 2)"

Figure 2. The search strategy applied to identify the relevant literature on asset life extension.

2.2 Distribution of publications

The selected 97 publications include twenty-one peer-reviewed journal papers and magazine articles (~22%) [5–25], seventy-one conference papers (~73%) [1, 6–95], one book chapter (~1%) [96], two technical reports (~2%) [97, 98], and two PhD dissertations (~2%) [99, 100]. The journal articles and conference papers have been published in, respectively, fifteen academic journals and forty-four conference proceedings. Table 1 presents the sources of scientific journals and international conferences and symposia in which the papers have been published.

“Table (No. 1)”

Table 1. Sources of journals and conference proceedings considered for this study.

Figure 3 represents a bar chart of number of publications concerning life extension of SCEs in five-year periods, from 1986 to 1990, 1991 to 1995, 1996 to 2000, 2001 to 2005, 2006 to 2010, and 2010 to 2015. As can be seen, majority of the publications have appeared during the last five years which indicates the increasing importance of the life extension programs in various industries across the world.

“Fig. (No. 3)”

Figure 3. A bar chart of the number of publications in five-year intervals.

2.3 Classification framework

In order to classify the published literature on life extension, all studies were reviewed and thoroughly analysed to identify relevant areas of application or issues they aimed to address. Our classification framework covers a wide and broad area of issues that need to be taken into account when undertaking a life extension program. Figure 4 illustrates the classification framework applied to this study to categorize the literature on life extension of SCEs. As shown, the framework addresses five elements to support the life extension decision making process:

1. Type of asset and industry sectors where the life extension has become of interest (electrical/electronics, oil and gas, transportation, nuclear power, renewable energy, automotive, software, maritime, defence, and petrochemical).
2. Standards and government guidelines for life extension.
3. Condition assessment techniques used for qualification of the assets for life extension (either qualitative or quantitative).
4. Life prediction models (physics of failure, data-driven or fusion approaches).
5. Life extension strategies (replacement/repowering, reconditioning, remanufacturing, retrofitting, re-use, refurbishment, reclaiming, retrofilling, and repair).

“Fig. (No. 4)”

Figure 4. A framework to classify the literature on life extension of safety critical assets.

A brief description of the reviewed publications according to each category of the proposed framework is presented in the next Section.

3. Classification results

Based on systematic review and content analysis of the publications, the outcome of each category of the classification framework is presented below.

3.1 Type of asset and industry sectors

Life extension programs can be executed in a wide range of safety critical industries with additional responsibility of physical asset management to their core business objective. This study identified ten different industries among which seven industries have reported an implementation of the life extension program. These are: electrical/electronics, oil and gas, nuclear power, transportation, defence software, and petrochemical. Figure 5 represents a pie chart showing percentages of studies (out of 97 reviewed research) in relation to life extension of SCEs in different industry sectors.

"Fig. (No. 5)"

Figure 5. Percentages of studies in relation to asset life extension in different industries.

As shown in Figure 5, the electrical/electronics industry sector with 39 reported studies has been the most contributor to asset life extension area of research, followed by the oil and gas industry with 34 and nuclear power with 12 studies. In what follows, the most important publications dealing with life extension of safety critical systems are reviewed and analysed.

- *Electrical/electronics*

In the electrical/electronics industry, several life extension case studies have been conducted on generators (see [27, 32]), circuit breakers (see [5]), transmission lines and High Voltage Direct Current (HVDC) systems (see [25, 42, 43, 55, 60, 81]), transformers (see [8, 12, 14, 22, 30, 31, 34, 44, 45, 46, 47, 58, 71, 87]), control and instrumentation systems (see [26, 41, 51, 72]), switch gears and relays (see [53, 76]), cables (see [61]), silicon coating ([21]), Static VAR compensator (see [91]) and power converters (see [24]).

- *Oil and gas*

The oil and gas assets include surface facilities, processing plants, refineries, loading facilities, pipelines and risers, wells, well heads, manifolds, flowlines, umbilicals, Floating Production Storage and Offloading (FPSO), etc. Jansen and Van [49] presented a risk based technique for life extension of deteriorating oil and gas pipelines. Rincón and González [54] presented case studies on life extension of subsea pipelines using integrity management practices. Franklin *et al*. [57] proposed an approach to support technical feasibility assessment of pipeline life extension programs in terms of the data and information that have to be gathered and the elements of life extension assessment. The proposed approach was validated using two case studies of subsea pipelines. Saunders and Sullivan [70] discussed various requirements, methods and technologies developed for life extension of flexible pipes. They also demonstrated through a case study that flexible pipe's life-span can be extended beyond their original design life with using proper integrity management systems. Leira *et al.* [95] discussed the procedures involved in qualifying oil and gas flexible risers for extended life operation and then, for the purpose of illustration, they provided a case study on a particular configuration of risers.

Grigorian *et al.* [40] proposed a modern analysis technique for structural reassessment of offshore platforms for a possible life extension with the objective of minimizing operational cost while maintaining a high level of reliability over the remaining service life. Ersdal [99] evaluated the feasibility of life extension for existing offshore jacket structures using structural reliability analysis, stress-cycle (S-N) fatigue analysis, fracture mechanics and risk assessment methodologies. Hudson [59, 62] presented a practical approach to ensure optimal use of assets, time and resources during the extended life of operation. A case study of topside equipment was used to illustrate the applicability of the approach. Marshall and Copanoglu [62] employed S-N fatigue assessment to predict the life extension period of existing oil and gas platforms. Solland *et al.* [75] outlined the procedures and processes required for structural assessment of existing oil and gas platforms for life extension purpose. These procedures and processes were illustrated using jacket structure as an example. Vaidya and Rausand [16] developed an effective model to support health assessment of critical systems during life extension period and applied it to a subsea oil and gas system. Brandt and Mohd Sarif [1] highlighted the technical challenges associated with life extension programs in the offshore oil and gas industry and then developed an integrated technical and economic technique for life extension decision-making of topside facilities. Copello and Castelli [83] in a study carried out reassessment of offshore jacket structures using calibrated structural response data and then demonstrated how monitoring data along with good quality maintenance data could facilitate life extension execution.

Pederson *et al.* [84] presented a case study on life extension of mooring systems through the use of subsea inspection technologies. Yin *et al.* [85] applied fatigue life assessment techniques for life extension of a semi-submersible mobile offshore drilling unit. Liu *et al.* [23] presented a life extension management framework for offshore SCEs and then demonstrated the efficacy of the model by applying it to a topside processing facility. Wang *et al*. [92] presented a procedure for structural integrity reassessment of FPSOs for life extension and relocation.

Adamou [86] developed a risk assessment approach for liquefied natural gas (LNG) recertification and applied it to life extension decision making of cryogenic tanks. Hutchison *et al*. [94] presented a finite element analysis (FEA) model for reassessment of life extension of pressure vessels in the offshore oil and gas industry. Ramírez and Utne [25] proposed a model for assessing the technical capabilities of repairable SCEs for life extension. A case study of fire water pump system was used to illustrate the findings.

- *Nuclear power*

Among the studies conducted in the nuclear power industry, the following ones are particularly worth mentioning: Bharteey and Hart [28] proposed a methodology to decide on life extension of low- and medium-voltage equipment in the nuclear industry. Smith [36] described the monitoring systems installed at Oconee nuclear station in South California and demonstrated how the data from these systems can be used to support life extension decision making process. Saldanha and Frutuoso e Melo [17] proposed a Modulated Power Law Process (MPLP) as a generalised non-homogenous Poisson process (NHPP) to determine the rate of occurrence of failure (ROCOF) of repairable systems during their extended life of operation. The model was then applied to a case study on service water pumps of a nuclear power plant. Asmolov *et al.* [20] discussed the concept of service life extension for power units installed at the Novovoronezh nuclear plant in Russia.

- *Transportation*

In the transportation industry (including road, rail, shipping, and aviation sectors), Leung *et al.* [79] proposed an asset life assurance program to support life extension decision making process of mass transit railways (MTR) in Hong Kong. The research concluded that the trains' service life can be prolonged up to 25 years beyond their original design life. Kandadai *et al.* [90] presented a method to determine the current condition of railway bridges and then suggested some protective measures to slow down the degradation of railway assets during the extended life phase. Wang *et al.* [18, 65] presented a service life extension program for long range surveillance radars in the aviation industry.

- *Defence*

In the defence industry, Blech [38] presented a life extension program for structure, subsystems and engine of Tornado aircraft. Jun *et al*. [89] explored the available Prognostics and Health Management (PHM) techniques to support service life extension of tactical missiles in early design phase. In this study, in addition to the application of classical techniques, engineering approaches to the architecture of data acquisition, life degradation factor analysis, and life prediction process were discussed and the associated technical problems were analysed.

- *Software*

Software aging is a phenomenon that refers to progressive performance degradation due to aging-related software faults. Machida *et al*. [80] presented a semi-Markov process technique for counteracting software aging by preventive operation to extend the lifetime of software execution. They showed that life-extension could provide a cost-effective and non-intrusive countermeasure to software aging.

- *Petrochemical*

In the petrochemical industry, Metzdorf *et al.* [82] presented a case study on how to extend the life of aging electrical distribution systems in a large chemical manufacturing facility.

3.2 Standards and government guidelines for life extension

In the safety critical industries, the consideration of assets for long-term operation requires sound decisions to be made by regulators. Regulations refer to varying compliance policies, procedures and standards that serve as a guideline for implementation of the life extension program. To the best of the authors' knowledge, there is no explicit standard for life extension in the nuclear power industry and the periodic safety review (PSR) approach is the main and the only regulatory process which has been adopted for authorisation of life extension programs in various countries (http://www.onr.org.uk/periodic-safety-review/). According to a report published by the International Association of Oil & Gas Producers (IOGP) in 2010 [101], there are 1384 standards available in the offshore oil and gas industry among which 225 references have been developed by the American Petroleum Institute (API) (www.api.org/). However, only three Norwegian petroleum industry (NORSOK) standards address the issues relating to life extension [67]. NORSOK N-006 [102] explains how to assess the integrity of existing load-bearing structures for life extension purpose. NORSOK Y-002 [103] and NORSOK U-009 [104] are applicable to life extension of pipeline transport systems and subsea systems, respectively. Nevertheless, the existing API and ISO standards on design and operation of offshore installations may still be applicable to life extension. No standard relating to life extension of electrical distribution and transmission networks was found. However, Sprague (2001) [105] suggested that ANSI/IEEE C37.16 [106] endurance requirements can be used to evaluate the service life of switchgears, low-voltage power circuit breakers and molded-case circuit breakers. In the UK's defence industry, life extension of aircraft fleets is carried out according to the Ministry of Defence regulation 5724 [107]. The literature search did not reveal any regulatory standards with respect to life extension in the petrochemical, renewable energy, rail transport and the shipping industry sectors.

3.3 Asset condition assessment techniques for life extension

Failures of safety critical systems and structures may have serious economic, safety and environmental implications. The use of asset condition assessment tools enables operators to perform routine integrity audits as a means to: (i) satisfying acceptable safety regulations; (ii) planning for inspection and maintenance interventions; (iii) certifying authorities' approval to extend the service life of assets.

There are various techniques available in the literature for assessing the condition of SCEs for life extension purpose. Lack of appropriate condition assessment techniques or use of inappropriate tools may cause infeasible or non-optimal life extension solutions. The existing asset condition assessment techniques can broadly be classified as quantitative or qualitative, depending on the nature of the collected information. Quantitative condition assessment techniques produce measurable indexes which could be used for determining inspection dates. While, qualitative condition assessment techniques produce color plots to demonstrate the deterioration grades of assets.

Table 2 presents a list of references by year of publication that have used quantitative or qualitative condition assessment techniques for asset life extension program. As shown in this table, 15 studies have employed qualitative tools while 23 studies have applied quantitative tools for asset condition assessment to support life extension decision making process. The rest of the studies are concerned with a semi-quantitative assessment of qualification of assets for life extension.

"Table (No. 2)"

Table 2. Classification of the literature of asset life extension based on condition assessment techniques.

Among the reviewed literature corresponding to qualitative asset condition assessment tools and application, the following studies are highlighted:

Knox and Redhead [33] adopted the approach of reviewing historical damage data as a means of condition assessment for reactor and boiler components. Ishac *et al.* [35] used visual inspection information as well as design documents to assess the condition of existing transmission facilities including conductors, wires, hardware, insulators and structures for life extension. Godswill *et al.* [58] and Sharafi [71] developed qualitative condition assessment approaches for life extension of power transformers using oil diagnostics, visual inspection and review of historical data. Hudson [69] applied a qualitative risk based assessment technique to determine the extent of technical vulnerability of SCEs on offshore platform for life extension. Ray *et al.* [15] employed visual examination and chemical wet method for health assessment of service-exposed radiant tube in an oil refinery for life extension. Leung *et al.* [79] used capability assessment template which is a qualitative technique to justify if railway rolling stock components could satisfy safety and operational requirements for extended-life. In Mehraban *et al.* [81] inspection information and expert judgement were used to assess the condition of systems and components of Oklaunion converter for life extension. Pederson *et al.* [84] developed a risk-based progressive inspection methodology to support fitness-for-purpose (FFP) assessment of mooring systems for life extension. Adamou [86] employed gap analysis to evaluate the condition of cryogenic tanks for recertification and life extension. Liu *et al.* [23] utilised the risk-based inspection (RBI) analysis based on API RP 580 [108] to assess the condition and extend the life of rotating machinery, vessels and piping on offshore oil and gas platform. The outcome of the assessment was interpreted using qualitative risk distribution diagrams. Mehraban *et al.* [91] applied detailed visual equipment check to assess the condition of existing electrical components undergoing life extension program. Carvalho *et al.* [93] utilised qualitative risk-based integrity assessment techniques to assess the condition of SCEs. The condition of assets was assessed using qualitative risk rankings of SCEs, obtained based on the gaps established between design and current operational data of various systems.

Qualitative asset condition assessment techniques mainly rely on the opinions and judgments of asset managers, inspectors and operators, and thus can be used in various industries worldwide. However, Due to uncertainty associated with engineering judgment and experience, the quantitative condition assessment tools may be subject to bias or error. Smith [36] used the Arrhenius equation to determine the integrity of the cables for life extension based on information from environmental qualification (EQ) test. Yastxebenetsky *et al.* [37] analysed the technical condition of nuclear power plant instruments for life extension using operating data. Dominelli *et al.* [12] developed an equipment rating tool for life assessment and extension of transformers. The tool analyses the health condition of transformers using the information collected from testing, inspection, operating history, etc. Sumereder *et al.* [51] analysed the results of laboratory testing programme such as dielectric test and disruptive discharge to determine the condition of a generator for life extension. Hudson [59] adopted a quantitative assessment technique developed by Det Norske Veritas (DNV) on the basis of empirical approach and risk-based methodology to assess physical condition of assets on an offshore platform. Srinivas *et al.* [61] developed an on-line condition assessment technology called CableWISE to assess the condition of existing cables and components for life extension. Albertini *et al.* [73] developed an analytical condition assessment technique which combines semi-empirical models and experimental methods. The technique was applied to life assessment of high-pressure gas wells by calculating rate of metal loss and conducting general fitness-for-service (FFS) assessment. Sun *et al.* [76] presented a life assessment method based on accelerated storage degradation test and Arrhenius model with random performance parameters. Vaidya and Rausand [16] applied failure mode, effects and criticality analysis (FMECA) approach to determine current condition of raw seawater processing system for life extension. Lee *et al.* [78] verified the integrity status of existing safety related cables by reviewing EQ reports and then applied the Arrhenius equation to determine their qualification for life extension. Asmolov *et al.* [20] applied analytical calculations and eddy-current examination to assess the condition of steam generator tubes for possible extension of service life. Jun *et al.* [89] developed a concept based on PHM technique for condition assessment and life extension of tactical missiles. The condition of the missile was analysed based on the acquired lifetime degradation data. Kandadai *et al.* [90] adopted a comprehensive quantitative condition assessment programme involving material testing and FEA to analyse current strength and loading capacity of bridges for life extension. Ramírez and Utne [25] developed an imperfect maintenance model based on virtual age and dynamic Bayesian network to determine technical condition of pumps for life extension.

3.4 Life prediction models

The technical and economic feasibility analysis of life extension decisions should incorporate a process to estimate the remaining useful life (RUL) of safety critical systems and structures by applying appropriate life prediction methods. In general, life prediction methods are classified using the following categories: physics of failure (PoF) approach, data driven approach and hybrid approach (see [109, 110]). This study applies same categories but the terminology "fusion approach" is used instead of hybrid method. The objective of this category is to ascertain the level of application of each approach to support life extension decision making process. The use of appropriate RUL technique in a life extension program will facilitate scheduling of maintenance works, assist in selecting suitable life extension and end-of-life strategies, improve operational performance and enhance company's profitability. Each of the three techniques is briefly discussed below.

- *Physics of failure (PoF) approach*

The physics of failure (PoF) approach is based on modeling of degradation behavior of safety critical components with taking into account different operating and environmental conditions such as load, stroke, velocity, acceleration, temperature, etc. The approach involves formulating theoretical (mathematical) models to describe equipment degradation and damage processes over time. To this aim, a good understanding of the physical operations of components and potential failure modes of the system (e.g. crack propagation, wear and corrosion) is required. This technique provides an opportunity to link data to physical condition of asset while this may not be possible through data-driven approach. However, this approach may require the use of assumptions and expert knowledge in describing operational process and estimating parameters. Expert knowledge and field experience are always an advantage in modelling various degradation processes. However, mathematical models are often expressed by means of differential equations or partial differential equations which are complex and need powerful computational solvers.

- *Data driven approach*

The data driven approach relies on the analysis of historical data of safety-related systems to establish relationships and predict future failure trends. However, sometimes in practice, there may not be sufficient data available to obtain health estimates and determine critical thresholds for failure prognostics, which can be a limitation of this approach. The two main concepts employed in this approach include *diagnostics* and *prognostics*. These are used to model the degradation processes of asset and also predict RUL using information from condition monitoring system (CMS). However, there is a fundamental difference between diagnosis and prognosis. According to [111], diagnostics are conducted to investigate or analyse the cause or nature of a condition, situation or a problem, whereas prognostics is concerned with calculating or predicting future trends by analysis of the available pertinent data. In data driven approach, data are acquired through the use of network sensors that monitor the system. Health condition information of the system are extracted from the sensor signals through a series of procedures and prediction tools such as support vector machine (SVM), Bayesian network (BN), Kalman filter, artificial neural network (ANN), etc.

- *Fusion approach*

The fusion-based approach combine the physics of failure and the data-driven methods to use their strengths and to compensate for or minimize their weaknesses (see [112]). This approach is based on the successful application of the PHM tools and techniques. It applies the knowledge and principles behind the physics of failure of the system to select an appropriate data-driven technique for diagnosis and prognosis (i.e., selection and placement of sensors). The information obtained from diagnosis and prognosis is then used to forecast the RUL and health status of the system considered for life extension.

Out of the 97 reviewed studies on asset life extension, a total of eleven studies have employed life prediction methods to support life extension decision making process. Among them, Allan [7], Arshad *et al.* [47], Brown and Willis [11], Li *et al.* [13], Hudson [59], Albertini *et al.* [73], Ray *et al.* [15] and Vaidya and Rausand [16] applied PoF approach to determine RUL of safety related systems, while Giuntini and Pooley [39] used the data-driven approach for the purpose of life extension. Two studies Bond *et al.* [56, 74] also applied the fusion approach to predict RUL of SCEs. A list of possible life prediction models used in the literature is shown in Figure 6.

"Fig. (No. 6)"

Figure 6. A list of life prediction tools to be used for life extension decision making.

3.5 Life extension strategies

This section of the paper presents and discusses various strategies that can be applied to extending service life of safety critical equipment across different industries. These strategies were identified by reviewing the published literature and face-to-face semi-structured interviews with some experts who are actively involved in undertaking life extension programs. Life extension strategies for SCEs include: replacement/repowering, reconditioning, remanufacturing, retrofitting, re-use, refurbishment, reclaiming, retrofilling, and repair. In what follows, a brief description of these strategies is presented.

- *Replacement / repowering*

Replacement / repowering is a popular life extension strategy used in many industries such as nuclear power, electrical utilities and renewable energy industries. For instance, by the end of year 2005, Denmark repowered two-third of its old wind turbines [113]. This strategy is described as the activities performed to substitute an existing system or component with a new one or to upgrade the system to higher nameplate capacity at the end of its original life irrespective of functional status. Replacement / repowering actions in most cases return the system to "as good as new (AGAN)" condition. However, they can be very cost-intensive, may cause safety risks and lead to long downtime periods. Therefore, some factors such as risk of asset unavailability and economic implications of the strategy must be considered when replacement / repowering is to be chosen as an end-of-life strategy.

- *Reconditioning*

This strategy involves taking appropriate actions at specific time periods to ensure that system continues to perform its required functions. It restores a system between AGAN and "as bad as old (ABAO)" condition, hence the output is less than original equipment manufacturer (OEM) stated output. Kin *et al.* [114] grouped reconditioning processes into five classes, namely: removal of dirty surfaces, exposure of defects, addition of extra materials, restoration of material properties, assembling and fastening and super surface finishing. From this classification, it can be concluded that a good knowledge of design principles and requirements, material properties and damage tolerance is necessary to implement reconditioning process. In this strategy, very few parts are required to be replaced and thereby it reduces material costs. However, labour cost will be high since many parts may need to be repaired.

- *Condition monitoring (CM)*

Safety critical equipment require monitoring, surveillance and diagnostics tools to assess component aging effects and update inspection plan if any changes has been made. Condition monitoring (CM) technology uses special devices and sensors to continually monitor the operation of critical components. The monitoring techniques include oil analysis, vibration analysis, temperature measurement, thickness test, acoustic analysis, etc. In the safety related industries, intelligent tools (e.g. smart pig technology, wireless technology) are deployed for continuous supervision and health monitoring of equipment beyond their design lifetime while the acquired data will be used for maintenance planning.

- *Remanufacturing*

Remanufacturing entails processes to return an existing system to at least OEM functional specifications with warranty. This strategy integrates processes or techniques such as reconditioning, replacement and repair of some parts. It has added advantages of reducing usage of materials, reducing workload and retaining profit by lowering production cost but it requires high investment on hardware and software. However, the SCEs which cannot be dismantled or disassembled will not be feasible to undergo remanufacturing process.

- *Retrofitting*

Retrofitting is the process of replacing old components or equipment on an installation with modern equivalents. It is conducive for equipment or components having high maintenance cost and/or failure rate. Retrofitting strategy results in improved functionality, availability, safety and also reduced equipment downtime. It can represent the best strategy when the aim of life extension is modernisation.

- *Use-up*

Use-up is an economic driven strategy which can be used for life extension purpose. It is the process of operating equipment or components on an installation until the end of their economic life, i.e., when the annual OPEX in terms of maintenance and service cost becomes over-excessive. The use-up can also lead to improving reliability, availability, and serviceability (RAS) of equipment in long-term. Factors such as old design, increasing rate of aging and the risk of maintenance-induced failures may compel asset managers to run the equipment until they fail and then dispose them. Experiences from use-up strategy can be used as basis to evaluate economic added-value of other life extension strategies.

- *Refurbishment*

Refurbishment refers to actions that are performed near the end of life in order to return a system to its functional state and achieve a performance higher than OEM functional requirement. This strategy integrates partial replacement, reconditioning and partial redesigning. The process involves high labour cost and addition of extra materials while ensuring high level of reliability during life extension phase of operation.

- *Reclaiming*

Reclaiming is a suitable strategy for service life extension of systems requiring regular lubrication over their lifetime (e.g. transformer). It is a process of refining lubricant oils by eliminating all contaminants and insoluble particles to attain an oil with characteristics similar to those of a new one. The methods employed in refining oil include the use of chemicals, sulphuric acid treatment and Fuller’s earthing. The advantages of using this technique as a life extension strategy are: (i) reduced system outage, hence less downtime, (ii) re-use of old oil, (iii) no disassembling and reduced material usage. However, the biggest danger involved is the possibility of injury caused by sulphuric acid.

- *Retrofilling*

This strategy is appropriate for extending the life of systems requiring regular lubrication over their lifetime (e.g. transformer). It is a process of replacing existing lubricant oils with natural ester dielectric coolant. Retrofilling presents similar advantages to reclaiming, however, unlike reclaiming, the old oil is disposed-off. There exist two different approaches for retrofilling. The “minimal effort” approach which requires draining of existing oil and immediately refilling the equipment with natural ester, while the “best effort” approach requires draining of existing oil, flushing with hot natural ester, extending drip time, vacuuming the residual oil dregs, and finally adding the natural ester.

- *Repair*

Repair, as a life extension strategy, restores a system to functional condition either when it fails or on a planned schedule. This strategy is adopted for life extension of complex engineering systems due to the fact that different sub-systems and components may have different life expectancy and also because this is less expensive as compared to the replacement / repowering strategy. Repair activities may be carried out using existing parts of system and some new parts provided by manufacturer.

Each of the above-mentioned life extension strategies have their potential advantages and disadvantages, and the choice of the most suitable strategy depends on several factors such as level of improvement, extent of materials required to be added, labour cost, economic added-value and complexity of implementation [115]. The strengths and weaknesses of each life extension strategy with respect to these factors are summarized in Table 3.

“Table (No. 3)”

Table 3. Strengths and weaknesses of life extension strategies.

A detailed distribution of the publications in terms of life extension strategies is shown in Table 4.

“Table (No. 4)”

Table 4. Distribution of the studies by life extension strategy.

4. Conclusion and future research directions

Life extension has been of principal interest to industrial practitioners, regulators, policy-makers and the academic community in the field of asset management for more than three decades. This has gained even more attention in safety-related industries such as nuclear power, offshore oil and gas, renewable energy, rail transport, shipping, etc. because a substantial number of facilities in these industries are approaching their anticipated service lives. Extending the service life of industrial assets can offer a broad range of economic, technical, social and environmental benefits as compared to other end-of-life management strategies such as decommissioning and replacement of equipment. This paper aimed to present a comprehensive literature review and classification framework for academic research and industrial practices published between 1986 and 2015 in relation to life extension of safety critical systems and installations. The establishment of such classification framework to categorize the life extension studies is an important contribution to research in this field, since the majority of the publications focused on application cases in different industries. To this aim, a systematic review was performed on the current state-of-the-art and new developments in the field of asset life extension. The critical issues involved in life extension decision making process were then highlighted and discussed, e.g. type of asset and industry sectors where the concept of life extension has been of interest, condition assessment techniques used for qualification of assets for life extension, life prediction models, life extension strategies.

The results of this study indicated that a sizable amount of research on the life extension of safety critical elements (SCEs) has been conducted. Nevertheless, there are still many unsolved issues which can be addressed in future studies. Some of these works are provided below:

1. When comparing the number of studies conducted on life extension of safety critical elements with other areas of study (such as design, installation, maintenance, and operations), this study establishes that life extension has received little attention in the relevant literature. Therefore, it will be of great interest to focus future studies on developing an integrated life extension decision-making model with considering design parameters, installation instructions, operation and maintenance guidelines, and decommissioning issues.
2. Life extension strategies such as replacement, conditioning monitoring, retrofitting, refurbishment, reclaiming, retrofilling and repair have been applied to industry cases, however, strategies such as reconditioning, remanufacturing and use-up are missing from the relevant literature.
3. Most of the life extension decision making models found in the literature tend to focus on addressing either technical issues only or economic issues only, which normally leads to inaccurate conclusions. Hence, future research must seek to develop a decision making model which integrates the technical, social, and economic decision making models, so that the strength of one can complement the weakness of the others.
4. Thirty-eight publications (out of 97 reviewed studies) have focused on the development and application of asset condition assessment tools to support life extension decision making process. Nonetheless, future research may be taken in this direction. For example, there is little knowledge on which of the available tools is most suitable for application and the challenges involved in utilising them.
5. The findings indicate that supporting life extension decision-making processes with accurate lifetime prediction models has received very little attention in the relevant literature. Hence, there is a need to raise awareness on the benefits of estimating remaining useful life (RUL) in a life extension program.
6. An interesting area of study could be the development of models for the selection of the most suitable life extension strategy, considering factors such as the type of industries, the strategic alternatives, type of system and the available resources, time, managerial capabilities, workforce, and skills. For this purpose, using Multi-Criteria Decision Making (MCDM) methods and/or Benefit-Cost Analysis (BCA) may be useful.

7. Despite the growing interest in life extension as a suitable end-of-life management strategy across several industries, very little studies have focused on maintenance decision making beyond the original design life. Thus, future research on determining the length of life extension (i.e. the additional operational period beyond original life) and the corresponding maintenance policy (i.e., frequency and degree/quality of repair actions) for safety critical assets is highly recommended.
8. Asset obsolescence management has been a challenge in most safety critical industries. This is because the control and automation systems supporting the operations of safety critical assets beyond their original design life must be state-of-the-art equipment due to the rapid changes in safety regulations and technologies. However, companies are unable to provide this kind of technical support for safety critical assets during life extension because most of the assets designed two or three decades ago are not compatible with current technology. Therefore, investigating how a safety critical asset designed long time ago can be compatible with state-of-the-art automation and control systems during life extension phase of operation will be an interesting research topic.
9. The technology through which the required data is gathered from all stages of the asset life cycle can have a significant impact on the overall life extension decision making process. However, lack of good quality data has been identified as one of the key obstacles during life extension activities. Therefore, asset managers in safety critical industries must invest resources in the development of platforms, policies and procedures to manage the data acquired at various lifecycle stages of the safety critical assets, in order to improve life extension decision making process.
10. One of the key challenges that hampers life extension decision-making is workforce ageing. Efforts have been made by many practitioners and academics within the safety critical industries to address the challenges of physical plant ageing and their impact during life extension phase of operation (e.g. see [116]), however very limited effort has been devoted to the study of human and organizational challenges such as workforce ageing. Future life extension decision making framework must direct effort at addressing the challenge of workforce ageing and its impact during life extension phase of operation.
11. Although this study indicates that some good practical cases on life extension have been analysed in the electrical/electronic, offshore oil and gas and nuclear power industries, there have been few cases published in scientific databases on other industries (e.g. offshore renewables, railway transport, shipping, etc.) and future research could focus on these industries.

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Table 1. Sources of journals and conference proceedings considered for this study.

	No	Source (in alphabetical order)
Journals	1	*Engineering Failure Analysis*
	2	*IEEE Industry Applications Magazine*
	3	*IEEE Power and Energy Magazine*
	4	*IEEE Transactions on Aerospace and Electronic Systems*
	5	*IEEE Transactions on Dielectrics and Electrical Insulation*
	6	*IEEE Transactions on Industry Applications*
	7	*IEEE Transactions on Nuclear Science*
	8	*IEEE Transactions on Power Delivery*
	9	*IEEE Transactions on Power Electronics*
	10	*IEEE Transactions on Power Systems*
	11	*Journal of Loss Prevention in the Process Industries*
	12	*Journal of Risk and Reliability*
	13	*Progress in Nuclear Energy*
	14	*Reliability Engineering & System Safety*
	15	*Thermal Engineering*
Conferences and symposia	1	*Abu Dhabi International Petroleum Exhibition and Conference*
	2	*American Control Conference*
	3	*Asia-Pacific Power and Energy Engineering Conference*
	4	*ASME Pressure Vessels and Piping Conference*
	5	*Austroads Bridge Conference*
	6	*Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference*
	7	*IEE Colloquium on Assessment of Degradation Within Transformer Insulation Systems*
	8	*IEE Proceedings A – Science, Measurement and Technology*
	9	*IEE/IMechE International Conference on Power Station Maintenance – Profitability Through Reliability*
	10	*IEEE Aerospace Conference*
	11	*IEEE Annual Reliability and Maintainability Symposium*
	12	*IEEE Asia International Conference on Modelling and Simulation*
	13	*IEEE Canadian Conference on Electrical and Computer Engineering*
	14	*IEEE Conference on Prognostics and Health Management*
	15	*IEEE International Conference on Condition Monitoring and Diagnosis*
	16	*IEEE International Conference on Systems, Man and Cybernetics*
	17	*IEEE International Symposium on Electrical Insulation*
	18	*IEEE Nuclear Science Symposium*
	19	*IEEE Nuclear Science Symposium and Medical Imaging Conference*
	20	*IEEE PES Transmission and Distribution Conference and Exposition*
	21	*IEEE Petroleum and Chemical Industry Technical Conference*
	22	*IEEE Power and Energy Society General Meeting*
	23	*IEEE Power Engineering Society Winter Meeting*
	24	*IEEE Radar Conference*
	25	*IEEE Students' Conference on Electrical, Electronics and Computer Science*
	26	*IEEE-IAS/PCA Cement Industry Technical Conference*
	27	*IET / IAM Asset Management Conference*
	28	*IET International Conference on AC and DC Power Transmission*
	29	*International Conference on Dielectric Materials, Measurements and Applications*
	30	*International Conference on Electricity Distribution*
	31	*International Conference on Life Management of Power Plants*
	32	*International Conference on Probabilistic Methods Applied to Power Systems*
	33	*International Conference on Properties and Applications of Dielectric Materials*
	34	*International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering*
	35	*International Conference on Refurbishment of Power Station Electrical Plant*
	36	*International Conference on Transmission and Distribution Construction and Live Line Maintenance*
	37	*International Offshore and Polar Engineering Conference*
	38	*International Symposium on Software Reliability Engineering*
	39	*NACE - International Corrosion Conference Series*

40	*Offshore Technology Conference*
41	*Offshore Technology Conference-Asia*
42	*SPE Asia Pacific Oil & Gas Conference and Exhibition*
43	*SPE Offshore Europe Conference & Exhibition*
44	*SPE Project and facilities challenges conference at MET*

Table 2. Classification of the literature of asset life extension based on condition assessment techniques.

Qualitative			**Quantitative**		
Year	Number	References	Year	Number	References
1994	1	Knox and Redhead [33]	1994	0	
1995	1	Ishac *et al.* [35]	1995	1	Smith [36]
1996	0		1996	0	
1997	0		1997	0	
1998	0		1998	1	Yastxebenetsky *et al.* [37]
1999	0		1999	0	
2000	0		2000	0	
2001	0		2001	1	Grigorian *et al.* [40]
2002	0		2002	0	
2003	0		2003	0	
2004	0		2004	0	
2005	0		2005	1	Ersdal [99]
2006	0		2006	2	Dominelli *et al.* [12]; Sumereder *et al.* [51]
2007	0		2007	0	
2008	2	Franklin *et al.* [57]; Godswill *et al.* [58]	2008	2	Hudson [59] ; Srinivas *et al.* [61]
2009	0		2009	1	Marshall and Copanoglu [64]
2010	2	Sharafi [71]; Hudson [69]	2010	0	
2011	2	Ray *et al.* [15], Solland *et al.* [75]	2011	3	Albertini *et al.* [73]; Vaidya and Rausand [16]; Sun *et al.* [76]
2012	2	Leung *et al.* [79]; Mehraban *et al.* [81]	2012	2	Lee *et al.* [78]; Saldanha and Frutuoso e Melo [17]
2013	1	Pederson *et al.* [84]	2013	3	Copello and Castelli [83]; Ramírez and Utne [19]; Yin *et al.* [85]
2014	3	Adamou [86]; Liu *et al.* [23]; Mehraban *et al.* [91]	2014	4	Asmolov *et al.* [20]; Jun *et al.* [89]; Kandadai *et al.* [90]; Wang *et al.* [92]
2015	1	Carvalho *et al.* [93]	2015	2	Hutchison *et al.* [94]; Ramírez and Utne [25].
Total	**15**		**Total**	**23**	

Table 3. Strengths and weaknesses of life extension strategies.

Strategy	Level of improvement	Material addition	Labour cost	Added value	complexity
Replacement / Repowering	Moderate	High	Moderate	High	Moderate
Reconditioning	High	Low	High	High	High
Condition monitoring	Moderate	Low	Moderate	High	Moderate
Remanufacturing	High	Low	High	High	High
Retrofitting	High	Moderate	Moderate	Moderate	Moderate
Use-up	Low	Low	Low	Low	Low
Refurbishment	High	Moderate	High	High	High
Reclaiming	Low	Low	Low	Moderate	Low
Retrofilling	Low	Low	Low	Moderate	Low
Repair	Moderate	Moderate	Low	Moderate	Moderate

Table 4. Distribution of the studies by life extension strategy

	Replacement/ Repowering	Reconditioning	Conditioning monitoring	Remanufacturing	Retrofitting	Use-up	Refurbishment	Reclaiming	Retrofilling	Repair
Brandt and Mohd Sarif [1]	√						√			
Slade *et al.* [5]					√					
Storms and Shipp [6]					√					
Sanwarwalla and Alsammarae [9]	√									
Paoletti [10]					√					
Cherney *et al.* [21]	√						√			
Cripps [26]	√									
Jackson *et al.* [27]							√			
Fero [29]			√							
Hill *et al.* [32]							√			
Pahlavanpour *et al.* [34]								√		
Valiquette [43]	√						√			
Kovacevic *et al.* [44]			√							
Mcshane and Rapp [45]									√	
Blanksby *et al.* [48]	√									
Marble and Tow [50]			√							
Sumereder *et al.* [51]	√									
Jánosy (2007) [52]							√			
Bisewski *et al.* [55]	√									
Hudson [59]	√									
Kirby *et al.* [60]							√			

	Replacement/ Repowering	Reconditioning	Conditioning monitoring	Remanufacturing	Retrofitting	Use-up	Refurbishment	Reclaiming	Retrofilling	Repair
Hudson [62]	√									
Lewis *et al.* [63]	√									
Windle and Broos [66]							√			
Hart *et al.* [68]	√									√
Bond *et al.* [74]			√							
Gallop and Pearson [77]							√			
Leung *et al.* [79]	√									
Mehraban *et al.* [81]							√			
Gibbs and Graf [88]										√
Chappa *et al.* [87]			√							
Mehraban *et al.* [91]							√			
Leira *et al.* (2015) [95]	√									√
International Atomic Energy Agency (IAEA) [97]	√						√			
Health and Safety Executive (HSE) [98]	√						√			
Counter [100]	√									

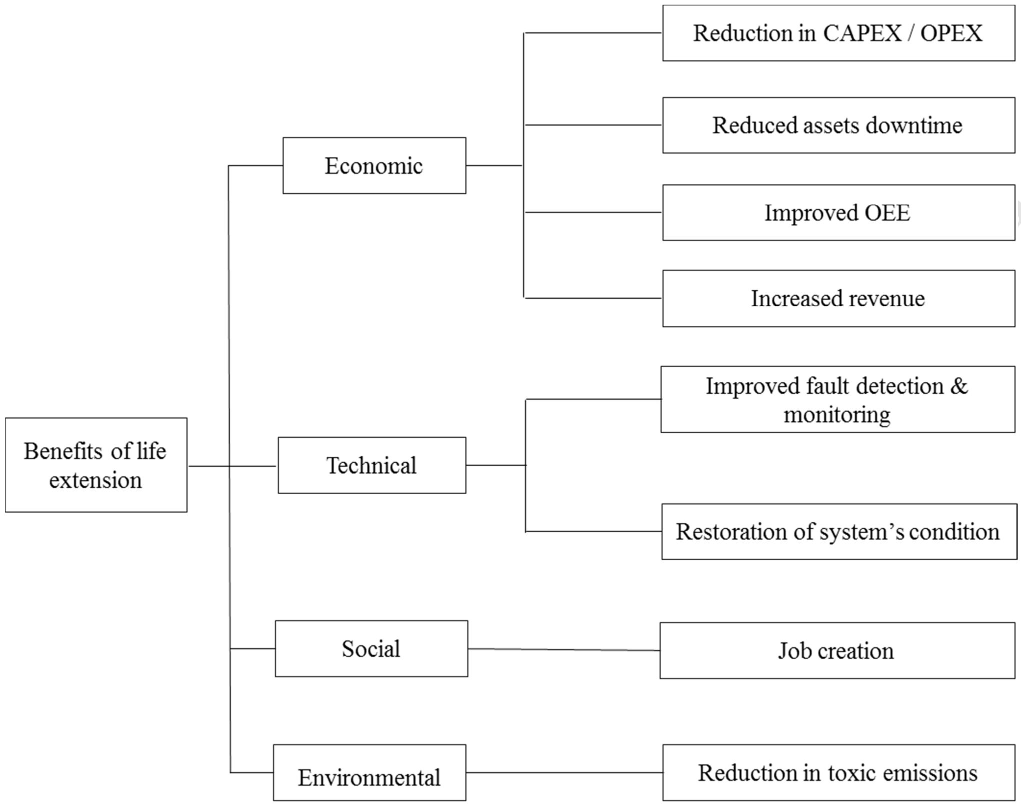

Figure 1. Benefits associated with life extension of safety critical systems.

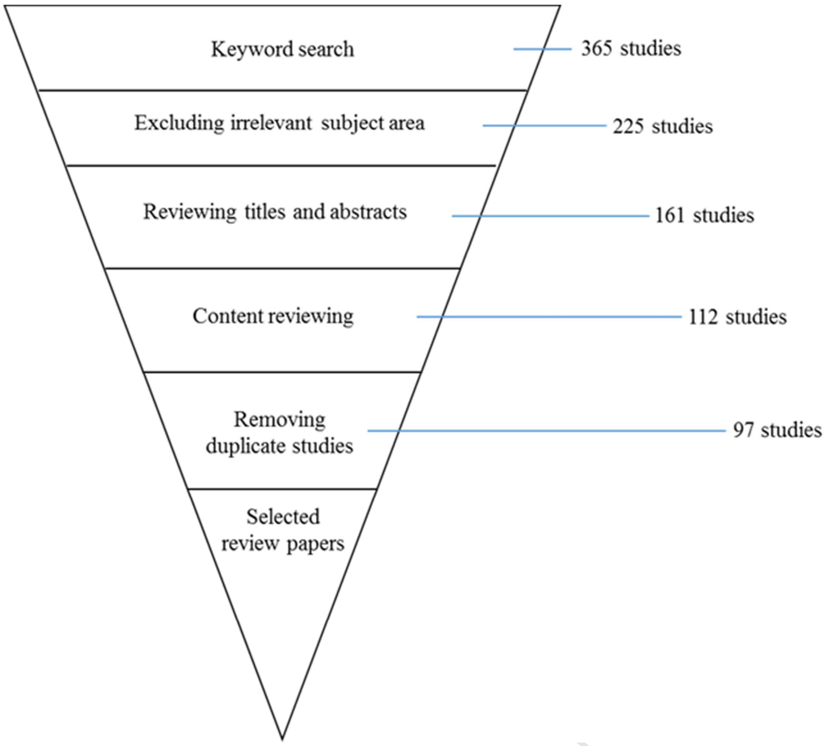

Figure 2. The search strategy applied to identify the relevant literature on asset life extension.

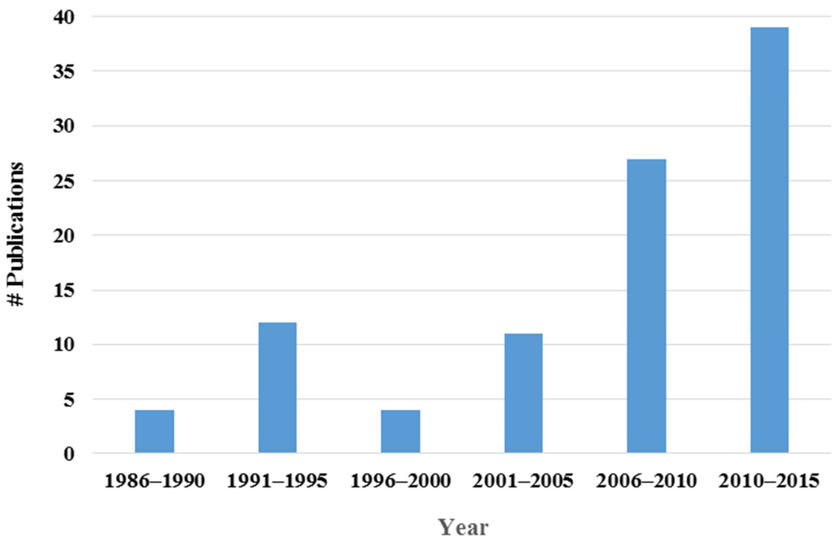

Figure 3. A bar chart of the number of publications in five-year intervals.

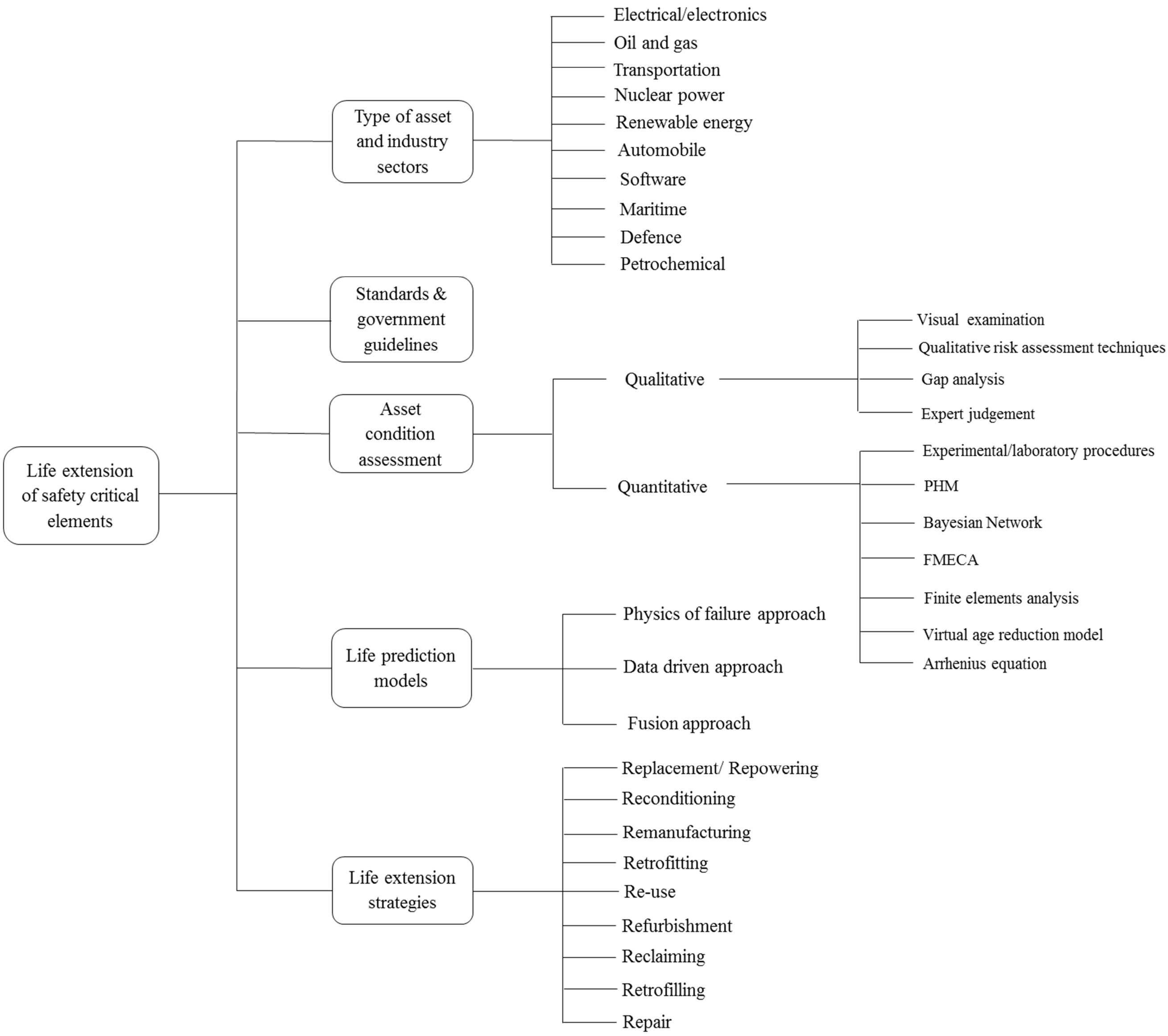

Figure 4. A framework to classify the literature on life extension of safety critical assets.

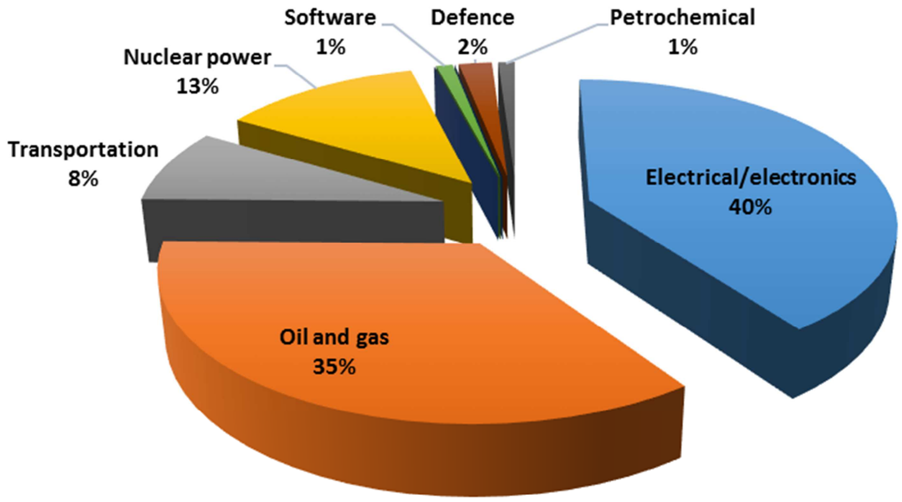

Figure 5. Percentages of studies in relation to asset life extension in different industries.

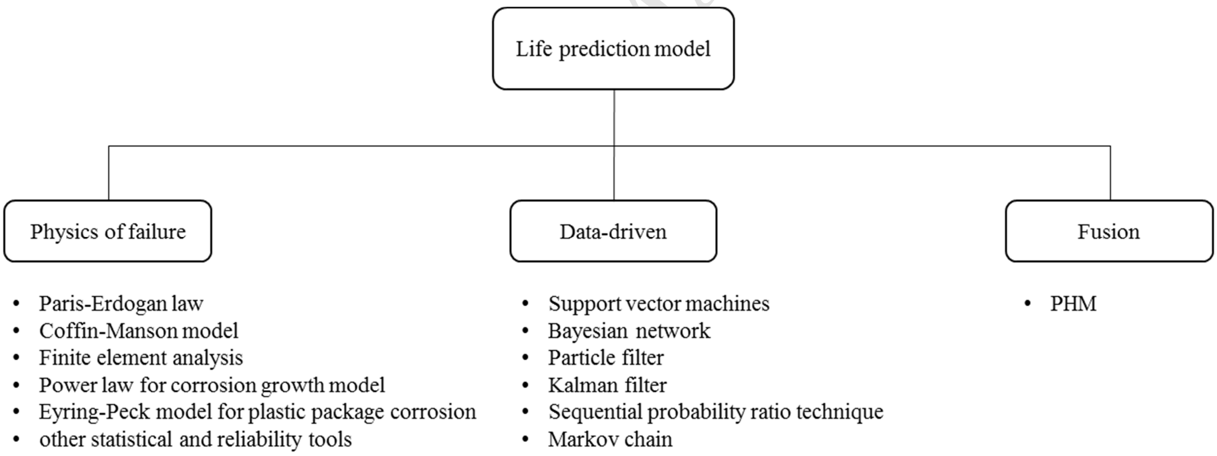

Figure 6. A list of life prediction tools to be used for life extension decision making.

RESEARCH HIGHLIGHTS

- A classification framework to support life extension decision making for safety critical systems
- A systematic review on the current state-of-the-art and new developments in the field of asset life extension
- To identify current key issues and approaches for life extension in various industries
- To outline the strengths and weaknesses of existing life extension decision-making tools
- To suggest directions of future research on asset life extension.

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Life extension decision making of safety critical systems: An overview

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