
Sustainability in strategic asset management frameworks: a systematic literature review

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Abstract: Decisions on strategic asset management often consider long lifetimes. The long-term perspective, varying types of assets, and other industry trends, such as sustainability requirements, have implications for strategic asset management frameworks. The stakeholders related to the assets are demanding actions that increase sustainability, and forward-looking organisations are adopting sustainability principles in their business. This study gives guidelines for the development of more holistic strategic asset management frameworks. Using a systematic literature review, 37 frameworks are identified and analysed based on their application area, decision level, uncertainty management practices, and asset management indicators. As a result, a conceptual sustainable strategic asset management framework is created.

Keywords: asset management; manufacturing; infrastructure; sustainability; literature review.

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1 Introduction

Infrastructure and production asset-related decision making often consider long lifetimes, even 100 years or more. These assets include physical machinery, equipment, and infrastructure. The long lifetimes typically increase the need for maintenance and have implications for asset-related decision making. Varying types of assets, the long-term perspective, and other industry trends, such as sustainability requirements, call for strategic decision support frameworks for managing these assets. In the context of this study, the focus is on physical assets and the factors affecting their performance including single assets, groups of assets and even whole asset systems that are managed by strategic asset management (SAM) frameworks.

Strategic asset management (SAM) frameworks help organisations to manage and develop their asset management (AM) system and practices. In this study, a SAM framework entails all types of decision support systems that aim to support SAM-related decisions, such as capability maturity models, key performance indicators (KPIs), and strategic maintenance performance measurement models. Critical success factors or KPIs that are derived from organisational strategy should guide the development of AM performance (Parida et al., 2015; Leidecker and Bruno, 1984; Tsang et al., 1999). This development is supported by the identification, development, and implementation of appropriate guidelines and KPIs (Parida et al., 2015). Capability maturity models can be utilised to assess the performance capabilities of an organisation (Hilson, 2003). SAM frameworks typically assess the performance of an organisation with a set of indicators and include measures of uncertainty.

Recently, sustainability aspects have been considered more in AM (e.g., ISO 55000, 2014; Hanski et al., 2013; Marlow, 2010; Liyanage, 2007). A common definition for sustainability is “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Sustainability integrates the “goals of a high quality of life, health and prosperity with social justice and maintaining the earth’s capacity to support life in all its diversity” (ISO 26000, 2010). It encourages companies to manage the environmental and social impacts of their decisions on various stakeholders in addition to their economic performance. However, expressing sustainability in clear and concrete operational terms has been challenging (Liyanage and Badurdeen, 2009; Labuschagne et al., 2005). There is a lack of guidance for linking important business processes to sustainability frameworks and approaches to address the importance of AM in achieving sustainability (Ojanen et al., 2012). Challenges and benefits of maturity and maintenance management frameworks have been assessed in earlier studies (e.g., Mahmood et al., 2015; Parida et al., 2015). Stakeholder and sustainability management, as well as climate change adaptation, are considered to be the areas that current AM maturity models do not fully cover (Mahmood et al., 2015).

This study gives guidelines for the development of more holistic SAM frameworks that include sustainability and other important perspectives based on the revealed gaps and emerging trends captured in the review of the AM literature. This paper aims to answer the following main research question:

- What kind of conceptual model and indicators would support the development of SAM frameworks towards a better application of sustainability principles?

In order to answer this, the following supporting questions must be considered:

- What are the generic characteristics of SAM frameworks?
- What kind of indicator groups are currently utilised in SAM frameworks?
- What are the sustainability principles in the context of strategic asset management?

The paper provides an overview of the existing papers, reports, and book chapters on SAM frameworks, demonstrates useful categorisations for analysing these, and proposes a conceptual model. The paper is based on a systematic review of literature, which is an iterative process consisting of data collection, descriptive analysis and category selection, and data evaluation (Tranfield et al., 2003; Seuring and Müller, 2008).

The organisation of the paper is as follows: the next chapter outlines the SAM frameworks. Section 3 discusses sustainability and presents sustainability principles that are utilised in the conceptual model. This discussion is followed by a description of the systematic literature review methodology. Section 5 discusses the characteristics of the reviewed SAM frameworks and their indicators and indicator groups. The conceptual framework and an analysis of the results presented in Sections 6 and 7 conclude the paper.

2 Asset management and strategic decisions

Institute of Asset Management (IAM) (2008) defines asset management (AM) as: “a set of disciplines, methods, procedures and tools to optimise the whole life business impact of cost, performance and risk exposures (associated with availability, efficiency, quality, longevity and regulatory/safety/environmental compliance) of the company’s physical assets”. This definition is connected with the maintenance-related activities of physical assets. ISO 55000 (2014) provides a more general definition for AM: “the coordinated activity of an organisation to realize value from assets”. AM should balance the financial, environmental and social costs, risks, quality of service, and performance related to assets. According to ISO 55000 (2014), AM should consider the sustainability and the long-term competitiveness of organisations and take into account the effects on various external and internal stakeholders. This definition is applicable to all types of assets, such as financial, physical and non-physical, infrastructure, or human assets.

In this study, the focus is on SAM frameworks for physical machinery, equipment, and infrastructure. In the context of this paper, the SAM framework is a decision support framework that either manages the whole AM system, a part of the system, a group of assets, or a single asset.

AM provides new management principles and perspectives on the planning and execution of maintenance tasks for asset-intensive organisations such as highway

agencies and energy providers (e.g., Schraven et al., 2011; Volker et al., 2013). AM is claimed to benefit organisations in many ways. It provides asset knowledge for related management and decision support activities (Hastings, 2010). AM enables asset managers to get more time to consider their options and select the most viable decision alternatives and ensure the availability of life cycle costs of alternative investment proposals through AM information (Povey and Peach, 2013). It helps asset managers to maximise asset value, minimise the risks involved (Moon et al., 2009), and meet regulatory requirements (Younis and Knight, 2014). It provides a holistic system view on assets, not just a view on discrete activities, e.g., maintenance (El-Akruti et al., 2013; Too, 2012). IPWEA (2006) lists the benefits of AM as enhanced service and customer satisfaction, improved governance and accountability, improved risk management, improved financial efficiency, and enabling more sustainable decisions.

AM strategy interacts with the objectives and the business strategy of an organisation (ISO 55000, 2014; Hastings, 2010). The alignment of AM objectives and organisational objectives can improve the effectiveness and efficiency of an organisation (ISO 55000, 2014). Attwater et al. (2014) have studied the current level of AM and asset performance measurement practices in several infrastructure sectors. According to their study, only a few of the asset performance measures are tracked, recorded, and reported, and the measures are usually not linked to business performance. Additionally, the emphasis of the organisations is on AM maturity assessment and not on the actual performance of the assets. There is a need for a framework that integrates AM into a strategic management system (Younis and Knight, 2014).

AM-related decisions are complex and involve multiple stakeholders with possibly conflicting needs and requirements (Liyanage, 2012). AM systems involve complex technologies, information systems, and organisational structures. There are some frameworks and maturity models for supporting AM decisions and defining processes for AM (ISO 55000, 2014; BS PAS 55, 2008; etc.). However, there are new issues that AM frameworks must face, i.e., sustainability, interaction between built assets and the natural environment, resilience, life cycle management, community demands, information management, and new types of governance arrangements (Brown et al., 2014). External and internal factors, such as changes in demand and the competitive environment, economic obsolescence, security of economy, climate change, compliance with requirements, technological development, acquisitions, changed operating practises and requirements, wear and aging, technical and environmental obsolescence affect an organisation's AM strategy (Hastings, 2010; Komonen et al., 2012; Liyanage, 2012). Additionally, the focus of AM maturity models is on operational and technical levels, and the important perspectives of strategy, policy, social and governance are neglected (Laue et al., 2014).

3 Sustainability

AM plays a major role in moving towards sustainability (e.g., ISO 55000, 2014; Marlow, 2010). ISO 55000 (2014) emphasises the environmental, economic, and social pillars of sustainability and the fulfilment of sustainability-based organisational objectives.

The overall goal of sustainability is to meet present needs without compromising the ecological systems, social justice, and welfare of future generations (Jorna et al., 2009; Brundtland, 1987). United Nations (2015) have set 17 sustainable development goals for

2030. The goals address the global challenges related to poverty, inequality, climate, environmental degradation, prosperity, and peace and justice. Directly, AM could support the achievement of several sustainable development goals including, e.g., industry, innovation and infrastructure, clean water and sanitation, recycling and climate action. Indirectly, through increased efficiency and effectiveness of use of assets during their life cycle, AM could support many other goals such as no poverty and zero hunger. There are several reasons why aspects of sustainability demand the attention of an organisation. These include costly non-compliance with regulations through, e.g., fines, legal costs and effects on the company's reputation (Epstein, 2008) and importance of community relations in order to gain the loyalty and trust of the company's various stakeholders (Epstein, 2008; Keeble et al., 2002; Lackmann et al., 2012). Additionally, sustainability may also bring greater revenues and lowered costs through enhanced reputation, reduced fines, and other costs (Epstein, 2008; Kiron et al., 2013). Sustainability can be a source of competitive advantage and value creation possibilities (Schaltegger and Wagner, 2006; Elkington, 1998). Organisations have a responsibility to manage sustainability because of their impact on society and the environment (Epstein, 2008).

Table 1 Sustainability principles [applied from Epstein and Roy (2003) and Epstein (2008)]

<i>Sustainability principle</i>	<i>Definition</i>
Ethics	Fair and honest standards and practices when dealing with stakeholders
Governance	Conscientious management of all resources with a focus on the interests of all stakeholders
Transparency	Open communication of past, present, and future performance
Business relationships	Suppliers are valued long-term partners, and there is a commitment to developing partners' social and environmental practices.
Financial return	A sustainable organisation balances the interest of all the stakeholders, promoting growth and long-term value.
Community involvement and economic development	The long-term interests of both the company and the community are the improvement of the community, its resources, and the lives of its members.
Value of products and services	Respecting the needs, desires, and rights of customers and also those of consumers and providing high-level product and service values
Employment practices	Promotion of personal and professional development, diversity, and empowerment. Employees are valued partners in the business and have their right to fair labour practices, competitive wages, and a safe, family-friendly working environment
Protection of the environment	Striving to protect and restore the environment and promote the sustainable development of processes, activities, products, and services

Epstein and Roy (2003) and Epstein (2008) present a set of principles to help organisations focus on sustainability in their decision-making processes: ethics, governance, transparency, business relationships, financial return, community involvement/ economic development, value of products and services, employment practices and protection of the environment. The sustainability of an organisation can be assessed using sustainability indicators and indicator frameworks. There are several frameworks available for organisations to measure and improve their sustainability (e.g.,

GRI, 2015; Long et al., 2016). Table 1 presents a general categorisation of sustainability indicator groups in accordance with the sustainability principles presented in Epstein and Roy (2003) and Epstein (2008).

The principle of ethics includes indicator groups, such as social contribution rate, welfare spending, and other expenditure to society, non-discrimination, freedom of association, and collective bargaining, ban of child, forced, or compulsory labour, supplier human rights assessment and grievance mechanisms, and reporting violations of standards (Long et al., 2016; GRI, 2015; Epstein, 2008). The governance principle includes enhancing both human and financial capital by taking into account resilience and security practices, a clear mission understood by employees, and strategy and performance metrics that are in line with the mission (Raworth, 2012; Epstein, 2008). Transparency indicators consist of accountability to internal and external stakeholders, environmental report release, and scarcity-, mining-, product-, company- and technology-related information (Epstein, 2008).

Business relationship indicators include, for instance, considering price, social, ethical, and environmental reasons for selecting suppliers and improving partners' social and environmental practises (Epstein, 2008; GRI, 2015). Financial return can be enhanced by compensating the providers of capital with a competitive return on investment and the protection of company assets that promote growth and long-term shareholder value in the organisation's strategies (Epstein, 2008). Additionally, it can be supported by recognising the interests of investors and lenders explicitly, and considering corporate profitability, capital turnover, debt-paying ability, indirect economic impacts and development ability (Long et al., 2016; GRI, 2015; Epstein, 2008).

Community involvement and economic development indicator groups include perspectives, such as local communities, anti-corruption and public policy, anti-competitive behaviour, compliance, supplier assessment for impacts on society, and grievance mechanisms for impacts on society (GRI, 2015; Epstein, 2008). The value of products and services consists of specifying the organisation's relation and obligations to its customers, its commitment to integrity, customer satisfaction and safety, the assessment of impacts of products and services on stakeholders, customer health and safety, product and service labelling, marketing communications, and customer privacy (GRI, 2015; Epstein, 2008).

Employment practices include employee satisfaction and respecting human rights, tuition payback, family leave time, child care, and career development opportunities, employment, labour/management relations, occupational health and safety, training and education, diversity and equal opportunity, equal remuneration for women and men, supplier assessment for labour practices, labour practice grievance mechanisms, income growth rate and employee injury rate (GRI, 2015; Epstein, 2008). The protection of the environment contains defining organisations' commitment to the natural environment. It aims at minimising the use of energy and natural resources (raw material, energy, freshwater, and land), and simultaneously decreasing effluents, waste, and emissions (COD, CO₂, SO₂ and other), improving energy and material efficiency and maximising the use of recycled material. It includes aspects such as the durability of products and minimising the packaging, minimising ecosystem impact and biodiversity; investment in pollution control and environmental protection, climate change mitigation and adaptation,

supplier environmental assessment and grievance mechanisms, and public satisfaction with local environmental quality and awareness with eco-industrial development (Korse et al., 2016; Long et al., 2016; Raworth, 2012; Epstein, 2008).

4 Methodology

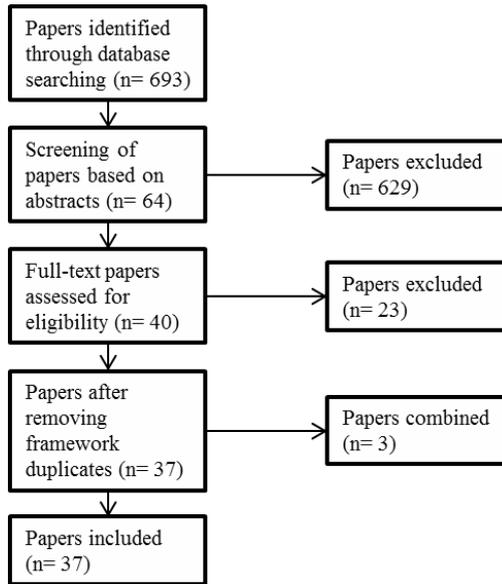
This paper utilises a comparative analysis of SAM frameworks based on systematic literature review. Systematic reviews adopt a replicable, scientific, and transparent process that aims to minimise bias through exhaustive literature searches of published and unpublished studies. This method provides an audit trail of the reviewers' decisions, procedures, and conclusions (Tranfield et al., 2003; Cook et al., 1997). The review uses an iterative process that is modified from methods presented in Tranfield et al. (2003) and Seuring and Müller (2008):

- 1 data collection
- 2 descriptive analysis and category selection
- 3 data evaluation.

4.1 Data collection

In the data collection phase (see Figure 1), the data to be collected was defined and delimited (Seuring and Müller, 2008). The systematic literature review was conducted using the eKnowledge database. The database enables access to a large amount of scientific databases, such as Scopus, Web of Science, ScienceDirect, and open access databases. Keywords for the search were asset management, engineering asset management, maturity model, framework, manufacturing and infrastructure. Four searches were conducted using the keywords 'asset management', 'manufacturing', 'infrastructure', 'maturity model' and 'framework' in the following combinations 'asset management' + 'maturity model' + manufacturing, 'asset management' + 'maturity model' + infrastructure, 'engineering asset management' + framework + manufacturing and 'engineering asset management' + framework + infrastructure.

The preliminary screening was conducted based on the titles and abstracts of the papers. Papers published between 2000 and 2016 were included in the review to include only the most recent papers. Additionally, relevant papers that were published before 2000 were not identified using the keywords. After the screening, 64 different papers were identified in this phase. Peer-reviewed articles, conference papers, and book chapters were included to provide a rich material for analysis. Upon further analysis of the papers, 40 papers describing SAM were selected. During this phase, a few new articles were discovered by analysing the key references in the original papers identified in the previous phase. In the final phase of the analysis, the same frameworks that were described in several papers were identified and combined. Altogether, 37 unique papers were selected for further analysis. The papers included in the literature review are presented in Appendices 1 and 2.

Figure 1 The data collection process

4.2 Descriptive analysis and category selection

During the descriptive analysis and category selection phase, the formal aspects of the data were assessed. Categories were selected and applied to the collected data (Seuring and Müller, 2008). The results of the literature review were classified and analysed according to the type of framework, application area, decision level, indicator groups, and uncertainty management practices. These classifications were used for the subsequent evaluation.

4.3 Data evaluation

In the data evaluation phase, the material was thematically analysed according to the selected categories (Seuring and Müller, 2008). The validity and reliability of results were increased by using an iterative process to create a conceptual framework. This iterative process included creation of several versions of the conceptual model based on further analysing the data and feedback received by the authors. When analysing the data, the researchers looked for emerging classifications, indicator groups, and patterns. The classifications were created based on the classifications used in the literature and findings from the data. The indicator groups were analysed in the context of the theoretical framework. In the end, the data set was analysed to identify the connections between strategic AM frameworks and sustainability principles.

5 Results

This chapter discusses the findings from the systematic literature review. The reviewed papers and their characteristics are presented in Appendices 1 and 2.

5.1 Classification of SAM frameworks

When analysing the data, three types of SAM frameworks were identified: guidelines and Key performance indicators (KPIs), asset maturity models, and other strategic maintenance or AM frameworks. The reviewed 37 frameworks were divided into groups as follows:

- 1 guidelines and key performance indicators (KPIs) for strategic AM (7 papers)
- 2 asset maturity model (8)
- 3 other strategic maintenance or AM frameworks (22).

Guidelines and KPIs refer to a list of indicators or guidelines for monitoring and improving AM and performance. As an example of guidelines and KPIs, Salonen and Bengtsson (2011) present a list of company-specific non-monetary KPIs related to overall company, production, and maintenance goals such as work-time distribution, overall equipment effectiveness, and technical availability.

The asset maturity model is a structured approach that aims at describing the performance of AM or the level of capabilities of an organisation for AM in comparison to other organisations. Identifying the maturity level of AM helps organisations develop their AM practises. Capability maturity models have been used to manage organisational capabilities (Chemweno et al., 2015). However they have certain limitations, for instance, their applicability in asset maintenance is limited because they usually do not include links between maintenance performance to organisational objectives, maintenance policies, and improvement actions (Wendler, 2012; Chemweno et al., 2015).

Other strategic maintenance or AM frameworks are a general term for the frameworks that support AM decisions at the strategic level. These frameworks typically present links between asset performance, AM system, and business performance in a process model. Examples of strategic maintenance or AM framework are presented in ISO 55000-2 (2014) and Attwater et al. (2014).

5.2 Application area

In general, the reviewed papers discuss frameworks that are designed to support infrastructure, manufacturing, or general unspecified AM. Based on the application area, the frameworks can be divided into groups as follows:

- 1 infrastructure (17 papers)
- 2 manufacturing (6)
- 3 general AM (14).

Infrastructure included articles in fields such as construction and facilities management, water sector, gas and electricity network, railway, dams, flood and coast defence, critical infrastructure, power supply, and tourist infrastructure (e.g., Attwater et al., 2014; Amaratunga et al., 2002; van der Lei et al., 2012). Manufacturing articles mainly considered general manufacturing and capital-intensive industries (e.g., Salonen and Bengtsson, 2014; Badurdeen et al., 2011; El-Akruti et al., 2013). Those frameworks that were not specifically designed for any application areas were labelled as general AM models or frameworks (e.g., Chemweno et al., 2015; Ouertani et al., 2008; Parida et al., 2015).

5.3 *Decision level*

The frameworks support either strategic decision-making or both strategic and operative decisions. Frameworks can be divided based on their decision level as follows:

- 1 purely strategic (26 papers)
- 2 strategic and operative (11).

As the scope of the review is on strategic frameworks, all the frameworks represent strategic level decision-making (e.g., Peppelman and Kramer, 2012; Stapelberg, 2011; Harpur and Brown, 2011). However, some of the frameworks also support operative decision making (e.g., van der Lei et al., 2012; Hall et al., 2004; Kersley and Sharp, 2014).

5.4 *Uncertainty management*

The frameworks include several means for uncertainty management, for instance, a continuous improvement and assessment phase to evaluate AM decisions in the event a decision environment changes (Attwater et al., 2014; Amaratunga et al., 2002; Mehairjan et al., 2012). Some of the practices and methods used for uncertainty management include monitoring opportunities and risks (Attwater et al., 2014; Peppelman and Kramer, 2012) risk assessment methodologies (Sun et al., 2012a; van der Lei et al., 2011), portfolio management (Peppelman and Kramer, 2012), real options, and serious gaming (van der Lei et al., 2012). Additionally, multi-criteria decision analysis methods (MCDA) (Parida, 2012; Volker et al., 2013; Macgillivray and Pollard, 2008; Macgillivray et al., 2007) and alternative scenarios (Hall et al., 2004; Nielsen et al., 2013) are utilised in complex decision situations.

In addition, decision criteria, such as risk, uncertainty, volatility, and flexibility (e.g., Stapelberg, 2011; Komonen et al., 2012), are used as means for uncertainty management. In some frameworks, the performance of indicators is complemented with a sensitivity analysis (e.g., Hall et al., 2004). Weighting methods are used to highlight the importance of certain decision criteria (Chemweno et al., 2015; Hall et al., 2004).

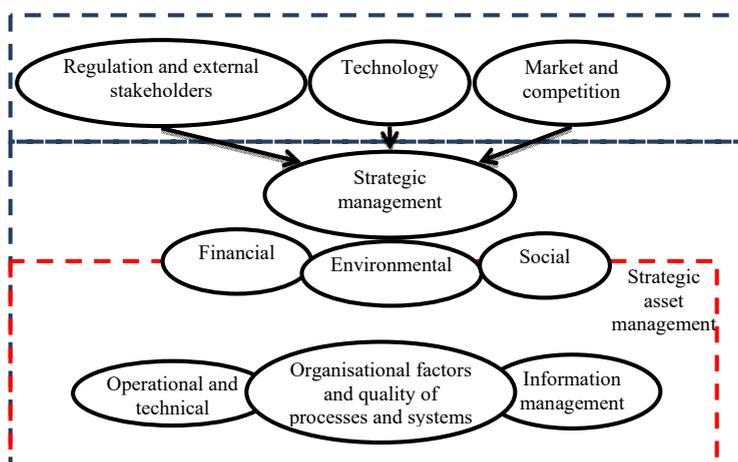
5.5 *Indicators used in the reviewed frameworks*

The frameworks included a large number of specific indicators. In some cases, the indicators were grouped into larger criteria groups. Based on the analysis of the frameworks, ten indicator groups were identified:

- 1 operational and technical
- 2 financial
- 3 environmental
- 4 social
- 5 data and information management
- 6 organisational factors and quality of processes and systems
- 7 strategic management
- 8 regulation and external stakeholders
- 9 technology
- 10 market and competition.

The indicator groups partially overlap. Both quantitative and qualitative indicators were identified. The first seven criteria groups represent a company internal perspective, whereas the last three groups describe the external operating environment and the future development of a company. External environment includes factors such as trends, regulation, laws, market, technology, and stakeholders. Strategic management at the corporate level consists of strategic management (corporate level, organisational plans and objectives) and strategic asset management functions (SAM framework, fleet, plant, and operative level perspectives, AM policy, strategic AM plan, support systems, asset portfolio, performance evaluation, and improvement (ISO 55000, 2014). Strategic management objectives guide the development of asset management strategies. Some financial, social, and environmental indicators could also be listed in external environment indicators. Figure 2 situates SAM and the indicator groups in the strategic decision-making context.

Figure 2 Indicator groups in SAM context (see online version for colours)



Note: Indicator groups are divided into three focus areas: external environment, strategic management at corporate level, and strategic asset management.

The regulation and external stakeholders group encompasses perspectives such as engagement with customers and other stakeholders (Macgillivray and Pollard, 2008; Macgillivray et al., 2007; Parsons, 2006) and the evaluation of service benefits (Sun et al., 2012b; Nielsen et al., 2013). External risks were used as an indicator in this category (Badurdeen et al., 2011).

The technology group contains perspectives such as internal and external asset specifications, technological change, flexibility, economic/technical inertia, and economic/technical life cycle (Komonen et al., 2012; van der Lei et al., 2011). The maturity of technology and the relative level of technology compared to benchmarked companies were used as indicators (Brimfield and Myer, 2011; Komonen et al., 2012; Volker et al., 2013).

The market and competition group encompasses perspectives such as product life cycle phases, barriers to entry, uncertainty in and volatility of market, industry structure, sources of differentiation, regulatory acts, competitive position, economic structure, scale of operations, dynamic product portfolio, and growth strategy (Komonen et al., 2012). The maturity of market and competition, and relative level of market and competition compared to benchmarked companies were used as indicators (Komonen et al., 2012; Volker et al., 2013).

The strategic management group incorporates several perspectives such as risk management (hardware, software, organisational, sustainability and human risks, capture interdependency of risk elements (external and internal)) (Volker et al., 2013; Badurdeen et al., 2011; Attwater et al., 2014), strategic planning and project implementation, and control (Ebinger and Madritsch, 2012; Madritsch and Ebinger, 2011), policies and procedures (Macgillivray and Pollard, 2008; Macgillivray et al., 2007), life cycle management (Kersley and Sharp, 2014), brand capital (Harpur and Brown, 2011), governance strategy, and the balance of AM and business plan (Parsons, 2006). The indicators in this group include value at risk (van der Lei et al., 2012), quantitative and likelihood-based risks (Badurdeen et al., 2011), impact and likelihood (Wijnia, 2012), vulnerability, survivability, dependability, complexity, uncertainty, and adaptability (Stapelberg, 2011).

The operational and technical indicator group includes perspectives such as maintenance, production performance and efficiency (e.g., Chemweno et al., 2015), reliability (e.g., Attwater et al., 2014; van der Lei et al., 2012), dependability, availability, quality and asset condition (e.g., Nielsen et al., 2013), services (Ebinger and Madritsch, 2012; Madritsch and Ebinger, 2011), roles and responsibilities (Macgillivray and Pollard, 2008; Macgillivray et al. 2007), material availability (Salonen and Bengtsson, 2014), asset characteristics (van der Lei et al., 2011), manufacturing, installation, system design, and operation (Tzimas et al., 2012). This criteria group contains the largest number of indicators, for instance, planned and unplanned maintenance tasks, the response time for maintenance (Nielsen et al., 2013), outages, failures to operate, output, asset utilisation rate, and overall equipment effectiveness (OEE) (Hastings, 2010).

The information management group contains perspectives such as information and data quality and the value of information (Ouertani et al., 2008), input and output data management, documentation and reporting (Macgillivray and Pollard, 2008; Macgillivray et al., 2007), data integration (Brimfield and Myer, 2011), asset knowledge management

(Kersley and Sharp, 2014), systems for capturing and storing asset performance, and condition data and information management processes (Haider, 2011). These criteria were measured mainly based on their perceived level and maturity.

The organisational factors and quality of processes and systems group includes perspectives such as enabling factors for process improvement (Peppelman and Kramer, 2012), AM competencies (Macgillivray and Pollard, 2008; Macgillivray et al., 2007), the flexibility of the AM system (van der Lei et al., 2012; Komonen et al., 2012), AM organisational entity, AM process, AM information system entity, AM resource entity, and AM events (Frolov et al., 2010), organisational factors, organisational learning (Parida, 2012; Macgillivray and Pollard, 2008; Macgillivray et al., 2007), human factors (Harpur and Brown, 2011), and people management (van der Lei et al., 2011). This category contains indicators such as the level of enabling factors for process improvement, for instance, commitment, ability, activities, evaluation and verification (Amaratunga et al., 2002) and the level of AM competencies such as issue identification & risk analysis, solution specification, portfolio planning, project execution and process improvement (Peppelman and Kramer, 2012). In addition, this category includes level of organisational factors such as information management, internal and external coordination, market approach, risk management, processes and roles, training and culture and leadership (Volker et al., 2013; Hastings, 2010).

The financial criteria group incorporates perspectives such as sustainability (e.g., Attwater et al., 2014; Marlow et al., 2010; Badurdeen et al., 2011), profitable growth, stability, capacity and productivity (Salonen and Bengtsson, 2014), and full lifecycle and multiple lifecycle approaches (e.g., Badurdeen et al., 2011). The indicators in this group include return on investment, various cost, value produced and asset depreciation (Attwater et al., 2014), whole-life cost (Kersley and Sharp, 2014), payload by weight, volume, value and value per truck-day (Hastings, 2010), overheads, direct costs, fixed contract income, non-energy turnover, operational capital, expenditure, overtime and staff absence (Hall et al., 2004), life cycle costs (LCC) of acquisition, ownership and disposal phases (Hoffart and Stür, 2012).

The environmental group includes perspectives such as sustainability (Attwater et al., 2014; Stapelberg, 2011; Badurdeen et al., 2011; Liyanage, 2007; Marlow et al., 2010), oil pollution (Hall et al., 2004) and full lifecycle and multiple lifecycle approaches. The group contains indicators such as environmental conditions (Badurdeen et al., 2011), damage to buildings or sensitive environments (Hastings, 2010), local authority improvement notices enforcement orders, oil pollution reported incidents and ISO 14001 accreditation (Hall et al., 2004).

The social group encompasses perspectives such as safety (e.g., Rezvani et al., 2009; Hall et al., 2004, Attwater et al., 2014), health (Nielsen et al., 2013; Hastings, 2010), sustainability (e.g., Marlow et al., 2010), security (Nielsen et al., 2013), and employee satisfaction (Parida, 2012). This group contains indicators such as the number of accidents or incidents, employee absentees, personal injury, or significant expenditure on employees (Nielsen et al., 2013; Hall et al., 2004), occupational safety and health injuries (Hastings, 2010), enforcement orders, asbestos pollution events and Reservoir Act enforcement actions (Nielsen et al., 2013).

6 Discussion

The reviewed AM frameworks support strategic level AM decisions. Most of the frameworks show links between asset performance, AM system, and business performance in a process model. Other frameworks include maturity models, guidelines or KPI. The reviewed SAM frameworks represent infrastructure and manufacturing sectors or are generally applicable for all sectors. Considering that some of the frameworks and methods are designed for safety-critical systems, the inclusion of uncertainty management methods and perspectives is not surprising. Using uncertainty management methods, such as risk and sensitivity analysis, scenarios, continuous improvement, and the weighting of indicators and indicator groups should be considered in the development of SAM frameworks.

SAM frameworks include a large amount of different indicators that can be divided into ten indicator groups. As stated in previous research (Laue et al., 2014; Mahmood et al., 2015), perspectives such as strategy, policy, social governance, stakeholder and sustainability management, and climate change adaptation are neglected in SAM frameworks, whereas operational and technical perspectives are emphasised. The results of the literature review are largely in line with these statements, however, some indicators representing these perspectives were also identified. Ten main indicator groups were identified. These groups were situated in the external environment, in strategic management at the corporate level and in SAM contexts. The operational and technical indicator group included the most indicators and was generally taken sufficiently into account in the frameworks. In general, the least attention was paid to external indicator groups such as technology, market, and competition, and internal indicator groups such as information management.

Sustainability is identified as an important factor affecting the selection of indicators for SAM frameworks. Even though sustainability was not selected as a specific indicator group, it should be represented in several indicator groups such as operational and technical, financial, environmental, and social.

The sustainability principles presented in Table 1 should be considered when developing SAM frameworks and indicators for the focus area and indicator groups. SAM supports the governance principle by enabling the effective management of an organisation's resources. It allows for process and product use data to be collected and analysed. This enables an increase in the quality and performance of an organisation's operations, products and services and the transparency to its community and stakeholders. Additionally, effective SAM supports the protection of the environment by enabling a decrease in emissions and the consumption of materials and energy and an increase in the share of materials that can be reused or recycled and, consequently, the life cycle of assets can be extended. Tables 2, 3 and 4 presents a conceptual framework for connecting the sustainability principles with the identified indicators and indicator groups in the different focus areas. Additionally, practical and managerial impact of sustainability principles is considered.

Table 2 A conceptual framework connecting sustainability principles and AM indicator groups: external environment

<i>Focus area</i>	<i>Indicator group</i>	<i>Indicators and perspectives identified in the literature review</i>	<i>Connected sustainability principle</i>	<i>Practical/managerial impact of sustainability principle</i>
External environment	Market and competition	Maturity of market and competition, relative level of market and competition compared to benchmarked companies, product life cycle phases, barriers to entry, uncertainty in and volatility of market, industry structure, sources of differentiation, regulatory acts, competitive position, economic structure, scale of operations, dynamic product portfolio, and growth strategy	Ethics Business relationships	Consideration of ethical perspectives related to market and competition Long-term commitment to partnerships and overall sustainability of industry
	Technology	Internal and external asset specifications, technological change, flexibility, economic/technical inertia, economic/technical life cycle, maturity of technology, relative level of technology compared to benchmarked companies	Protection of environment	Benchmarking maturity of technology from the perspective of environmental protection, tracking the environmental impacts of alternative technologies Ensuring sustainability of technologies over their life cycle
	Regulation and external stakeholders	Engagement with customers and other stakeholders, evaluation of service benefits, external risks	Value of products and services Community involvement and economic development Ethics Transparency Value of products and services	Co-development with customers and stakeholders Fair and honest standards when dealing with stakeholders Open communication of organisation's performance Value and risks of organisation and its solutions from the perspective of sustainability

Table 3 A conceptual framework connecting sustainability principles and AM indicator groups: strategic management at corporate level

<i>Focus area</i>	<i>Indicator group</i>	<i>Indicators and perspectives identified in the literature review</i>	<i>Connected sustainability principle</i>	<i>Practical/managerial impact of sustainability principle</i>
Strategic management	Strategic management	Risk management including hardware, software, organisational, sustainability and human risks, interdependency of risk elements, strategic planning and project implementation, and control, policies and procedures, life cycle management, brand capital, governance strategy, and the balance of AM and business plan, risks, impact and likelihood, vulnerability, survivability, dependability, complexity, uncertainty, and adaptability	Governance	Consideration of interests of all stakeholders when developing and executing strategies
		Sustainability, oil pollution, full lifecycle and multiple lifecycle approaches, environmental conditions, damage to buildings or sensitive environments	Transparency	Open communication of organisation's performance
	Environmental	Safety, health, sustainability, security, employee satisfaction, number of accidents or incidents, employee absentees, personal injury, or significant expenditure on employees, occupational safety and health injuries and enforcement orders	Protection of environment	Protecting and restoring environment and sustainable practices are crucial part of strategic management
Social	Social	Sustainability, oil pollution, full lifecycle and multiple lifecycle approaches, environmental conditions, damage to buildings or sensitive environments	Value of products and services	Considerations of environmental value of organisation and its solutions
		Sustainability, oil pollution, full lifecycle and multiple lifecycle approaches, environmental conditions, damage to buildings or sensitive environments	Employment practices	Consideration of personal and professional development, diversity, empowerment, fair labour practices, competitive wages and safety management practices
Financial	Financial	Sustainability, oil pollution, full lifecycle and multiple lifecycle approaches, environmental conditions, damage to buildings or sensitive environments	Ethics	Fair and honest sustainability driven strategic management practices
		Sustainability, oil pollution, full lifecycle and multiple lifecycle approaches, environmental conditions, damage to buildings or sensitive environments	Value of products and services	Consideration of social value of organisation and its solutions
Financial	Financial	Sustainability, oil pollution, full lifecycle and multiple lifecycle approaches, environmental conditions, damage to buildings or sensitive environments	Financial return	Consideration of balanced stakeholder interests, growth and long-term value
		Sustainability, oil pollution, full lifecycle and multiple lifecycle approaches, environmental conditions, damage to buildings or sensitive environments	Value of products and services	Consideration of financial value of organisation and its solutions

Strategic management at corporate level

Table 4 A conceptual framework connecting sustainability principles and AM indicator groups: strategic asset management

<i>Focus area</i>	<i>Indicator group</i>	<i>Indicators and perspectives identified in the literature review</i>	<i>Connected sustainability principle</i>	<i>Practical/managerial impact of sustainability principle</i>
Information management	Operational and technical	Information and data quality and the value of information, input and output data management, documentation and reporting, data integration, asset knowledge management, systems for capturing and storing asset performance, and condition data and information management processes	Governance	Enabling conscientious management of organisations resources with a focus on the interests of all stakeholders
		Maintenance, production performance and efficiency, reliability, dependability, availability, quality and asset condition, services, roles and responsibilities, material availability, asset characteristics, manufacturing, installation, system design, and operation, planned and unplanned maintenance tasks, the response time for maintenance, outages, failures to operate, output, asset utilisation rate, and overall equipment effectiveness (OEE)	Transparency	Ensuring open communication of performance for stakeholders
		Enabling factors for process improvement, AM competencies, the flexibility of the AM system, AM organisational entity, AM process, AM information system entity, AM resource entity, and AM events, organisational factors, organisational learning, human factors, and people management, level of enabling factors for process improvement, for instance, commitment, ability, activities, evaluation and verification and the level of AM competencies such as issue identification & risk analysis, solution specification, portfolio planning, project execution and process improvement, level of organisational factors such as information management, internal and external coordination, market approach, risk management, processes and roles, training and culture and leadership	Governance	Conscientious management of all assets with a focus on the interests of all stakeholders
Organisational factors and quality of processes and systems		Enabling factors for process improvement, AM competencies, the flexibility of the AM system, AM organisational entity, AM process, AM information system entity, AM resource entity, and AM events, organisational factors, organisational learning, human factors, and people management, level of enabling factors for process improvement, for instance, commitment, ability, activities, evaluation and verification and the level of AM competencies such as issue identification & risk analysis, solution specification, portfolio planning, project execution and process improvement, level of organisational factors such as information management, internal and external coordination, market approach, risk management, processes and roles, training and culture and leadership	Employment practices	Enabling of personal and professional development, diversity, empowerment, fair labour practices, competitive wages and safety
			Ethics	Fair and honest sustainability driven management practices
			Transparency	Open communication of performance for stakeholders

Strategic asset management

Perspectives and indicators in the market and competition group currently focus on market characteristics and how the organisations offering answers to competition and market demands. While important, this group should also emphasise fair and honest standards and practices and long-term commitment to partnerships and overall sustainability of industry. The technology group focused on the relative level of technology and the uncertainty related to the technology. However, it should pay attention also to respecting the needs, desires, and rights of customers and consumers, to providing high-level product and service values, to striving for protecting and restoring the environment, and promoting the sustainable development of processes, activities, products, and services. Customer engagement, service benefits and external risks were identified as perspectives that are related to the regulation and external stakeholders group. In addition, this group should aim for fair and honest standards when dealing with stakeholders, the open communication of performance, the long-term development of the community they operate in, and provide high-level product and service values.

The operating environment limits and guides strategic management. Various perspectives and indicators such as risk management, strategic planning and control, governance, uncertainty and adaptability were identified for the strategic management group. This group should emphasise the conscientious management of all resources with a focus on the interests of all stakeholders. Environmental, social, and financial indicator groups could be situated in both the strategic management and SAM categories and similar sustainability principles affect them at both organisational levels. They are considered as a part of strategic management that provides environmental, social and financial perspectives and indicators for the strategic management at corporate level. Environmental, social and financial indicators for SAM are then derived from the indicators at the higher level.

Identified indicators and perspectives related to environmental indicator group include environmental sustainability, environmental pollution and damage and lifecycle perspective. In line with the identified indicators, the environmental group should highlight protecting and restoring the environment and promoting the sustainable development of processes, activities, products, and services. Perspectives and indicators in the social indicator group focus on safety, health, security and employee satisfaction. To complete these important indicators, the social group should focus on fair and honest standards and practices when dealing with stakeholders and the promotion of personal and professional development, diversity, and empowerment. The financial group indicators and perspectives include, e.g., profitable growth, stability, capacity and productivity, lifecycle approaches, return on investment, and value produced and asset depreciation. This group should focus on balancing the interest of all stakeholders in promoting growth and long-term value. Environmental, social, and financial groups should all focus on respecting the needs, desires, and rights of customers and consumers and to providing high-level product and service values.

Strategic management sets the objectives for SAM. The information management group includes indicators and perspectives such as data quality, information value, data management, documentation and reporting, asset knowledge management, IT systems and information management processes. Information management should be enabler in achieving the conscientious management of all resources with a focus on the interests of all stakeholders and open communication of past, present, and future performance. Operational and technical group has a major role in reaching organisations' strategic goals for environmental, social and financial sustainability. Indicators and perspectives in

this group include maintenance, production performance and efficiency, reliability, dependability, availability, quality and asset condition, services, roles and responsibilities, material availability, asset characteristics, manufacturing, installation, system design, and operation, failures, output, asset utilisation rate, and overall equipment effectiveness. These indicators and perspectives support the aim of this group, which should be the conscientious management of all resources with a focus on the interests of all stakeholders. Organisational factors and quality of processes and systems group includes indicators related to, e.g., process and roles, organisational factors and learning, leadership, AM competencies, internal and external coordination, processes and roles, training and culture. This group should emphasise the conscientious management of all resources with a focus on the interests of all stakeholders, the promotion of personal and professional development, diversity and empowerment, fair and honest sustainability driven management practices and open communication of past, present, and future performance.

As described in Figure 1, the indicator groups between the different focus areas in SAM context are interconnected, and thus, the sustainability principles, some of which can be found on several focus areas, are also interconnected. The developed conceptual model aims at providing an integrated and holistic overview on connecting the principles and AM indicator groups, to provide a platform for more economically, socially and environmentally sustainable development of SAM in the organisations.

7 Conclusions

The study presented a conceptual framework and guidelines for the development of more holistic SAM frameworks. The framework takes into account sustainability principles and identifies SAM indicator groups. The framework is based on a systematic review of AM literature. The generic characteristics and indicator groups used in existing SAM frameworks were identified in the study, and indicator groups were connected to sustainability principles in the context of strategic asset management.

A systematic literature review was conducted, and 37 SAM frameworks were identified. The main characteristics, such as application area, decision level, and decision criteria, were analysed. Three types of frameworks were identified: guidelines and KPIs, the asset maturity model, and other strategic maintenance or SAM frameworks. The definitions partially overlap. Three general groups of frameworks were recognised based on their application area. About half of these were infrastructure-related, whereas the rest were either general AM- or manufacturing-related frameworks or methods. All the frameworks support strategic decision-making, however, about one third of them also support operative decision-making. Several different uncertainty management methods and processes were identified in the SAM frameworks.

This paper makes two main contributions:

- 1 it reviews the characteristics of SAM frameworks focusing on the indicator groups used in the frameworks
- 2 it presents a conceptual model for enhancing the sustainability of SAM frameworks, which has not been systematically addressed in previous studies.

This paper creates a foundation for the development and evaluation of strategic AM frameworks. For instance, the identified indicator groups guide both the development of new application-area-specific SAM frameworks and company-specific frameworks. The conceptual framework also gives guidelines on the sustainability perspectives that should be covered by different focus areas of the organisation. Additionally, examples of gaps in the coverage of sustainability perspectives in the existing SAM frameworks and specific indicators for the different groups are introduced.

The analyses showed that, so far, only a limited number of journal papers have been published on the topic, and there are also many conference papers among the reviewed papers. This, together with the limitation of the review period to publications between 2000 and 2016, leaves room for some self-criticism related to the validation of the reviewed frameworks. However, the related articles were carefully selected using a step-by-step analysis to confirm their relevancy. In addition, using the same keywords for 2017–2019, only three novel frameworks were identified. The analyses of the scientific articles in this specific area also revealed the trend of an emerging interest in the topic and the need for strongly taking sustainability aspects into account. Therefore, further research will be needed to conduct both generic and detailed analyses of SAM frameworks. For instance, there is a need to analyse the decision criteria that are used in each application area or sector and in each decision context. The emphasis of future research should be on the company or company network external decision criteria groups, such as technology, market, and competition, and future research should create a balanced set of decision criteria for the frameworks. Similarly, the methods for uncertainty management used in strategic AM frameworks require further analysis.

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Appendix 1

Systematic literature review

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Appendix 2

Systematic literature review – analysis table

Table 5 Literature review results

No.	Article	Classification of AM frameworks ^a	Application area ^b	Decision level	Examples of uncertainty management practices	Examples of indicators used in the reviewed frameworks
1	Amaratunga et al. (2002)	2	1	1		Enabling factors for process improvement (commitment, ability, activities, evaluation, verification)
2	Attwater et al. (2014)	3	1	1		Maintenance/production performance indicators at strategic, tactical, and operational levels (production efficiency, consumed time, and manpower) Financial indicators (return on investment, various cost, value produced, asset depreciation) Safety Reliability, availability, maintenance Sustainability
3	Badurdeen et al. (2011)	3	2	1	Risk management practices	Impacts on three areas: economy, environment, and society, full lifecycle and multiple lifecycle approaches, external (industry-dependent) and internal (four sources of failure: hardware, software, organisational, and human) risks, quantitative, capture interdependency of risk elements Sustainability criteria (TBL), external and internal sources of failures, quantitative and likelihood-based, interdependency of risk elements
4	Brimfield and Myer (2011)	2	1	1		Data integration, technological maturity, condition monitoring, system capability
5	Chemweno et al. (2015)	2	3	1		Maintenance/production performance indicators at strategic, tactical, and operational levels (production efficiency, consumed time, and manpower)
6	Ebinger and Madritsch (2012) and Madritsch and Ebinger (2011)	2	1	1	Multiple criteria radar plot	Fifteen criteria such as strategic planning, project implementation and control, maintenance, operations, services and space management

Notes: ^aClassification of AM frameworks:

- 1 guidelines and key performance indicators (KPIs) for strategic AM
- 2 asset maturity model
- 3 other strategic maintenance or AM framework.

^bApplication area:

- 1 infrastructure
- 2 manufacturing
- 3 general AM.

^cDecision level:

- 1 Purely strategic
- 2 Strategic and operative.

Table 5 Literature review results (continued)

No.	Article	Classification of AM frameworks ^a	Application area ^b	Decision level ^c	Examples of uncertainty management practices	Examples of indicators used in the reviewed frameworks
7	El-Akruti et al. (2013) and El-Akruti and Dwight (2013)	3	2	2		Analysis and evaluation, decision making, coordination and planning, work task control, measurement and monitoring, control and reporting
8	Frolov et al. (2010)	3	3	1		All the phases of AM and their subcategories represented: AM organisational entity, AM process, AM information system entity, AM resource entity, AM event
9	Grigg (2005)	1	1	2		Technical – the change in performance in terms of service quality and the level of risk. Financial – the amount of investment required and the return on this investment through lower operating costs. Regulation – how any investment fits within the regulatory framework. Environmental considerations
10	Haider (2011)	3	2	1		Management and alignment of operational and information technologies related to asset management
11	Hall et al. (2004)	3	1	2	Scenarios, weights sensitivity analysis, uncertainty taken into account due to the great uncertainties related to the critical infrastructure in question	Operational criteria/indicators (outages, output, etc.) Environmental criteria Safety
12	Harpur and Brown (2011)	3	3	2		Six dimensions: human asset specificity, physical asset specificity, site spec., dedicated asset spec., brand capital spec., temporal asset spec.

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Table 5 Literature review results (continued)

No.	Article	Classification of AM frameworks ^a	Application area ^b	Decision level ^c	Examples of uncertainty management practices	Examples of indicators used in the reviewed frameworks
13	Hastings (2010)	1	3	2		<p>A list of criteria for several sectors (railway, water supply, electricity transmission, trucks) such as:</p> <ul style="list-style-type: none"> • % of planned train-kilometres delivered per month • % of services no more than 5 minutes late • train cancellations % • sewer discharge or overflow • sewage entering drain or watercourse • personal injury or significant health risk • damage to buildings or sensitive environments • outages frequency • outages duration • system-minutes lost • truck utilisation, • numbers of used and unused trucks, • payload by weight, volume, value • distance travelled • value per truck-day. <p>OEE = availability * utilisation * quality</p> <p>A list of maintenance related performance indicators</p> <p>LCC of acquisition, ownership, and disposal phases</p>
14	Hoffart and Stiller (2012)	3	1	1	Sensitivity analyses	

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Table 5 Literature review results (continued)

No.	Article	Classification of AM frameworks ^a	Application area ^b	Decision level ^c	Examples of uncertainty management practices	Examples of indicators used in the reviewed frameworks
15	Kersley and Sharp (2014)	3	1	2	Multiple criteria radar plot	Review and improvement, strategy and planning, whole-life cost justification, lifecycle management and delivery, asset knowledge management, capability development
16	Komonen et al. (2012)	3	2	1		Technology (internal and external asset specific, technological change, flexibility, economic/technical inertia, economic/technical life cycle) market (product lifecycle phases, barriers to entry, uncertainty in and volatility of, industry structure, sources of differentiation, regulatory acts)
17	Liyanage (2007)	3	2	1		Competition (competitive position, economic structure, scale of operations, dynamic product portfolio, growth strategy) TBL criteria: business performance specs, manufacturing asset performance criteria, performance accountabilities, and critical success factors for operations and maintenance
18	Maegillivray and Pollard (2008) and Maegillivray et al. (2007)	2	1	1	Multiple criteria radar plot	Scope, integration, verification and validation, organisational learning, stakeholder engagement, competence, resources, documentation and reporting, roles and responsibilities, policies and procedures, input and output data management
19	Marlow et al. (2010)	1	3	1		Sustainability
20	Meharjian et al. (2012)	2	1	1	Continuous improvement approach, multiple criteria radar plot	Transition, vision and pilot for RCM, organisation and processes, policy and criteria, information and systems, data quality, portfolio, and performance

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Table 5 Literature review results (continued)

No.	Article	Classification of AM frameworks ^a	Application area ^b	Decision level ^c	Examples of uncertainty management practices	Examples of indicators used in the reviewed frameworks
21	Nielsen et al. (2013)	3	1	1		<p>Structure condition, load carrying capacity, rate of deterioration of individual bridge elements, maintenance repair, rehabilitation, the optimisation and the RSP (remaining service potential) of both the overall structure and its individual elements:</p> <ol style="list-style-type: none"> 1 Structure related indicators: <ul style="list-style-type: none"> • availability • performance • quality • condition. 2 Maintenance-task-related indicators <ul style="list-style-type: none"> • quality for maintenance tasks • planned maintenance tasks • unplanned maintenance tasks • response time for maintenance 3 Health safety security and the environment indicator <ul style="list-style-type: none"> • number of accidents/incidents. 4 Employee satisfaction indicator: <ul style="list-style-type: none"> • employee absences. <p>Information quality, value of information Financial indicators (return on investment, various cost, value produced, asset depreciation)</p>
22	Ouertani et al. (2008)	3	3	1		

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Table 5 Literature review results (continued)

No.	Article	Classification of AM frameworks ^a	Application area ^b	Decision level ^c	Examples of uncertainty management practices	Examples of indicators used in the reviewed frameworks
23	Parida (2012)	3	3	2		Asset indicators, O&M indicators, cost indicators, health, safety and environment indicators, learning and growth indicators, customer satisfaction indicators, employee satisfaction indicators. Indicators are different at strategic, tactical and operational levels
24	Parida et al. (2015)	3	3	1		A comprehensive list of criteria used in various maintenance performance frameworks
25	Parsons (2006)	3	1	1		Stakeholder engagement, governance, policy and strategy, management, processes, systems, data, analysis, reporting, balance
26	Peppelman and Kramer (2012)	2	3	1	Portfolio management practices, monitoring and evaluation of risks and opportunities	Asset management competencies (issue identification and risk analysis, solution specification, portfolio planning, project execution, and process improvement)
27	Rezvani et al. (2009)	3	3	1		Costs, production, quality, safety, social and environmental factors
28	Salonen and Bengtsson (2014)	1	2	1		Criteria such as material availability, dependability, profitable growth, availability, stability, capacity, productivity, equipment availability, capacity, and productivity, etc.
29	Stapelberg (2011)	1	1	1		Hazards: vulnerability, survivability, dependability, complexity, uncertainty, adaptability, sustainability

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Table 5 Literature review results (continued)

No.	Article	Classification of AM frameworks ^a	Application area ^b	Decision level ^c	Examples of uncertainty management practices	Examples of indicators used in the reviewed frameworks
30	Sun et al. (2012a)	3	3	2	-	-
31	Sun et al. (2012b)	1	3	1	-	-
32	Too (2012)	1	1	1	-	-
33	Tzimas et al. (2012)	3	3	2		Material, manufacturing, installation, line design, environmental conditions, power system design and operation
34	Van der Lei et al. (2011)	3	1	2		Asset characteristics, environment (market, technology), key lifecycle phase, management (KPI, etc.)
35	Van der Lei et al. (2012)	3	1	2	Real options, serious gaming, etc.	Financial indicators (return on investment, various cost, value produced, asset depreciation)
36	Volker et al. (2013)	2	1	1		Reliability, availability, maintenance Flexibility of AM system Risks, value at risk
37	Wijmia (2012)	3	3	1		Organisational factors: information management, internal coordination, external coordination, market approach, risk management, processes and roles, and culture and leadership Impact, likelihood

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