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# Designing a hybrid methodology for the Life Cycle Valuation of capital goods

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ABSTRACT

Decision-makers are increasingly required to assess the value created by complex physical systems over their entire life cycle. The commonly applied Life Cycle Costing approach fails to fully capture value, as it is primarily aimed at costs, takes a reductionist approach, and does not account for continuously changing industrial environments. To address these shortcomings, the Life Cycle Valuation methodology is proposed, designed as a hybrid of LCC and Life Cycle Assessment. LCV facilitates the assessment of costs and benefits from multiple complementary perspectives and can be tailored to specific decision contexts, as demonstrated by applying LCV during Asset Management decision-making.



## Introduction

### *Generating value from enduring physical assets*

Enduring physical assets form the backbone of many manufacturing systems. Machinery, production lines, buildings, and infrastructure need to perform in safe, cost-effective, and reliable ways in order to produce a steady supply of high-quality products [1]. The lifespans of these assets are commonly expressed in decades, rather than years, as is common for describing the lifespans of products that these assets produce. Furthermore, these capital assets are very expensive to acquire or replace. For physical assets, the majority of the Life Cycle Costs (LCC) are attributed to the in-service phase of these systems, with maintenance costs often exceeding the initial capital investment over the lifetime of the asset [2]. This means that a consideration of the entire lifecycle is indispensable when committing to costly decisions that affect, or are affected by, these long-lived assets. To comprehend the full potential of physical assets, a deep and thorough understanding of their complete lifetimes is needed [3].

Therefore, a significant challenge in managing these long-lived assets lies in the fact that, despite a sound understanding of the lifecycle of the asset itself, the context in which it operates is subject to continuous change. Developments in governance, (geo) politics, the economy, society, demography, and technology all need to be taken into account when managing assets [4]. In automotive industries, for example, strategic and tactical decision-making and flexibility are essential for adapting manufacturing systems to ever-changing environments and for warranting optimal performance [5]. "*Because of increasing market dynamics and competition, companies in the manufacturing industry have to consider the flexibility of their manufacturing system in early planning phases and especially in investment decisions*" [6]. Among these investment decisions are those concerning mid-life upgrades of capital equipment, which can be used to extend the useful life and functionality of the asset, adding value during this period [7]. Furthermore, many capital goods consist of, or are part of, interconnected and/or complex systems that are often being used for purposes beyond their original mission [8]. As such, there is an increasing emphasis on making decisions that not only take the costs, potential benefits, and long lifespan into account but also need to include the systems perspective alongside long-term strategic objectives. Therefore, rational and lifecycle-oriented decision-making surrounding these physical systems is crucial, especially given the lasting and considerable consequences of committing to these types of decisions. Comprehensive and rigorous LCC applications are rare, even in literature [9]. Because

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LCC is often considered to be too laborious [10]. In practice, many firms, therefore, seem to rely on relatively simple payback calculations to make asset replacement decisions.

Asset Management (AM) is a commonly used systematic approach aimed at the realization of value from physical systems over their entire lifecycle. It involves the balancing of costs, opportunities, and risks against the desired performance of assets, to achieve the organizational objectives of the managing organization (ISO 55000, [11]). A striking example of the challenge of managing long-lived physical assets in a rapidly changing future context is found in the Energy Transition. The main characteristics of this transition in Europe are the liberalization of the energy sector, the shift towards renewable energy sources, decentralization of energy production, and changes in energy consumption patterns [12]. In energy production, the share of wind energy has grown exponentially over the last two decades and is likely to continue to do so [2]. The emergence of distributed energy resources, such as distributed generation, local storage, electric vehicles, and demand response, is driving changes in power systems [13]. These changes mean that the requirements and needs of future energy systems are different from those of the past. Decisions at the individual asset lifecycle level therefore have a larger consequence on the possibilities and limitations of the surrounding architecture than ever. Furthermore, a large part of the infrastructure and industrial assets in Western Europe is currently approaching its expected end-of-life [14,15]. Despite their age, assets designed and built decades ago still fulfill vital functions in manufacturing, as well as in society at large [1]. The combination of constant investment needs and long-term socio-technical developments of the energy transition requires rational decision-making and a long-term strategic perspective.

### *Problem identification*

Life Cycle Costing (LCC) is a commonly used instrument for supporting investment decisions concerning physical systems with long lifespans. LCC allows for the assessment and reduction of costs in the short, medium, and long-term, making it an essential instrument for long-term planning [16,17]. LCC can therefore be regarded as a major contributor to successful Asset Life Cycle Management [18]. From its early beginnings in the 1950s, the understanding of LCC has progressed from a relatively straightforward cost calculation concept to a management system in its own right. White and Ostwald [19], for example, define LCC as "*the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life*". [20], on the other hand, regard LCC as "*a managerial system that is focused on the modeling, quantification, and control of all the costs that are present during the design and operation stages which ends with [the] disposal of a physical asset.*"

From the perspective of AM decision-making, however, the application of LCC is not without limitations. LCC is already criticized because it has difficulties assessing complex systems, challenges in data collection, lack of transparency and trust, and long-term uncertainties, and thus poses both practical and methodological challenges for the development of Product Service Systems [21–23]. Similar challenges also form limitations when using LCC to support AM centered decisions. The first of these limitations is that AM is focused on realizing value from physical assets [24], whereas the principles of LCC are mainly focused on the costs borne by asset owners. Therefore, LCC does not include the consideration of various stakeholders associated with the asset [25]. AM supports the realization of value while balancing financial, environmental, and social costs, risk, quality of service, and performance related to assets (ISO 55000, [11]). This value-oriented perspective shifts the focus of life cycle cost analysis from the minimization of the cost of ownership of a product to the perception of service and maintenance cost as 'design variables' in order to form a trade-off with product features and performances [22]. Realizing value by means of trade-offs can be achieved in multiple ways, such as value-driven maintenance planning [26], future-proofing assets by applying changeable system design [27], functional product (re)design [28] or the development of sustainable business models [29]. Despite the existence of these approaches, however, the concept of value remains largely subjective, making it difficult for individuals to articulate exactly what makes a complex system valuable [30]. For applications in AM, the financial perspective, therefore, must be supplemented by a non-financial perspective to form a satisfactory basis for the evaluation of asset value.

The second limitation is that LCC assessments tend to take a reductionist approach, focusing on one cost object at a time, such as single processes or stand-alone instances of products, services, or time [31]. Focusing on a single cost object at a time does not provide an appropriate cost estimation because many manufacturing systems consist of interconnected and interacting cost objects [22,23]. Furthermore, AM organizations may choose to manage their assets in three distinct ways: (1) at the individual asset level, (2) in portfolios of multiple assets of similar types or classes, and (3) in groupings of assets that comprise an asset system (ISO 55000, [11]). The latter two of these management perspectives also seem incompatible with the reductionist nature of LCC. Roda and Garetti [18] argue that "*in order to support managerial decisions, LCC models also need to assume a similarly integrated and systemic focus as AM*".

The third and last limitation is that despite the long and rich history of LCC, a general application framework for LCC appears to be missing. In both theory and practice, there is a shortage of guiding principles and standards for LCC [9]. Unlike the Life Cycle Assessment (LCA) methodology, LCC is not structured in accordance with an international standard, with the exception of the ISO 15686-5:2008 standard which only applies to the building sector [32]. Additionally, the IEC 60300-3-3 standard on dependability management [33] standard provides a general introduction to the concept of LCC but is predominantly aimed at assessing the cost associated with the dependability of an item. Kambanou and Lindahl [23] indicate that LCC is always tailored to fulfill the requirements of its intended use, and that this tailoring will be reflected in the cost object, scope, and boundaries of the assessment. Likewise, it appears that the guidelines on how to apply LCC are also mostly tailored to specific application contexts, and that a more generally applicable guideline for LCC is still missing. A potential avenue to explore is to look at the aforementioned framework for LCA. Rebitzer and Hunkeler [34] indicate that "*a general LCC guidance [framework], similar to the ISO* 14040 *series for LCA, seems to be desirable*". Swarr et al. [35] also state that there needs to be a consensus on an international standard for applying LCC, which parallels the ISO 14040 standard for LCA. Hunkeler and Rebitzer [36] called for the prioritization and development of an accepted and standardized methodology for LCC, a code of practice, an international standard for the framework, and indicated the need for methodological compatibility of LCC with LCA.

### *Research motivation*

Decisions that shape the lifecycle of capital goods, such as the physical systems in use in energy grids, have an enormous impact on AM organizations and for society as a whole. LCC, though widely adopted, is methodologically limited in supporting the types of decisions that, for example, AM organizations are now required to make in the ever-changing context of the energy transition. Given the lack of a generic guiding framework for LCC and the existence of conceptual overlap between LCC and LCA, various researchers see the application of the principles and framework of LCA as a promising starting point for the development of guiding principles for LCC, which can be used to improve the methodology. Rebitzer et al. [37] argue that the Life Cycle Inventory (LCI) of LCA is an "excellent basis for allocating LCC to the entire lifecycle of a product. Huppes et al. [38] indicate that "*the procedural standards for LCA as specified in ISO14040 may, with slight adaptations, be used for LCC as well*". ISO 14040 states that the principles and framework described in the standard can be beneficially applied to LCC and asset (life cycle) management (ISO 14040, [39]). Sakao and Lindahl [40] took inspiration from LCA for the development of their method for evaluating and improving LCC-based industrial Product-Service Systems (PSS). Similarly, [41] combined LCA and LCC for the development of a PSS for high-energy consuming equipment. In this regard, the framework and principles of LCA seem to be at least partially compatible with LCC, providing a promising basis for research on how they can be combined.

This article, therefore, aims to explore the concept of combining the guiding principles of LCA with those of LCC, to form a hybrid evaluation methodology that is aimed at providing a multi-dimensional and adaptable perspective on the asset life cycle. Considering the relevance and widespread acceptance of LCC in the assessment of asset cost and performance, LCC is used as the conceptual starting point for the development of the proposed Life Cycle Valuation (LCV) methodology. In addition, the LCV methodology borrows from the guidelines and framework of LCA but is tailored to the requirements of AM and aimed at assisting decision-makers in evaluating and articulating what makes a complex system valuable during its lifecycle.

## Literature on LCC and LCA

Existing research on the application of life cycle-oriented assessment methods reveals that despite the lack of a unified framework for LCC, the methodology is often combined with other lifecycle-oriented methodologies to gain a broader understanding of the lifecycle impact beyond mere costs. A common strategy to account for the limitations in LCC is combining it with the environmental perspective of LCA. Peças et al. [42] argue that LCC and LCA should be applied in an integrated manner to serve as core elements of Life Cycle Engineering (LCE). Swarr et al. [35] have developed a code of conduct that aims to apply LCC in parallel with LCA, by integrating the former into the latter. Heijungs et al. [43] propose that the matrix-based computational structure of LCA can be applied to LCC in order to enable the simultaneous assessment of LCC and LCA in a single study. Miah et al. [44] developed a new framework for merging LCC and LCA by combining six existing frameworks. Atia et al. [45] propose a framework that integrates LCC and LCA by looking at the sequence of activities in a particular value chain. Hoogmartens et al. [46] investigated the connections between various sustainability assessment tools and how they relate to arriving at a triple bottom line Life Cycle Sustainability Assessment (LCSA). Neugebauer et al. [47] have developed a macroeconomic impact pathway that combines assessment perspectives from LCA, LCC, and Social LCA in order to support an LCSA. Additionally, economic input-output models are used to link macroeconomic activities with a broad spectrum of environmental burdens, allowing the two to be assessed simultaneously [48,49].

Besides the parallel application of LCC and LCA, another research focus can be found in the investigation of the methodological differences and similarities between the two. Norris [50] investigated the differences between LCA and LCC to better understand how they can be applied in parallel to assist in combined economic- and environmentally-focused decision-making in the private sector. Huppes et al. [38] investigated the fundamental differences between LCA, Cost-Benefit Analysis (CBA) and Budget-focused LCC approaches in order to develop a meta-framework. They cite dimensions of cost categories, cost bearers, cost models, and cost aggregation methods as the main differentiators between life cycle methodologies. Bierer et al. [51] investigated mutual points of contact and methodological relationships between LCC and LCA with the aim of integrating the two methods. Overall, there appears to be a significant conceptual overlap between the LCC and LCA methodologies, with differences manifesting in the adopted evaluation concepts (see Table 1).

Existing research streams appear to primarily focus on combining LCC and LCA. As such, they retain their respective advantages and disadvantages when combined into a single application. Even though this combined application provides a broader value perspective than financial or environmental impact alone, the outcomes of such assessments are inherently limited to the quantitative aspects of economic and environmental impacts. Furthermore, the combined application of these methodologies remains primarily reductionist and object-focused in nature and is therefore ill-suited to deal with external uncertainties such as long-term systemic changes or continuously shifting organizational goals, as discussed in Section "Problem identification".

In the literature on production environments, an increasing focus on value creation can be observed as the conventional producer-consumer model has begun to be replaced by the concept of value creation in society, which can be viewed from multiple viewpoints and disciplines [52]. Kumar et al. [53] present value as an ever-changing flow of value creation during manufacturing, value consumption in the use phase, and post-use reclamation of value during recovery in order to establish the most valuable strategy at different life cycle stages. Ross et al. [27] describe how flexibility, adaptability, scalability, modifiability, and robustness can be used as design strategies to create and maintain a system's life cycle value, as well as providing perspectives from

**Table 1**
Conceptual overlap of and differences between LCC and LCA.

| | Conceptual overlap | Conceptual difference | | | | | |
|---|---|---|---|---|---|---|---|
| | | purpose | inventory | flows | units | time treatment | aggregation |
| **LCC** | Lifecycle-oriented<br>Need for system boundaries<br>Need for defining scenarios<br>Reliance on forecasting, estimation & assumptions<br>Reliance on sensitivity an improvement analysis | Assessing cost-effectiveness | Activity-based<br>Cost engineering<br>Annual timeline | Cashflows<br>Mainly OPEX & CAPEX | Monetary (€, $, etc.) | Timing is critical due to the time value of money | Cumulative<br>NPV<br>Annuity<br>Rate-of-return |
| **LCA** | | Assessing environmental performance | Process-based, supply chain oriented<br>Adoption of a functional unit | Mass, energy, and pollutant flows | Primarily mass, energy and volume | Timing of emissions are irrelevant<br>Broad temporal scopes apply | Multiple impact areas<br>Weighted indication of the overall impact |

which to perceive value. Bosch-Mauchand et al. [54] use a combined product lifecycle management and knowledge management approach to model value for different stakeholders in the value chain. as providing perspectives from which to perceive value. Bosch-Mauchand et al. [54] use a combined product lifecycle management and knowledge management approach to model value for different stakeholders in the value chain. Value is also discussed in the context of the development of Product Service Systems (PSS). A potential explanation for this trend could be that the costs of providing a service via PSS are considered by many to be equivalent to the cost of an in-service stage of a durable product, requiring increased attention to how the outcome of the PSS relates to its costs [55]. Matschewsky et al. [56] therefore provide an approach to analyze and improve PSS value capture over the entire lifecycle. In these examples from literature, as well as colloquially, value is generally understood as something desirable, positive, important, or useful. Renkema and Berghout [57], however, use a multidimensional view on positive and negative aspects of financial and non-financial consequences to clarify the concepts used in the evaluation of IT investment evaluation. Martinsuo et al. [58] also frame the value of infrastructure projects as being multi-dimensional and having both positive and negative dimensions. In LCC, the convention is to quantify costs using positive numbers, resulting in cost savings having a negative cost impact. Likewise, in LCA, environmental impact is conventionally quantified using positive numbers (and avoided impacts using negative numbers). Because the LCV methodology is intended to evaluate both positive and negative values in the life cycle and is rooted in both LCC and LCA, it is positioned as a methodology that is aimed at the assessment of both positive and negative value factors. In this research, 'bad' factors such as costs and environmental impacts are represented using positive numbers. As such, the LCV methodology is positioned as a valuation approach, aimed at evaluating and assigning value factors in the life cycle using monetary units.

## Design science research

The methodology used to structure the development of the proposed LCV methodology is Design Science Research (DSR) which is defined as "*an explicitly organized, rational, and wholly systematic approach to design; not just the utilization of scientific knowledge of artefacts, but design in some sense as a scientific activity itself*" [59]. DSR is an advantageous approach given the professional engineering settings where the aforementioned problems arise, indicating the need for a new guiding framework for lifecycle-oriented assessment. Denyer et al. [60] characterize the design sciences paradigm by (1) research questions being driven by an interest in field problems, (2) an emphasis on the production of prescriptive knowledge, and (3) a justification of research products largely based on pragmatic validity. Holmström et al. [61], indicate that DSR is different from many other applied research areas because it aims to bridge practice with theory, rather than theory with practice. DSR, therefore, starts with the identification and motivation of a relevant research problem (see Sections "Problem identification"–"Research motivation"), the development of a design that fulfills certain objectives and criteria, and results in the application and evaluation of a design in a real-world context [62,63].

The type of DSR applied in this article is called 'exaptation', a process by which features acquire functions for which they were not originally adapted or selected, extending existing solutions to new problems [64,65]. An example of technological exaptation can be found in the re-adherable strip that is used in sticky notes, which was discovered in an experiment that was originally aimed at finding a more permanent adhesive. In this research, the proposed solution is established by adapting the guiding framework and principles of LCA to the application of LCC, creating a new, hybrid methodology. This new methodology is then applied to the new problem of assessing the life cycle value of physical assets in Asset Management.

Testing the application of designed artefacts in the real world comprises an essential step in DSR [63]. The application of the Life Cycle Valuation methodology is demonstrated, tested, and evaluated in multiple decision-making instances at the Asset Management department of Distribution System Operator (DSO) Liander, which operates in the Netherlands. As the largest DSO in the country, Liander is responsible for distributing natural gas and electricity to homes, businesses, and industrial customers. Liander's 3.1 million electrical grid customers are supplied by complex distribution grids consisting of physical systems with long lifespans such as transformers, overhead and underground cables, switchgear, constructions that house installations, and other capital goods. An important challenge in the management of these physical systems is that while some systems have a long lifespan (e.g. transformers) and others have a short lifespan (e.g. digitization components), they often need to be considered simultaneously as part of a larger system or asset portfolio. The LCV methodology was used in these types of decision contexts that previously relied on LCC as the main assessment instrument. It has been used to guide and support the assessment of multiple asset life cycle-related decisions within the electrical side of the AM

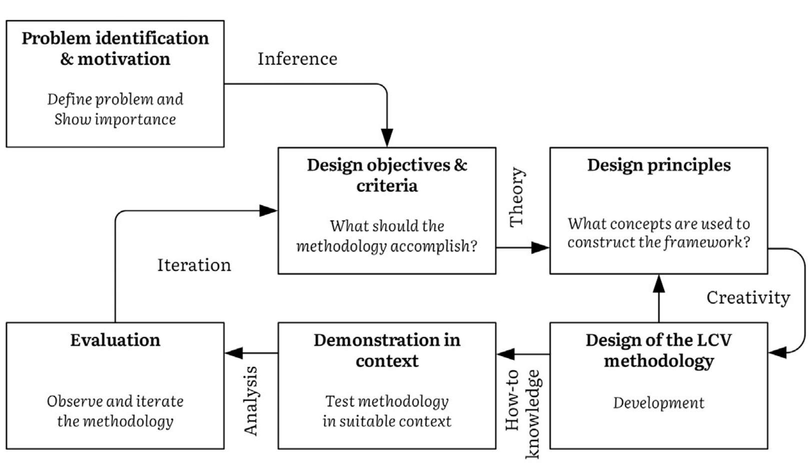



**Fig. 1.** Design Science Research methodology (adapted from [62]).

organization of Liander (excluding the distribution of natural gas). Given the variances in lifespan and asset objects (i.e. individual assets, asset portfolios, and complex systems) this set of application contexts was selected to mirror the broad range of AM decision-making contexts, as discussed in the introduction.

Hevner [66] indicates that in DSR the artefact not only needs to provide utility in practice (relevance) but that it must also contribute to the knowledge base (rigor). The outcome of DSR therefore not only leads to pragmatic designs (often referred to as artefacts) but also results in a better understanding of the problem and the solution, thus providing theoretical knowledge as well. Sein et al. [67] stress the need for reconceptualizing the highly organization-specific solutions into generalizable design principles for classes of problems, capturing the knowledge gained throughout the design process. As such, the efficacy of the design is not just evaluated according to its design objectives and criteria, but also includes a reflection on the most important design principles that form the core of the design of the LCV method. Lastly, unstructured interviews with the AM staff that were involved in the practical application of the LCV methodology were used to evaluate whether the methodology is practicable. The overall structure of the used DSR methodology is summarized in Fig. 1, based on the outline provided by Peffers et al. [62].

*Design objectives and criteria*

As discussed in the introduction, the practice of applying LCC and LCA does not necessarily provide a complete picture of the value generated in the asset lifecycle when regarded from an AM perspective. In order for the design of the LCV methodology to sufficiently support AM decision-making, several design criteria are used that are tailored to the specific characteristics and requirements of AM decision-making (see Table 2).

The first criterium is that a successful design should be able to consider the entire lifecycle of an asset and should apply to all stages within an asset lifecycle [11,68,69]. The second criterium is that the design should be able to consolidate information, data, and expertise from multiple disciplines and management perspectives [3]. Furthermore, the design should be able to account for and differentiate between, multiple financial and non-financial value factors such as economic, environmental, social, and technical impacts as well as the needs of relevant stakeholders [25,70]. It also must be able to apply to different system definitions, such as at the level of individual assets, portfolios of similar assets, or (complex) systems of assets [11,18]. And lastly, the designed methodology should be able to link decisions at the level of the asset life cycle to the level of the organizational strategy [71,72].

## Design principles

The design of the LCV methodology borrows from various design principles from different methodologies. To clarify the role of these principles in the design of the LCV methodology, their origins and implementations are briefly discussed.

*Life Cycle Costing and the time value of money*

AM is concerned with continuous improvement and alignment of financial and non-financial functions (ISO 55010, [70]), therefore, life cycle cost control forms an important activity [71]. As such, the conceptual starting point for the design of the LCV methodology is rooted in Life Cycle Costing. For the purposes of this article, LCC can be understood as: “*An analysis technique which encompasses all costs associated with a product*” [73], “*from its conception and fabrication through its operation to the end of its useful life*” [19], “*with the goal of estimating the costs associated with the existence of a product*” [34].

Unlike in the case of LCA, where no explicit differentiation is made between emissions as well as impacts at different moments in time, the financial perspective does have a time preference due to (1) changes in price levels, (2) pure time preference, (3) productivity of capital and diminishing marginal utility of consumption and (4) uncertainties [74]. An important characteristic of LCC is that it accounts for the ‘time value of money’. In LCC, cash flows that occur at different moments in time are discounted back to a base period by using the Net Present Value (NPV) technique [17]. The ‘time value of money’ concept is used in the design of the LCV framework in two ways: the first is the use of discounting using the NPV technique (see Eq. 1), the second is the application of Equivalent Annual Annuity (EAA) (see Eq. 2). The latter allows for a comparison based on a discounted yearly average [75], enabling a fair comparison of mutually exclusive options with unequal lifespans. A common practice for AM organizations is to base the discount rate on the firm’s Weighted Average Cost of Capital (WACC), as was the case at case company Liander

$$NPV = \frac{R_t}{(1+i)^t} \quad (1)$$

NPV = Net Present Value; $R_t$ = net cash flow; i = discount rate; t = year of the impact.

$$EAA = \frac{i(NPV)}{1-(1+i)^{-n}} \quad (2)$$

EEA = Equivalent Annual Annuity; i = discount rate; n = elapsed number of years.

*Four stage Life Cycle Assessment framework*

Even though LCC is the conceptual starting point for the design of the LCV methodology, another prominent design principle is the adoption of the four stages of LCA (see Fig. 2). The basic outline of the four iterative steps of defining the goal and scope, performing an inventory analysis, assessing the resulting impact, and interpreting the whole can be adapted to provide general guidance and structure other types of life cycle assessments than just LCA [39,76].

*Defining the system of interest*

Complex system environments are characterized by ill-defined and potentially tacit, divergent, or pluralistic goals that are value-

**Table 2**
Summary of the AM-based design criteria for the LCV methodology.

| Criterion | |
|---|---|
| 1 | Ability to consider the entire lifecycle of an asset and apply to all stages within an asset lifecycle |
| 2 | Ability to consolidate information, data, and expertise from multiple disciplines and management perspectives |
| 3 | Ability to account for, and differentiate between, multiple financial and non-financial value factors such as economic, environmental, social, and technical impacts as well as the needs of relevant stakeholders |
| 4 | Ability to apply to different system definitions, such as at the level of individual assets, portfolios of similar assets, or (complex) systems of assets. |
| 5 | Ability to link decisions at the level of the asset life cycle to the level of the organizational strategy |

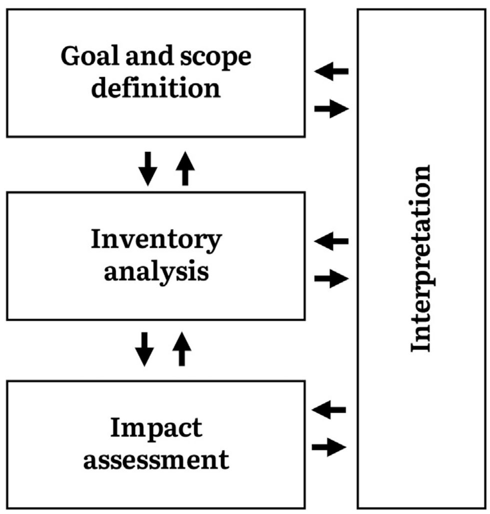



**Fig. 2.** Four stages of Life Cycle Assessment (ISO 14040, [76]).

laden, shifting, and challenging to make entirely explicit [77]. Therefore, another LCA-inspired design principle consists of defining the 'system of interest', which is similar to the concept of the system boundary in LCA. This can be used to distinguish between what is exogenous and endogenous to the system, it clarifies the level of granularity in examining what happens within the system's boundaries, which can be viewed as the actions performed on or outcomes related to the system of interest [31].

*Combined breakdown structures*

Another design principle that has been applied to the LCV framework is the application of a breakdown of individual lifecycle elements, a concept that is similar to the breakdown into cost elements in LCC [78]. This concept borrows from Cost Breakdown Structures (CBS) but allows for the breaking down into more aspects of value creation than just costs. These breakdown structures constitute a logical subdivision by functional activity, area, a major element of a system, and/or more discrete classes of common items that can be used to link objectives to activities and available resources [79]. A common CBS is that of Activity-Based Costing (ABC), which links life cycle costs to activities that occur throughout the lifecycle [80,81]. This allows resource consumption to be traced to distinct activities. The breakdown structure applied in the LCV methodology functions similarly but adopts a three-dimensional breakdown structure, similar to the structures of Kawauchi and Rausand [78] and Götze et al. [82]. The breakdown structure that we propose is briefly explained below and illustrated in Fig. 3.

In the breakdown structure of LCV, all activities in the lifespan of an asset are made up of individual 'lifecycle elements'. Multiple lifecycle elements can be placed on a timeline that represents the (remaining useful) lifespan of the asset, creating an Activity Breakdown Structure (ABS). Each lifecycle element can have an impact that can affect one or more types of value, as structured by the Value Breakdown Structure (VBS). Combinations of multiple lifecycle elements are then used to build a modular, three-dimensional representation of the lifecycle which allows for either a value-based perspective (using aggregated activities from the ABS) or an activity-based perspective (using aggregated values from the VBS) of value creation over time during the asset lifespan in segments of individual years.

*Monetary valuation*

Conventional LCC does not require an impact assessment phase, because all inventory data comprises a single unit of measure, namely currency [35]. As indicated in design criterion 3, the LCV framework needs to simultaneously consider multiple financial and non-financial value factors, which the aforementioned VBS required. Various value-related impacts are therefore aggregated and expressed in financial terms.

Monetary valuation is the practice of converting measures of social and biophysical impacts into monetary units and is used to determine the economic value of non-market goods, i.e. goods for which no market exists [83]. In AM, monetary valuation is typically already implicitly applied as part of risk management, where resources are allocated to mitigate different kinds of risk. Risk matrices are commonly used to identify, analyze, and evaluate risks, based on likelihood, consequence, and risk tolerance criteria [84]. As such, the realization of value through managing risk and opportunity already depend on balancing of cost, risk, and performances (ISO 55000, [11]). The performance indicators for

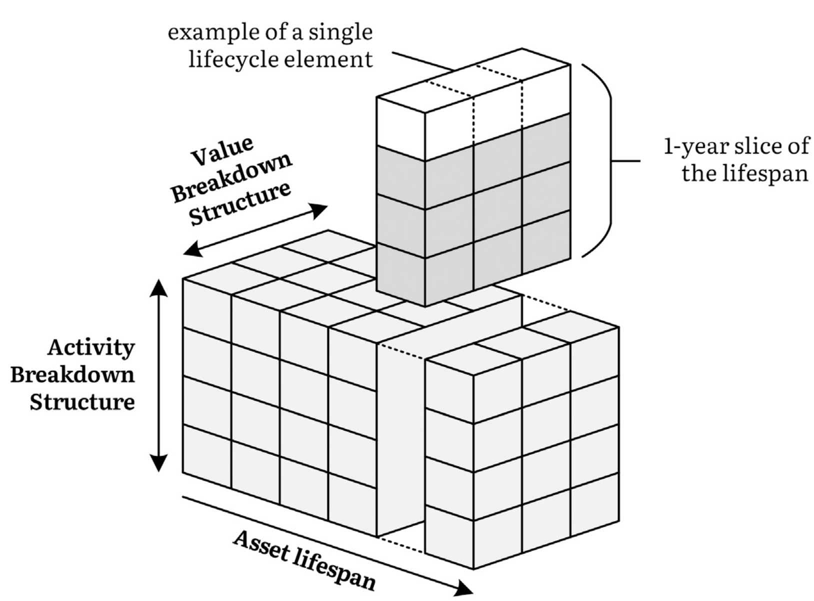



**Fig. 3.** Three-dimensional breakdown structure of an LCV model adapted from Kawauchi and Rausand [78] and Götze et al. [82].

checking the desired objectives or targets during the operation and maintenance phase of a product or system can be arrived at by taking reliability, availability, maintainability, and safety (RAMS) into consideration [85]. Risks can be modeled as a single life cycle element by multiplying the expected likelihood and consequence for each risk [84]. While risk and opportunity are usually managed from an internal company perspective, taking the consequences for other stakeholders into account is also increasingly expected. Simplified indicators of environmental and social impact can be translated into external social and environmental costs, allowing the integration with conventional cost assessment such as LCC [86]. These 'shadow costs' are expressions of environmental impact in monetary terms, using financial units (e.g. € or $) and are usually based on abatement or damage costs.

## Design and demonstration of the life cycle valuation (LCV) methodology

The Life Cycle Valuation (LCV) methodology consists of two main elements: (1) a four-phased framework (see Fig. 4) that guides the process of performing an LCV assessment, and (2) a combination of calculations and the aforementioned modeling principles that have been programmed into an LCV tool using commonly available spreadsheet software.

### *Step 1: formulation of the goal and scope*

*Determining the goal*

The first step in performing an LCV assessment is to determine the goal. This makes it explicit what the main reason for performing the assessment is and what the requirements of a successful assessment are. For example, in AM, the goal can be operational (such as optimization as a part of a continuous improvement cycle) or strategic in nature (such as: linking to a specific organizational long-term goal).

It also provides the opportunity to state whether the assessment is of an attributional or a consequential type. An attributional assessment is aimed at identifying which value is created over the lifecycle of the asset, thus requiring the LCI to include all relevant impacts associated with the lifecycle. A consequential assessment may leave out certain elements that are the same for all alternatives within the scope, for example in comparative studies.

*Defining the system of interest*

The system of interest is used to determine which system or systems is or are considered to be the main subject of study and provides or provide the opportunity to clarify which parts of the system or systems is or are included in the assessment and which parts are considered out-of-scope. The system definition is also used to indicate whether the system of interest consists of a single asset, a portfolio of similar assets, or a complex system of multiple interdependent assets. If necessary, allocation and attribution procedures can be explained in this step as well.

*Determining the temporal scope*

The time frame is used to specify the scope of the LCV assessment concerning its temporal dimension. It is used to determine the section of time that the LCV assessment covers, by indicating the starting year of the assessment and the duration up to and including the last year. For AM, the lifespan or remaining useful life of the asset can be used to guide the determination of the time frame.

Another aspect of the temporal scope is the discount rate that is used to calculate the NPV of impacts that occur at different moments in time.

*Determining the value breakdown structure (VBS)*

The Value Breakdown Structure (VBS) is used to indicate which value factors are included in the assessment and how they are quantified. These value factors can depend on the goal of the assessment, or be coordinated within an AM organization. This is similar to, for example, a component of risk management, in that it allows for differentiation between multiple value factors such as:

- Financial impacts such as capital expenses (CAPEX) and operational expenses (OPEX)
- Technical impacts such as reliability & availability of the system (e.g. failure rate)
- Externalities such as environmental impacts (e.g. $CO_2$ emissions) or safety (accident rate)
- Other relevant value factors

In order to allow for calculation, these 'impacts' need to be expressed in units (e.g. €, kg, m3, min) and have a value equivalent per unit of impact (e.g. €/kg, €/m3 €/min.). By differentiating between different impacts in the VBS, their relative contributions can later be traced back to the aggregated impact results. Table 3 shows a selection of the most frequently used impacts in the VBS which were used during the application of the LCV methodology at the AM organization of DSO Liander. The value equivalences (€/unit) for Liander are considered sensitive information and are therefore not shown. Note that impacts in the VBS can have a

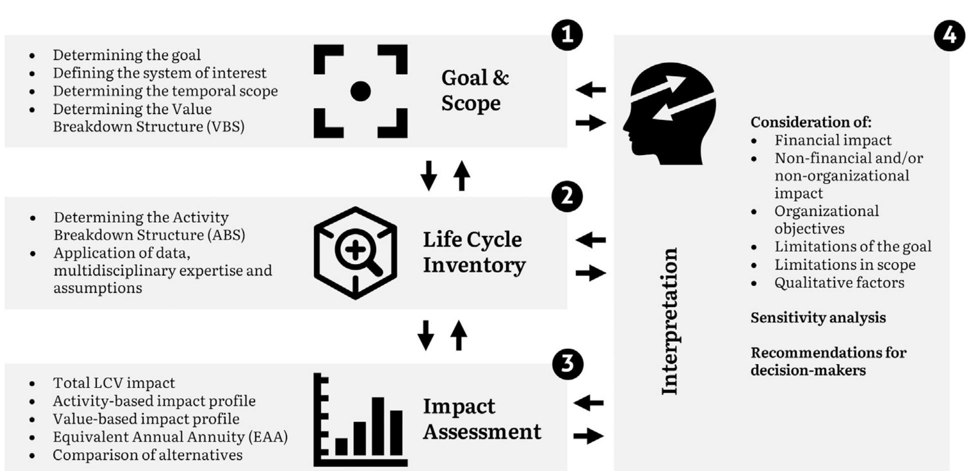



**Fig. 4.** Life Cycle Valuation (LCV) assessment framework (adapted from ISO 14040).

**Table 3**
Examples illustrating a selection of commonly used impacts in the VBS at Liander.

| Impact | Unit | Financial impact for the AM organization (€) | Non-organizational and/or non-financial impact (€ eq.) |
|---|---|---|---|
| Capital Expenses (CAPEX) | € OPEX | 1€ | |
| Operational Expenses (OPEX) | € CAPEX | 1€ | |
| System Average Interruption Duration Index (SAIDI) | minutes | . . . € / min (actual costs to re-establish power distribution) | . . . € / min (inconvenience of outage for customers) |
| Global Warming Potential (GWP) | kg $CO_2$-equivalent | | . . . € / kg $CO_2$-equivalent (environmental damages) |

financial impact for the AM organization, a non-financial and/or non-organizational impact, or a combination of both.

*Step 2: life cycle inventory*

The Life Cycle Inventory (LCI) is constructed using discrete 'lifecycle elements' that can have one or multiple impacts associated with them. For example, a lifecycle element of one day of operation can result in the cumulative impact of €100 of OPEX and the emission of 24 kg of $CO_2$-equivalents (see the example in Table 4). These elements can be constructed using data, expertise and, if necessary, assumptions.

Multiple lifecycle elements can be placed on a timeline to construct a complete LCI of all relevant aspects and activities within the lifecycle of the asset, forming an Activity Breakdown Structure (see example in Fig. 5). Multiple units can be entered for each lifecycle element on the timeline. The ABS enables the user to trace the overall LCV impact resulting from individual lifecycle elements and that occur at specific moments in time.

The creation of the lifecycle elements and the timeline is likely to require the integration of multiple disciplines, as it should describe all relevant activities in the asset lifecycle. Lifecycle elements can be updated individually, with the changes propagating into an overall impact score.

*Step 3: impact assessment*

After modeling and placing each lifecycle element on the timeline, the total impact can be calculated. For example, if the user enters '2 days of Operation' on the timeline as input in a specific year, this would result in a total LCV impact of €24,320 (2 x €100 × 1€ OPEX + 2 × 24 × €090 $CO_2$ equivalents), as indicated in Table 5. Note that the LCV impact is expressed in EUR (€), but that this does not necessarily represent financial value alone, as it may also include non-financial impacts.

As LCV deals with different impacts at different moments in time, a discount rate should be provided to support the calculation of the Net Present Value of all impacts throughout the lifecycle. When dealing with comparative assessments with different timeframes, the Equivalent Annual Cost technique can be used to compare impacts based on yearly averages.

The combined implementation of the Activity Breakdown Structure and the Value Breakdown Structure, using discrete lifecycle elements, allows for a multi-perspective insight into the results of the assessment. In order to support interpretation, the dashboard of the LCV tool offers multiple options and cross-sections (also referred to as impact profiles), such as:

- Adjustment of parameters (e.g. discount factors) and related assessment perspectives (see Fig. 6)
- Overview of impact over time (see Figs. 7–9)
- Activity-based breakdowns of the LCV impact (see Fig. 8)
- Value-based breakdown of the total LCV impact (see Fig. 9)

**Table 4**
Examples illustrating two lifecycle elements and their associated impacts.

| Lifecycle element | Unit | Amount | Unit |
|---|---|---|---|
| Acquisition | apiece | 10.000 | € CAPEX |
| Operation | day(s) | 100 | € OPEX |
| | | 24 | kg $CO_2$-equivalent |

*Step 4: interpretation*

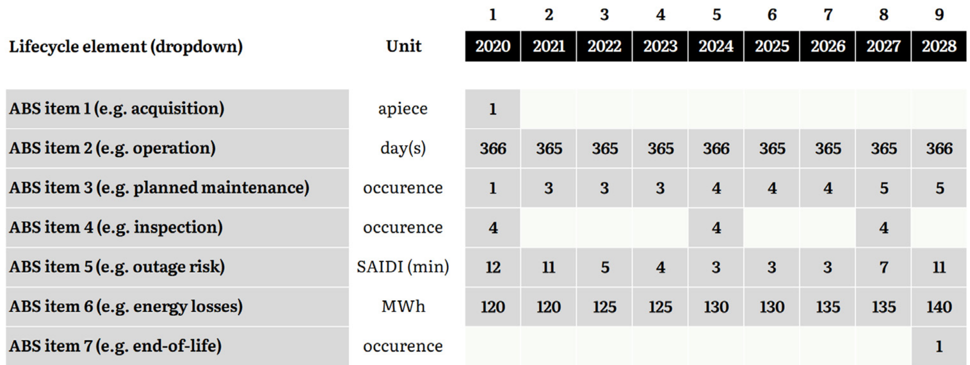
The profiles in the dashboard support the interpretation of the results in several ways. It allows for a quantitative overview of the financial and non-financial value of everything within the assessment scope. It can be used to trace the origin of these impacts back to individual lifecycle elements. This can be used to support additional investigation and development of the assessment outcome by means of sensitivity analysis, completeness & consistency checks, and improvement analysis.

The total LCV impact (expressed in monetary units such as €) can be used to indicate the lifecycle option that has the best overall impact score. In straightforward situations, it may be possible to shorten the sensemaking process to a simple 'information' phase, but in complex, ambiguous, multi-level situations it is necessary to allow for, and foster, sensemaking interactions [87]. For example, elements for which quantification is not (yet) possible should not be neglected [36] and considered in the decision of which lifecycle option is preferred. Furthermore, due to the strategic nature of many AM goals, the option with the best LCV impact is not necessarily the most valuable one. More than in LCC and similar to LCA, the interpretation phase of LCV and its reflection on the limitations in the goal and scope of the assessment is a critical final step in making sense of the assessment outcome.

## Evaluation of the LCV methodology

The application of the LCV methodology at the AM organization of Liander revealed both anticipated and unanticipated outcomes. Using observation, unstructured interviews during the application of the LCV method, and evaluation sessions after each application, these outcomes were linked to the design principles, summarized in Table 6, providing a condensed overview of how the LCV functions in practice.

Overall, the general outline of the four stages of the LCA framework (as illustrated in Fig. 2) seemed to be well suited for structuring LCV assessments of different types of assets in different lifecycle stages. The four iterative phases were seen by Liander's AM staff as both rational and reasonable, but also as something clearly different from the way LCC has been assessed within the organization in the past. The explicit discussion of the goal, scope, and system of interest stimulated a long-term and lifecycle-oriented perspective that is broader in scope than conventional

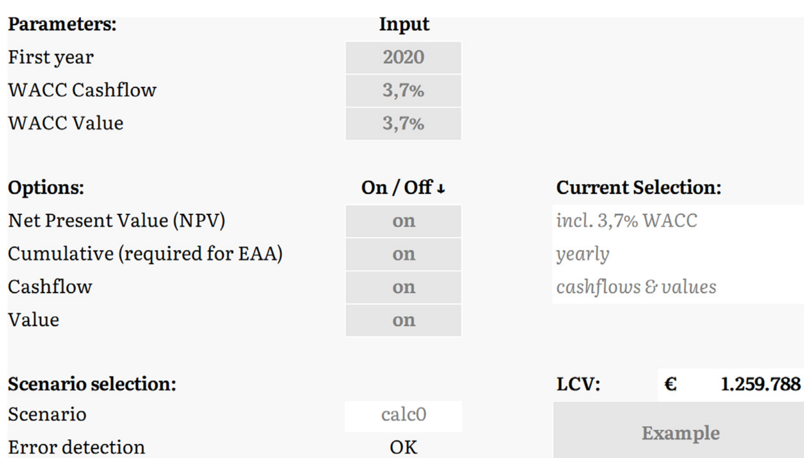


| Lifecycle element (dropdown) | Unit | 1<br>2020 | 2<br>2021 | 3<br>2022 | 4<br>2023 | 5<br>2024 | 6<br>2025 | 7<br>2026 | 8<br>2027 | 9<br>2028 |
|---|---|---|---|---|---|---|---|---|---|---|
| ABS item 1 (e.g. acquisition) | apiece | 1 | | | | | | | | |
| ABS item 2 (e.g. operation) | day(s) | 366 | 365 | 365 | 365 | 366 | 365 | 365 | 365 | 366 |
| ABS item 3 (e.g. planned maintenance) | occurence | 1 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 |
| ABS item 4 (e.g. inspection) | occurence | 4 | | | | 4 | | | 4 | |
| ABS item 5 (e.g. outage risk) | SAIDI (min) | 12 | 11 | 5 | 4 | 3 | 3 | 3 | 7 | 11 |
| ABS item 6 (e.g. energy losses) | MWh | 120 | 120 | 125 | 125 | 130 | 130 | 135 | 135 | 140 |
| ABS item 7 (e.g. end-of-life) | occurence | | | | | | | | | 1 |

**Fig. 5.** Activity breakdown showing discrete lifecycle elements placed on a timeline.

**Table 5**
Breakdown of the total LCV for 2 days of the lifecycle element 'Operation'.

| Lifecycle element | | | Value Breakdown | | | LCV impact | |
|---|---|---|---|---|---|---|---|
| Name | Amount | Unit | Amount | Unit | Value eq. | Value eq. | Sum |
| Operation | 2 | day(s) | 100<br>24 | € OPEX<br>kg $CO_2$ equivalent | € 1<br>€ 090 | € 200<br>€ 4320 | € 24,320 |



| Parameters: | Input | |
|---|---|---|
| First year | 2020 | |
| WACC Cashflow | 3,7% | |
| WACC Value | 3,7% | |
| **Options:** | **On / Off ↓** | **Current Selection:** |
| Net Present Value (NPV) | on | incl. 3,7% WACC |
| Cumulative (required for EAA) | on | yearly |
| Cashflow | on | cashflows & values |
| Value | on | |
| **Scenario selection:** | | **LCV:** € 1.259.788 |
| Scenario | calc0 | Example |
| Error detection | OK | |

**Fig. 6.** Parameters of the LCV assessment.

LCC applications. As such, the LCV methodology was effective in stimulating the consideration of the entire lifecycle and proved to apply to multiple lifecycle stages (design criterion 1). A grid architect reflected on this new way of supporting decisions: "*the decisions of a grid architect used to be focused on short-term financial impact instead of long-term value*". The goal and scope definition also initiated discussions about what to include in the assessment, how to include it, and how to ensure a fair assessment. Despite the benefits of discussing the goal and scope, however, this activity did not come 'naturally' to the AM staff, who tended to skip this step and start the assessment with data collection. Early design iterations, therefore, included the introduction of a brief kick-off session where the goal, scope, and system of interest are specifically discussed and defined.

The application of the LCV methodology proved to be appropriate for different types of objects that were included in the decision-making contexts described in Table 7. This evaluation included individual assets, portfolios of assets, and (complex) systems of assets (design criterion 4) and allowed for investigating multiple value perspectives for each case. For example, the Energy Flexibility case studies included not only the financial impact for Liander but also accounted for the costs incurred by Liander's customers, as well as the environmental impact associated with potentially having to restrict the production of renewable energy. A junior grid architect reflected that without these considerations, *"the grid architects would likely make a decision based solely on [Liander's] immediate costs and not consider a broader value perspective at all"*.

In many cases, the data, information, and results of previous LCV assessments could be re-used in other assessments. The information required in the LCI phase rarely came from a single source but tended to be spread throughout the organization, corresponding with the different disciplines that are required in different life cycle stages. In creating the LCI and the ABS, the decision-makers not only gathered data expertise and information, but they also needed to develop a plan for the (remaining) lifecycle of the asset, usually consisting of competing alternatives or divergent future scenarios. Within an LCV assessment, the activity of Life Cycle Planning (LCP) and the information found in existing life cycle plans therefore played key roles. Integrating these multidisciplinary perspectives required an iterative process of modeling and verification, which increases the time required for

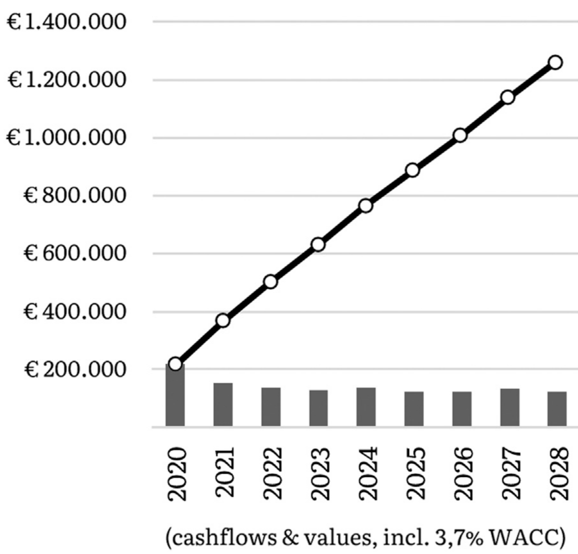



**Fig. 7.** An example of total LCV over time (annual and cumulative views combined).

performing LCI and can be considered a disadvantage. However, the main advantage of this approach lies in the fact that involving multiple disciplines reduces the potential for omitting relevant factors, which builds support for, and trust in, the outcome of the assessment. A senior AM policy advisor reflected: "*The LCI is all about collecting perspectives which are formed by different 'realities' that emerge from divergent understandings and needs. It is these perspectives that you try to capture in the model, in such a way that it is recognizable for everyone involved*". As such, the design of the LCV fulfills design criterion 2 by consolidating information, data, and expertise from multiple disciplines and management perspectives.

The three-dimensional breakdown structure of an LCV model allows for an assessment of three complementary perspectives of the impact. One breakdown of the impact is possible in the time dimension, which is a necessity in LCC but typically ignored in LCA. The time dimension is necessary for LCV because of the time value of money involved in asset investments as well as the role of timing in LCP. Another breakdown of the impact can be made using the VBS, enabling the assessment of multiple financial and non-financial value factors such as economic, environmental, social, and technical impacts as well as the costs and benefits of relevant stakeholders, fulfilling design criterion 3. The last breakdown of the impact can be made using the ABS, making it possible to assess impacts at the level of activities in the asset life cycle. This allows these activities to be linked to either operational performance or organizational strategy, depending on the goal and scope of the assessment (design criterion 5). In this regard, the impact assessment phase of the LCV methodology resembles that of LCA, as multiple impact categories can be assessed simultaneously or individually. This profiling step differs from LCC, where it is commonplace to aggregate all costs into a single LCC figure or an aggregated sum of the Total Cost of Ownership (TCO). Even though it was technically possible to perform a financially focused (LCC style) assessment by including only financial impacts, every LCV assessment at Liander included relevant quantitative value factors that were either a non-financial impact or affected the finances of other stakeholders, such as those of the customers who rely on the energy grid in order to generate their revenues. To conceptually distinguish the financial perspective from the non-financial one during the impact assessment stage, different terminology was used by various decision-makers (see Table 8). This not only indicates the desire to be able to conceptually separate the two but also a need to combine both perspectives during decision-making. A decision-maker responsible for future-proof grid design phrased this as follows: "*You shouldn't blindly aggregate all costs and benefits*

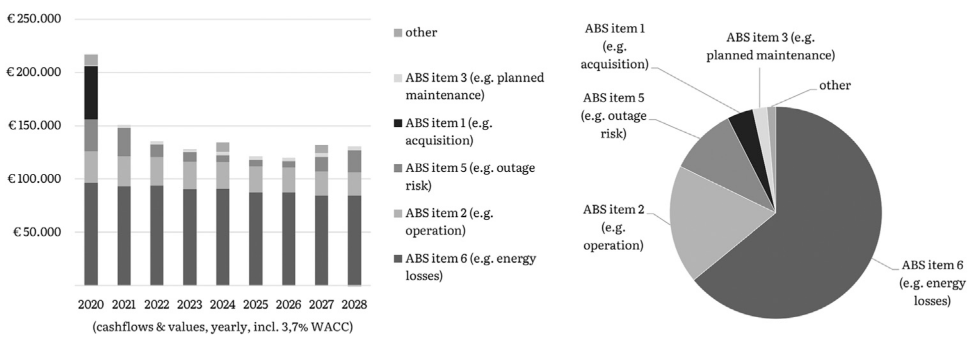



**Fig. 8.** Example of activity-based breakdown over time (left) and overall impact contribution (right).

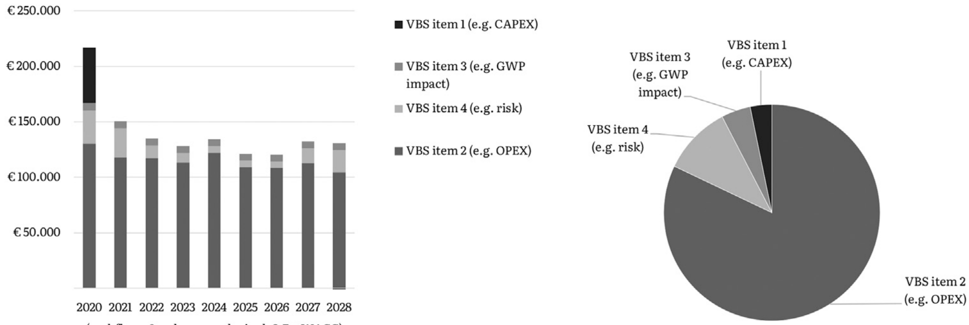



**Fig. 9.** Example of value-based breakdown over time (left) and overall impact contribution (right).

**Table 6**
Design principles of the LCV methodology and their consequences.

| Design principles | Outcomes |
| --- | --- |
| Formulation of the goal & scope, and the definition of the system of interest | • Focused the attention of the AM staff to the entire asset lifecycle (instead of only the initial phases) and stimulated a long-term timeframe and future-oriented mindset.<br>• Initiated discussions about the consequences of asset lifecycle decisions at the systems (energy grid) and/or asset portfolio levels (and how these effects should be included in the assessment).<br>• The goal, scope, and system of interest were often initially perceived by the AM staff as self-evident (thus sometimes even skipped entirely), but regularly needed further investigation, adjustment, and explanation in the later stages of the assessment. |
| Value Breakdown Structure (VBS) & Monetary Valuation | • Enabling the assessment of quantitative factors with a broad value scope beyond only LCC (e.g. including factors such as environmental impact or stakeholder value)<br>• Clarified which quantitative elements are included in the assessment, how they are quantified and what (monetary equivalent) value they are given.<br>• Required the coordination of the quantification procedures and monetary valuation factors within the AM organization (e.g. how to measure and value $CO_2$ emissions). |
| Life Cycle Inventory (LCI) and Activity Breakdown Structure (ABS) | • Initiated the formulation of a life cycle plan for the activities and consequences in the remaining useful life of the asset.<br>• Required the creation of LCI's for multiple alternative solutions and/or future scenarios.<br>• Required the collection of expertise, data, and assumptions from multiple disciplines (related to all relevant elements in the asset lifecycle).<br>• Tended mainly to include dominant cost & value drivers (thus cutting-off less significant impacts) to speed up and simplify assessment. |
| Impact Assessment | • Allowed for a simultaneous quantitative assessment of financial and non-financial impacts (as determined in the VBS).<br>• Enables the comparison between a conventional LCC impact (sum of all OPEX and CAPEX) and 'LCV impact' (LCC + other quantitative value factors).<br>• Allows the tracking of specific impacts that result from individual life cycle elements facilitating sensitivity and improvement analyses. |
| Interpretation phase | • Provides the opportunity to acknowledge and discuss relevant decision-related factors that are not (easily) quantified.<br>• Provides the opportunity to acknowledge and discuss the sensitivity of the assessment to long-term changes. |

**Table 7**
Decision-making cases that were used to test and demonstrate the LCV methodology and their key value perspectives.

| Decision context | | Description | Asset objects | Lifespan | Key value factors |
| --- | --- | --- | --- | --- | --- |
| 1 | Fault Detection | Finding optimal placement of fault detection & localization components in electrical grids | Local energy grids (complex system) | 15 years | • Life Cycle Costs<br>• Outage risk<br>• Alternative configurations |
| 2 | Ageing Transformers | Considering revision or replacement options for aging transformers in a substation | Individual asset(s) | 40 years | • Life Cycle Costs<br>• Outage risk<br>• Climate change<br>• Replacement moment |
| 3 | Substation | Solving a capacity issue for a substation and its components by means of replacement or revision | Individual asset(s) | 60 years | • Life Cycle Costs<br>• Alternative configurations<br>• Energy losses<br>• Climate change |
| 4 | Grid Architecture | Studying significant revision of the network architecture of the grid in a dense urban area | Major energy grid (complex system) | Continuous | • Life Cycle Costs<br>• Network architecture<br>• Availability of labor<br>• Timing and planning concerns |
| 5 | Demand Flexibility | Using demand flexibility as a viable option for solving (temporary) congestion issues | Local energy grids (complex system) | 3–5 years | • Life Cycle Costs (DSO)<br>• Customer costs<br>• Climate change (when dealing with congestion of renewable energy sources) |
| 6 | Switchgear Procurement | Performing a pilot study on the inclusion of a streamlined form of LCA in the procurement of Medium voltage switchgear | Portfolio of assets | 40 years | • Costs<br>• Technical performance<br>• Photochemical Ozone<br>• Formation<br>• Climate Change<br>• Fossil Depletion<br>• Fine Particulate Matter formation |

**Table 8**
Terminology used by decision-makers to differentiate between financial and non-financial impacts.

| Terminology used to describe financial impact for the organization | Terminology to describe non-financial or non-organizational impact |
| --- | --- |
| Hard value, cash-out, cashflow, financial impact, costs, expenses, cost optimization (and reduction) | Soft value, social impact, societal money, environmental impact/costs, externalities, multiple benefits |

*in a single figure. We want distinct insights into all direct, indirect and societal impacts before making a decision*".

Conventional LCC does not require an impact assessment phase, because all inventory data comprises a single unit of measure, namely currency [35]. LCV however, is designed to assess multiple value factors simultaneously and takes into account that a reductionist perspective on a single asset lifecycle may be too limited for AM purposes. The LCV supported decisions at Liander were usually sensitive to only a limited number of lifecycle elements or impact categories. This meant that for some assessments at Liander, the results were not sensitive to rough assumptions and limited data quality when they applied to non-dominant impacts, greatly reducing the time required to arrive at an informed LCV-supported decision. The interpretation phase is also useful in considering qualitative factors for which quantification is not (yet) possible. Such factors are often neglected in both LCC as well as social assessments [36]. The interpretation phase provides the opportunity for the decision-maker to judge the most important quantitative, qualitative, and normative factors related to the decision. Senior AM policy advisor 2 commented on the role of structuring the LCV assessment in this way: "*LCV is not about the act of calculation, but about the process of arriving at an appropriate calculation*". LCV interpretation is therefore not aimed at arriving at a definitive answer to how valuable a life cycle option is, but rather, it invites the decision-maker to view the assessment (which has an inherently limited) scope, from a much broader and holistic (AM) perspective.

## Discussion and conclusion

LCV is designed based on the premise that the decisions of AM organizations need to consider changing environments, shifts in organizational goals, and continuously changing notions of what makes an asset valuable beyond its costs. While LCC can be an extremely useful instrument for organizations that manage and invest in capital goods, it is also inherently limited in assessing to what extent these assets create and maintain value over the course of their entire lifespan. Firstly, LCC is primarily focused on costs, whereas AM is fundamentally value-focused and aims to balance and align various financial and non-financial value factors, such as asset performance, risk, environmental and social impacts, and stakeholder needs, alongside life cycle costs and profits. Secondly, LCC is traditionally a reductionist and single object-focused approach, making it less suitable for assessing complex systems, assets with interconnected or interacting objects, or portfolios of multiple similar types of assets. Lastly, the unguided application of LCC takes long-term changes and uncertainty beyond the technical scope of the asset lifecycle itself into account inadequately. This leaves conventional LCC essentially 'blind' to long-term organizational goals, technological developments, (geo)political shifts, and societal changes that may render an asset obsolete before its technical end-of-life. LCA on the other hand already provides a mature systems-oriented framework for the comprehensive assessment of various types of non-financial impacts and explicit guidance on how to manage the goal and scopes of such assessments. LCA, however, is usually focused on environmental, and to a lesser extent, social impacts, forming a perspective that may be valuable and rich in information but fails to fully align with the objectives of AM, which also requires the consideration of the aforementioned factors such as technical performance, cost, and risk.

Given these limitations of LCC and LCA with respect to AM decision-making, a combined application of LCC and LCA would be insufficient as it would inherit the downsides of both methodologies. Instead, a hybrid approach is proposed that selectively combines the most effective design principles from LCC and LCA, and aims to avoid their respective limitations for AM decision-making. The resulting Life Cycle Valuation methodology can be considered a novel hybrid approach that is methodologically distinct from applications that merely combine applications of LCC and LCA. The LCV methodology combines five main design principles that are borrowed from both LCC and LCA, including (1) using the four-stage framework for LCA, (2) defining the system of interest, (3) accounting for the time value of money, (4) combining activity-based and value-based breakdown structures, and (5) using monetary valuation as a means to aggregate financial with non-financial results.

LCV models make it possible to quickly and easily view the value created over the lifecycle from multiple, complementary perspectives. LCV goes beyond simply adding non-financial impacts to LCC, as it allows for viewing the same life cycle model from different perspectives, including a financial one. These perspectives can be tailored to the specific goals and preferences of the organization or even other stakeholders and can include value factors alongside costs, such as environmental impact, technical performance, risk, or any other relevant metric. By viewing the assessment outcome from these different perspectives, it is possible to gain a better understanding of how different costs and benefits in the life cycle contribute to value creation (or destruction) and which parameters and life cycle activities present themselves as being the most critical or important concerning the decision context. Because of the existence of multiple value perspectives and the subjective nature of valuation, the LCV methodology does not necessarily aim to seek the most optimal allocation of resources, as what is considered optimal by one stakeholder, may be sub-optimal to another. Instead, LCV utilizes the 4 phase framework of LCA to focus on making the assessment and valuation process itself as transparent and objective as possible, thereby helping professionals better understand and articulate what makes a complex system valuable in a specific decision context. The LCV methodology, therefore, consists not just of a flexible and adaptable calculation method for value that can be tailored to specific organizational contexts, but also emphasizes the process that facilitates the assessment itself. As suggested by other researchers, the guidelines and principles that were originally developed to guide LCA applications, proved to be highly effective in practice, as demonstrated by the case study at Liander.

### *Limitations and future research*

Even though the LCV methodology calls for an explicit formulation and reflection on the goal and scope of the assessment, the process of arriving at a suitable formulation for this remains a challenge in practice that requires attention in future research. Similarly, the Value Breakdown Structures that quantitatively capture value factors for an AM organization, proved to be challenging to develop and agree upon in practice, not only because some of these value factors can be subjective, but also because they were in continuous flux during the research period. An interesting avenue for future research could be to help structure VBS for particular organizations or industrial sectors using similar principles as those employed in impact assessment methods for LCA.

Additionally, the application of the LCV methodology at DSO Liander mainly resulted in modeling and avoiding 'bad' impacts, such as costs, outage risk, and environmental damages. 'Good' impacts such as revenue were possible but were also much less common, and sometimes only described qualitatively, instead of being included in the model quantitatively. Whether this is due to the challenging nature of articulating value, or because this is a remnant of the tendency of both LCC and LCA, which LCV is based on, to focus on 'bad' impacts, remains a question that requires further investigation.

## Declaration of interest

The authors have no competing interests to declare.

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## References

[1] Ruitenburg, R.J., Braaksma, A.J.J., 2017, Mitigating Change in the Goals and Context of Capital Assets: Design of the Lifetime Impact Identification Analysis. CIRP Journal of Manufacturing Science and Technology, 17:50–59. http://dx.doi.org/10.1016/j.cirpj.2016.05.008.
[2] Igba, J., Alemzadeh, K., Durugbo, C., Eiriksson, E.T., 2017, Through-life Engineering Services of Wind Turbines. CIRP Journal of Manufacturing Science and Technology, 17/November 2014: 60–70. http://dx.doi.org/10.1016/j.cirpj.2016.08.003.
[3] Ruitenburg, R.J., Braaksma, A.J.J., van Dongen, L.A.M., 2014, A Multidisciplinary, Expert-Based Approach for the Identification of Lifetime Impacts in Asset Life Cycle Management. Procedia CIRP, 22:204–212.
[4] Pudney, S., 2010, Asset Renewal Decision Modelling with Application to the Water Utility Industry. Faculty of Built Environment and Engineering, . Ph.D. (November), 271.
[5] Lanza, G., Peters, S., Herrmann, H.G., 2012, Dynamic Optimization of Manufacturing Systems in Automotive Industries. CIRP Journal of Manufacturing Science and Technology, 5/4: 235–240. http://dx.doi.org/10.1016/j.cirpj.2012.09.002.
[6] Kampker, A., Burggräf, P., Wesch-Potente, C., Petersohn, G., Krunke, M., 2013, Life Cycle Oriented Evaluation of Flexibility in Investment Decisions for Automated Assembly Systems. CIRP Journal of Manufacturing Science and Technology, 6/4: 274–280. http://dx.doi.org/10.1016/j.cirpj.2013.07.004.
[7] Khan, M.A., West, S., Wuest, T., 2019, Midlife Upgrade of Capital Equipment: A Servitization-Enabled, Value-Adding Alternative to Traditional Equipment Replacement Strategies. CIRP Journal of Manufacturing Science and Technology, 29:232–244. http://dx.doi.org/10.1016/j.cirpj.2019.09.001.
[8] Madni, A.M., Sievers, M., 2014, System of Systems Integration: Key Considerations and Challenges. Systems Engineering, 17/3: 330–347. http://dx.doi.org/10.1002/sys.21272.
[9] Korpi, E., Ala-Risku, T., 2008, Life Cycle Costing: a Review of Published Case Studies. Managerial Auditing Journal, 23/3: 240–261.
[10] Kunttu, S., Välisalo, T., Kettunen, O., Aulanko, Sakari, 2016, Air Conditioning. in Koskinen KK.T.T, Kortelainen HH., Aaltonen JJ., Uusitalo Teuvouo, Komonen KK., Mathew JJ., Laitinen JJ., (Eds.) in: Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015), Lecture Notes in Mechanical Engineeringpp.381–388. http://dx.doi.org/10.1007/978-3-319-27064-7_36.
[11] ISO. 2014, ISO 55000: Asset Management - Overview, Principles and Terminology..
[12] Verbong, G., Geels, F., 2007, The Ongoing Energy Transition: Lessons from a Socio-Technical, Multi-Level Analysis of the Dutch Electricity System (1960-2004). Energy Policy, 35/2: 1025–1037. http://dx.doi.org/10.1016/j.enpol.2006.02.010.
[13] Ruester, S., Schwenen, S., Batlle, C., Pérez-Arriaga, I., 2014, From Distribution Networks to Smart Distribution Systems: Rethinking the Regulation of European Electricity DSOs. Utilities Policy, 31/1: 229–237. http://dx.doi.org/10.1016/j.jup.2014.03.007.
[14] Haarman, M., Delahay, G., 2016, Value Driven Maintenance & Asset Management. Mainovation.
[15] Tinga, T., 2013, Principles of Loads and Failure Mechanisms: Application in Maintenance, Reliability and Design. in Pham HH., (Ed.) Den Helder. Springer London Heidelberg New York Dordrecht, The Netherlands. http://dx.doi.org/10.1007/978-1-4471-4917-0.
[16] Taylor, W.B., 1981, The Use of Life Cycle Costing in Acquiring Physical Assets. Long Range Planning, 14/6: 32–43. http://dx.doi.org/10.1016/0024-6301(81)90058-3.
[17] Woodward, D.G., 1997, Life Cycle Costing—Theory, Information Acquisition and Application. International Journal of Project Management, 15/6: 335–344.
[18] Roda, I., Garetti, M., 2014, The Link between Costs and Performances for Total Cost of Ownership Evaluation of Physical Asset: State of the art Review. 2014 International Conference on Engineering Technology and Innovation (ICE), . http://dx.doi.org/10.1109/ICE.2014.6871544.
[19] White, G.E., Ostwald, P.F., 1976, Life Cycle Costing. Management Accounting, 57/7: 39–42.
[20] Duran, O., Roda, I., Macchi, M., 2016, Linking the Spare Parts Management with the Total Costs of Ownership: An Agenda for Future Research. Journal of Industrial Engineering and Management, 9/5: 991–1002. http://dx.doi.org/10.3926/jiem.2083.
[21] Aurich, J.C., Mannweiler, C., Schweitzer, E., 2010, How to Design and Offer Services Successfully. CIRP Journal of Manufacturing Science and Technology, 2/3: 136–143. http://dx.doi.org/10.1016/j.cirpj.2010.03.002.
[22] Bertoni, A., Bertoni, M., 2018, PSS Cost Engineering: A Model-Based Approach for Concept Design. CIRP Journal of Manufacturing Science and Technology, 29:176–190. http://dx.doi.org/10.1016/j.cirpj.2018.08.001.
[23] Kambanou, M.L., Lindahl, M., 2016, A Literature Review of Life Cycle Costing in the Product-Service System Context. Procedia CIRP, 47:186–191. http://dx.doi.org/10.1016/j.procir.2016.03.054.
[24] Heitz, C., Goren, L., Sigrist, J., 2016, Decision Making in Asset Management: Optimal Allocation of Resources for Maximizing Value Realization. in: Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015) (Springer, Cham), pp.259–268. http://dx.doi.org/10.1007/978-3-319-27064-7_25.
[25] Srinivasan, R., Parlikad, A.K., 2017, An Approach to Value-Based Infrastructure Asset Management. Infrastructure Asset Management, 4/3: 87–95. http://dx.doi.org/10.1680/jinam.17.00003.
[26] Rosqvist, T., Laakso, K., Reunanen, M., 2009, Value-driven Maintenance Planning for a Production Plant. Reliability Engineering & System Safety, 94/1: 97–110. http://dx.doi.org/10.1016/j.ress.2007.03.018.
[27] Ross, A.M., Rhodes, D.H., Hastings, D.E., 2008, Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining System Lifecycle Value. Systems Engineering, 3/11: 246–262.
[28] Janz, D., Sihn, W., Warnecke, H.-J.J., 2005, Product Redesign Using Value-Oriented Life Cycle Costing. CIRP Annals Manufacturing Technology, 54/1: 9–12. http://dx.doi.org/10.1016/S0007-8506(07)60038-9.
[29] Marlow, D.R., Beale, D.J., Burn, S., 2010, A Pathway to a More Sustainable Water Sector: Sustainability-Based Asset Management. Water Science & Technology, 61/5: 1245–1255. http://dx.doi.org/10.2166/wst.2010.043.
[30] Browning, T.R., Honour, E.C., 2008, Measuring the Life-cycle Value of Enduring Systems. Systems Engineering, 3/11: 187–202. Retrieved from*http://ezproxy.lib.ucf.edu/login?url=http://search.proquest.com/docview/926281441?accountid=10003%5Cnhttp://sfx.fcla.edu/ucf?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:journal&genre=article&sid=ProQ:ProQ:civilengineering&atitle=Model+Based+Syste*.
[31] Settanni, E., Newnes, L.B., Thenent, N.E., Parry, G., Goh, Y.M., 2014, A Through-Life Costing Methodology for Use in Product-Service-Systems. International Journal of Production Economics, 153:161–177. http://dx.doi.org/10.1016/j.ijpe.2014.02.016.
[32] Toniolo, S., Tosato, R.C., Gambaro, F., Ren, J., 2020, Life Cycle Thinking Tools: Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment. Life Cycle Sustainability Assessment for Decision-Making, . http://dx.doi.org/10.1016/b978-0-12-818355-7.00003-8. Elsevier Inc..
[33] IEC. 2017, Dependability Management - Part 3-60303: Application Guide - Life Cycle Costing (IEC 60300-60303-3:2017)..
[34] Rebitzer, G., Hunkeler, D., 2003, Life Cycle Costing in LCM: Ambitions, Opportunities, and Limitations. The International Journal of Life Cycle Assessment, 8/5: 253–256.
[35] Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A.C., Pagan, R., 2011, Environmental Life-Cycle Costing: A Code of Practice. The International Journal of Life Cycle Assessment, 16/5: 389–391. http://dx.doi.org/10.1007/s11367-011-0287-5.
[36] Hunkeler, D., Rebitzer, G., 2005, The Future of Life Cycle Assessment. The International Journal of Life Cycle Assessment, 10/5: 305–308. http://dx.doi.org/10.1065/lca2005.09.001.
[37] Rebitzer, G., Hunkeler, D., Jolliep, O., 2003, LCC-the Economic Pillar of Sustainability: Methodology and Application to Watewater Treatment. Environmental Progress, 4:241–249.
[38] Huppes, G., Rooijen, Mvan, Kleijn, R., Heijungs, R., Koning, Ade, Oers, Lvan, 2004, Life Cycle Costing and the Environment. Report of a Project Commissioned by the Ministry of VROM-DGM for the RIVM Expertise Centre LCA, . (April.
[39] ISO. 2006, ISO 14044: Life Cycle Assessment - Requirements and Guidelines..
[40] Sakao, T., Lindahl, M., 2015, A Method to Improve Integrated Product Service Offerings Based on Life Cycle Costing. CIRP Annals Manufacturing Technology, 64/1: 33–36. http://dx.doi.org/10.1016/j.cirp.2015.04.052.
[41] Zhang, W., Guo, J., Gu, F., Gu, X., 2018, Coupling Life Cycle Assessment and Life Cycle Costing as an Evaluation Tool for Developing Product Service System of High Energy-Consuming Equipment. Journal of Cleaner Production, 183:1043–1053. http://dx.doi.org/10.1016/j.jclepro.2018.02.146.
[42] Peças, P., Götze, U., Henriques, E., Ribeiro, I., Schmidt, A., Symmank, C., 2016, Life Cycle Engineering - Taxonomy and State-of-the-Art. Procedia CIRP, 48:73–78. http://dx.doi.org/10.1016/j.procir.2016.04.085. Elsevier B.V.
[43] Heijungs, R., Settanni, E., Guinée, J., 2013, Toward a Computational Structure for Life Cycle Sustainability Analysis: Unifying LCA and LCC. The International Journal of Life Cycle Assessment, 18/9: 1722–1733. http://dx.doi.org/10.1007/s11367-012-0461-4.
[44] Miah, J.H., Koh, S.C.L., Stone, D., 2017, A Hybridised Framework Combining Integrated Methods for Environmental Life Cycle Assessment and Life Cycle Costing. Journal of Cleaner Production, 168:846–866. http://dx.doi.org/10.1016/j.jclepro.2017.08.187.

[45] Atia, N.G., Bassily, M.A., Elamer, A.A., 2020, Do Life-cycle Costing and Assessment Integration Support Decision-Making towards Sustainable Development?. Journal of Cleaner Production, 267122056. http://dx.doi.org/10.1016/j.jclepro.2020.122056.
[46] Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M., 2014, Bridging the Gap between LCA, LCC and CBA as Sustainability Assessment Tools. Environmental Impact Assessment Review, 48:27–33.
[47] Neugebauer, S., Forin, S., Finkbeiner, M., 2016, From Life Cycle Costing to Economic Life Cycle Assessment-Introducing an Economic Impact Pathway. Sustainability (Switzerland), 8/5: 1–23. http://dx.doi.org/10.3390/su8050428.
[48] Kjær, L.L., Pagoropoulos, A., Hauschild, M., Birkved, M., Schmidt, J.H., McAloone, T.C., 2015, From LCC to LCA using a Hybrid Input Output Model - A Maritime Case Study. Procedia CIRP, 29:474–479. http://dx.doi.org/10.1016/j.procir.2015.02.004.
[49] Nakamura, S., Kondo, Y., 2009, Waste Input-Output Analysis, LCA and LCC. in Suh SS., (Ed.) Handbook of Input-Output Economics in Industrial Ecology. pp.561–572. Springer Science. Retrieved from*http://link.springer.com/10.1007/978-1-4020-5737-3_27*.
[50] Norris, G.A., 2001, Integrating Life Cycle Cost Analysis and LCA. The International Journal of Life Cycle Assessment, 6/2: 118–120.
[51] Bierer, A., Meynerts, L., Götze, U., 2013, Life Cycle Assessment and Life Cycle Costing – Methodical Relationships, Challenges and Benefits of an Integrated Use. Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering (Singapore 17-19 April, 2013), pp.415–420.
[52] Kaihara, T., Nishino, N., Ueda, K., Tseng, M., Váncza, J., Schönsleben, P., Takenaka, T., 2018, Value Creation in Production: Reconsideration from Interdisciplinary Approaches. CIRP Annals Manufacturing Technology, 67/2: 791–813. http://dx.doi.org/10.1016/j.cirp.2018.05.002.
[53] Kumar, V., Shirodkar, P.S., Camelio, J.A., Sutherland, J.W., 2007, Value Flow Characterization during Product Lifecycle to Assist in Recovery Decisions. International Journal of Production Research, 45/18–19: 4555–4572. http://dx.doi.org/10.1080/00207540701474633.
[54] Bosch-Mauchand, M., Belkadi, F., Bricogne, M., Eynard, B., 2013, Knowledge-Based Assessment of Manufacturing Process Performance: Integration of Product Lifecycle Management and Value-Chain Simulation Approaches. International Journal of Computer Integrated Manufacturing, 26/5: 453–473. http://dx.doi.org/10.1080/0951192X.2012.731611.
[55] Settanni, E., Thenent, N.E., Newnes, L.B., Parry, G., Goh, Y.M., 2015, To Cost an Elephant: An Exploratory Survey On Cost Estimating Practice in the Light Of Product-Service-Systems. Journal of Cost Analysis and Parametrics, 8/1: 1–22. http://dx.doi.org/10.1080/1941658x.2015.1016588.
[56] Matschewsky, J., Lindahl, M., Sakao, T., 2020, Capturing and Enhancing Provider Value in Product-Service Systems Throughout the Lifecycle: A Systematic Approach. CIRP Journal of Manufacturing Science and Technology, 29:191–204. http://dx.doi.org/10.1016/j.cirpj.2018.08.006.
[57] Renkema, T.J.W., Berghout, E.W., 1997, Methodologies for Information Systems Investment Evaluation at the Proposal Stage: A Comparative Review. Information and Software Technology, 39/1: 1–13. http://dx.doi.org/10.1016/0950-5849(96)85006-3.
[58] Martinsuo, M.M., Vuorinen, L., Killen, C., 2019, Lifecycle-oriented Framing of Value at the Front End of Infrastructure Projects. International Journal of Managing Projects in Business, 12/3: 617–643. http://dx.doi.org/10.1108/IJMPB-09-2018-0172.
[59] Cross, N., 2001, Designerly ways of Knowing: Design Discipline Versus Design Science. Design Issues, 17/3: 49–55. http://dx.doi.org/10.1162/074793601750357196.
[60] Denyer, D., Tranfield, D., Van Aken, J.E., 2008, Developing Design Propositions through Research Synthesis. Organization Studies, 29/3: 393–413. http://dx.doi.org/10.1177/0170840607088020.
[61] Holmström, J., Ketokivi, M., Hameri, A.-P., 2009, Bridging Practice and Theory: a Design Science Approach. Decision Sciences, 40/1: 65–87. http://dx.doi.org/10.1111/j.1540-5915.2008.00221.x.
[62] Peffers, K., Tuunanen, T., Rothenberger, M., Chatterjee, S., 2007, A Design Science Research Methodology for Information Systems Research. Journal of Management Information Systems, 24/3: 45–77. http://dx.doi.org/10.2753/MIS0742-1222240302.
[63] Wieringa, R.J., 2014, Design Science Methodology for Information Systems and Software Engineering.Springer-Verlag, Berlin Heidelberg. http://dx.doi.org/10.1007/978-3-662-43839-8.
[64] Costa, E., Soares, A.L., de Sousa, J.P., 2020, Industrial Business Associations Improving the Internationalisation of SMEs with Digital Platforms: A Design Science Research Approach. International Journal of Information Management, 53/December 2019: 102070. http://dx.doi.org/10.1016/j.ijinfomgt.2020.102070.
[65] Gregor, S., Hevner, A.R., 2013, Positioning and Presenting Design Science Research for Maximum Impact. MIS Quarterly, 37/2: 337–355. http://dx.doi.org/10.2753/MIS0742-1222240302.
[66] Hevner, A.R., 2007, A Three Cycle View of Design Science Research. Scandinavian Journal of Information Systems, 19/2: 87–92http://aisel.aisnet.org/sjis/vol19/iss2/4.
[67] Sein, M.K., Henfridsson, O., Purao, S., Rossi, M., Lindgren, R., 2011, Action Design Research. MIS Quarterly: Management Information Systems, 35/1: 37–56. http://dx.doi.org/10.2307/23043488.
[68] Haffejee, M., Brent, A.C., 2008, Evaluation of an Integrated Asset Life-Cycle Management (ALCM) Model and Assessment of Practices in the Water Utility Sector. Water SA, 34/2: 285–290.
[69] Schuman, C., Brent, A.C., 2005, Asset Life Cycle Management: Towards Improving Physical Asset Performance in the Process Industry. International Journal of Operations & Production Management, 25/6: 566–579. http://dx.doi.org/10.1108/01443570510599728.
[70] ISO. 2019, ISO 55010: Asset management - Guidance on the Alignment of Financial and Non-Financial Functions in Asset Management..
[71] El-Akruti, K., Dwight, R., Zhang, T., 2013, The Strategic Role of Engineering Asset Management. International Journal of Production Economics, 146/1: 227–239. http://dx.doi.org/10.1016/j.ijpe.2013.07.002.
[72] Komonen, K., Kortelainen, H., Räikkönen, M., 2012, Corporate Asset Management for Industrial Companies: An Integrated Business-Driven Approach. Asset Management, 47–63. http://dx.doi.org/10.1007/978-94-007-2724-3. Springer Netherlands.
[73] Sherif, Y.S., Kolarik, W.J., 1981, Life Cycle Costing: Concept and Practice. OMEGA The International Journal of Management Science, 9/3: 287–296.
[74] Hellweg, S., Hofstetter, T.B., Hungerbühler, K., 2003, Discounting and the Environment. The International Journal of Life Cycle Assessment, 8/1: 8–18. http://dx.doi.org/10.1007/BF02978744.
[75] Rødseth, H., Schjølberg, P., Kirknes, M., Bernhardsen. Inge, T., 2016, Increased Profit and Technical Condition Through New KPIs in Maintenance Management. in Koskinen KK.T.T, Kortelainen HH., Aaltonen JJ., Uusitalo Teuvouo, Komonen KK., Mathew JJ., Laitinen JJ., (Eds.) in: Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015), Lecture Notes in Mechanical Engineeringpp.505–511. http://dx.doi.org/10.1007/978-3-319-27064-7_49.
[76] ISO. 2006, ISO 14040: Life Cycle Assessment - Principles and Framework..
[77] Keating, C., Rogers, R., Unal, R., Dryer, D., Sousa-poza, A., Safford, R., Rabadi, G., 2003, System of Systems Engineering. Engineering Management Journal, 15/3: 36–45. http://dx.doi.org/10.1080/10429247.2003.11415214.
[78] Kawauchi, Y., Rausand, M., 1999, Life Cycle Cost (LCC) Analysis in Oil and Chemical Process Industries.September .
[79] Fabrycky, W.J., Blanchard, B.S., 1991, Life-cycle Cost and Economic Analysis. Prentice-Hall.
[80] Durairaj, S.K., Ong, S.K., Nee, A.Y.C., Tan, R.B.H., 2002, Evaluation of Life Cycle Cost Analysis Methodologies. Corporate Environmental Strategy, 9/1: 30–39. http://dx.doi.org/10.1016/S1066-7938(01)00141-5.
[81] Emblemsvåg, J., 2003, Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks.John Wiley & sons, New Jersey.
[82] Götze, U., Koriath, H.J., Kolesnikov, A., Lindner, R., Paetzold, J., 2012, Integrated Methodology for the Evaluation of the Energy- and Cost-Effectiveness of Machine Tools. CIRP Journal of Manufacturing Science and Technology, 5/3: 151–163. http://dx.doi.org/10.1016/j.cirpj.2012.04.001.
[83] Pizzol, M., Weidema, B., Brandão, M., Osset, P., 2015, Monetary Valuation in Life Cycle Assessment: A Review. Journal of Cleaner Production, 86:170–179. http://dx.doi.org/10.1016/J.JCLEPRO.2014.08.007.
[84] Syed, Z., Lawryshyn, Y., 2020, Multi-criteria Decision-Making Considering Risk and Uncertainty in Physical Asset Management. Journal of Loss Prevention in the Process Industries, 65/September 2019: 104064. http://dx.doi.org/10.1016/j.jlp.2020.104064.
[85] Fourie, C.J., Tendayi, T.G., 2016, A Decision-Making Framework for Effective Maintenance Management using Life Cycle Costing (LCC) in a Rolling Stock Environment. The South African Journal of Industrial Engineering, 27/4: 142–152. http://dx.doi.org/10.7166/27-4-1526.
[86] Kara, S., Manmek, S., Kaebernick, H., Kaebemick, H., 2007, An Integrated Methodology to Estimate the External Environmental Costs of Products. CIRP Annals Manufacturing Technology, 56/1: 9–12. http://dx.doi.org/10.1016/j.cirp.2007.05.004.
[87] Thiry, M., 2001, Sensemaking in Value Management Practice. International Journal of Project Management, 19/2: 71–77. http://dx.doi.org/10.1016/S0263-7863(00)00023-5.