# Life Cycle Costing in physical Asset Management: a multiple case study

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**Abstract**

Life Cycle Costing (LCC) is a powerful instrument in the Asset Management (AM) of physical systems. It is a valuable tool that can be used to support rational decision making and provide transparency and accountability about various operational, tactical and strategic AM decisions and their expected consequences.
However, the application of LCC may not always be straightforward. In order to effectively use LCC in this context, it is important to further the understanding of the main challenges that practitioners face during the application of LCC in AM decision making.
This publication summarizes the main descriptions and assumptions found in the literature on LCC into five postulates. These postulates are subsequently compared with empirical findings from four practical case studies within a Dutch utility provider on the use of LCC in AM decision making. Whereas some empirical findings agreed with the postulates, other findings were at least partially in disagreement, indicating inconsistencies between the theory of LCC and the practice of AM.
The results suggest fundamental challenges in the use of LCC in AM, specifically regarding the objectives of using LCC and the scope of what is included in the assessment. Practitioners can use this article to avoid the pitfalls of using LCC in the context of AM and researchers can use the findings to guide further work on developing methods and tools that support AM.

*Keywords: Life Cycle Costing, Asset Management*.

## 1. Introduction

### *1.1 Asset Management*

Enduring physical assets typically fulfil indispensable societal functions and services such as the production of goods or providing the infrastructure for transporting people, freight and energy. Asset Management (AM) organizations are responsible for the safe, reliable and affordable functioning of the physical systems that support these services. The management of these often complex systems requires an integrated lifecycle approach, which includes the design, commissioning, operation, maintenance, repair, modification, replacement and decommissioning of these assets.
Assets can be managed either individually, relating to singular objects, or in groups when asset portfolios or asset systems are concerned. Additionally, the objectives of AM can either be operational, tactical or strategic in nature (ISO 55000:2014).
The aforementioned activities involve many different processes and resources. AM can therefore be defined as “a multidisciplinary practice that applies human, equipment and financial resources to physical assets over their whole life cycle to achieve defined asset performance and cost objectives at acceptable levels of risk whilst taking account of the relevant governance, geo- political, economic, social, demographic and technological regimes” (Pudney, 2010).

### *1.2 LCC in Asset Management*

As physical assets typically require considerable capital investments and continuous operational expenses during their generally long lifespan, it stands to reason that LCC play an important role in the management of these assets. LCC can be regarded as a major contributor to successful Asset Life Cycle Management (Roda and Garetti, 2014). Rather than emphasizing the acquisition costs of an asset, AM needs to consider the costs over the entire asset lifecycle. The application of LCC within the context of AM is by no means a straightforward exercise. The challenge in managing the entire asset life cycle effectively lies in the fact that costs are isolated and addressed in a fragmented way through the various stages (Schuman and Brent, 2005). Furthermore, in order to support managerial decisions, LCC models also need to assume a similarly integrated and systemic focus as AM (Roda and Garetti, 2014). Despite the apparent relevance of considering LCC in AM, it practitioners may be faced by a number of challenges that may limit the effective application of LCC in this context.

## 2. Methodology

The aim of this paper is to develop theoretical insights into the challenges that are faced by practitioners in the application of LCC in AM. This problem-oriented exploration will be used to guide further work on developing scientifically rigorous methods and tools that support AM. Furthermore, the findings can help practitioners in avoiding some of the pitfalls of using LCC in this context.

The applied methodology is similar to that of Meredith (1987), Veldman et al. (2011) and Braaksma et al. (2013), formulating postulates based on conceptual insights found in literature and confirming or disconfirming these postulates based on the findings from a multiple case study. The term postulate refers to a commonly accepted truth that serves as a starting point for deducing or inferring other (theory dependent) truths (Braaksma et al., 2013).

The use of case studies allows for an investigation to retain the holistic and meaningful characteristics of real-life events including individual life cycles, organizational and managerial processes and the maturation of industries (Yin, 2003). Furthermore, case studies represent an effective research strategy for exploratory research as it investigates a contemporary phenomenon within its real-life context, especially when the boundaries between object of study and context are not clearly evident (Dul and Hak, 2008).

Data from the case studies are collected through the application of Action Research (AR), a scientifically rigorous approach to exploratively study the gap between managerial theory and practice (Holmström et al., 2009). As suggested by AR, the researcher has taken the role of practitioner in the case studies in order to develop practically relevant, theoretical insights which are reflected in the empirical findings of this paper.

## 3. Postulates

A prevalent technique for evaluating physical life cycles can be found in the framework for Life Cycle Assessment (LCA) (ISO 14040:2006). Even though this standard is intended for the evaluation of environmental impact, it does provide a life cycle oriented management framework for impact assessment. The principles and framework of LCA can be appropriately adapted for the assessment of LCC (Rebitzer and Hunkeler, 2003) (Swarr et al., 2011) (Heijungs et al., 2013) (Bierer et al., 2013) (Sakao and Lindahl, 2015). The postulates in this paper are based on the four phases of the LCA framework (Figure 1).

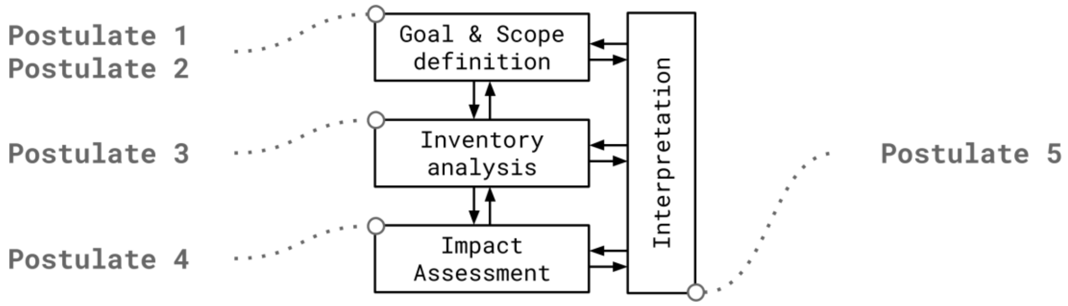


*Figure 1. Life Cycle Assessment framework (ISO 14040:2006) and the five postulates.*

### *3.1 Postulate 1: Goal definition of LCC in AM*

LCC is predominantly (and originally) an engineering tool for providing decision support in the design and procurement of major open systems, infrastructure, and so on (Emblemsvåg, 2003). These activities often include the consideration of various alternative options with the aim of optimal decision making. “Product suppliers can optimize their designs by evaluation of alternatives and by performing trade-off studies” (Okano, 2001). These trade-offs and engineering decisions are crucial for Asset Management as it advocates maximising performance, minimising risk, ensuring equal or higher return on investment and minimising total asset life cycle costs (Tywoniak et al., 2008).

Woodward (1997) recognizes the role of LCC as an optimization strategy: “LCC is a concept which aims to optimise the total costs of asset ownership, by identifying and quantifying all the significant net expenditures arising during the ownership of an asset.”

Purpose of LCC in AM appears to be that of a decision support tool and a cost optimization strategy. This leads to the first postulate:

**Postulate 1:** LCC is a decision support tool that is aimed at minimizing life cycle costs.

### *3.2 Postulate 2: Scope definition of LCC in AM*

The scope of LCC indicates what is included in the assessment of LCC and to what extent it is analyzed. From a practical point of view, LCC is always tailored to fulfil the requirements of its intended use and can be seen as a reflection of its cost object, the scope and boundaries, etc. (Kambanou and Lindahl, 2016). This adaptation of the scope to LCC to suit its intended goal is acknowledged by Korpi and Ala-Risku (2008) who distinguish between different scopes in a review on published LCC case studies.

The questions “to what extent LCC are to be analyzed? ” and “what is included in LCC ?” are not commonly recognized, let alone explicitly formulated in individual LCC cases. This leads to the recognized assumption that the scopes of LCC analyses are easily defined and that they implicitly match their intended use. This leads to the second postulate:

**Postulate 2:** The scope of LCC assessments are easily defined.

### *3.3 Postulate 3: Inventory of LCC*

In order to calculate LCC, an inventory is required of all relevant cost elements. LCC seeks to optimize the cost of acquiring, owning and operating physical assets over their useful lives by attempting to identify and quantify all the significant costs involved in that life, using the present value technique (Woodward, 1997). Life cycle costs can be classified as the ‘capital expenditure’ (CAPEX) incurred when the asset is purchased and the ‘operating expenditure’ (OPEX) incurred throughout the asset’s life (Márquez et al., 2012).

Cost Breakdown Structures (Fabrycky and Blanchard, 1991) can be used to systematically identify and summarize cost elements. Methods such as Activity Based Costing (Emblemsvåg, 2003) assigns costs to specific activities in the lifecycle, thus making it possible to trace the origin of LCC to specific activities in the lifecycle.

In principle, the inventory and calculation of LCC appears to involve the aggregation of all relevant operational and capital cost elements in the lifecycle. This leads to the third postulate:

**Postulate 3:** LCC inventory is a straightforward exercise in listing all relevant cost elements in the lifecycle.

### 3.4 Postulate 4: Identification of LCC

One of the key characteristics of LCC is that it is an application of life cycle thinking. LCC, by definition, refers to an analysis technique which encompasses all costs associated with a product from its inception to its disposal (Sherif and Kolarik, 1981). Multiple definitions reflect this lifecycle oriented approach: “The LCC of a physical asset begins when its acquisition is first considered, and ends when it is finally taken out of service for disposal or redeployment” (Woodward, 1997). “The predicted total life cycle cost is determined by combining all the relevant cost elements associated with the costs incurred for the acquisition, operation, support and disposal of a system. These reflect the total cost of ownership” (Stavenuiter, 2002). The life cycle cost of a product are “the total costs that are incurred, or may be incurred, in all stages of the product life cycle” (Emblemsvåg, 2003).
There appears to be a consensus on including the entire lifecycle within the scope of LCC assessments. This leads to the fourth postulate:

**Postulate 4:** LCC assessments consider the entire lifecycle of an asset.

### 3.5 Postulate 5: Interpretation of LCC impact

Once all relevant cost elements have been inventoried and modelled, the result of the LCC assessment will become evident. “It becomes apparent that when an attempt has been made to evaluate all significant costs during the life of a physical asset [...] managers have the means to quantify options and select the optimum asset configuration” (Taylor, 1981).
As the outcomes of LCC analyses are expressed quantitatively and the inventory process consist of summarizing cost figures, it is reasonable to expect that the interpretation of results should be a straightforward process that allows for a clear judgement of the outcome. This leads to the fifth postulate:

**Postulate 5:** LCC assessment results are interpreted easily.

## 4. Case studies

### 4.1 Company profile

Liander is responsible for the distribution of electricity to 3,1 million and gas to 2,5 million customers. It operates and maintains the electricity and gas grids that distribute this energy throughout various regions in the Netherlands. Liander Asset Management is responsible for the management of the assets that comprise her electricity and natural gas distribution networks. Examples of typical assets under Liander’s management are transformers, power cables and switchgear in the electrical grid and gas mains, pressure-regulating stations and service lines in the gas distribution system.
Not only is Liander responsible for a continuously safe, reliable and affordable energy network, it also needs to be prepared for future challenges. The foremost strategic challenge for Liander is formed by the “energy transition” (Verbong and Geels, 2007), which refers to the liberalization of the energy sector, decentralization of energy production and changes in energy consumption patterns, for example due to electric vehicles or residential energy installations such as solar panels or heat pumps.
Due to the typically long lifespan of Liander’s assets, proactive AM has been recognized as an important means in dealing with the energy transition (Ruitenburg, 2017). As a public enterprise, transparency and accountability are not only mandatory, they are becoming increasingly important due to Liander’s pivotal role in the energy transition.

*4.2 Case selection*

To confront the postulates with the practice of AM, four cases studies were selected from the AM organization of Liander. To provide a diverse sample of practical applications to study and discuss, the selected cases differed in their goal and asset types. These case studies spanned operational, tactical and strategic goals and include assets that can be managed as individual assets, asset portfolios or as asset systems (Figure 2).

The subjects of the four cases involve the condition based replacement of circuit breakers (CBRK), the configuration of fault detection & localization assets (CONF), the development of an electrical grid architecture (ARCH) and a case study on resolving congestion issues with energy flexibility (FLEX).

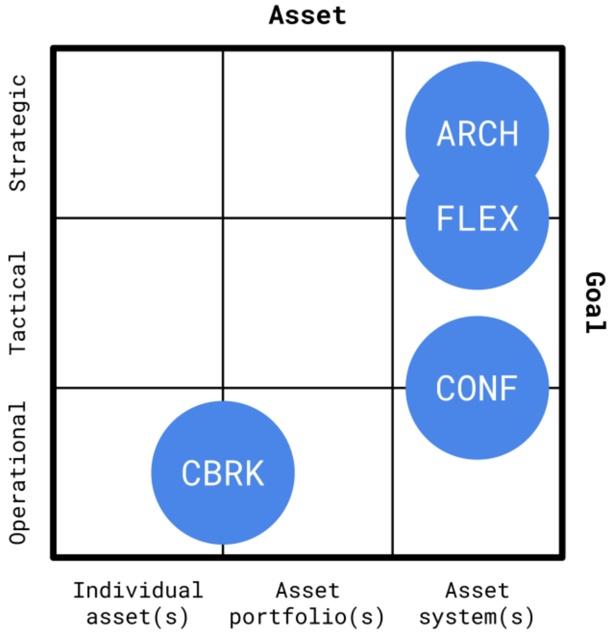


*Figure 2. Perspectives on Asset Management goals and assets.*

*4.3 Circuit breaker case (CBRK)*

The circuit breaker case (CBRK) involved the calculation of the optimal moment for individual circuit breakers to be replaced, based on their condition and the expected LCC of their replacements. This case involved a portfolio consisting of multiple individual circuit breakers that are in use across Liander's electrical distribution grids.

*4.4 Configuration of assets case (CONF)*

The second case was aimed at finding the optimal configuration of assets (CONF) for fault detection and localization in various local electrical distribution grids. Based on architecture of these local grids and multiple possible asset configurations, various alternatives could be compared with respect to their functionality, reliability, (un)availability and LCC performance.

*4.5 Grid Architecture case (ARCH)*

The third case concerns the evaluation of the expected LCC of two alternative distribution network architectures (ARCH) in a dense urban area. This case revolves around the strategic consideration of possibly proactively replacing large parts of the electrical network infrastructure in this area with a more future-proof network architecture and matching assets in the context of the energy transition. The interests and plans of various stakeholders, such as municipal authorities and the high-voltage grid operator, need to be taken into account and aligned in order to develop a sufficient social foundation for Liander's decision.

### 4.6 *Energy flexibility case (FLEX)*

The fourth case involved the resolution of expected congestion issues with respect to energy production and consumption due to urban development in the area. At peak moments, the existing network was in danger of exceeding its redundant design capacity. This congestion issue would only be temporary, as a long term solution is to be provided by a new substation in the near future. Alongside conventional solution proposals was the plan of using the congestion issue as a test case for developing energy flexibility and trading capabilities (FLEX), where energy supply and demand are managed by third parties at peak moments according to the Universal Smart Energy Framework (USEF).

## 5. Empirical findings

### 5.1 *Empirical findings: Goal definition of LCC in AM*

In CONF, the goal of using LCC was to establish optimal asset configurations for fault detection & localization in electrical grids. The decision making process revolved around the tradeoff between LCC and the required technical performance with regard to reliability, availability, maintainability and safety (RAMS). No singular optimum was identified in this case study. Rather than a straightforward cost minimization calculation, LCC was used to assess the tradeoff between cost effectiveness and improved technical performance.

In FLEX, life cycle costs were also assessed alongside RAMS factors as well as $CO_2$ emissions, though these factors had only a limited contribution towards the end result. The FLEX case also included the consideration of developing organizational capabilities in energy flexibility, which poses an additional goal alongside the goal of resolving the congestion issue.

### 5.2 *Empirical findings: Scope definition of LCC in AM*

The FLEX case was deliberately divided into two subsequent analyses with different scopes. The rough initial assessment provided a general overview of the expected LCC, which was subsequently used to approve the commission of a more detailed LCC analysis of the same case. This detailed analysis differed from the first because of the increased level of detail of the dominant cost drivers, the inclusion of an additional alternative, an expanded time frame and the inclusion of a sensitivity analysis.

The ARCH case was initiated with the objective of finding the optimal replacement option for an ageing electrical distribution substation in a dense urban area. The scope of this case was quickly broadened beyond the lifecycle of the new substation, as it was discovered that the choice for a new substation would have a significant consequences for the LCC of future network developments. Rather than optimizing the LCC of the only the substation, the scope of the case was expanded to also include the LCC of future electrical grid architectures, considerably broadening the original scope.

### 5.3 *Empirical findings: Inventory of LCC*

In CBRK, the failure modes and condition data of the circuit breakers were already documented, facilitating the inventory process. In CONF, the expected benefit of improving availability and reliability of the grid was monetized and compared against the expected LCC of various configurations of fault detection and localization assets. In both cases, the lifecycle costs of the replacement assets were fairly straightforward to model due to the relatively predictable and straightforward life cycles of the respective assets.

The ARCH and FLEX cases were aimed at investigating the LCC consequences of certain decisions. In order to create an inventory of these consequences, input from many different disciplines were required. Various aspects such as asset acquisition, technical performance, grid architecture, energy losses, end-of-life or case specific elements such as energy flexibility needed to be taken into account for all alternatives under consideration. However, not all inventory information was readily available or could be determined with sufficient certainty.

In these case studies, data needed to be extrapolated from portfolio averages or findings from similar case studies. Furthermore, decisions about allocation were also required, as some financial consequences could not be attributed completely to the decision or assets under study. An example of this is the attribution of residual value to the assets that were no longer required at the conclusion of the FLEX case. This residual value was calculated based on their remaining useful life in applications beyond the FLEX case.

In the more strategic asset system cases (ARCH and FLEX), extensive expert knowledge from multiple disciplines was required to model all relevant cost elements and relations. Moreover, determining the point at which the LCC were sufficiently assessed to serve as the basis of decision making, was not straightforward and required an iterative process of inventory and re-assessment of the results in consultation with the same experts.

### *5.4 Empirical findings: Identification of LCC*

For the electrical grid in the ARCH case study, no clear start or end-of-life could be identified. Firstly, the functionality of the electrical grid is practically required indefinitely, indicating a continuous lifecycle instead of one with a definite beginning and end-of-life. Secondly, the different components in the electrical grid are projected to be replaced or repaired in nonsynchronous intervals, meaning no fair cut-off point could be chosen between multiple alternatives. In order to resolve this issue, the timeframe of this LCC assessment was set to start in the present year and end 40 years later, at a point where projected plans or strategies were no longer available.

The timeframe of the FLEX case was chosen to correspond with the projected congestion problem, rather than the (difficult to establish) lifecycle of the local electrical grid. Like the ARCH case, the present was chosen as the starting point of the LCC analysis. This decision was justified by the argument that costs incurred in the past were identical for all proposed alternatives, thus not contributing to the decision making process for solving the congestion issue. Similarly, the end point of the time frame was set in the near future, well before the end of the technical end-of-life of the individual assets in the grid. This decision was justified by the argument that the congestion problem would be solved within this timeframe, ending their effective functional lifespan in the local grid, rather than their technical lifespan.

### *5.5 Empirical findings: Interpretation of LCC impact*

In CBRK and CONF, the end results proved to be fairly straightforward to interpret. In both cases, the calculations were automated, presenting the user with a dashboard view that summarized the outcome. This overview sufficed in identifying the optimal replacement moments of individual switchgear, within limits of uncertainty, facilitating asset replacement prioritization and planning.

Though the outcome of the FLEX case presented a clear overview of the LCC of multiple alternatives, this result was not unambiguously interpreted. Some asset managers would advocate the alternative with the lowest projected LCC. Others would also acknowledge the lower LCC of this alternative, but advocate a different perspective on which decision would be preferred based on the outcome.

One argument for this perspective was that one of the more expensive alternatives would also bring additional benefits in the form of developing new capabilities in energy flexibility. Therefore, the additional costs could be seen as an investment in these capabilities, while also solving the congestion issue, essentially “killing two birds with one stone”. Another perspective lay in the observation that a decision based on this case would also affect the options available for the design of the new substation, potentially reducing the flexibility or affordability of solving this future challenge.

## 6. Implications

### *6.1 Implication: Goal definition of LCC in AM*

During the assessment of LCC, relationships between various, sometimes contradictory project goals can become clear. The empirical findings show that LCC has fulfilled the role of decision support, as indicated in the first postulate, but that the goal of using LCC is not necessarily to minimize costs. Instead it involved the consideration of multiple other criteria alongside LCC, such as RAMS performance and $CO_2$ emissions. The use of LCC alone may not always provide a definitive solution to the most optimal AM decision, as multiple performance factors and goals may apply simultaneously. However, the act of identifying these factors and goals does facilitate the decision making process by developing insights into the underlying tradeoffs.

### *6.2 Implication: Scope definition of LCC in AM*

From the empirical findings regarding the second postulate, it became apparent that multiple scopes could apply to the same case study simultaneously. Furthermore, in both the ARCH and FLEX cases, the scopes were adjusted multiple times to suit the shifts in objective, the system boundaries and the progressive insight into the case and its alternatives. These changes were not without consequences, as adjustments in the scope were also reflected in the projected outcome of the LCC assessment. This indicates that LCC may be subject to intentional or unintentional scope creep, the process where the applied scope deviates from its original definition, even after the assessment itself has been initiated. The scope that is determined at the start of an LCC assessment may therefore not always be static, but can be subject to change during the assessment process.

### *6.3 Implication: Inventory of LCC*

The third postulate, which assumes that LCC requires a straightforward inventory of all relevant capital and operational expenses over the entire lifecycle, is only partly supported. The considered timeframe may not always cover the entire asset lifecycle (see the implications of postulate 4). Furthermore, the inventory process may be "easier said than done". The practice of LCC inventory can be a very challenging and resource intensive exercise, as it requires dealing with uncertainties, assumptions, allocation and demands multidisciplinary input from across the entire asset lifecycle.

The term "relevant cost elements" can also be rather subjective, providing little guidance to practitioners on whether to include or exclude certain details, cost elements or cost models in their LCC assessment. Instead, consultation and consensus between experts may be required to determine the point at which LCC are sufficiently assessed. Practitioners need to strike a balance between including enough cost elements and accuracy in their LCC models and assessments to sufficiently support decision making, while at the same being effective with the resources (time, effort, expertise, etc.) to do so. How this balance can be achieved requires further research.

### *6.4 Implication: Identification of LCC*

The empirical findings indicate that the timeframe of an LCC assessment in AM may not necessarily reflect the entire asset lifecycle from beginning to end-of-life, as indicated by the fourth postulate.

In contrast to individual assets, practitioners may find it difficult to determine the point at which an asset system's lifecycle begins or ends. Asset systems such as the electrical grid, typically consist of multiple individual assets, each with their own lifespan and replacement cycles. It seems that these systems can practically be sustained indefinitely by replacing its constituent parts. The end-of-life of these systems therefore appear to be not only determined by its technical lifespan, but can also be subject to functional or technological obsolescence.

Another reason for practitioners not to include the entire lifecycle can be found in the observation that many assets in an AM organization's portfolio may already be well beyond their beginning-of-life. Costs that have occurred in the past of these aged assets are of little interest to decision makers, as they cannot be changed. Instead, practitioners may choose to assess only the LCC of the remaining useful life of these assets.

### *6.5 Implication: Interpretation of LCC impact*

The fifth postulate argues that LCC assessments are interpreted easily. The empirical findings indicate that the process of interpreting the results of an LCC assessment may not always be as straightforward as its mathematical disposition suggests.

Even though the outcome all four case studies provided a clear quantitative overview of the LCC impact of certain decisions, the FLEX case demonstrated that multiple, sometimes conflicting goals may be applicable at the same time. These conflicting goals resulted in similarly contradictory perspectives on the most appropriate decision, despite being based on the same assessment.

Furthermore, the scope of an individual LCC assessment may be too limited or too broad to appropriately reflect the full extent of the cost consequences of a decision. In the ARCH case for example, the strategy of optimizing the life cycles of individual substations led to potential sub-optimizations with respect to the electrical grid they are part of. Vice versa, optimizing the electrical grid system architecture may lead to the premature obsolescence, and therefore lifecycle cost-effectiveness, of individual assets.

These factors indicate that the interpretation of LCC requires a well-grounded understanding of the context, especially with regard to the goal and scope of the assessment. Even though LCC may not always be useful in directly calculating the most appropriate solution, LCC can be beneficial as it can provide a clear basis for understanding and discussing a complex AM problem by providing a transparent overview of the LCC consequences.

## 7. Conclusion

LCC can be a powerful instrument in the AM of physical systems. However, AM practitioners that are looking to adopt LCC may experience a gap between the commonly accepted "truths" of LCC theory and the practice of AM. In order to effectively use LCC in this context, it is important to further the understanding of the challengers that practitioners face. Especially since AM organizations such as Liander may need to invest considerable amounts of (public) money to strategically prepare for long term developments, such as the energy transition. Furthermore, AM organizations are increasingly required to demonstrate accountability related to their decisions. By taking a proactive life cycle perspective, long term cost performance may be improved.

In this study, five postulates were formulated that summarized commonly accepted "truths" about LCC (Table 1). These postulates were subsequently investigated in a real world context using four case studies on the use of LCC in AM practice.

| | |
|---|---|
| **Postulate 1**: | LCC is a decision support tool that is aimed at minimizing life cycle costs. |
| **Postulate 2**: | The scope of LCC assessments are easily defined. |
| **Postulate 3**: | LCC inventory is a straightforward exercise in listing all relevant cost elements in the lifecycle. |
| **Postulate 4**: | LCC assessments consider the entire lifecycle of an asset. |
| **Postulate 5**: | LCC assessment results are interpreted easily. |

*Table 1. Summary of the postulates.*

The results from these case studies indicate that not all postulates are entirely supported by the empirical findings, illustrating an apparent gap between LCC theory and the empirical findings from AM practice. These gaps provided a number of theoretical insights into the challenges in the applicability of LCC in AM. Practitioners can use the empirical findings in this paper to avoid some of the pitfalls of using LCC in the context of AM.

Firstly, the holistic nature of AM allows for the recognition of operational, tactical and strategic goals, sometimes simultaneously. Furthermore, LCC optimization efforts for a specific AM goal or particular asset selections, such as individual assets, asset portfolios or asset systems, may lead to sub-optimization with respect to other goals or asset selections. As LCC assessment are a reflection of their goal and scope, practitioners should be aware that the results of LCC assessments and their corresponding decisions can be therefore be framed in more than one way, depending on the perspective or context. When complex cases are considered, consensus may be required between experts to determine the appropriate goal, scope and level of detail, which may result in intentional or unintentional scope creep. In sum, the nature of LCC in AM may not always be as objective as its quantitative nature suggests.

Secondly, LCC are not necessarily the only criterion of interest in AM. Alongside cost objectives, asset managers need to balance multiple aspects such as asset performance (e.g. RAMS), risk levels or environmental and social factors, not all of which require a quantitative approach. This means that LCC alone may not always provide a definite proposition for the most optimal AM decision, as multiple criteria and objectives need to be balanced simultaneously. Instead, the results of such an assessment can be used as a powerful decision support instrument that provides a quantified overview of the LCC consequences in the context of a certain decision, using a lifecycle perspective.

## 8. Limitations and future research

Even though the formulated postulates are not always supported by the empirical findings, this does not mean that they are of no value to asset managers. The postulates may still be used as a helpful starting point for practitioners.

The conclusions of this paper are limited by both the number of cases that are included in this study, as well as the selection of cases from only a single AM organization. Additional and more diverse case studies are needed to increase the generalizability of the findings.

The main objective of this research is further study the role and application of LCC within the domain of Asset Management. Future research includes:

- Expanding and testing the generalizability of the findings from this paper by performing additional case studies on multiple types of assets at and AM organizations.
- The development of scientifically rigorous methods and tools that support the process of assessing of Life Cycle Costs in the context of AM, which are aimed at effectively dealing with the challenges indicated in this paper.
- Studying the potential of quantifying non-financial life cycle impact to allow the quantitative assessment of multiple AM criteria alongside LCC.
- Studying the temporal validity of LCC assessments of assets with a long lifespan in the context of continuous changes to their environment and requirements.

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