Life cycle costing: a review of published case studies

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Abstract

Purpose: Despite existing life cycle costing (LCC) method descriptions and practicable suggestions for conducting LCC analyses, no systematic analyses on actual implementations of LCC methods exist. This article reviews reports on LCC applications to provide an overview of LCC uses and implementation feasibility.

Methodology/Approach: A review of LCC cases reported in academic and practitioner literature. Case reports were compared against each other and against the defining articles in the field.

Findings: Most of the reported LCC applications were far from ideal. Compared to the methods suggested in the literature many of the case study applications: (i) covered fewer parts of the whole life cycle, (ii) estimated the costs on a lower level of detail, (iii) used cost estimation methods based on expert opinion rather than statistical methods, and (iv) were content with deterministic estimates of life cycle costs instead of using sensitivity analyses.

Research limitations/implications: This review is limited to reported LCC applications only. Further research is encouraged in the form of a field-based multiple-case study to reveal context-specific dimensions of LCC analysis and implementation challenges in more detail.

Practical implications: This review highlights the difficulty of conducting a reliable LCC analysis, and points out typical problems that should be carefully considered before drawing conclusions from the LCC analysis.

Originality/value of the paper: First systematic analysis of LCC applications that gives directions for further research on the LCC concept.

Paper type: literature review

Keywords: Life cycle cost, Life cycle costing, LCC, product life cycle, literature review, multiple-case analysis
Introduction

“The life cycle cost of an item is 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” (White and Ostwald, 1976). Such life cycle costs of a product can be many times the initial purchase or investment costs (Woodward, 1997), and according to several sources 70-90% of these total life cycle costs become defined already in the design phase (Bescherer, 2005; Dowlatshahi, 1992; Lindholm and Suomala, 2005). Yet initial investment costs are most often used as the primary and sometimes the only criteria in purchase decision (Lindholm and Suomala, 2004; Woodward, 1997). In spite of the obvious long-term benefits of the life cycle costing (LCC), its adoption has been relatively slow (Lindholm and Suomala, 2004; Woodward, 1997). Possible reasons for the slow adoption include the lack of standard or formal guidelines and the lack of reliable past data (Ardit and Messiha, 1999).

The amount of cross-case studies in the field of life cycle costing is extremely low and most of them either are limited to a single industry (Ardit and Messiha, 1999; Lindholm and Suomala, 2004; Sterner, 2000) and/or just cover some superficial features of life cycle cost analysis like the adoption rate (Hyvönen, 2003; Lukka and Granlund, 1996). The purpose of this study is to explore with a multiple-case analysis based on a literature review, what are the business contexts where LCC is used and what kinds of methods are applied to LCC analyses. Although the findings of this review represent only the reported LCC case studies, the results nevertheless indicate (i) the extent of attention of academics studying LCC, and (ii) the variety of LCC applications and resulting complication of LCC methods.

Based on literature related to LCC methods we formulated a framework for analyzing published LCC cases. Using several publication databases we identified relevant LCC case studies for our analysis. The most interesting results of these analyses are presented in this paper with the following structure. In the next section we will discuss the literature of life cycle costing and the dominating methods of doing life cycle cost analysis. The third section presents the research design used to gather data and analyze the case studies. The following section will go through the results of our multiple-case analysis. The fifth section considers the limitations of the study and after that the conclusions of this research are discussed. In the final section future research suggestions are given.

Literature review

Background

LCC was originally designed for procurement purposes in the U.S. Department of Defence (White and Ostwald, 1976) and is still used most commonly in the military sector as well as in the construction industry (Woodward, 1997). The adoption of life cycle thinking has been very slow in the other industries (Lindholm and Suomala 2004). Public sector has also been a relevant promoter for life cycle cost calculations (Woodward, 1997).
There are relatively few articles written about the frequency of LCC use and the results of these articles are somewhat heterogeneous. In a Finnish study only 5% of large industrial companies had used life cycle costing (Hyvönen, 2003). In a Swedish building industry study 66% of the companies used life cycle costing to assist on decision making (Sterner, 2000) and in a U.S. study 40% of city administrations used life cycle cost analysis when assessing their building projects (Ardit and Messiha, 1999).

In addition to LCC there are other traditions taking a wider perspective on product life cycle. Most notable of these are total cost of ownership (TCO) and life cycle assessment (LCA).

“Total cost of ownership (TCO) is a purchasing tool and philosophy which is aimed at understanding the true cost of buying a particular good or service from a particular supplier” (Ellram, 1995). It is often used for two purposes: supplier selection and supplier evaluation (Bhutta and Huq, 2002). Thus, it focuses mainly on transaction costs and the costs of the operational phase are not considered (Lindholm and Suomala, 2004). Another tradition that has a life cycle perspective is life cycle assessment (LCA), but it concentrates on environmental issues and is not really concerned with the cost aspect (Emblemsvåg, 2001).

From our perspective, LCC is the most relevant cost management method, as TCO neglects operations and maintenance costs, and LCA promotes environmental impacts instead of being a costing tool.

**LCC purposes**

Life cycle costing is said to focus primarily on capital or fixed assets (Ellram, 1995). Asiedu and Gu (1998) on the other hand state that life cycle costing can be used for all sorts of products: The purpose and nature of the analysis however depends on the product.

As discussed above life cycle costing was originally designed for procurement purposes i.e. to be used from a point of view of a client. Many of the most prominent LCC methods (Fabrycky and Blanchard, 1991; Woodward, 1997) are intended to be used to support design decision making, but nevertheless from a client’s perspective. From a manufacturer perspective, Dunk (2004) presents motivational factors for using LCC: Manufacturers with a strong customer-focus may recognize LCC as a customer service leading to competitive advantage. However, the ability of a manufacturer to perform life-cycle costing is affected by the quality of information available.

A useful frame of reference detailing LCC purposes that accounts for both client and supplier perspectives is presented in (Barringer and Weber, 1996):

- **Affordability studies**- measure the impact of a system or project’s LCC on long term budgets and operating results.
- **Source selection studies**- compare estimated LCC among competing systems or suppliers of goods and services.
- **Design trade-offs**- influence design aspects of plants and equipment that directly impact LCC.
• **Repair level analysis**- quantify maintenance demands and costs rather than using rules of thumb such as “…maintenance costs ought to be less than _?_% of the capital cost of the equipment”.

• **Warranty and repair costs**- supplier’s of goods and services along with end-users need to understand the cost of early failures in equipment selection and use.

• **Suppliers sales strategies**- can merge specific equipment grades with general operating experience and end-user failure rates using LCC to sell for best benefits rather than just selling on the attributes of low, first cost.

**Life cycle costing methods**

Durairaj et al. (2002) have presented and compared different life cycle cost analysis methods in their article. Some of the methods presented in the article are extremely narrow by scope and hence are not useful for a general analysis. Out of the eight methods three were found to be relevant in describing life cycle costing methods. We used these three publications (Emblemsvåg, 2001; Fabrycky and Blanchard, 1991; Woodward, 1997) and another defining article in the field of life cycle costing (Asiedu and Gu, 1998) to build the framework against which we compared the methods used in the case studies.

Life cycle is usually divided from an individual product’s perspective into three or four steps. Fabrycky and Blanchard (1991) used a four-step division to categorize the costs of an individual product (Figure 1). Despite this formal categorization, LCC has been criticized for lack of consideration of design costs (Ellram and Siferd, 1998).

**Figure 1. Life cycle cost categories (Fabrycky and Blanchard, 1991)**

Life cycle cost analysis is a forecast of the future. That’s why different cost estimation methods must be applied. The use of different cost estimation methods depends on, for example, availability of data and the phase in which the calculations are done (Fabrycky and Blanchard, 1991). Fabrycky and Blanchard introduce three different ways to estimate costs: (i) estimating by engineering procedures, (ii) estimating by analogy and (iii) parametric estimating methods. In estimating by engineering procedures costs are assigned to each element at the lowest level of design detail and then combined into a total for the product or system. The problems with this method are the need of detailed data and hours of effort needed to perform the calculations. However, estimating by engineering procedures might result in an accurate estimate if all the needed data is available and the estimator doesn’t cut any corners.

In estimating by analogy, as its name already states, the cost estimator draws analogies between different products or their features. Estimating by analogy can be done either on system level or on task level. Maybe the most significant problem of estimating by analogy is the high degree of judgment required. This is the cheapest of these three methods because not much data is needed, but also the most inaccurate, especially if the
analogies are drawn on a system level. The experience and expertise of the estimator are crucial, if accurate estimates are desired. This method is suitable for new products when extensive databanks are not available.

Parametric estimation utilizes different statistical techniques and seeks for the factors on which the life cycle costs depend. Parametric method requires quite a lot of data. According to Fabrycky and Blanchard (1991) this method should be preferred in most of the situations.

Also more advanced methods of cost estimation have been suggested for life cycle costing. Emblemsvåg (2001) suggests activity-based costing (ABC) to be used in life cycle cost analysis. However, ABC is not easily adopted to be used in conjunction with unique investments, because it requires extensive activity-cost databases.

Since LCC takes into account future costs, the time-value of money needs to be accounted for in the calculations (Fabrycky and Blanchard, 1991). That’s why future cash flows should be discounted to present value especially if the life of the asset is long. In fact, many LCC methods (Fabrycky and Blanchard, 1991, Woodward, 1997) take also inflation into account. Nevertheless, choosing the right discount and inflation rate for the situation might be a challenge, and it also may have a notable effect on the LCC results.

All of the defining articles in the field of life cycle costing (Asiedu and Gu, 1998; Emblemsvåg, 2001; Fabrycky and Blanchard, 1991; Woodward, 1997) acknowledge the stochastic nature of LCC calculations. These sources suggest sensitivity analyses to be done in order to cope with the uncertainty. Some of the methods (Emblemsvåg, 2001; Fabrycky and Blanchard, 1991) also suggest the use of monte carlo simulation to deal with the uncertainty.

There are at least two commercial standards intended to assist on life cycle cost analysis. One is intended to be used only in the building industry (ASTM international, 2002) and the other is suitable for more general use (International Electrotechnical Commission, 2004). There are also some military and public sector standards and handbooks on LCC.

**Research design**

Our research started by establishing potential categories according to which the case studies could be classified. This step was based on an extensive literature review. Some of the categories were used to classify the operating environment and others the methods used in the life cycle cost analysis. The next step was to decide how to collect the material and to actually choose the case studies suitable for the review. After that the articles chosen were classified according to the different categories on operating environment and LCC methods. In this classification phase lots of judgment was needed because many of the issues we investigated were not clearly reported in the case studies and thus had to be interpreted from the text. In the next phase, interactions between all the different categories were investigated in order to find out: (i) What kinds of characteristics of the operating environment encourage the adoption of life cycle costing, (ii) What are the main purposes for conducting LCC, (iii) How do LCC implementations conform with the methods suggested in literature, (iv) How do the characteristics of the operating environment affect the methods used in LCC analysis. In this article the most relevant findings of these analyses are presented.
Data collection

Based on our literature review, the literature in the field of life cycle costing was quite fragmented. Therefore, we decided to use several databases instead of individual journals to identify LCC case studies. The databases chosen for the review were AIP Scitation American Society of Civil Engineers, ABI Inform: ProQuest Direct, EBSCOhost-databases, Elsevier: ScienceDirect, Emerald Library, Google Scholar, IEEE XPLORE, JSTOR, Springer Verlag: LINK and Wiley Interscience. The databases were chosen according to our access to different databases and according to the contents of these databases. In the review, we sought for articles dated after the defining book of Fabrycky and Blanchard (1991). The following two search terms were used: (i) “life cycle cost” AND case, and (ii) “life cycle costing” AND case. These words were searched from the abstract, title and keywords sections of the articles during July 2006. We felt that, if life cycle costs and case study were not mentioned in these sections of the article then they didn’t play a significant role in the article and should not be included in the review. In Google Scholar it was not possible to define article sections to narrow down the search, so we decided to limit the search only to article title.

A total of 205 articles were found under these criterions. Some of these articles were dismissed because of the following reasons: (i) we didn’t have access to the full text version of the article (18 rejections), (ii) the article was not meeting our criteria for suitable case studies: life cycle costing played only a very minor role in the article or there was no case study in the article (132 rejections). Thus, we were left with 55 case studies that were suitable for the review. All the suitable articles were relatively new: A total of 38 cases were from this century. The included case studies are listed in Appendix 1.

There were only seven journals with more than one suitable case study: Renewable Energy, Building and Environment, Energy, Structural Safety, Construction Management and Economics, Energy and Buildings and Applied Energy. Articles from a total of 43 journals were used in the study.

Case analyses

Nine different features were analyzed from all of the case studies. Four of the features described operating environment and another four described the methods used in the analysis. The purpose of LCC analysis in the cases was assessed with a single category. The different categories and our classification on these features are presented in table 1. Each of the classifications is described in more detail in the results section.
### Table 1. Dimensions of case analysis

#### Operating environment

<table>
<thead>
<tr>
<th>Item</th>
<th>Classification</th>
<th>Based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry</td>
<td>Construction</td>
<td>SIC divisions (U.S. DoL, 2006), with two alterations</td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manufacturing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td></td>
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<tr>
<td></td>
<td>Research</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Real estate</td>
<td></td>
</tr>
<tr>
<td>Public sector influence</td>
<td>Public</td>
<td>Woodward (1997)</td>
</tr>
<tr>
<td></td>
<td>Private</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Client</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td></td>
</tr>
<tr>
<td>Nature of the product</td>
<td>Continuous production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recurring investments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unique investments</td>
<td></td>
</tr>
</tbody>
</table>

#### Purpose of the analysis

<table>
<thead>
<tr>
<th>Item</th>
<th>Classification</th>
<th>Based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose of the analysis</td>
<td>Affordability studies</td>
<td>Barringer and Weber (1996), with two alterations</td>
</tr>
<tr>
<td></td>
<td>Source selection studies – vendor</td>
<td></td>
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<tr>
<td></td>
<td>Source selection studies – product</td>
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<tr>
<td></td>
<td>Design trade offs – optimization</td>
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<tr>
<td></td>
<td>Design trade offs – comparison</td>
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<tr>
<td></td>
<td>Repair level analysis</td>
<td></td>
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<td></td>
<td>Warranty and support costs</td>
<td></td>
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<tr>
<td></td>
<td>Supplier’s sales strategies</td>
<td></td>
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</tbody>
</table>

#### LCC methods

<table>
<thead>
<tr>
<th>Item</th>
<th>Classification</th>
<th>Based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life cycle phases included in the analysis</td>
<td>Research &amp; development (R&amp;D)</td>
<td>Fabrycky and Blanchard (1991)</td>
</tr>
<tr>
<td></td>
<td>Production &amp; construction (production)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operations &amp; maintenance (O&amp;M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Retirement &amp; disposal costs (disposal)</td>
<td></td>
</tr>
<tr>
<td>Information sources</td>
<td>Public statistics</td>
<td>Descriptions in analyzed cases</td>
</tr>
<tr>
<td></td>
<td>Internal sources</td>
<td></td>
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<tr>
<td></td>
<td>Other firms</td>
<td></td>
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<tr>
<td></td>
<td>Other articles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other sources</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Information sources not reported</td>
<td></td>
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<tr>
<td></td>
<td>Estimating by analogy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parametric estimating</td>
<td></td>
</tr>
<tr>
<td>Nature of the analysis</td>
<td>Stochastic</td>
<td>e.g. Fabrycky and Blanchard (1991), Emblemsvåg (2001)</td>
</tr>
<tr>
<td></td>
<td>Deterministic</td>
<td></td>
</tr>
</tbody>
</table>
Research results

**Operating Environment**

**Industry and public sector influence**

We used SIC divisions (U.S. Department of Labor, 2006) to classify the industries in which the case studies were done. We had to make two minor alterations into the SIC divisions in order to better describe the case studies. We added energy category into our classification, because a notable part of the cases were concerned with energy use and/or production. One of the cases didn’t fit to any of the existing SIC divisions, thus we denoted it with the research category in Table 2.

In addition, the cases were analyzed to identify the possible influence of public sector, i.e. whether the case analyses were performed for the needs of public or private sector. This analysis was done as public sector has been stated to be a relevant promoter for life cycle cost calculations (Woodward, 1997).

<table>
<thead>
<tr>
<th>Industry</th>
<th>In total</th>
<th>Public</th>
<th>Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>34</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td>Energy</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Transportation</td>
<td>9</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Research</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Real estate</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Our findings [Table 2] in this category support the literature in the field only partially. Almost two thirds of the articles were from the construction industry, so the construction cases dominated even more than one could have expected on the basis of the literature. On the other hand only one of the cases was from the military sector (In Table 2, it is included in the transportation category). One might have expected more military cases to be found because of the fundamental role of the U.S. Department of Defense in the development of life cycle costing. Other industries widely represented in the review were energy, transportation and manufacturing. Six cases had features of both energy and construction divisions and therefore these cases are shown in both of these categories. Research and real estate divisions are discarded in further analysis because of their low count.

Although there was only one military case, a large portion of the cases (40 %) were written to fulfill the needs of the public sector [Table 2]. One article was written by a standard committee and it isn’t included neither in the public nor in the private sector cases.

**Perspective of the analysis**

If the analysis was done from the perspective of the party responsible for the costs accumulated during the operations and maintenance phase, the case was added to client
category. If the analysis was done by the manufacturer of the product in question, the case was naturally added to manufacturer category. If neither of these points applied to the party who did the calculations, the case was added to category other. In almost two thirds of the cases there was a client (owner/user) perspective [Figure 2]. A quarter of the cases had been written from the point of view of the manufacturer. Five cases considered life cycle costs from the point of view of the society or economy. Three of the cases in this category have been allocated to client, one case to manufacturer category and one had neither perspective so it is included in the category other. The portion of cases reported from manufacturer’s perspective was in fact quite large considering the dominant position of client view in the LCC method literature.

![Perspective by industries](image)

**Figure 2. Case perspective and association with industry**

The perspective wasn’t very clear in all of these case studies, because most of the cases had been written by academics with rather unclear contacts to the actual companies. In fact 37 articles had a quite strong academic focus, which made it somewhat difficult to interpret the perspective.

The industry had clearly an effect on the perspective used [Figure 2]. Manufacturer was much more likely to do the analysis in the transportation industry than in the other industries. Cases with energy industry focus were done mostly from client perspective.

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1 From the category other two cases were done from a perspective of a party that purchases a component, but installs it as a part of a system produced for an external client and thus is not responsible for the costs incurred in the O&M phase. One case was from a point of view of a LCC software provider, another from a point of view of a standard committee and the last case in that category was an academic article with neither a client nor a manufacturer perspective.
When analyzing the private/public sector influence on the perspective of the analysis, manufacturer perspective was found to be more common in the cases done for the needs of the private sector. 71% of the manufacturer cases were from the private sector, whereas almost half (46%) of the client cases were done for the needs of the public sector.

**Nature of the product**

We grouped the products of the case studies into three categories: (1) Products that are produced continuously, (2) recurring investments and (3) unique investments. First we made the classification from both manufacturer and client perspectives and then we classified the products from the perspective of the party who had done the calculations (analyzer). We made this classification in two steps for two different reasons. First of all it wasn’t possible to classify the products universally because the different parties experienced the products in a different way. For example, a hot water boiler can be regarded as continuous production from the supplier’s perspective and as a recurring investment from client’s point of view. We were also interested to see what kind of differences there were between the different parties.

![How do the different parties see the products?](image)

**Figure 3. Product classification in terms of decision making recurrence from different perspectives**

Figure 3 shows that manufacturers considered most of the products as recurring investments or continuous production whereas clients considered the same products as unique or recurring investments. This difference in the way how the different parties considered the products is quite natural. Manufacturers after all do produce more units of the same products than what the clients are likely to buy. An interesting observation was that the analyses of continuous products were almost exclusively done in the transportation and manufacturing divisions, making the construction and energy cases...
focus mainly on investments. However, most of the investment analyses in construction cases considered rather subassemblies than entire project deliverables.

The most typical product was one that manufacturers considered as recurring production and the clients as unique investments. 42 % of the products had this combination. Most of the parties that did the calculations thought that the product was an investment (recurring or unique, 80 %). Making the calculations in an investment situation enables taking the special characteristics of the operating environment into consideration. On the other hand doing these calculations for continuous production would enable a wider application of the calculations. The fact that most of the analyses were indeed done in investment situations suggests that it is important to take the actual operating environment of the product into account.

**Purpose of the analysis**

We used Barringer and Weber’s (1996) list of possible functions for LCC use with small modifications in order to classify the purposes in which the analyses were made. We divided two of the categories into two subcategories each. Source selection studies were divided into vendor and product categories and design trade-offs were divided into optimization and comparison categories. The first modification into Barringer and Weber’s model was done in order to illustrate that most of the source selection studies compared different products or systems with each other, instead of different suppliers. The reason for the second alteration was to illustrate the existence of two quite different types of design trade-off calculations. In some of the cases an optimal design is searched and in the others a few different design options are only compared with each other.

Categories in the table 3 are not exclusive: One case study can have multiple purposes.

**Table 3. Purpose of LCC in the case studies**

<table>
<thead>
<tr>
<th>Purpose of LCC use</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Affordability studies</td>
<td>6</td>
</tr>
<tr>
<td>Source selection studies -- vendor</td>
<td>1</td>
</tr>
<tr>
<td>Source selection studies -- product</td>
<td>20</td>
</tr>
<tr>
<td>Design trade-offs – optimization</td>
<td>9</td>
</tr>
<tr>
<td>Design trade-offs – comparison</td>
<td>16</td>
</tr>
<tr>
<td>Repair level analysis</td>
<td>7</td>
</tr>
<tr>
<td>Warranty and repair costs</td>
<td>3</td>
</tr>
<tr>
<td>Suppliers sales strategies</td>
<td>1</td>
</tr>
</tbody>
</table>

All of the categories in the Barringer and Weber’s model were represented in at least one case study. Most common uses of life cycle costing were source selection studies for different products and design trade-offs, both comparison and optimization.

In a few articles also two other notable benefits of LCC analyses were mentioned: (i) They were able to systematically take into account the cost aspect in design decision making, and (ii) they were able to find out the factors that had the largest effect on the total life cycle cost.

Industry seemed to have some effect on the purpose for which life cycle costing analyses were used. Five of the six affordability studies were done in the construction division and
four of them were done for the needs of public sector. 29% of the public sector construction cases were in fact affordability studies. Energy cases focused on the source selection studies for different products. 80% of all energy cases belonged to this category. There were a lot of design trade-offs done for the needs of the private sector (59% of the private sector cases). Source selection studies dominated the public sector cases (50% of the public sector cases).

The nature of product had some surprising effects on the purpose of the LCC study. Two thirds of the affordability studies were done for recurring investments although one might have expected these studies to be done almost exclusively for large, unique investments. Another surprising thing was that three quarters of the source selection studies for different products were done for unique investments and the rest of the cases for recurring investments. One might have expected that there were more recurring and continuous production products in this category. The lack of continuous production cases among source selection studies might be explained by the search terms used in case selection: Based on our literature review this sort of products might be mostly considered in the total cost of ownership literature.

**Methods and coverage**

**Life cycle phases included in the analysis**

We investigated which life cycle phases were included in the case study analyses. The results can be found in table 4. In one case study there was no distinction between life cycle phases. In all the other cases operations and maintenance support (O&M) costs were dealt with at least partially. In some of the case studies for example only energy costs were included from the O&M phase. Production and construction costs were also very commonly included in the case studies. On the other hand research and development (R&D) costs as well as retirement and disposal costs were included only in about a quarter of the cases. Our interpretation of the term initial costs might be a partial reason for the low percentage of the R&D category. If the costs were not specified in detail, we interpreted that initial costs include only production and construction costs, not R&D costs. Also in some situations there aren’t any research and development costs, for instance if you compare one existing solution with another one. It was interesting and quite depressing to notice that only three case studies had included costs from all of the four phases of the life cycle in the analysis. In a few case studies where LCC was used for comparative purposes the authors had explained the exclusion of some cost categories by stating that the costs are roughly the same in different alternatives.

<table>
<thead>
<tr>
<th>Life cycle phase</th>
<th>Use / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research and development</td>
<td>20</td>
</tr>
<tr>
<td>Production and construction</td>
<td>87</td>
</tr>
<tr>
<td>Operation and maintenance support</td>
<td>98</td>
</tr>
<tr>
<td>Retirement and disposal</td>
<td>26</td>
</tr>
</tbody>
</table>

There were only minor differences between the industries. Transportation industry emphasized design costs (44% of the transportation cases included design costs) and de-emphasized retirement and disposal costs (none of the cases included these costs).
The perspective from which the cases had been done had some logical effect on the life cycle phases covered. Manufacturers focused more on the earlier parts of the life cycle and the clients on the other hand focused more on later parts of the life cycle [Table 5].

**Table 5. Life cycle phases associated with case perspective**

<table>
<thead>
<tr>
<th>Perspective</th>
<th>R&amp;D</th>
<th>Production</th>
<th>O&amp;M</th>
<th>Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>29 %</td>
<td>93 %</td>
<td>100 %</td>
<td>7 %</td>
</tr>
<tr>
<td>Client</td>
<td>14 %</td>
<td>83 %</td>
<td>97 %</td>
<td>31 %</td>
</tr>
</tbody>
</table>

The function of the LCC analysis had some effect on the life cycle phases considered in the analysis. Disposal costs were covered in 67 % of affordability studies in contrast to 20 % of the other cases. In repair level analyses other than O&M costs were not much covered: R&D costs were covered in 14 % of these cases and disposal costs were covered in the same fraction of cases. Production costs were also covered in only 43 % of the repair level analyses.

Within the above cost categories the division into smaller categories has been very limited in most of the articles. By far the most often recurring subcategory is energy costs (in 22 cases), which in the cost breakdown structure of Fabrycky and Blanchard (1991) is included in the O&M costs.

**Information sources**

In method literature of life cycle costing mainly internal sources of information are dealt with (Fabrycky and Blanchard, 1991; Woodward, 1997). Unfortunately the internal sources of cost information were not described so deeply in the case studies. As a matter of fact the use of internal sources of cost information was reported only in one third of the articles. Based on the descriptions in the case studies, we decided to use a division of information sources shown in table 6.

**Table 6. Information sources used in the case studies**

<table>
<thead>
<tr>
<th>Information sources</th>
<th>Public statistics</th>
<th>Internal sources</th>
<th>Other firms</th>
<th>Other articles</th>
<th>Other sources</th>
<th>Not reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>50 %</td>
<td>21 %</td>
<td>26 %</td>
<td>24 %</td>
<td>21 %</td>
<td>15 %</td>
</tr>
<tr>
<td>Energy</td>
<td>70 %</td>
<td>10 %</td>
<td>40 %</td>
<td>60 %</td>
<td>20 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Transportation</td>
<td>33 %</td>
<td>33 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>33 %</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>17 %</td>
<td>83 %</td>
<td>0 %</td>
<td>17 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>44 %</td>
<td>33 %</td>
<td>22 %</td>
<td>20 %</td>
<td>15 %</td>
<td>15 %</td>
</tr>
</tbody>
</table>

Public statistics was the most common reported source of information, especially in the energy and construction divisions [Table 6]. Internal sources were the second most common source and it was used extensively in the manufacturing division (83 %). In 15 % of the cases the sources of cost information were not reported at all. Reporting of information sources was especially inadequate in the transportation division: In one third of the cases cost information sources were not reported at all and in all the other cases there was only one reported source of information. Collaboration and information sharing were quite rare in the case studies. There was reported information sharing whatsoever between the different parties in the supply chain in only 12 cases. Out of these twelve cases in six cases only purchase price information was shared, and in only three cases detailed information from for example O&M costs was distributed to the other party.
Manufacturers’ reporting of information sources was deficient. In 36 % of the cases done from the point of view of the manufacturer, information sources were not reported at all. Manufacturers didn’t receive any cost information from their customers to support life cycle cost analyses in any of the case studies. There would be a clear opportunity to acquire data from the customers and thus be able to estimate the O&M costs more reliably and accurately.

**Cost estimation methods**

Figuring out the cost estimation method wasn’t very straightforward because the authors of these articles did not explain the method that had been used. In fact a lot of judgment and interpretation was needed. There were two good indicators of the method used. The first indicator was the calculations. In some cases the method was evident from the numbers and formulae used, and another good indicator was the source of information and the level of detail of this information. For example, external information (public statistics or other publications) often had to be adapted to the purpose by using analogy or expert opinion. In many cases a combination of two or three estimation methods had been used.

**Table 7. Cost estimation methods used in the case studies**

<table>
<thead>
<tr>
<th>Cost estimation methods</th>
<th>count</th>
<th>Per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric</td>
<td>25</td>
<td>45 %</td>
</tr>
<tr>
<td>Analogy</td>
<td>7</td>
<td>13 %</td>
</tr>
<tr>
<td>Engineering</td>
<td>2</td>
<td>4 %</td>
</tr>
<tr>
<td>A mix of parametric and analogy</td>
<td>14</td>
<td>25 %</td>
</tr>
<tr>
<td>A mix of parametric and engineering</td>
<td>1</td>
<td>2 %</td>
</tr>
<tr>
<td>A mix of analogy and engineering</td>
<td>1</td>
<td>2 %</td>
</tr>
<tr>
<td>A combination of all three methods</td>
<td>1</td>
<td>2 %</td>
</tr>
<tr>
<td>unclear</td>
<td>4</td>
<td>7 %</td>
</tr>
</tbody>
</table>

According to Fabrycky and Blanchard (1991), parametric estimation should be preferred in most of the situations. From these case studies only less than half used purely parametric cost estimation methods [Table 7]. Activity-based costing had been used in only one analysis.
Industry had a clear effect on the cost estimation method used [Figure 4]. Construction and energy divisions used a lot of analogy with the estimates. In construction and energy divisions lots of data from secondary sources [Table 6] is used and this increases the need for expert judgment and the proportion of cases applying analogical methods. Transportation and especially manufacturing divisions use more parametric cost estimation methods.

The function of the analysis had an exceptionally strong effect on the cost estimation methods used. Repair level analysis and warranty and support cost estimation cases were all purely parametric. This implies that these analyses relied more on data. The optimization cases were also very data intensive. None of the optimization cases were purely analogical and 67 % of the cases were either purely parametric or purely engineering. Source selection studies were on the other hand the least data intensive. Only a quarter of these cases were done with purely parametric methods compared to 57 % of the other cases. The proportion of purely analogical cases was instead really high with the source selection studies: 25 % of the studies were purely analogical compared with 6 % of the other cases.

Cost estimation methods had also an effect on the life cycle phases considered in the analyses. Especially R&D and production costs were not taken into account in many of the parametric cases. R&D costs were covered in 12 % of the parametric studies compared to the 27 % of the other studies. Production costs were considered in 76 % of
the parametric studies compared to the 97% of the other studies. This lower percentage of production and construction costs can be at least partially explained by the purpose of the analysis. All the repair level analyses and warranty and support cost estimations are parametric and on the other hand these analyses don’t take the production and construction costs into account in many cases. The differences in R&D costs couldn’t be explained with the purpose of the analysis. One possible reason for this difference might be lack of suitable data: It is probably hard to find quantitative data on R&D costs.

**Nature of the analysis**

Considering the methods suggested in the LCC literature the amount of deterministic life cycle cost analyses was a surprise. Almost half (49%) of the analyses were deterministic. This means that almost half of the studies ended up with a single number without taking into account the uncertain nature of the cost estimations. A few determining factors for this worrying result were also found when comparing this category with other ones.

The industry seemed to have a strong effect on this issue [Table 8]. Construction cases were relatively stochastic but transportation and manufacturing cases were extremely deterministic by nature.

**Table 8. The nature of life cycle cost analyses in the case studies**

<table>
<thead>
<tr>
<th></th>
<th>Deterministic</th>
<th>Stochastic</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>41%</td>
<td>59%</td>
<td>34</td>
</tr>
<tr>
<td>Energy</td>
<td>50%</td>
<td>50%</td>
<td>10</td>
</tr>
<tr>
<td>Transportation</td>
<td>67%</td>
<td>33%</td>
<td>9</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>83%</td>
<td>17%</td>
<td>6</td>
</tr>
</tbody>
</table>

Information sources used in the analysis also had an effect on the fact, whether the analysis was deterministic or stochastic. Most interesting finding of this analysis was that use of public statistics in the construction industry had a clear effect on this: 47% of the cases where public statistics had been used were stochastic, while the share of stochastic studies was 71% for the studies where statistics hadn’t been used. A possible explanation for this finding is that the public statistics are mostly in a form of single numbers, not distributions, making the statistics seem as universal truths and hiding the variability of the costs. In fact, sensitivity analyses should be emphasized more when relying on public statistics because fitting the information from public statistics into the particular situation always requires expert judgment and thus induces more uncertainty to the calculations.

One factor that increases the significance of sensitivity analysis is the discount rate that needs to be used when addressing future life cycle costs. Choosing the right discount rate isn’t easy, because it depends for example on the risk-level of the project, market situation, credit rating of the company and on many other factors (Brealey and Myers, 2003). The authors of the case study articles had acknowledged the importance of discounting: In only one article the future costs hadn’t been discounted at all and discount rate was also the most common factor for sensitivity analysis.

The number of studies lacking proper sensitivity analysis was disappointing, when you consider that energy-related costs constituted a large proportion of total life cycle costs in many case studies and the price of energy has been highly volatile and very hard to forecast (see e.g. Huisman and Mahieu, 2001).
Limitations of the study

One limitation of this study is related to terminology used in the research design. We didn’t attempt to find out and classify all the case studies about cost management practices with a life cycle view. Instead we concentrated on what has been reported under the term of life cycle costing. For example one of the findings of our study might be explained with our search term: There was only one source selection study for continuous products among the case studies. According to our literature review, this type of cases might be covered more in total cost of ownership case studies. Focusing explicitly on life cycle cost cases in this study was however justified, as, by definition, other identified life cycle cost management traditions excluded some of the life cycle phases we were interested in. There seems nevertheless to be overlap in the uses of the different costing traditions.

Maybe the most notable limitation of our study is that it is limited only to the reported case studies and the reported studies do not necessarily represent all the practices used in the field. In some situations the deficiencies in reporting might have lead to interpretations underestimating the actual methods. For example, the calculations may have been reported at a lower level of detail than at which they have actually been performed. Another reporting related limitation arises from the fact that a notable proportion of the case studies were written from an academic perspective and this may have had an effect for example on the information sources used and reported. In fact, articles with a strong academic focus were typically using analogous cost estimation methods as the access to internal information sources was limited (22 % of articles with academic focus, vs. 56 % of others used internal sources of cost information).

A third limitation related to reporting practices is that the aspects we wanted to find out from the case studies were not always clearly presented. Judgment and interpretation was needed in these categories. Especially problematic was “cost estimation method”-category. Other categories where considerable amount of judgment was needed were “nature of the product” and “perspective of the analysis”.

Conclusions

The purpose of this study was to explore through the analysis of published LCC case studies: (i) What kinds of characteristics of the operating environment encourage the adoption of life cycle costing, (ii) What are the main purposes for conducting LCC, (iii) How do LCC implementations conform with the methods suggested in literature, (iv) How do the characteristics of the operating environment affect the methods used in LCC analysis. We address the research questions in the subsequent sections.

As a general observation, LCC case studies don’t have a strong tradition in any scientific journal. Thus, the case studies are unconnected and are not founded on previous discourse. The focus of the case studies themselves wasn’t in developing LCC further, but in displaying its use in a specific context and especially in justifying the superiority of one product/design aspect over another, despite the higher initial cost of the former.
The lack of a general discourse was obvious from some of the case studies: The shortage of standards and formal procedures was complained in several case studies, although there are at least two commercial standards (ASTM international, 2002; International Electrotechnical Commission, 2004). On the basis of our research the reason for the low adoption rate of the standards seems to be the strong context-specific nature of LCC methods. The methods used depend strongly at least from the purpose of the analysis and the availability of information. Thus, while agreeing with the statement that the slow adoption rate of life cycle costing results from lack of standard or formal guidelines and the lack of reliable past data (Ardit and Messiha, 1999), we amend it by noting that the variety and context-specific nature of LCC methods makes the establishment and application of formal guidelines fairly complicated.

**Characteristics of operating environment**

The statements of Woodward (1997) that the main LCC users come from construction and military, as well as public sector having a notable role in encouraging the use of LCC received partial support. The proportion of case studies done for the needs of public sector was indeed notable (40 % of cases). Construction division dominated the reported cases very strongly (62 %), but military cases were almost absent. However, this is likely to be due to the reporting bias discussed above.

The majority of the analyses were done from the client perspective, but the share of cases reported from manufacturer’s perspective was in fact quite large (25 %) considering the dominant position of client view in the LCC method literature. This is surprising also in the light that the manufacturers were not reported to receive any information from their products’ users regarding the O&M and disposal phase costs, although all of the manufacturer cases were reported to include the operations and maintenance costs.

Most of the analyses were done to support investment decisions rather than continuous procurement or production decisions. This indicates that life cycle costing is mostly performed in situations where the specific end use of the product needs to be taken into account.

**Purposes for LCC analyses**

Life cycle costing had been used for wide range of different purposes. All of the six categories in the classification by Barringer and Weber (1996) were represented in at least one case study. In general, most common uses of life cycle costing were source selection studies for different products and design trade-offs, both comparison and optimization. There were some differences in the LCC purposes by industry: Construction industry is the main user of affordability studies, and cases from energy division focused mostly on the source selection studies for different products. Quite understandably, the public sector uses life cycle costing mostly in sourcing decisions, while the private sector uses LCC as a design support tool.
Life cycle costing methods

The reported LCC methods were overall fairly unsatisfactory, in terms of all of the analyzed aspects of the cases (life cycle phases considered, information sources used, cost estimation methods used, and the deterministic nature of analyses).

All the life cycle phases (Fabrycky and Blanchard, 1991) were taken into account in only three case studies. Additionally the level of detail of the calculations was very low. Only a few articles had presented the costs at a similar, high level of detail, what the LCC method publications suggest (Fabrycky and Blanchard, 1991; Woodward, 1997). The design phase was neglected in the LCC analyses (presented only in 20 % of cases), which is much in line with remarks from Ellram and Siferd (1998). It must, however, be noted that this negligence is not as such a feature of LCC methods (cf. Fabrycky and Blanchard, 1991), but rather a feature of the reported LCC implementations.

According to Fabrycky and Blanchard (1991) parametric estimation should be preferred in most of the situations. From these case studies only less than half used purely parametric cost estimation methods. Construction and energy divisions performed especially poor in this category mainly because these industries did not report having internal cost databases and therefore had to rely heavily on external sources of data (public statistics and other articles). As a whole, the reporting of the use of internal sources of information has been quite rare. It is however possible that this is partially due to shortcomings of the reporting or the academic nature of the cases.

The purpose of the analysis had an extremely strong effect on the cost estimation methods used. Repair level analyses and warranty and support cost estimations were all purely parametric. Design optimizations were also very data intensive. On the other hand source selection studies involved lots of expert judgment and analogy. While the strong relationship between purpose and method selection is not surprising, it indicates a need for further development of context-specific LCC methods or standards.

The deterministic calculation methods of almost half of the case studies were quite alarming. These analyses didn’t pay any attention to the fact that future costs are always uncertain. In cases where uncertainty was addressed, the most common factor for sensitivity analyses was discount rate. Considering the fundamental role of highly volatile energy costs in many analyses, including the deterministic ones, the need for a sensitivity analysis is ever greater.

Further research

As the reviewed case studies focused heavily on the characteristics of products or designs, there seems to be room for case studies focusing on the implementations of different LCC applications. The current case studies are by no means encouraging for readers looking for insights on how to conduct life-cycle costing in practice.

To address the limitations in this study, we suggest two lines of further research: (i) A similar literature-based multiple case analysis for other cost management terms with a life cycle focus to generate an overview of life cycle costing traditions, and (ii) A multiple case study of actual applications of LCC methods used in the industry. The framework
we have developed for this review could serve as a good starting point for both of these analyses, especially for the study of actual applications of LCC methods in the industry. With a multiple case study of actual applications in the industry, one could circumvent the inherent limitations of our research design, namely the bias caused by reporting and the extent to which judgment is needed in interpreting the reporting. Such a field study of actual LCC methods could reveal context-specific dimensions of LCC analysis and enable the development of a more detailed formal guideline for performing LCC analyses. Field studies are fairly resource intensive, and to minimize the costs of recording an individual case, a tested framework of analysis is very valuable. We hope the framework we have used here in analyzing reported cases can serve also with field studies of LCC applications.

References


White, G.E., and Ostwald, P.F., (1976), “The life cycle cost of an item is 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” Management Accounting, Vol. 57, No. 7, pp. 39-42.

Appendix 1. LCC case studies included in the review


