

A method-based survey of life cycle costing literature pertinent to infrastructure design and renewal

Paul N. Christensen, Gordon A. Sparks, and Kent J. Kostuk

Abstract: Motivated by Canada's infrastructure crisis, the Intelligent Sensing for Innovative Structures (ISIS) Canada Research Network has developed and demonstrated the efficacy of innovative materials and monitoring technologies to support infrastructure design and renewal efforts. To quantify the potential benefits of these technologies across a diverse range of infrastructure applications, a rational, pragmatic and flexible method of life cycle costing (LCC) is needed. The purpose of this paper is to review and broadly classify LCC methods evident in pertinent literature. Through this process, a state-of-the-art LCC method is identified and described. Its noted strengths and limitations suggest promising avenues for future research.

Key words: life cycle cost, infrastructure, design.

Résumé : Motivé par la crise des infrastructures au Canada, le réseau d'excellence de centres d'excellence sur les innovations en structures avec systèmes de détection intégrés a développé et démontré l'efficacité de matériaux innovateurs et de technologies de surveillance pour soutenir la conception et les efforts de renouvellement des infrastructures. Afin de quantifier les bénéfices potentiels de ces technologies à travers une vaste gamme d'applications sur les infrastructures, il faut une méthode rationnelle, pragmatique et flexible d'établissement des coûts du cycle de vie (LCC « Life Cycle Costing »). Le but du présent article est de passer en revue et de classer sommairement les méthodes LCC évidentes dans la littérature pertinente. Par ce processus, une méthode LCC de pointe est identifiée et décrite. Ses forces et ses limitations suggèrent des voies prometteuses pour la recherche future.

Mots clés : coûts du cycle de vie, infrastructure, conception.

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1. Introduction

The pressing needs of Canada's aging civil infrastructure have been recently valued at a staggering CAN\$44 billion (ISIS Canada 2001). This crisis motivates research, development, demonstration, and training activities within the Intelligent Sensing for Innovative Structures (ISIS) Canada Research Network, one of Canada's Networks of Centres of Excellence. The mission of the ISIS Canada Research Network is to "... advance civil engineering to a world leadership position, through the development and application of FRPs and integrated intelligent FOS technologies, for the benefit of Canadians through innovative and intelligent infrastructure."

Life cycle costing (LCC) can be used to estimate the magnitude of benefits Canadians might enjoy where innovative technologies prove to be superior to conventional infrastructure technologies. Yet, the method of LCC employed must adequately address real-world challenges pertinent to involved costing investigations. First, the method used must prove to be adaptable to a wide and diverse array of potential infrastructure applications. Second, it must be capable of addressing uncertainty and complexity inherent to the evaluation of long-lived structures (especially structures incorporating new technology). Finally, the method used should support an efficient process of related engineering design and decision-making efforts.

Surveys of LCC literature conducted in past years focus on (i) cataloguing LCC investigations and (or) (ii) the mechanics of LCC per se. Gupta and Chow (1985), for instance, catalogue a 25-year history of LCC literature. Dhillon (1989) catalogues and describes a range of LCC techniques and models employed by many researchers and practitioners over time. Asiedu and Gu (1998) focus on the mechanics of life cycle (or concurrent) engineering and costing as it pertains to complex product systems. Despite the comprehensiveness and quality of each review, none survey and organize previous work in the field of LCC with an eye to method.

In contrast, the literature survey summarized here reviewed pertinent LCC literature for broad methodological

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content. This serves to (i) encourage clear statement of methodological approaches evident in LCC literature, (ii) organize papers according to a logical progression of methodological sophistication and concomitant flexibility, and (iii) identify a state-of-the-art method best able to cope with challenges inherent to infrastructure design and renewal in Canada and beyond.

The principal objective of this paper is to review and organize LCC investigations according to the degree of methodological sophistication employed. Through this process, a current state-of-the-art LCC method is identified, a method relevant to the evaluation of both innovative and conventional technologies across a wide range of infrastructure applications. Computational mechanics are irrelevant to this study. Basic techniques of LCC are well known and widely published (calculating equivalence measures, cost estimating techniques, etc.). Moreover, the authors have no desire to confuse computational wizardry for genuine methodological progress.

While the field of LCC includes literally thousands of publications, this review focuses principally on those involving infrastructure and new technology. Combined with literature pertinent to methodological insight, this subset of publications furnishes breadth sufficient to build and demonstrate a logical classification scheme pertinent to critical review of virtually any LCC study.

A number of steps coincide to satisfy the principal objective of this study – steps reflected in the organization of this paper. In Sect. 2, the historical context of LCC is first explored to learn its intent as originally envisioned. This establishes a benchmark against which methods of LCC may be compared. Attention then turns, in Sect. 3, to methodological classification of LCC studies reviewed. A “root method” capturing the basic flow of virtually all LCC investigations is first defined. Sequential addition to the root method captures increasing levels of sophistication and, therefore, general applicability. Through this process, a state-of-the-art LCC method is ultimately identified. The strengths and limitations of the state-of-the-art method are discussed with an eye to future research opportunities. Concluding remarks are found in Sect. 4.

2. A brief history of life cycle engineering and costing

The roots of LCC may be traced, arguably, to the activities of researchers within the Massachusetts Institute of Technology Radiation Laboratory (RadLab) during World War II. To facilitate rapid development and deployment of microwave radar systems for wartime use, managers at RadLab created and implemented innovative systems design processes (see Fortune 1945). Inspired in large part by his work with RadLab, Wiener (1948) developed a theory of communication termed “cybernetics” (Wiener 1948). Relevant to the regulation of both natural and mechanical systems, cybernetics relies heavily on the concept of feedback in goal seeking. The pertinence and influence of Wiener’s insight on engineering design is clear. Today, feedback (or iteration) is a standard feature of any systematic design method intending to satisfy design goals through the application of

engineering knowledge, skills, and creativity (Asimow 1962; Nowacki 1980; Suh 1990; Ertas and Jones 1993).

The goals of an engineering design process are quite naturally reflected in the criteria employed within the process itself. Charged with the design of a product or infrastructure system, for example, is the design team seeking to optimize reliability, manufacturability (constructability), durability, maintainability, or some combination of the above? Clearly, alternative criteria can lead to alternative outcomes. For this reason, it is important to ask the question: what criterion (or criteria) is “best” employed?

From procurement guidelines of both US and Canadian armed forces (Reiche 1970; Gansler 1974), a widely accepted answer to this important question has emerged: minimize total life cycle costs. In 1960, officials within the US Department of Defense (DoD) noted that operations and support costs for a weapons system could account for 75% or more of total costs incurred over its useful life span (Gupta and Chow 1985). This observation influenced subsequent military procurement policies that ultimately propelled development of life cycle engineering and costing concepts where considerations regarding the total costs of manufacture (construction), operation, use, maintenance, support, and phase-out of product and infrastructure systems explicitly enter and inform the engineering design process (Earles 1974; Fabrycky 1987; NRC 1991).

The Design for “X” literature keenly reflects the development of life cycle engineering and costing concepts spurred by the insights of DoD and others (Dean and Unal 1992; Asiedu and Gu 1998). Keys (1990), for instance, argues that all Design for “X” approaches should ultimately fall under the umbrella of a primary goal: Design for Life Cycle. In Keys’ opinion, engineering design concepts, such as Design for Assembly and Design for Manufacture, are strictly subordinate to Design for Life Cycle, where cost estimates accompany all aspects of interrelated life cycle engineering activities to determine feasible, cost-minimizing designs that best satisfy customer needs.

Properly construed, LCC implies a synthesis of costing analysis and engineering design principles employed to develop product and infrastructure systems that satisfy necessary technical requirements (reflecting customer needs) at minimum life cycle cost. Hence, the logic of LCC suggests that all phases of the engineering design process (conceptual, preliminary, and detailed) are required to explicitly incorporate cost considerations to reach design decisions that gradually converge on the “best” feasible product or infrastructure system relevant to the challenge at hand (Blanchard 1979).

Of course, intent and action are different things. To ensure promise extends to practice, it is necessary to develop credible and pragmatic methods of LCC sufficiently flexible to address a broad range of challenges facing professional engineers. In the section to follow, methods of LCC teased from surveyed literature are traced from the most straightforward to the most comprehensive (the latter representing, in the opinion of the authors, the current “state-of-the-art”). As the review demonstrates, the increasing complexity of methods employed simply reflects the reality of the challenging process that is engineering design.

3. A step-wise review of life cycle costing methods

Practitioners and researchers surveying LCC literature will discover a diverse and potentially bewildering array of techniques and applications. In some instances, LCC appears to be little more than a straightforward application of standard engineering economic principles. In other cases, LCC criteria support sophisticated mathematical programming techniques seeking optimal infrastructure maintenance and repair policies. Still other instances of LCC illustrate some mix of sensitivity, risk, and (or) multi-attribute decision analyses.

A methodological classification of LCC literature may help sort through the dizzying array of techniques and applications summarized in thousands of publications. To reach a satisfactory classification in this regard, it is necessary to (i) identify and organize the progressive development of LCC methods in a logical and meaningful way, (ii) separate genuine methodological advancements from sophisticated application of straightforward LCC principles, and (iii) separate credible from questionable developments in the theory and practice of LCC. The purpose of this section is to address these three challenges in a step-wise review of LCC methods.

3.1. Deterministic method of life cycle costing

All LCC methods implied in literature reviewed for this paper embody a basic structure reflected in a strictly deterministic approach to LCC. Differences among methods stem from extensions to this “root” structure. A review of this basic structure sets the stage for step-by-step progression in methodological sophistication.

The basic deterministic method underlying virtually all LCC investigations is illustrated as a flow diagram in Fig. 1. As shown, the process begins with customer needs and ultimately ends with the customer selecting a preferred design option. In this context, the LCC procedure employed exists to support a decision-making process focused on customer satisfaction.

To illustrate the root method underlying LCC investigations, consider the case of bridge deck replacement. The needs of the infrastructure owner (customer) are translated to a set of technical requirements that proposed, mutually exclusive design options must meet to satisfy feasibility (Ehlen 1997; Arrien et al. 2001). Once a set of feasible bridge deck options emerge, each must be analyzed in the context of life cycle cost. The first step in this procedure is to generate cost profiles corresponding to each considered option. Each cost profile is a series of planning, construction, maintenance, support, use, and phase-out cost estimates streamed over the intended service life of the corresponding bridge deck design option. Next, each cost profile is translated to an equivalence measure to support a common and credible basis of comparison among considered design options. This involves the straightforward application of time – value of money factors to convert a forecasted stream of costs to a single comparable index (Riggs et al. 1986). Common equivalence measures used to compare feasible design options include annual worth and present worth (ASTM 2002). Third, the results of the time – value of money computations are used to

rank the options according to life cycle cost – where the bridge deck design option posting the least life cycle cost (measured in annual or present worth terms) ranks above all other feasible design options and is therefore presented as the recommended option. Finally, the results of the LCC procedure are passed on to the infrastructure owner to support rational decision making.

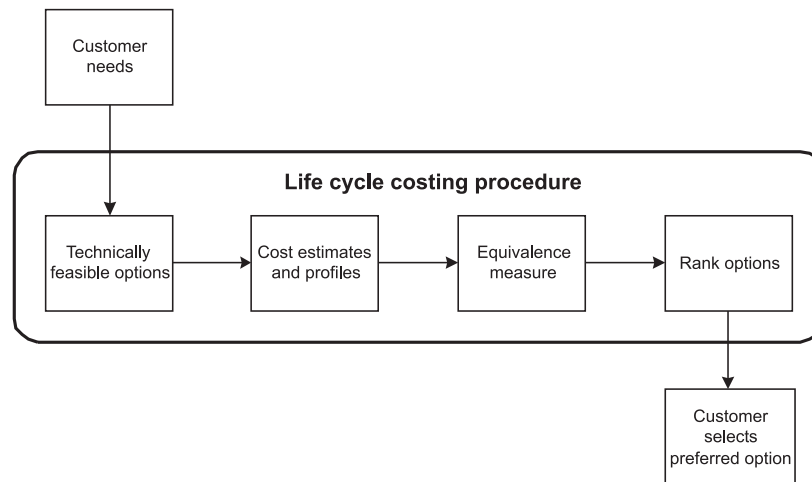
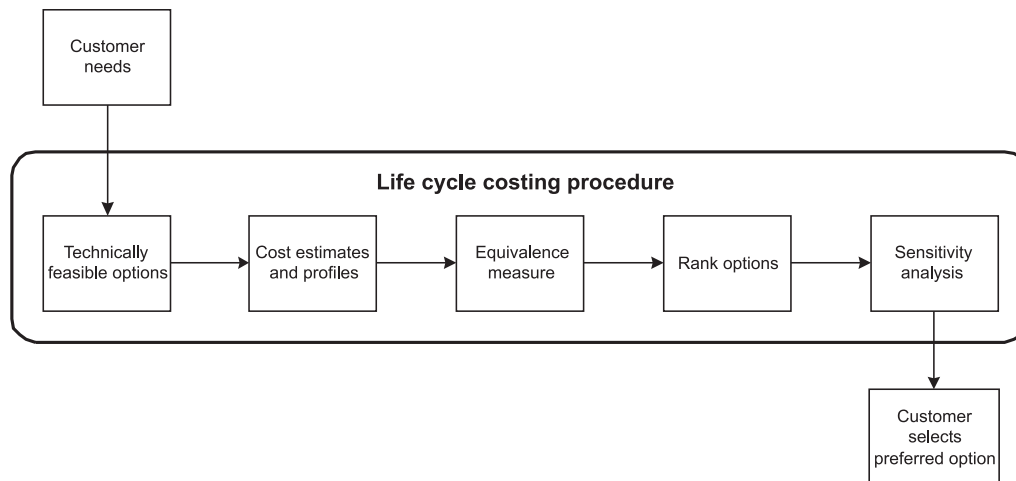
It is important to note that the derivation of cost profiles for each option analyzed within a LCC procedure ranges from straightforward to sophisticated. Straightforward derivation of cost profiles involving, for example, innovative infrastructure technologies (in this case fibre reinforced polymer and structural health monitoring technologies) may be found in Ehlen and Marshall (1996), Ehlen (1997, 1999), Maharsia and Jerro (2002), Meiarashi et al. (2002), and Nystrom et al. (2003). More sophisticated means of deriving cost profiles for LCC investigations include the combining of optimization techniques and (stochastic) life cycle performance predictions in developing optimal maintenance strategies pertinent to bridge and other infrastructure systems (Kulkarni 1984; Frangopol et al. 1999; Das 2001). Regardless of the computational sophistication involved, however, the derivation of cost profiles pertinent to infrastructure-related options within LCC investigations will rely on supporting cost estimating techniques relevant to the options at hand (Jelen and Black 1983; Dhillon 1989; Stewart 1995; FHWA 1998).

The root method underlying LCC investigations provides a logical ordering of analytical activities and a credible means of ranking feasible options pertinent to the construction, rehabilitation, and on-going management and support of infrastructure. However, this straightforward deterministic approach provides little guidance to the engineer attempting to adequately represent the complexity and uncertainty inherent to LCC investigations. For this reason, the basic method is typically extended within LCC applications to permit a logical means of addressing these shortcomings. Of these, a common extension to the basic method of LCC involves the use of sensitivity analysis – a straightforward yet insightful means of addressing uncertainty in the context of LCC investigations.

3.2. Sensitivity analysis and life cycle costing

In general, sensitivity analysis involves the perturbation of model variables over predetermined bounds to determine their relative effect on model outcome. Through this process, analysts can (i) identify some subset of model variables that exert significant influence on model results and (or) (ii) determine break-even points that alter the ranking of considered options. Each of these goals provide important insight to decision makers who are rightly sceptical of fixed values and attendant results. Sensitivity analysis, then, is a direct admission that uncertainty often plagues even the most careful and judicious deterministic analyses. Note that a straightforward introduction to sensitivity analysis is found in Clemen (1996).

Figure 2 reflects the progressive addition of sensitivity analysis to the basic LCC method. As can be seen, following an initial deterministic ranking of feasible design options, sensitivity analysis is employed to establish the sensitivity of model results (i.e., annual or present worth measures) and

Fig. 1. The root method of life cycle costing studies.**Fig. 2.** Life cycle costing with sensitivity analysis.

rankings across model variables of particular concern to analysts and decision makers. In the LCC literature, demonstrations of this method may be found in many articles. Examples pertinent to the application of innovative technologies include Ehlen and Marshall (1996), Hartmann et al. (2000), Kent and Murphy (2000), Maharsia and Jerro (2002), which includes an excellent demonstration of break-even analysis, and Meiarashi et al. (2002).

While pertinent literature demonstrates the ease with which sensitivity analysis may be employed to derive important insights regarding model results and attendant rankings, the arbitrary application of sensitivity analysis can prove misleading. As discussed in Holloway (1979), information employed in sensitivity analyses must be based on some sense of likely maximum and minimum values. For example, in a LCC exercise an analyst may draw on expert engineering judgement to estimate the upper and lower bounds corresponding to certain costing variables. To ensure the bounds established are consistent across model variables, the analyst should encourage the engineer to estimate minimum and maximum values based on, for instance, a confidence interval of 95% (i.e., the engineer is 95% certain that the actual

value lies between the two estimates provided). This avoids arbitrary variations in LCC model variables that may or may not reflect the likelihood that the "true" value falls within the established bounds, effectively skewing insights drawn from the sensitivity analysis. Examples of this basic error within LCC literature are many and include Ehlen and Marshall (1996) and Maharsia and Jerro (2002).

3.3. Risk analysis and life cycle costing

While sensitivity analysis provides decision-makers some insight regarding the malleability of model results across a range of variable estimates and corresponding bounds, it suffers three important shortcomings. First, it may fail to identify a dominant alternative among considered design options (this is certainly the case where perturbations in model variables disturb the ranking of feasible design options). Second, since sensitivity analysis typically involves the independent perturbation of each model variable, engineers and, therefore, customers do not gain a sense of the combined and simultaneous influence of several "perturbed" model variables on LCC results and rankings. Finally, in the absence of defined probability distributions, the likelihood that particular

values occur is left unexplored. The purpose of risk analysis is to address these shortcomings through probabilistic comparison of considered options.

In risk analysis, values assigned model variables are described by probability mass functions or frequency distributions. Through exact or random sampling methods, the probabilistic assessment of model variables is employed within the relevant computational procedure to generate a cumulative distribution of model outcomes corresponding to each option included in the analysis. The cumulative distributions, in turn, form the basis of comparison among considered options, most generally in terms of expected values and rules of stochastic dominance. Comprehensive yet readable introductions to risk analysis, relevant probability and sampling concepts, and pertinent measures of comparison are found in Holloway (1979) and Clemen (1996).

Employed properly, risk analysis addresses the bulk of limitations associated with sensitivity analysis. First, model variables are more completely described through the introduction of probabilities (i.e., random variables replace deterministic variables). Second, since sampling techniques implicitly and repeatedly “combine” a random assortment of likely values, the cumulative distribution assigned to each option included in the analysis represents the combined influence of all model variables on model outcome. Finally, while a dominant alternative may still fail to emerge, the cumulative distribution assigned to each option provides a clearer and more descriptive picture of associated outcomes for purposes of comparison.

Figure 3 extends Fig. 2 in that it adds a risk analysis component. Despite the introduction of risk analysis, however, note that sensitivity analysis remains a part of any well-ordered LCC method. The reason for this is strictly pragmatic. Obtaining probabilistic data for model variables can be a costly and time-consuming process (even where expert engineering judgement is employed to efficiently extract useful information). Hence, it is best to focus data gathering activities around model variables that hold significant sway over LCC results and rankings. In the experience of the authors, it is typically the case that sensitivity analysis reveals only a handful of model variables that exert substantive influence on LCC results and rankings (reflecting a “90/10 rule” where, in practice, 90% of model variability is explained by 10% of model variables). Clearly, identifying these key variables provides focus to subsequent data gathering activities needed to support risk analysis. Note that the key linkage of sensitivity and risk analyses is fundamental to the practice of decision analysis (Matheson and Howard 1968).

Not surprisingly, a number of researchers recommend the inclusion of risk analysis within well-ordered LCC investigations. From a broadly methodological standpoint, relevant literature includes Blanchard (1979, 1999), Gupta (1983), Feller (1986), Womer (1983), Fabrycky and Blanchard (1991), FHWA (1998), ASTM (2002), and Hawk (2003). A good example of risk analysis employed to evaluate innovative infrastructure designs is found in Ehlen (1999). In fact, Ehlen’s approach is embedded in the software technology BridgeLCC 2.0 available free of charge through the National Institute of Standards and Technology. A generic example of

risk analysis employed in a LCC investigation involving conventional and high performance bridge designs may be found in Appendix C of Hawk (2003). Hawk’s approach is reflected in a bridge life cycle cost analysis software package available free of charge through the National Cooperative Highway Research Program.

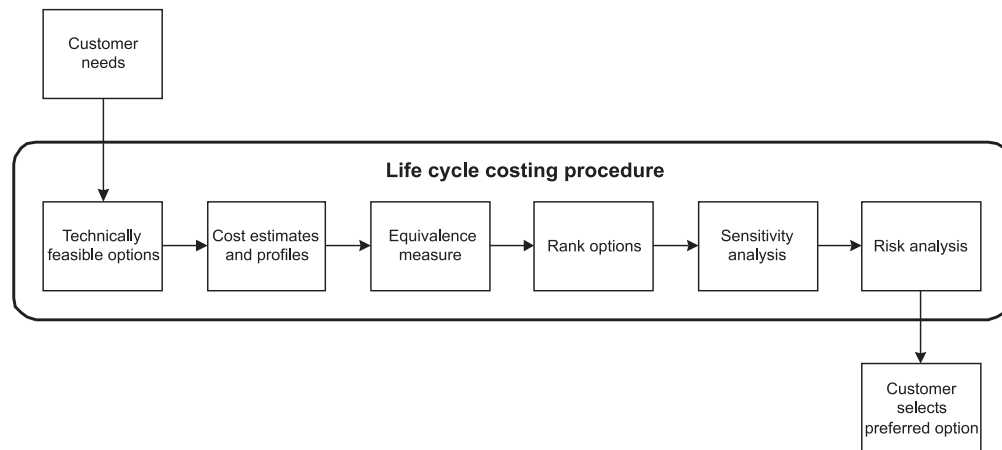
It should be noted that risk analysis often involves a reassessment of considered options in the context of risk preference (Raiffa 1968; Howard 1970). Although adequate treatment of this subject is beyond the scope of this paper, its role in a LCC process is contingent on the attitudes of decision makers towards risk. Where owners are risk neutral, comparison of alternatives may proceed on the basis of expected monetary value alone. However, where attitudes are risk averse or risk seeking, the probabilistic distribution of life cycle costs is translated to some measure of utility. The measure of utility assigned to each alternative then forms the basis for ranking. For the purposes of this discussion paper, however, attention is limited to the case of risk neutrality – a common and frequently defensible practice where public infrastructure investment is concerned. With regards to this issue, Townley (1998) includes pertinent and readable discussions involving individual versus collective risk and the Arrow-Lind theorem.

3.3.1. Risk and multi-attribute decision analysis

Where risk analysis fails to identify a dominant alternative in the eyes of the customer, a number of authors recommend the application of multi-attribute decision analysis (MADA) to reach a final decision (Keeney and Raiffa 1993; Clemen 1996). The authors include: French (1983) and Tao et al. (1994), who illustrate MADA in the context of reliability-based structural design and maintenance optimization; Ehlen and Marshall (1996); Hastak and Halpin (2000), who employ a related analytical hierarchy process (AHP); and ASTM (2002).

In the context of LCC investigations, the first step in a MADA approach involves the selection of attributes deemed pertinent to life cycle engineering decisions (e.g., performance attributes of considered options, initial investment costs, on-going maintenance efforts, traffic delay during repair, etc.). The attributes are subsequently “scored” and “weighted” to derive a quantitative utility index for each design option. Finally, considered design options are ranked according to corresponding utility indices.

The authors of this paper discourage a MADA approach to LCC for three reasons. First, where properly described, the customer needs that drive a LCC process define the performance and other attributes required of considered design options. Hence, any technically feasible design options included within a LCC exercise must meet the specified attribute targets. Revisiting attributes during a MADA–LCC process may therefore muddle the nature of the predetermined target, leading potentially to a comparison of “apples and oranges”. Note that a consistent and meaningful definition of LCC in this regards may be found in Part II of Hawk (2003). Second, the life cycle engineering process involves dollar-valued expenditure, not “utility points”. Hence, the genuine relevance of various attributes, each boasting a unique scoring mechanism, becomes similarly confused. The

Fig. 3. Life cycle costing with sensitivity and risk analyses.

danger, of course, is that “good money” is spent chasing somewhat arbitrary attributes. Finally, as the experience of the authors suggest, MADA exercises are subject to the distorting preferences of decision makers, leading to model constructs and results that reflect a bias and incentive structure running counter to sound economic rationale. In contrast, while decisionmakers may still override the results of a money-metric LCC process, they cannot argue the decision reached is supported by credible economics.

3.4. State-of-the-art: an iterative approach to life cycle costing

To this point, the methods of LCC reviewed reflect an inherently linear process; each step in the process leads logically and inevitably to the selection of a preferred design option by the customer. However, while the ordered introduction and application of sensitivity and risk analyses address inherent uncertainty in a sensible way, the issue of complexity is not adequately addressed in the linear process advocated.

Whether the engineering design process involves new building, reconstruction, maintenance policies, logistic and support plans, phase-out activities, or some combination of these, the decisions involved in determining life cycle cost-minimizing designs reflect a complex interplay of many voices and factors. The systematic incorporation of feedback in the design process itself reflects this complexity – iterative “communication” among engineers and pertinent design factors permits convergence on a relatively “good” design from the customer’s standpoint. In this context, is it not natural to incorporate feedback within LCC investigations? Clearly it is. Since LCC is intended to facilitate the selection of “good” designs, it is only logical to incorporate feedback within any reasoned LCC exercise.

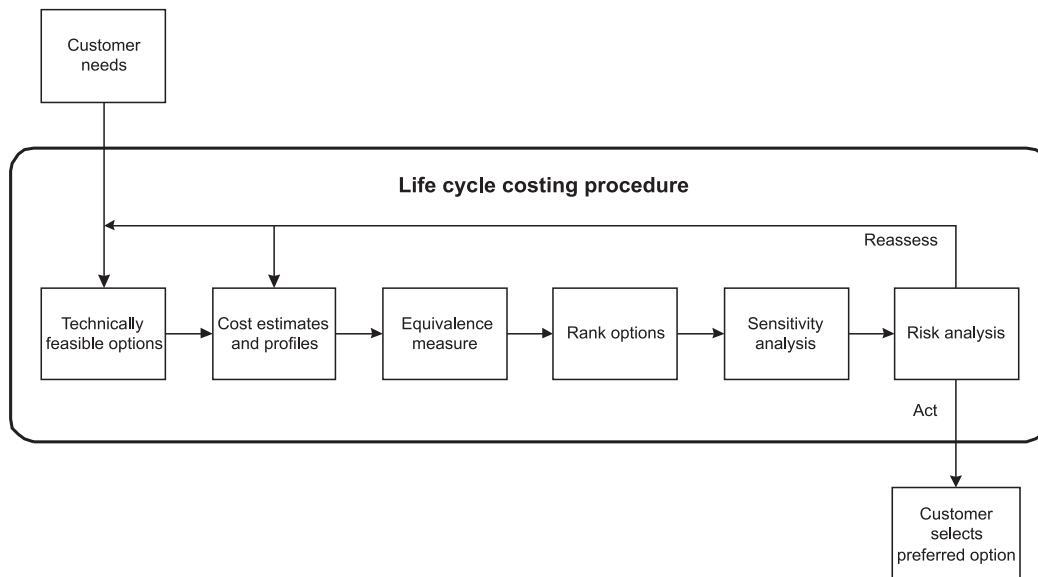
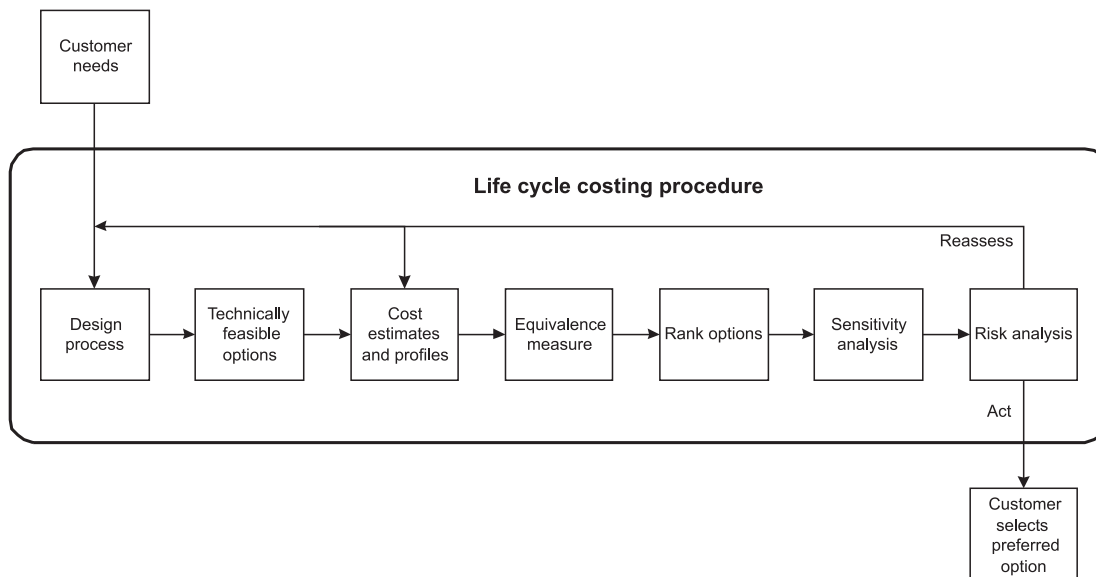
The incorporation of feedback within the LCC process reflects a key insight of cybernetics: feedback supplies valuable information to successive iterations of processes designed to converge on good (if not optimal) solutions. Indeed, the very term “cybernetics” is derived from the Greek word for “steersman” – referring to feedback mechanisms used to control steering of large marine vessels and thereby provide superior directional control under varying environmental conditions (Wiener 1948). Not surprisingly, feedback

can be employed to great advantage in a pragmatic method of LCC designed to adequately address the inherent uncertainty and complexity characteristic of LCC investigations.

Figure 4 reflects the iterative process advocated by Fabrycky and Blanchard (1991). As shown, the process emulates Fig. 3, excepting the role of feedback used to successively refine the analytical conduct of the LCC exercise. Following risk analysis, an important question rests with the analyst and customer: do the LCC results support a definitive decision (i.e., select and implement a preferred design option), or is it best to reiterate and thereby refine the analytical process? If the decision is “act”, then the customer simply selects a definitive option and proceeds. If the decision is “reassess”, then the customer advocates a successive round of LCC, where engineers revisit considered alternatives and (or) cost estimates to refine the LCC results ultimately derived.

The advantage of an iterative approach to LCC is more clearly revealed in the context of the overall design process—a practice that embeds feedback as a matter of course. Figure 5 reflects in a straightforward way the integration of the design process within a LCC investigation (a more detailed overview is found in the works of Blanchard and Fabrycky (1990). In this case, feedback from previous iterations informs each stage of the design process (conceptual, preliminary, and detailed), to successively refine the considered feasible design options and associated life cycle implications and costs. In this context, LCC can be used to first eliminate conceptual designs that clearly result in higher costs. In subsequent iterations, LCC is used to facilitate both preliminary and detailed design stages that gradually converge on a definitive design where all phases of the life cycle have been explicitly considered to a reasonable degree.

In the opinion of the authors, the iterative LCC method proposed by Blanchard and Fabrycky (1990) represents the current state of the art. First, it addresses uncertainty through explicit inclusion of sensitivity and risk analyses. Second, it acknowledges and addresses the complexity of the design process per se through the explicit inclusion of feedback. Finally, the chosen arrangement of analyses and iteration supports a pragmatic and sensible approach to LCC that permits gradual convergence to a credible and well-specified

Fig. 4. Iterative life cycle costing method.**Fig. 5.** State-of-the-art life cycle costing method.

design, regardless of the design activity pursued by the engineer (i.e., new building, rehabilitation, on-going management efforts, etc.). In this context, the proposed method sticks to the original intent of life cycle engineering and costing – to support the engineer striving to develop a design that “best” satisfies customer needs.

3.4.1. Strengths and limitations of state-of-the-art life cycle costing method

The state-of-the-art iterative process of LCC reflected in Fig. 5 is both pragmatic and flexible. Underlying the process, however, are two important assumptions, one of which limits the efficacy of the approach and therefore provides room for improvement. First, the iterative approach suggests subjective judgement supports LCC efforts. Second, the pro-

cess implicitly assumes the cost of successive iteration is zero, a clearly untenable assumption.

Regardless of the analytical wizardry employed, the process of design relies on the subjective judgement of experienced engineers (Breipohl 1974; McNichols 1979). This is reflected in the design literature where the judgement of experienced engineers naturally infuses the iterative process of design. In this regards, for instance, Asimow (1962) includes excellent discussion regarding a philosophy of engineering design. While laws of science, empirical data, mathematical models, optimization techniques, etc., support the design of product and infrastructure systems, the ultimate output of any thoughtful design process reflects to some degree the collective experience, and therefore subjective judgement, of engineers involved in the process.

Like the design process it properly accompanies, LCC analysis is never entirely objective. For instance, a fundamental task of any LCC investigation is to forecast a stream of costs over an intended service life for each product or infrastructure design option under consideration. Not only is this task plagued with uncertainty and complexity, it is also inherently subjective. Who, for instance, can forecast traffic levels and composition over a given bridge 25 years hence in the absence of judgements regarding the scope, accuracy, and usefulness of any “objective” forecasting procedures employed? What analytical process can perfectly capture the uncertainties surrounding construction scheduling and costs of considered bridge deck designs? Where might we find life cycle performance models that identically emulate the reliability and durability of bridge structures over time and across repair policies to facilitate accurate – indeed optimized – maintenance cost forecasts? Clearly, regardless of the analytical horsepower employed to derive the requisite stream of costs (and associated probabilities), the subjective judgement of experienced engineers will influence all tasks necessary in the conduct of the LCC investigation.

Yet by its very nature, subjective judgement sets limits on the conduct and accuracy of analytical exercises. Whether efforts involve formation of alternatives, data gathering, model construction, interpretation of results, etc., the exercise of subjective judgement establishes the point at which “enough is enough”. The question is, when is this point reached?

In the context of LCC investigations, “enough is enough” when a definitive decision is reached by the customer. For example, in the process of selecting among a handful of preliminary bridge deck designs, the analysis ends when a favoured option is selected. In evaluating the designs, however, the engineer must exercise judgement regarding the scope and intensity of analytical activities undertaken. If the degree of effort undertaken leads to a definitive decision, the LCC process ends. Otherwise, the engineer must exercise judgement yet again to refine and revisit the scope and intensity of a subsequent analytical iteration. As reflected in the work of Blanchard and Fabrycky (1990) (and expressed most fully in Fig. 5), the iterative exercise of subjective judgement continues until a definitive decision is reached. At that point, ideally, the “limits” imposed by the subjective judgement of the engineer are the limits *just* required to support a definitive selection among considered design options. So it is that subjective judgement and iteration march naturally together during the conduct of LCC investigations to support definitive and defensible decisions by the customer served.

Unfortunately, the iterative approach advocated by Blanchard and Fabrycky (1990) implicitly presumes that the cost of subsequent iteration and analytical refinement is zero. Clearly, this cannot be the case; otherwise, “enough would never be enough” and iteration would continue ad infinitum. At some point, design engineers and (or) customers decide to end the iterative process, select a preferred option, and move forward – in effect concluding that the cost of subsequent iteration exceeds any concomitant value that might be obtained. The question is, at what point does the cost of subsequent iteration exceed any value that might be

obtained? While the iterative approach to LCC advocated by Blanchard and Fabrycky is both pragmatic and flexible, it simply cannot address this question.

3.4.2. Value of information and life cycle costing

To adequately address the question posed above, the iterative LCC process advocated by Blanchard and Fabrycky (1990) must be extended to include an explicit value of information (VOI) component (indeed, the need for VOI-like computations within an iterative engineering design process was identified by Asimow (1942) over 40 years ago). In the context of LCC investigations, a VOI component provides two important advantages. First, it determines an upper-bound, quantitative estimate of potential life cycle cost savings attributable to subsequent iterations of the analytical process. Since each iteration of the LCC process is a costly endeavour, requiring the time and efforts of costly labour and other inputs to gather data, refine computational procedures, re-run models, etc., it is worthwhile comparing these costs with any value that might be obtained. Where the likely value of additional iteration clearly exceeds the expected cost, it is worthwhile initiating a subsequent round of LCC analysis. However, where the expected cost of additional information exceeds any value that might be obtained, it is best to end the analytical process and simply choose among considered design options.

Second, incorporating a VOI component within the LCC process permits a detailed segregation of information requirements at each iteration according to relative value. For example, probabilistic comparison of alternative bridge deck designs may include stochastic characterization of up-front construction costs, on-going maintenance and repair costs, delay-related user costs, expected service life, etc. Should risk analysis fail to identify a clearly dominant alternative in the eyes of the infrastructure owner, VOI computations can be employed to determine where additional analytical activities are best targeted. In this regards, VOI computations will first establish the potential value of seeking better construction cost estimates, maintenance and repair cost estimates, service life estimates, corresponding computational procedures, and so on. Next, the value-based ranking of such improvements can be compared with associated cost estimates to specifically target the efforts of engineers involved in the overall LCC investigation. This ensures that inherently costly efforts are directed towards the most valuable areas of investigation during each iteration of the LCC process.

Since LCC investigations can become quite complex and therefore costly, it is clearly important to guide the efforts of participating engineers in productive directions. While the iterative LCC method advocated by Blanchard and Fabrycky (1990) satisfies this objective to some degree (through a systematic integration of sensitivity and risk analyses), the absence of a VOI component can promote wasteful analytical activities in the context of the overall LCC process (e.g., the common blight of excessive data gathering). For this reason, the authors advocate the incorporation of a VOI component within the iterative LCC process illustrated in Fig. 5.

Estimating VOI involves the application of concepts and computational techniques developed in the field of statistical decision theory (Raiffa and Schlaifer 1961; Howard 1966;

Pratt et al. 1996). Statistical decision theory combines elements of decision theory and Bayesian statistics, a field of statistics based on a subjective view of probability assessment (Dyckman et al. 1969; Holloway 1979) – employed to support iterative decision-making processes in the face of uncertainty. To adequately describe the manner in which statistical decision theory is employed within the iterative LCC process is, however, a non trivial exercise. For this reason, description is postponed to a forthcoming paper outlining a proposed method of LCC and illustrating its application on a real-world test case.

4. Summary and conclusions

In this paper, LCC literature was surveyed from the standpoint of methodological content. This supported the development of a classification scheme with which to organize and scrutinize the practice of LCC as it pertains, most especially, to complex civil infrastructure systems embracing promising, innovative technologies. In due course, this helped identify a broadly applicable method of LCC that the authors believe represents the current state of the art.

In this regards, the authors believe the iterative LCC method advocated in the works of Blanchard and Fabrycky (1990) (Fig. 5) stands as the current state-of-the-art method for LCC investigations. Both pragmatic and flexible, the iterative method advanced neatly and logically handles both the complexity and uncertainty inherent of any but the most trivial LCC studies. Moreover, by explicitly incorporating features common to the engineering design process, the iterative LCC method of Blanchard and Fabrycky best satisfies the original intent of life cycle engineering and costing – to facilitate, in a sensible and pragmatic way, design processes that explicitly acknowledge and account for corresponding life cycle implications. By following through this process, both engineers and, most importantly, their customers can be reasonably assured that the design ultimately selected and pursued will deliver the required performance at minimum life cycle cost.

While pragmatic, flexible, and defensible, however, the state-of-the-art iterative LCC method lacks a VOI component necessary to efficiently guide the analytical activities of engineers involved in LCC exercises. An iterative approach to LCC implicitly acknowledges an important feature of any LCC study: the data and computational procedures employed to reach decisions rest ultimately on subjective judgement, and where subjective judgement is involved, iterative refinement naturally accompanies the LCC process. Since iteration implies effort and cost, it is important to estimate the potential value additional iteration that might supply and efficiently “target” corresponding analytical activities. Value of information computations provide such guidance. For this reason, the authors of this paper advocate the incorporation of a VOI component within the iterative LCC process of Blanchard and Fabrycky (1990).

Although a subject beyond the scope of this literature review, the theoretical grounds and practical means supporting VOI calculations are well-founded and indeed routinely employed within the field of decision analysis (Matheson and Howard 1968; Raiffa 1968; Holloway 1979; Clemen 1996). In a forthcoming paper, the authors will review and demon-

strate the means by which value of information calculations can be incorporated within an iterative LCC process to address the needs of ISIS Canada and others in the civil engineering community.

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