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PROBABILISTIC DESIGN FRAMEWORK FOR SUSTAINABLE REPAIR AND REHABILITATION OF CIVIL INFRASTRUCTURE



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Abstract

This paper presents a probabilistic-based framework for the design of civil infrastructure repair and rehabilitation to achieve targeted improvements in sustainability indicators. The framework consists of two types of models: (i) service life prediction models combining one or several deterioration mechanisms with a suite of limit states and (ii) life cycle assessment (LCA) models for measuring the impact of a given repair, rehabilitation, or strengthening. The first type of model estimates the time to the first repair (from the time of initial construction) and – given the structural condition after a repair – the time to any subsequent repair. The second type of model estimates the impact of the chosen repair or rehabilitation based on a process-based LCA of individual repair activities. Both models (service life or LCA) are formulated stochastically so that the time to repair and total impact are described by a probability density function. This leads to a fully probabilistic calculation of accrued cumulative impacts (which can be annualized) throughout the service life of a structure from initial construction up to the time of functional obsolescence (end of life). These are then compared to design targets taken from policy goals such as the Intergovernmental Panel on Climate Change's 4th Assessment Report (IPCC AR4).

Keywords: Civil infrastructure, sustainable, probabilistic design, repair, life cycle assessment

1 Introduction

In 1992, the UN Framework Convention on Climate Change was adopted to "stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate" and scientists recommended capping atmospheric CO_2 concentrations below 550ppm (IPCC, 1992). For large societal systems, such as transportation and energy production, many strategies have been proposed to meet these goals in the next 50 years (Pacala and Socolow, 2004). Comprising a major part of these strategies, civil infrastructure lies at the nexus of two major sustainability challenges; emissions from transportation and construction materials production. Transportation comprises 30% of US CO_2 emissions (US EPA, 2008), while portland cement production emits approximately 5% of global anthropogenic CO_2 emissions (van Oss, 2003). Using current materials and construction processes for infrastructure repair and renewal, it is unlikely we will meet aggressive greenhouse gas reduction goals necessary for atmospheric stabilization.

Responding to these challenges, the design and construction of civil infrastructure that is more environmentally, socially, and economically responsible over its full life cycle from extraction of raw construction materials to end of life is a new goal for infrastructure designers worldwide. But the lack of quantitative targets for "sustainable" design, quantitative metrics for measurement and comparison of infrastructure designs, and a probabilistic-based design approach that is translatable to engineering practice expectations of rational design procedures that manage uncertainty in infrastructure design, construction, and operation, remains a large barrier to more sustainable civil infrastructure systems. Such probabilistic approaches are the hallmark of current civil engineering design theories (e.g. Eurocode 2, *etc.*).

This paper presents a new framework for the design,construction and operation of more sustainable civil infrastructure using probabilistic-based approaches that allow for rational decision-making among green design alternatives based on their econoimc costs, the liklihood that they will quantifiably reduce environmental impacts as compared to the status quo, and the collective risk borne by not meeting future emission reduction targets.

2 Probabilistic Sustainability Design Using Integrated Life Cycle Assessment (LCA) and Infrastructure Service Life Models

Quantification of sustainability metrics using integrated life cycle assessment (LCA) approaches and service life models is the foundation of the proposed framework. This requires probabilistic knowledge of (i) what construction and repair and rehabilitation events will take place (along with their environmental impacts) over the structure life cycle and (ii) when these events will happen. Thus, an integrated life cycle assessment and infrastructure service life model is proposed. The dual nature of the framework comprises both physical modeling of material and structural condition and conceptual modeling of life cycle performance. The highly connected nature of these two components must also be pointed out, such that the design and construction of an individual repair heavily influences many parts of the life cycle impact model.

The proposed framework is based on a limit-state governed, probabilistic approach for design and evaluation of sustainable construction, repair, and rehabilitation of civil infrastructure. This begins with measurement of the cumulative environmental impact of construction, repair, and rehabilitation activities up to functional obsolescence (end of life). This is shown in **Fig. 1a**.

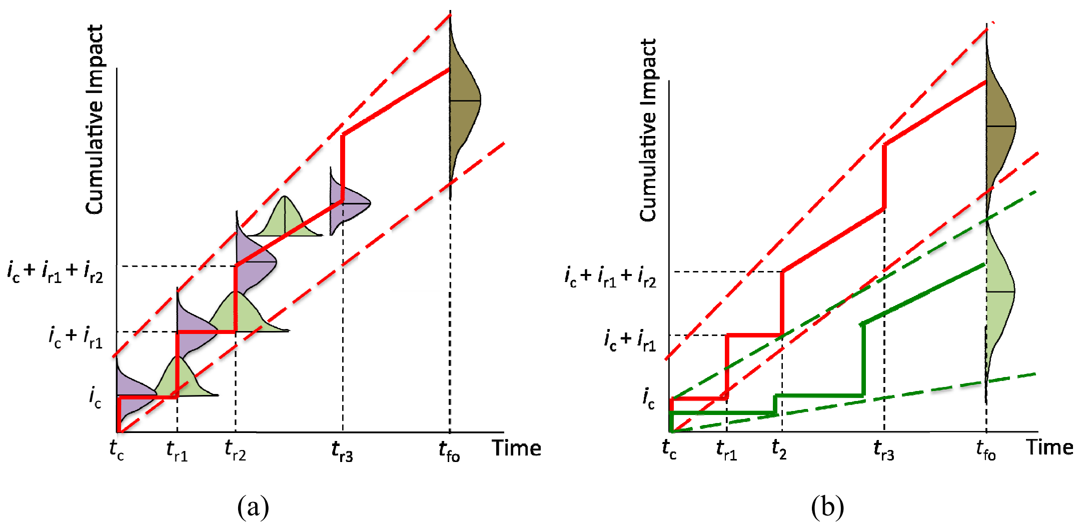

Fig. 1 (a) Cumulative sustainability impact from initial construction to functional obsolescence and (b) comparison of probabilistic envelopes for initial construction (t_c) to functional obsolescence (t_{fo}) for two alternative construction/repair technologies and associated timelines

As seen, the time at which any repair is made (t_{rj}) is probabilistically characterized based on reaching the end of a repair service life limit state analogous to that defined by the *fib* Model Code for durability design of concrete infrastructure (e.g. the probability of load exceeding capacity for the structure reaches an unacceptable level) (*fib*, 2006). The distribution of time of repair, t_{rj}, is shown as quasi-normal for for illustrative purposes only. The probabilistic time between repairs ($t_{rj+1} - t_{rj}$) is based on the chosen construction/repair strategy, the quality of the execution, the variable nature of exposure and load conditions, *etc*.

In addition to the probabilistic determination of the time of repairs, the amount of impact associated with each repair is also probabilistic in nature. This is further shown in **Fig. 1a**. The amount of impact associated with a given construction or repair event, i_c or i_{rj}, can vary due to uncertainty in construction processes actually used, uncertainty in the supply chain of repair materials, uncertainty in the effects on infrastructure users (e.g. how many automobiles are actually disrupted by the construction), *etc*. Combining the probabilistic models for both repair timeline (t_{rj}) and amount of impact (i_c, i_{rj}), a probabilistic envelope is constructed for the entire infrastructure service life from the time of initial construction (t_c) up to the time of functional obsolescence (t_{fo}). Based on this envelope (shown in **Fig. 1a** using dashes), an aggregated probabilistic assessment for cumulative impact at any time, t, for the structure can be determined.

However, the limit state by which “sustainability” is achieved has not yet been identified. At this point, only cumulative impacts from initial construction up to the functional obsolescence have been probabilistically modeled. The definition of sustainable development can be very broad and highly subjective. Therefore "sustainable development" is charaterized by those projects which reduce environmental impact midpoint indicators to meet specified by policy targets, such as global warming potential (CO_2 equivalents) targets proposed by the Intergovernmental Panel on Climate Change (IPCC, 2007). In this regard, the decision of “what is a sustainable” is left to policymakers while the measurement of impacts and design for reduction is left to engineers and planners.

As an example, to achieve a stabilized atmospheric CO_2-eq concentration of 490 to 535ppm (IPCC Scenario II), a 30% to 60% reduction in annual CO_2-eq emissions is needed by Year 2050 (Year 2000 baseline) (IPCC, 2007). At these emission levels, a global average in temperature increase of 2.4°C to 2.8°C is expected along with sea level rise (thermal expansion) of 0.5m to 1.7m. With such reductions in mind, an alternative repair and rehabilitation scenario can be designed to improve upon the *status quo*. Such an alternative comparison is shown in **Fig. 1b**.

In this way, the reductions using an alternative or new construction technology versus the *status quo* can be estimated at any time in the future and associated with a level of confidence for actually realizing future reductions (or the probability of failing to meet reduction goals). Such a probability of failure would be computed similar to that shown in Equation 1.

$$P_f = P\left(\frac{I_{old}(t_G) - I_{new}(t_G)}{I_{old}(t_G)} - G(t_G) \geq 0\right) \tag{1}$$

where P_f is the probability of not meeting the target reduction in environmental midpoint indicator, $I_{old}(t_G)$ is the cumulative impact of the *status quo* construction/repair strategy, $I_{new}(t_G)$ is the cumulative impact of the alternative construction/repair strategy, G is the target (or goal) reduction in environmental midpoint indicators recommended by policy, and t_G is the time in the future at which the goal reduction should be achieved. Using this framework, engineers are encouraged to achieve reduction targets at lowest economic cost, provided that the level of confidence that future reduction targets are met remains constant among alternatives. Tradeoffs between confidence levels at which a given target is met and the cost to achieve that confidence can also be considered.

3 Conclusions

Presented herein is a new framework for integrating probabilistic life cycle assessment techniques, probabilistic durability design and service life estimation of infrastructure, and policy-based targets for achieving broad environmental sustainability midpoint indicators such as global warming potential. While potentially years from implementation, this approach provides a rational method to design for sustainability that allows infrastructure engineers to evaluate the tradeoffs between implementing *status quo* construction technologies and proposed alternatives. Additionally, engineers can evaluate the level of confidence (or probability of failure) at which sustainability goals will be met in the future, along with the cost tradeoffs for meeting those goals at a given level of certainty.

Prior to the implementation of this design framework however, a great deal of fundamental research must be carried out. Some of this research includes (1) improving probabilistic service life, environmental load and deterioration models for civil infrastructure, (2) improving probabilistic life cycle assessment models for civil infrastructure construction and repair activities, (3) developing civil infrastructure design, construction techniques, and operation strategies that effective and reliably reduce life cycle impacts as measured through probabilistic life cycle assessment, (4) development of design codes and provisions that incorporate probabilistic sustainability assessments into practice, and (5) creation of rational targets for environmental sustainability midpoint indicators that are science-driven rather than policy/economics-driven.

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