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Life-365 Service Life Prediction Model™ Version 2.0

Widely used software helps assess uncertainties in concrete service life and life-cycle costs

BY MARK A. EHLEN, MICHAEL D.A. THOMAS, AND EVAN C. BENTZ

Ten years ago, members of the concrete industry used a consensus approach to begin developing a tool to estimate the service life and life-cycle costs of concrete structures subject to exposure conditions that cause corrosion of reinforcing steel. The origins of this approach can be traced back to 1998, when the ACI Strategic Development Council (SDC) publicly identified the need for a standard concrete service life model and associated life-cycle costing analysis model. Ultimately, a consortium of industry representatives was formed under the SDC including Master Builders, Inc. (now BASF Construction Chemicals); Grace Construction Products; and the Silica Fume Association. This consortium funded M.D.A. Thomas and E.C. Bentz to develop a state-of-the-art life-cycle prediction model and released it in 2001 as the Life-365 Service Life Prediction Model™.

Since then, Life-365 has been used to evaluate concrete mixture proportions and corrosion protection strategies that increase service life and reduce life-cycle costs. This version of the software, however, did not address uncertainties in the concrete material properties, structure geometry, boundary conditions, and project costs—particularly those for high-performance concrete (HPC) mixtures.

To address these and other concerns, a second consortium of industry representatives was formed. It consisted of representatives from the Concrete Corrosion Inhibitors Association, the National Ready Mixed Concrete Association, the Slag Cement Association, and the Silica Fume Association. The second consortium funded E.C. Bentz and M.A. Ehlen to develop Life-365 v2.0 and introduced it to the engineering and construction industry in 2008.

BASIC LIFE-365 CONCEPTS

In the Life-365 model, service life is based on the assumption that corrosion of reinforcing steel resulting from chloride ingress is the primary mode of degradation. In turn, life-cycle costs are based on the selected protection strategies and estimated construction, mitigation, and repair costs.[1] The model is useful for marine and other structures exposed to external sources of chlorides, like parking garages, bridge decks, and transportation infrastructure.

To complete a Life-365 analysis, the model:

- Calculates an estimated time to initiation of reinforcement corrosion;
- Calculates estimates of the costs of initial construction, optional barriers, and repairs to deteriorated portions over the design service life;
- Computes the life-cycle costs, expressed on a present-worth basis; and
- Calculates how sensitive these service life and life-cycle cost results are to variations in underlying assumptions.

The user must provide inputs that include:

- Type and dimensions of concrete structural members;
- Geographic location of the structure;
- Depth of clear concrete cover to the reinforcing steel;
- Details of each alternative corrosion protection strategy (water-cementitious materials ratio [*w/cm*], supplementary cementitious materials [SCMs], corrosion inhibitors, barriers applied to the surface, and type of reinforcing steel);
- Costs of the concrete constituent materials (mixture ingredients, reinforcement, corrosion protection strategies); and

- Details and costs of the concrete repair strategy (frequency of repairs, average percent repaired, cost per unit area of repair, and inflation and discount rates).

Life-365 provides default values for many of the required inputs, but it is strongly suggested that the user update these values based on the exposure conditions and economic factors pertinent to the project at hand.

Concrete service life prediction

Life-365 uses the general definition of service life of reinforced concrete as the sum of the time to initiation of corrosion and the propagation time required for corroding steel to cause sufficient damage to require repair. Life-365 calculates the initiation period using one- or two-dimensional Fickian diffusion modeling. Therefore, saturated uncracked concrete is modeled. The default propagation time is 6 years for uncoated and stainless steels and 20 years for epoxy-coated steel.

Life-365 models a number of corrosion protection strategies including low *w/cm*, the use of SCMs, epoxy-coated and stainless steel reinforcement, corrosion inhibitors, and membranes and sealers. It also compares up to six alternative corrosion protection strategies, calculates service life and life-cycle costs, and generates summary reports.

Life-cycle costs

Life-365 v2.0 follows ASTM E917-05, "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems,"[2] to estimate life-cycle costs. The design life is initially set at 75 years and the values for inflation and discount rates are those established by U.S. government agencies to compute the life-cycle costs of federal projects. The user, however, can change these default values.

UPDATES IN V2.0

Life-365 v2.0 can also evaluate uncertainties about the underlying assumptions for concrete mixture performance and costs. First, the model augments its deterministic estimated values of service life and life-cycle cost with probabilistic ranges of corrosion initiation period, which affects service life, repair costs, and—ultimately—life-cycle costs (it does not, however, calculate uncertainties in propagation period). Second, it calculates how sensitive the life-cycle cost results are to potential changes in service life and concrete, barrier, and repair costs. Finally, it provides a new user-friendly interface that allows rapid calculation of these deterministic and probabilistic values, as well as the effects of a broader set of uncertainties.

Initiation period uncertainties

Using a stochastic approach,[3] Life-365 v2.0 estimates the distribution of possible service lives for a given concrete mixture and corrosion protection strategy. Figure 1(a) illustrates the probability distribution for the service life of two concrete mixtures. The vertical dashed line under each curve represents the deterministic, single-point estimate of service life calculated by Life-365.

The probability distribution in Fig. 1(a) illustrates the basic differences between conventional concrete (in red) and HPC (in blue). The conventional Base Case concrete has a narrow distribution, a higher peak, and a lower mean service life of 16 years. The HPC Alternative 1 has a broader distribution and a lower peak but a higher mean service life of 68 years. The two curves together suggest that while Alternative 1 has a longer service life in a deterministic sense, there is more uncertainty in the prediction of this service life.

To determine whether Alternative 1 also has a longer service life in a probabilistic sense, we need to look at the Life-365 service life cumulative density function (CDF), shown in Fig. 1(b). The *y* coordinate of each point on a line is the probability that the concrete will have a

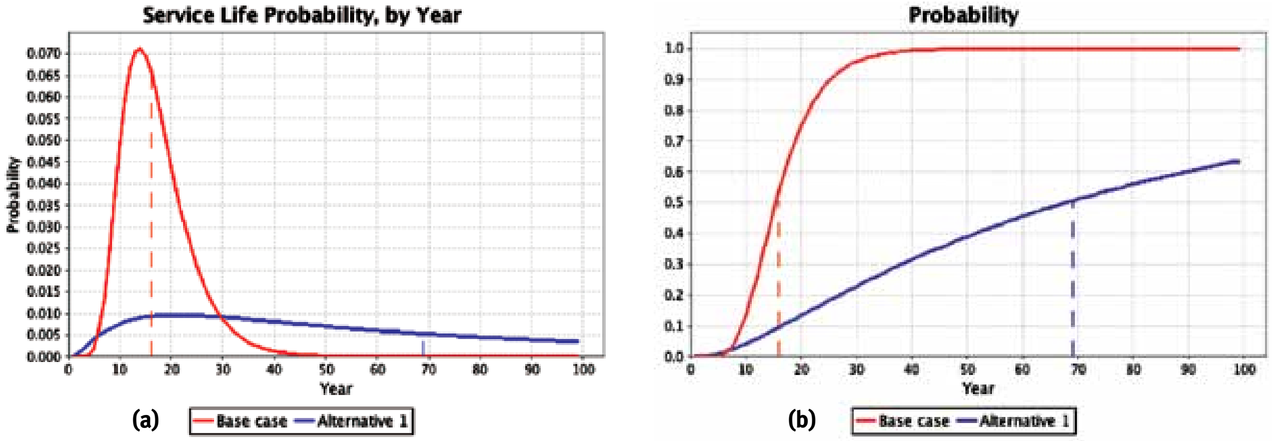

Fig. 1: Service life probability and cumulative probability distributions

service life less than or equal to the number of years given on the *x*-axis. If one alternative's CDF line is below the CDF lines of all other alternatives (as Alternative 1 does for nearly all years), then this alternative has the highest probability of having the longest service life regardless of the particular year. Said differently, Alternative 1 has the longest service life in a probabilistic sense.

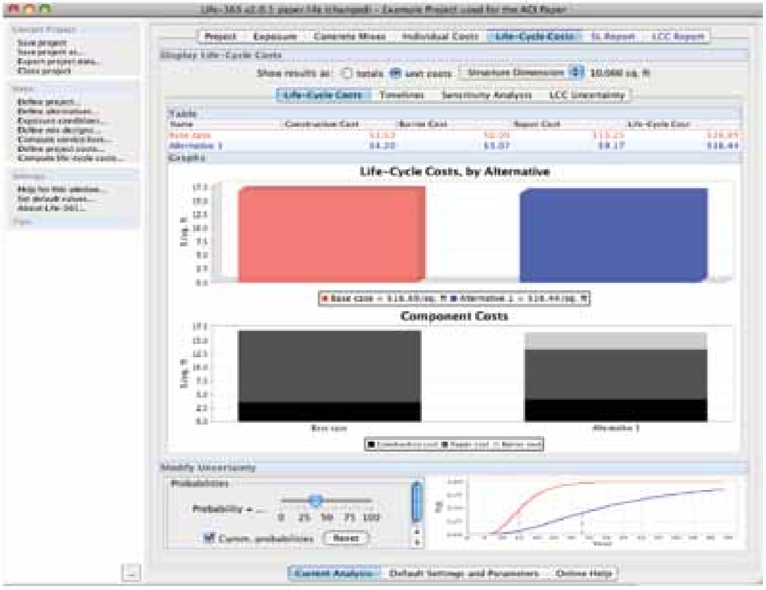

Fig. 2: Service life modifier panel in Life-365

To determine whether this uncertainty in service life affects which alternative is cost effective from a life-cycle cost perspective, Life-365 v2.0 provides the Service Life Modifier panel shown at the bottom of Fig. 2. The panel allows the user to manually change the probability of corrosion having occurred that the user is willing to accept at the time of corrosion initiation. Thus, for projects where owners are particularly concerned about visible signs of corrosion, for example, a lower probability could be selected, and repairs would be predicted to be needed earlier. The option to change the desired probability also helps the user evaluate whether the optimal repair strategy is sensitive to the expected natural variability of the predicted time to corrosion initiation. By testing across all possible service life probabilities with the probability slider bar, the user can determine whether the most effective alternative for life-cycle cost remains so under these potential changes in predicted service life. Note that the propagation period and the repair strategy itself are not determined probabilistically.

Life-cycle costing with sensitivity analysis

Life-365 v2.0 allows the user to determine if the life-cycle cost of a concrete mixture option is sensitive to changes in one or more of the underlying construction, barrier, repair, or economic parameters. The user selects a parameter that impacts life-cycle cost and a percent variation in this cost. Life-365 v2.0 then computes the life-cycle costs of each alternative as this parameter is varied and displays it in a graph, allowing the user to see if and under what conditions the more cost-effective alternative changes.

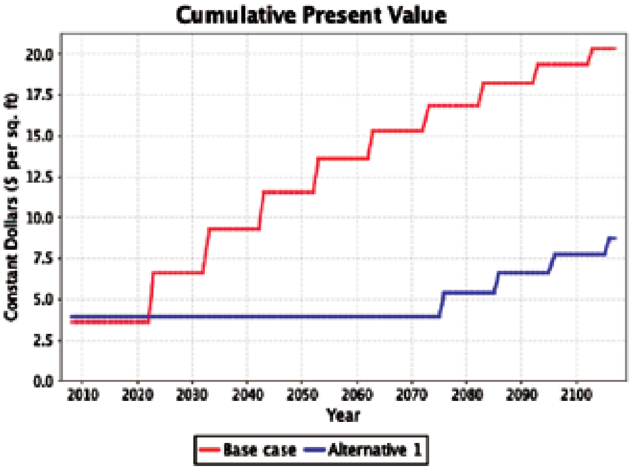

Fig. 3: Life-cycle costs of two concrete mixtures considered for use in a parking garage in New York, NY

EXAMPLE LIFE-365 V2.0 ANALYSIS

The importance of these new features is illustrated by an analysis of two concrete mixtures considered for use in the construction of a reinforced concrete slab for a parking garage in New York, NY. In this example, both mixtures use concrete with a *w/cm* of 0.40 and uncoated reinforcement with a clear concrete cover of 2.5 in. (65 mm). The Base Case uses a mixture containing portland cement as the only cementitious material. Alternative 1 uses 20% slag cement and 4% silica fume by mass of the cementitious materials and a corrosion-inhibiting admixture at a dosage of 2 gal./yd^3 (10 L/m^3). The model uses a propagation time of 6 years for both mixtures. At the end of the service life, an estimated 10% of the parking garage slab is repaired every 10 years for the remainder of the 100-year design life.

Deterministic costs

The Base Case mixture has an estimated service life of 16 years, and Alternative 1 has a service life of 68 years. Using concrete cost and other economic values input by the user, Fig. 3 shows the life-cycle costs of each alternative in terms of total costs, component costs (construction and repair), and costs over time.

The deterministic analysis thus far suggests that Alternative 1 is preferred based on its predicted life-cycle cost. It has higher initial construction cost due to the mixture composition, but it has lower repair cost due to the delayed time when corrosion repairs are needed and fewer repair events. While the differences in service life and life-cycle costs look significant, the user cannot ascertain whether Alternative 1 is the more effective alternative in a probabilistic sense. The inclusion of SCMs and inhibitor could create greater uncertainty in the corrosion initiation period that translates into greater uncertainty of the predicted life-cycle costs. Furthermore, the life-cycle costs of either or both alternatives may be highly sensitive to one or more cost parameters. To address these issues, we can apply the Life-365 service life and cost uncertainty analysis tools.

Probabilistic costs

First, Life-365 is used to compute the probability distributions and CDF of service life. The probability distribution shown in Fig. 1(a) indicates that Alternative 1 has a much greater average service life, but there is also a much greater uncertainty in its predicted value. In Fig. 1(b), we see that for most years in the design life of the project, Alternative 1 has a lower probability of having a service life less than or equal to that value, allowing us to conclude that the Alternative 1 mixture has the higher probabilistic service life.

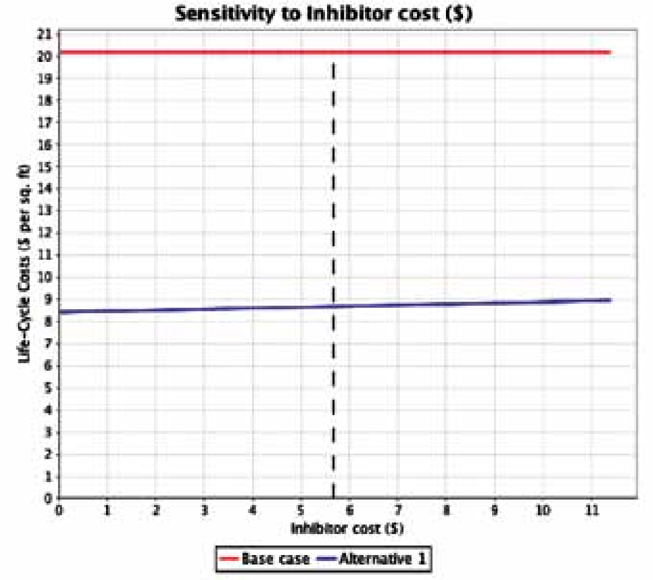

Fig. 4: Sensitivity analysis for corrosion inhibitor cost

Using the Service Life Modifier Panel, we can see whether Alternative 1 is more cost effective based on life-cycle cost in a probabilistic sense, that is, over the range of possible service life probabilities. By modifying the slider in this panel, we can determine that for all probabilities greater than 3%, Alternative 1 has a lower life-cycle cost. Based on this small set of probabilities over which the Base Case is the more effective mixture based on life-cycle cost, it's reasonable to conclude that Alternative 1 has a lower probabilistic life-cycle cost.

Deterministic sensitivity analysis

The project will likely have cost factors that vary widely and therefore could significantly impact life-cycle cost. Using the Life-365 tools, we can see which, if any, of these factors influence the cost-effective alternative. First, Alternative 1 has higher initial construction costs. Using the sensitivity analysis window specific to the cost of corrosion inhibitor (Fig. 4), we can see that the more effective alternative based on life-cycle cost is not significantly affected by a wide range of corrosion inhibitor cost.

Second, because the two mixtures have different numbers of repairs at different points in time, it's possible

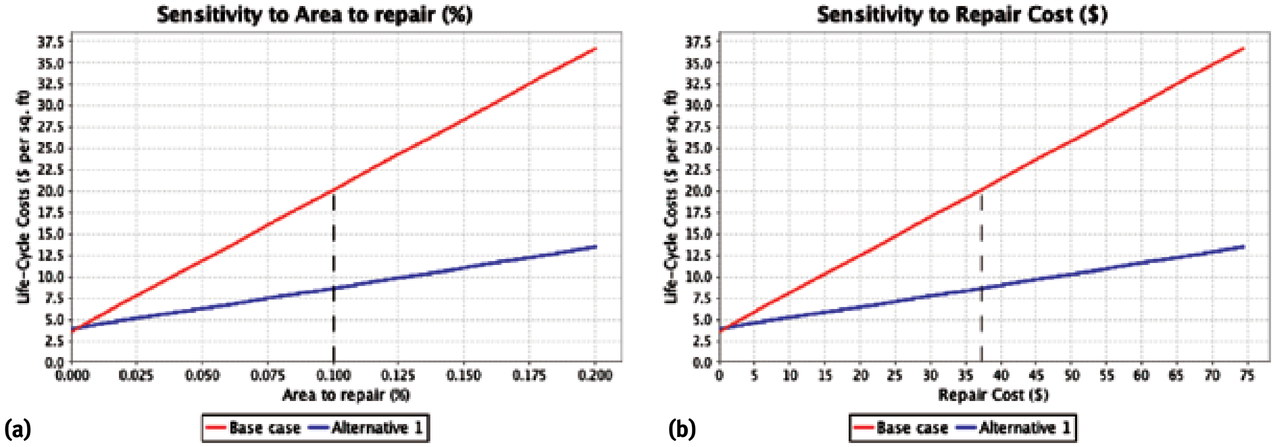

Fig. 5: Sensitivity analysis: (a) repair area; and (b) repair cost

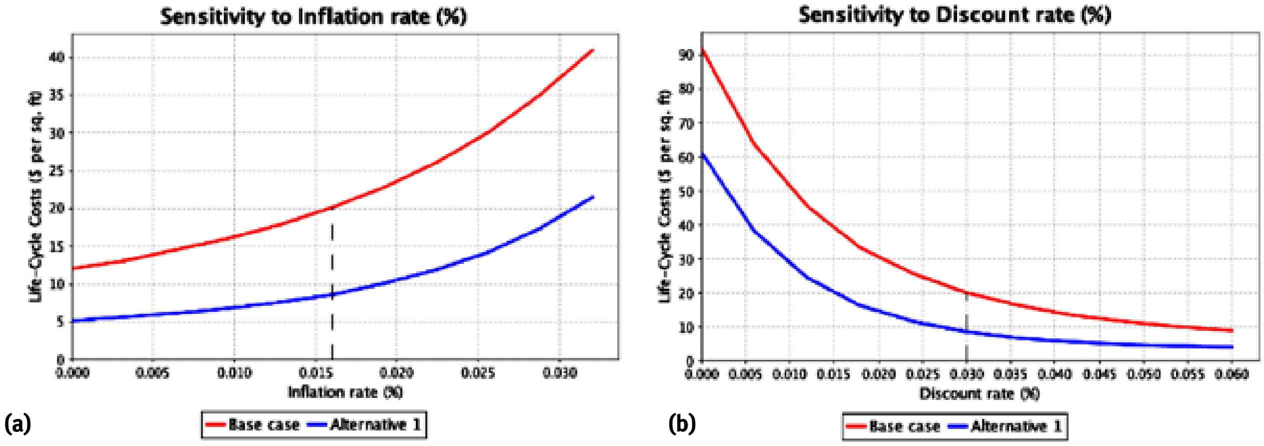

Fig. 6: Sensitivity analysis: (a) inflation rate; and (b) discount rate

that changes in repair area or repair cost could affect the cost effectiveness of Alternative 1. The plots in Fig. 5 illustrate that Alternative 1 is no longer cost effective when the repair area is less than 1% or the repair cost is less than $1/ft^2 ($10.76/m^2).

Third, the actual values of inflation and discount rate will likely be different than those assumed in the analysis (Fig. 6); by varying them, we can see that Alternative 1 remains more cost effective across all reasonable values of these two rates.

Broader sensitivity and uncertainty analysis

Finally, the broadest application of this sensitivity analysis process is to manually test whether Alternative 1 is cost effective under potential changes in any or all of the parameters. To conduct this broader analysis, the user simply changes one or more of the parameters, recalculates the service life and life-cycle costs of the two alternatives, and then compares their deterministic values.

As an example of this, Table 1 summarizes the impacts that geographic location has on service life and life-cycle costs. The table shows that Alternative 1 is the cost-effective alternative for all cities considered.

FUTURE OF LIFE-365

The Life-365 Consortium II of industry representatives (Concrete Corrosion Inhibitors Association, National Ready Mixed Concrete Association, Slag Cement Association, and Silica Fume Association) is actively continuing the

TABLE 1:
EFFECTS OF LOCATION ON LIFE-CYCLE COST OF A SAMPLE PARKING STRUCTURE

Location	Maximum surface chloride concentration, % by weight of concrete	Chloride buildup time, years	Service life, years		Life-cycle cost, \$/ft^2	
			Base case	Alternative 1	Base case	Alternative 1
New York, NY	0.8	7.4	15.9	68.4	$20.16	$8.68
Toronto, ON	1.0	3.8	13.3	55.9	$20.62	$10.61
Detroit, MI	1.0	6.2	14.6	57.8	$20.62	$10.52
Salt Lake City, UT	0.8	13.3	18.8	73.6	$19.72	$7.52
St. Louis, MO	0.8	12.9	18.5	72.6	$19.72	$7.57

Note: \$1/ft^2 = \$10.76/m^2.

process of soliciting user comments, updating the software, developing and executing training programs, and helping define concrete performance testing methods that improve the utility of the program and its predictive capability. Details about continuing Life-365 efforts can be found at **www.life-365.org**.

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Selected for reader interest by the editors.

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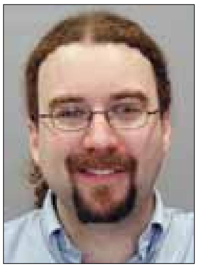

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