Life-Cycle Costs of Commercial Roof Systems

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Abstract: The roofing industry in the United States generates annual revenues in excess of $23 billion. This represents a significant annual investment in infrastructure maintenance cost and the opportunity cost of these resources can significantly detract from an owner's ability to invest in other areas. In addition, a failed or failing roof system represents a heightened opportunity for failure in the building envelope and inherently increases the risk of additional costs. Present roof asset management practice typically bases replacement decisions on fixed intervals, inspection results, maintenance issues, and, occasionally, failure risk. This paper develops a model for evaluating occupant costs and considering their impact in the roof management decision process through a total life-cycle cost (LCC) model that includes user/occupant cost model and correlates minimum total cost with improved intervention points in the asset deterioration cycle. The model is estimated from and applied to the extensive roof systems at Carnegie Mellon University in Pittsburgh, Pa. For these roofs, we find that the least cost roof service lives are roughly 30 years, but there can be considerable variation around this average for individual roofs.

DOI: 10.1061/(ASCE)1076-0431(2010)16:1(29)

CE Database subject headings: Life cycles; Roofs; Building envelope; Costs; Benefit cost ratios.

Introduction

In 2002, the roofing industry in the United States generated annual revenues in excess of $23 billion (U.S. Census Bureau 2002) including new work, additions, alterations, maintenance, and repairs. From a property owner's perspective, this represents a significant annual investment in infrastructure maintenance cost and, if poorly managed, necessarily detracts from the owner's ability to invest in other areas. In addition, a failed or failing roof system represents a heightened opportunity for failure in the building envelope.

The present practice in roof system management generally bases replacement decisions on fixed intervals (e.g., warranty schedules), inspection results (e.g., physical or infrared), or reports of ongoing maintenance problems. Even the more sophisticated techniques provided by engineered roof management systems ignore the financial impact on the occupants (users) in making roof management decisions (Bailey et al. 1989).

The current state of roof management and decision making research is primarily related to the development of techniques to predict the remaining service life of building envelope components and procedures to optimize their maintenance (Kyle et al. 2002) and in the development of data intensive processes developed to assist building owners in minimizing expenditures on roof maintenance while improving the serviceability of their roof stock (Morcous and Rivard 2003). Current roof management system cost models focus almost exclusively on the optimization of the owner's costs with regard to maintenance solutions (Morcous and Rivard 2003). In the U.S. Army Civil Engineering Research Laboratory's Engineered Management System, ROOFER, the current standard in roof management decision models (Lounis and Vanier 2000; Construction Engineering Research Laboratory (CERL) 2009], occupant costs are not considered in a quantitative fashion in calculating system life-cycle costs (LCC) (Bailey et al. 1989).

Some models do incorporate consideration of failure risk (Vanier and Nesje 1998). Occupant costs, especially those related to envelope failure, are expected to relate to the "value and vulnerability of the building contents" as well as factors such as relocation, energy, and other opportunity costs (Lounis 1999) and are primarily included through the inclusion of a "collateral damage" code and a risk of failure (Kyle et al. 2002). However, using risk as a method of valuating occupant costs is recognized as a less ideal and simplified method of establishing a LCC model intended to be useful as a decision tool (Kyle et al. 2002).

In this paper, we use a survey model of occupant costs due to leaks (Coffelt and Hendrickson, "Occupant costs in roof management decision making," unpublished, 2008) and experience with owner costs to estimate a total LCC assessment. The next section describes the Carnegie Mellon roof data set used in this work, followed by a discussion of the components of system costs. Discounted LCCs and minimum cost replacement are then considered. A subsequent paper (Coffelt and Hendrickson 2008) considers the relationship between LCCs and roof inspection results as inputs for replacement decisions.

Carnegie Mellon Roof Data Set

The data set for this research was formed from the roof asset inventory at Carnegie Mellon University. Carnegie Mellon's roof infrastructure forms a data rich laboratory of almost 100,000 m^2 of roof space covering 38 buildings. The roof systems include representative samples from a wide variety of slope and low-slope roof systems ranging in age from newly installed to more than 50

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Note. This manuscript was submitted on June 25, 2008; approved on June 3, 2009; published online on February 12, 2010. Discussion period open until August 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Architectural Engineering***, Vol. 16, No. 1, March 1, 2010. ©ASCE, ISSN 1076-0431/2010/1-29–36/$25.00.

years old. Using an average replacement cost of \$215–\$323 (\$269 per square meter in 2006\$), this roof network represents a physical asset valued at between \$22M and \$32M (\$269M in 2006).

Table 1 below contains a brief summary of typical roof systems installed on the buildings represented in this study. In this study, we focus on low-slope roofs since they are the most prone to leak. Among roof systems constructed within the last 10 years, the most common low-slope systems are ethylene propylene diene terpolymer (EPDM) and styrene butadiene styrene (SBS) modified bitumen. These may generically be considered representative systems for the data in this study. Roofing system details can vary significantly. However, a low-slope roof cross section is fairly typical and illustrated in Fig. 1 below. Insulation is a common feature of recent roofs to reduce heating and cooling costs. The insulation currently used is a solid closed cell foam. For the period from July 1998 through December 2006, the Carnegie Mellon maintenance database included 1,781 roof system leak-related maintenance and repair work records, representing an average of 200 leaks per year or 5.2 leaks per building per year.

Components of Life-Cycle Roof Costs

The cost model for the roof systems reflects three primary categories. Owner annual costs include the maintenance and repair of the roof systems themselves. Owner replacement cost includes the major expense of removing and replacing the roof systems. Occupant or user costs are the result of leaks and roof failure. A more general model of roof decision making would include consideration of alternative roof system designs, such as changes in the amounts of insulation or addition of green roofs to reduce storm-water runoff. As noted earlier, the Carnegie Mellon roof systems already include the required amount of insulation for the local weather (Pennsylvania Department of Labor and Industry 2009). As a result, our LCC model is simpler than a general roof design model.

Table 2 shows the various owner roof costs incurred by Carnegie Mellon University from 1998 to 2006. In this table, owner annual costs are divided into regular maintenance costs and repair costs. Costs are reported in nominal and in real (inflation adjusted) amounts using the *Engineering News-Record* (ENR) building cost index (Coffelt 2008). The capital costs represent a roof replacement cost of \$269/m^2 (2006\$), so the \$4.5M expenditure replaced 16,900 m^2 of roof (17% of total) in a 9-year period.

Based on the survey of lost time and repair costs, each roof leak had an average occupant cost of \$1,232 per leak (Coffelt and Hendrickson, "Occupant costs in roof management decision making," unpublished, 2008; Coffelt 2008), where "lost time" represents salary costs of reduced or zero productivity. With 1,781 leaks over the study period, the total occupant cost is \$2.2M, or significantly larger than the owner maintenance and repair costs alone, but smaller than the capital roof replacement costs.

A LCC analysis requires forecasts of expected costs into the future with assumptions of different roof replacement dates. In this study, we considered a 40-year planning horizon (1998–2037), so forecasts are required from 2007 to 2037 based upon data from 1998 to 2006. Our decision analysis then seeks to identify the replacement date for which discounted total cost is lowest.

We used a regression quadratic cost model to estimate costs in the future. This model form is easy to use and reflects our expectation that leaks (and related costs) will increase in a nonlinear fashion as a roof ages. As an example, the owner maintenance and

Table 1. Carnegie Mellon Typical Roof Systems

Roof system	Description	Relative cost	Service life (years)	Use (%)	Comments
EPDM	Rubber (ethylene propylene diene terpolymer) membrane system held in place primarily through the use of ballast, fasteners, or adhesive.	0.75	15	20	2% min slope required and achieved in older structures with tapered insulation.
Membrane	Welded seam systems including polyvinyl chloride (PVC), thermoplastic polyolefin (TPO), etc., system held in place using adhesives or fasteners.	0.85	10–20	6.5	2% min slope required and achieved in older structures with tapered insulation.
Modified bitumen membrane	Waterproofing provided by an elastomeric modified bitumen in a fiberglass reinforced mat.	1.0	20–25	30	SBS or styrene butadiene styrene; APP or atactic polypropylene are common thermoplastic modifiers.
Modified Built-up	Includes elastomeric modified sheet, but primary waterproofing is through multiple asphalt/felt layers.	0.96	15–20		Elastomeric cap or base sheets are used. Asphalt applied built-up sheets are the primary waterproofing.
Conv. Built-Up	Asphalt applied fiberglass reinforced mat.	0.92	10–15	6.5	
Coal tar pitch	Mopped on coal tar pitch. Can be applied on 1% or less slope. Tapered insulation is not required.	0.96	20–30	<1	Steel roof decks and thicker insulation has reduced the service life of this product.
Slope systems	Metal, tile, slate, shingle, tin.	1.0–3.0	30–75	37	All systems with $>2\%$ slope.

Note: Low slopes are defined here as systems with 1/4 in. per foot ($<2\%$) or less of slope. Costs are relative to a two-ply modified bitumen roof system specific to 2006 pricing in the Pittsburgh, Pa. market. Price factors related to materials are volatile due to the impact of oil prices on roofing materials such as asphalt and insulation. Insulation thickness is a primary influence on material cost. Figures represent R-20 or 3.5 in. Costs for tapered insulation are factored into cost estimates for all low-slope roof systems except coal tar pitch. Listed service lives are estimates based on the expected manufacturer's warranty for a typical installation. Figures can vary by system specifications and manufacturer. Actual experienced service life varies widely.

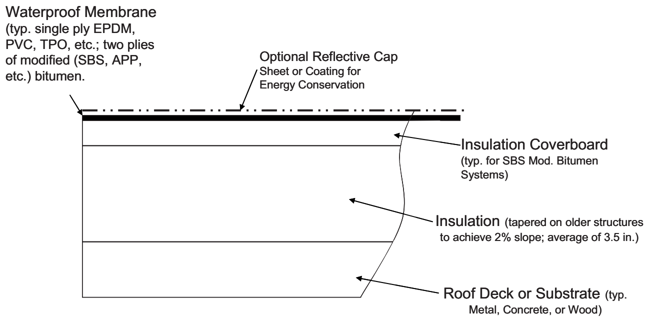

Fig. 1. Typical low-slope roof cross section

repair cost model for a particular building was estimated as (Coffelt 2008)

$$Y = 0.080^{*}X^{2} - 0.309^{*}X + 0.529 R^{2} = 0.86$$

$$(2.1) \quad (-0.8) \quad (0.6) \tag{1}$$

where X represents the index year of a new roof with 1998=1 for Roberts Hall; Y represents the expected M&R cost in 2006$/m^2 for some value of X; and numbers in parentheses are t statistics. For 2010, the forecast M&R costs would be $Y=0.080(13^2)-0.309(13)+0.529=13.56-4.01+0.529=10.08$. Other extrapolation model forms could also be used, but they tended to have lower explanatory power. An alternative to using an individual roof forecasting model such as Eq. (1) would be to estimate a general roof deterioration model and apply it to all roofs. Since our experience with different roofs suggests significant differences in long term performance, we opted for a roof specific forecasting model.

Discounted Life-Cycle Costs of Roof Systems

The present value total cost (PVTC) may be calculated using Eq. (2) below as the discounted sum of roof replacement in year t and annual occupant and owner costs. Note that the index of annual costs is reset with a new roof in year t so that these costs are drastically reduced with a new roof in place

$$\begin{aligned} \mathrm{PVTC}(t) = & \sum_{i=1}^{t} [\mathrm{UC}(i) + \mathrm{M\&R}(i)]/(1+r)^{(t-1)} \\ & + \text{replacement cost}/(1+r)^{(t-1)} \\ & + \sum_{i=t+1}^{40} [\mathrm{UC}(i-t) + \mathrm{M\&R}(i-t)]/(1+r)^{(t)} \end{aligned} \tag{2}$$

where t=replacement year; r=discount rate; i=evaluation year; UC=user cost; M&R=maintenance and repair cost; and replacement cost=estimated cost to replace roof. Table 3 shows the annual and total costs for a roof replacement in year 2001 and a discount rate of 15% as an example.

Table 4 below summarizes these calculations again for a hypothetical replacement in 2018. Table 5 below utilizes Eq. (2) to calculate the present value and uniform annual value of total roof costs for Roberts Hall for different replacement years through 2037.

The predicted minimum LCC including occupant cost is $91.48 with a replacement in 2018, while the predicted minimum LCC excluding user cost occurs in 2022 at a value of $44.77. In addition, once the minimum value is reached, the total cost curve increases very gradually out to the end of the evaluation period. This information is presented graphically in Fig. 2 below for Roberts Hall.

Table 6 shows the results of applying the same methodology to five different case studies, where the "ideal" case is a composite of several different buildings. In each case, a minimum cost time for replacement could be identified. The minimum cost service life ranged from 21 (Roberts Hall) to 38 (composite) years, with an average of 31 years.

Sensitivity of Life-Cycle Costs and Minimum Cost Replacement Times

Our results certainly have considerable uncertainty. In this section, we consider the impacts of different discount rates, roof

Table 2. Summary of Carnegie Mellon Total Roof Management Costs in 1998–2006

Evaluation year	Owner maintenance costs ($)	Owner repair costs ($)	Owner maintenance and repair costs ($)	Inflation adjusted owner maintenance and repair costs (2006$)	Owner capital costs ($)	Inflation adjusted owner capital costs (2006$)
1998	13,674	15,416	29,090	37,778	0	0
1999	14,016	116,417	130,433	165,614	5,271	6,693
2000	13,998	78,955	92,952	116,347	0	0
2001	13,928	78,029	91,957	114,146	437,593	543,184
2002	13,802	121,572	135,374	165,141	252,517	308,041
2003	16,899	132,506	149,404	176,560	573,385	677,602
2004	17,405	114,906	132,311	142,486	1,617,715	1,742,118
2005	18,180	103,753	121,933	125,078	1,230,086	1,261,813
2006	19,202	200,338	219,541	219,541	0	0
9-year total	141,104	961,891	1,102,995	1,262,690	4,116,568	4,539,450

Table 3. Roberts Hall Total Present Cost Calculation for Example Replacement in 2001

Roberts Hall present value calculations								
Year	Year index[a]	User cost (2006\$/m^2)[b]	M&R cost (2006\$/m^2)[c]	User cost if replacement (2006\$/m^2)[d]	M&R cost if replacement (2006\$/m^2)[e]	Replacement cost (2006\$/m^2)[f]	Total cost (2006\$/m^2)[g]	Present value total cost[h]
1998	1	0.00	0.22	0.00	0.22	0.00	0.22	0.22
1999	2	1.39	0.41	1.39	0.41	0.00	1.80	1.56
2000	3	0.00	0.20	0.00	0.20	0.00	0.20	0.15
2001	4	0.69	0.32	0.69	0.32	269.00	270.01	177.54
2002	5	3.46	1.04	0.00	0.22	0.00	0.22	0.13
2003	6	10.46	2.73	1.39	0.41	0.00	1.80	0.89
2004	7	5.97	1.48	0.00	0.20	0.00	0.20	0.09
2005	8	7.30	2.59	0.69	0.32	0.00	1.01	0.38
2006	9	8.62	4.76	3.46	1.04	0.00	4.51	1.47
2007	10	10.29	5.47	10.46	2.73	0.00	13.19	3.75
2008	11	11.47	6.85	5.97	1.48	0.00	7.45	1.84
2009	12	12.64	8.38	7.30	2.59	0.00	9.89	2.12
2010	13	13.80	10.08	8.62	4.76	0.00	13.38	2.50
2011	14	14.95	11.94	10.29	5.47	0.00	15.75	2.56
2012	15	16.10	13.96	11.47	6.85	0.00	18.31	2.59
2013	16	17.23	16.14	12.64	8.38	0.00	21.02	2.58
2014	17	18.35	18.48	13.80	10.08	0.00	23.88	2.55
2015	18	19.47	20.98	14.95	11.94	0.00	26.89	2.50
2016	19	20.57	23.64	16.10	13.96	0.00	30.05	2.43
2017	20	21.67	26.46	17.23	16.14	0.00	33.37	2.34
2018	21	22.76	29.44	18.35	18.48	0.00	36.83	2.25
2019	22	23.83	32.58	19.47	20.98	0.00	40.45	2.15
2020	23	24.90	35.89	20.57	23.64	0.00	44.21	2.04
2021	24	25.96	39.35	21.67	26.46	0.00	48.13	1.93
2022	25	27.01	42.97	22.76	29.44	0.00	52.20	1.82
2023	26	28.05	46.76	23.83	32.58	0.00	56.42	1.71
2024	27	29.08	50.70	24.90	35.89	0.00	60.79	1.61
2025	28	30.10	54.81	25.96	39.35	0.00	65.31	1.50
2026	29	31.11	59.08	27.01	42.97	0.00	69.99	1.40
2027	30	32.12	63.50	28.05	46.76	0.00	74.81	1.30
2028	31	33.11	68.09	29.08	50.70	0.00	79.79	1.21
2029	32	34.09	72.84	30.10	54.81	0.00	84.91	1.12
2030	33	35.07	77.74	31.11	59.08	0.00	90.19	1.03
2031	34	36.03	82.81	32.12	63.50	0.00	95.62	0.95
2032	35	36.99	88.04	33.11	68.09	0.00	101.20	0.87
2033	36	37.93	93.43	34.09	72.84	0.00	106.93	0.80
2034	37	38.87	98.98	35.07	77.74	0.00	112.81	0.74
2035	38	39.80	104.69	36.03	82.81	0.00	118.85	0.67
2036	39	40.72	110.56	36.99	88.04	0.00	125.03	0.62
2037	40	41.63	116.59	37.93	93.43	0.00	131.37	0.56
							Total PV	236.489

Note: Replacement cost=269; discount rate=15%; and replacement year=2001.

[a]Index year counting from 1997=0.

[b]User cost in 2006\$/m^2 for the year being evaluated. Estimate based on leak reports to 2006 and regression analysis beyond.

[c]M&R cost in 2006\$/m^2 for the year being evaluated. Estimate based on leak reports to 2006 and regression analysis beyond.

[d]Column "User cost (2006\$/m^2)" up to including the year of replacement. Resets to Year 1 value in the year following replacement based on a renewal of the roof system.

[e]Column "M&R cost (2006\$/m^2)" up to including the year of replacement. Resets to Year 1 value in the year following replacement based on a renewal of the roof system.

[f]Replacement cost in 2006\$/m^2=\$269 for the year of evaluated replacement. \$0 for all other years.

[g]Sum of columns "User cost if replacement (2006\$/m^2)," "M&R cost if replacement (2006\$/m^2)," and "Replacement cost (2006\$/m^2)."

[h]Discounted value of total cost (2006\$/m^2) using total cost (2006\$/m^2)/[$(1+15\%)^{(\text{index year}-1)}$].

Table 4. Roberts Hall Total Present Cost Calculation for Example Replacement in 2018

Roberts Hall present value calculations								
Year	Year index[a]	User cost[b]	M&R[c]	UCw/R[d]	M&Rw/R[e]	Replacement cost[f]	Total cost[g]	Present value total cost[h]
1998	1	0.00	0.22	0.00	0.22	0.00	0.22	0.22
1999	2	1.39	0.41	1.39	0.41	0.00	1.80	1.56
2000	3	0.00	0.20	0.00	0.20	0.00	0.20	0.15
2001	4	0.69	0.32	0.69	0.32	0.00	1.01	0.66
2002	5	3.46	1.04	3.46	1.04	0.00	4.51	2.58
2003	6	10.46	2.73	10.46	2.73	0.00	13.19	6.56
2004	7	5.97	1.48	5.97	1.48	0.00	7.45	3.22
2005	8	7.30	2.59	7.30	2.59	0.00	9.89	3.72
2006	9	8.62	4.76	8.62	4.76	0.00	13.38	4.37
2007	10	10.29	5.47	10.29	5.47	0.00	15.75	4.48
2008	11	11.47	6.85	11.47	6.85	0.00	18.31	4.53
2009	12	12.64	8.38	12.64	8.38	0.00	21.02	4.52
2010	13	13.80	10.08	13.80	10.08	0.00	23.88	4.46
2011	14	14.95	11.94	14.95	11.94	0.00	26.89	4.37
2012	15	16.10	13.96	16.10	13.96	0.00	30.05	4.25
2013	16	17.23	16.14	17.23	16.14	0.00	33.37	4.10
2014	17	18.35	18.48	18.35	18.48	0.00	36.83	3.94
2015	18	19.47	20.98	19.47	20.98	0.00	40.45	3.76
2016	19	20.57	23.64	20.57	23.64	0.00	44.21	3.57
2017	20	21.67	26.46	21.67	26.46	0.00	48.13	3.38
2018	21	22.76	29.44	22.76	29.44	269.00	321.20	19.63
2019	22	23.83	32.58	0.00	0.22	0.00	0.22	0.01
2020	23	24.90	35.89	1.39	0.41	0.00	1.80	0.08
2021	24	25.96	39.35	0.00	0.20	0.00	0.20	0.01
2022	25	27.01	42.97	0.69	0.32	0.00	1.01	0.04
2023	26	28.05	46.76	3.46	1.04	0.00	4.51	0.14
2024	27	29.08	50.70	10.46	2.73	0.00	13.19	0.35
2025	28	30.10	54.81	5.97	1.48	0.00	7.45	0.17
2026	29	31.11	59.08	7.30	2.59	0.00	9.69	0.20
2027	30	32.12	63.50	8.62	4.76	0.00	13.38	0.23
2028	31	33.11	68.09	10.29	5.47	0.00	15.75	0.24
2029	32	34.09	72.84	11.47	6.85	0.00	18.31	0.24
2030	33	35.07	77.74	12.64	8.38	0.00	21.02	0.24
2031	34	36.03	82.81	13.80	10.08	0.00	23.88	0.24
2032	35	36.99	88.04	14.95	11.94	0.00	26.89	0.23
2033	36	37.93	93.43	16.10	13.96	0.00	30.05	0.23
2034	37	38.87	98.98	17.23	16.14	0.00	33.37	0.22
2035	38	39.80	104.69	18.35	18.48	0.00	36.83	0.21
2036	39	40.72	110.56	19.47	20.98	0.00	40.45	0.20
2037	40	41.63	116.59	20.57	23.64	0.00	44.21	0.19
							Total PV	91.48

Note: Replacement cost=269; discount rate=15%; and replacement year=2018.

[a]Index year counting from 1997=0.

[b]User cost in 2006\$/m^2 for the year being evaluated. Estimate based on leak reports to 2006 and regression analysis beyond.

[c]M&R cost in 2006\$/m^2 for the year being evaluated. Estimate based on leak reports to 2006 and regression analysis beyond.

[d]Column "User cost" up to including the year of replacement. Resets to Year 1 value in the year following replacement based on a renewal of the roof system.

[e]Column "M&R up" to including the year of replacement. Resets to Year 1 value in the year following replacement based on a renewal of the roof system.

[f]Replacement cost in 2006\$/m^2=\$269 for the year of evaluated replacement. \$0 for all other years.

[g]Sum of columns "UCw/R," "M&Rw/R," and "Replacement cost."

[h]Discounted value of the column "Total cost" using total cost/$[(1+15\%)^{(\text{index year}-1)}]$.

Table 5. Present Value and Uniform Annual Roof Costs for Roberts Hall for Different Replacement Years

Roberts Hall present value total cost for roof replacement in different years

Year	Present value total cost including user cost[a]	Present value total cost excluding user cost[b]	Annual uniform cost including user cost[c]	Annual uniform cost excluding user cost[d]
1998	358.67	311.48	54.0	46.9
1999	312.97	270.86	47.1	40.8
2000	272.04	235.40	41.0	35.4
2001	237.00	204.66	35.7	30.8
2002	208.56	178.37	31.4	26.9
2003	188.16	156.35	28.3	23.5
2004	167.96	136.69	25.3	20.6
2005	151.34	120.03	22.8	18.1
2006	138.04	106.26	20.8	16.0
2007	127.17	94.51	19.1	14.2
2008	118.37	84.65	17.8	12.7
2009	111.32	76.42	16.8	11.5
2010	105.74	69.59	15.9	10.5
2011	101.40	63.97	15.3	9.6
2012	97.80	59.21	14.7	8.9
2013	95.36	55.51	14.4	8.4
2014	93.62	52.57	14.1	7.9
2015	92.47	50.25	13.9	7.6
2016	91.78	48.46	13.8	7.3
2017	91.48	47.11	13.8	7.1
2018	91.48	46.13	13.8	6.9
2019	91.72	45.46	13.8	6.8
2020	92.14	45.04	13.9	6.8
2021	92.70	44.82	14.0	6.7
2022	93.37	44.77	14.1	6.7
2023	94.11	44.84	14.2	6.8
2024	94.89	45.02	14.3	6.8
2025	95.70	45.27	14.4	6.8
2026	96.52	45.59	14.5	6.9
2027	97.34	45.94	14.7	6.9
2028	98.15	46.33	14.8	7.0
2029	98.93	46.73	14.9	7.0
2030	99.70	47.14	15.0	7.1
2031	100.43	47.55	15.1	7.2
2032	101.10	47.95	15.2	7.2
2033	101.76	48.34	15.3	7.3
2034	102.39	48.72	15.4	7.3
2035	102.97	49.08	15.5	7.4
2036	103.52	49.43	15.6	7.4
2037	104.02	49.76	15.7	7.5

[a]PVTC calculated per Eq. (2).

[b]PVTC calculated per Eq. (2). User cost is set to $0.

[c]EXCEL PMT function calculates uniform payment equal to PVTC (1).

[d]EXCEL PMT function calculates uniform payment equal to PVTC (2).

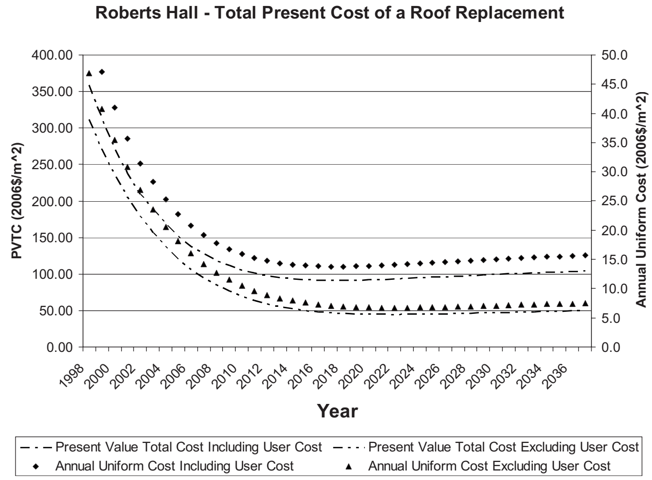

Fig. 2. PVTC and UAC with and without user costs—Roberts Hall

replacement costs, and occupant costs per leak (or equivalently, different levels of leakage).

Fig. 3 shows the effect of different discount rates and roof replacement costs on the lowest cost roof replacement case for the five case studies shown in Table 6. The various scenarios of assumptions are

1. High discount rate (20%) and low replacement cost ($200/m^2$);
2. High discount rate (20%) and observed replacement cost ($269/m^2$);
3. Owner discount rate (15%) and low replacement cost ($200/m^2$);
4. Base case of owner discount rate (15%) and observed replacement cost ($269/m^2$);
5. Owner discount rate (15%) and high replacement cost ($300/m^2$);
6. Low discount rate (5%) and observed replacement cost ($269/m^2$); and
7. Low discount rate (5%) and high replacement cost ($300/m^2$).

For these scenarios, the lowest cost replacement time varies by up to 12 years. The biggest effect is caused by a lower discount rate (5% for Cases 6 and 7), with more rapid replacement to avoid high maintenance and occupant costs.

Similar results are found by varying the occupant cost parameters. In Fig. 4, Cost Scenario 1 reduces occupant costs per leak by 50% while Scenario 3 represents a 50% increase in occupant costs. The minimum cost year for replacement varies by up to 8 years, with higher occupant costs corresponding to short replacement periods as might be expected.

Variations in input values certainly affect the estimated annual costs and roof replacement dates. However, the roof replacement years themselves are relatively insensitive to large changes in these input parameters.

Conclusions

We have demonstrated the estimation of LCC models for roofs and the existence of lowest cost replacement years. The increase in roof leaks over time and the consequent increases in both occupant and owner costs influence this lowest cost replacement year. For the roof designs and climate in Pittsburgh, Pa, minimum cost roof service lives are roughly 30 years, but there can be considerable variation around this average for individual roofs.

Table 6. Costs and Lowest Cost Replacement Years for Five Case Studies

	Present value total cost results summary characteristic				
	Ideal	ROBT—Case Study 1	Building WEAN—Case Study 2	PURN—Case Study 3	6555—Case Study 4
Total cost curve-period of minimum LCC (year)[a]	2035	2018	2013	2037	2030
Total cost curve-value at minimum (2006$/$m^2$)	$36.45	$91.48	$131.30	$21.02	$28.32
uniform annual cost[b] (UAC) at Min LCC (2006$/$m^2$)[c]	$5.5	$13.8	$19.8	$3.2	$4.3
Total user cost to defer (2006$)[d]	$55.55/$m^2$ or $738K	$100/$m^2$ or $185K	$1,095/$m^2$ or $4.8M	$17/$m^2$ or $79M	$30/$m^2$ or $272K
Total value of user costs (2006$)[e]	$463/$m^2$ or $6.1M	$864/$m^2$ or $1.6M	$4,173/$m^2$ or $18M	$211/$m^2$ or $lM	$186/$m^2$ or $1.7M
Total cost ratio[f]	1.9	0.6	3.2	0.7	0.3
Estimated age of roof network in 2006 (years)[g]	9	9	29.5	8	9
Annualized leaks (1998–2006)	154 or 0.012/m^2	56 or 0.03/m^2	174 or 0.04/m^2	12 or 0.002/m^2	48 or 0.005/m^2

[a]Period where minimum present value total cost (PVTC) is reached. Min PVTC=minimum life-cycle cost value=economic optimum replacement period.
[b]LCC at period in row "Total cost curve-period of minimum LCC (year)."
[c]Uniform annual payment required at the minimum PVTC.
[d]Undiscounted estimate of user cost incurred between time period listed in row "Total cost curve-period of minimum LCC (year)" and time period of minimum PVTC where the user cost is fixed at $0.
[e]Undiscounted estimate of user costs for 40-year economic evaluation period.
[f]Total user cost/total M&R cost over 40-year evaluation period.
[g]Number of leaks reported during the period indicated and total number of leaks divided by roof area (Note: Purnell is 1999 through 2006).

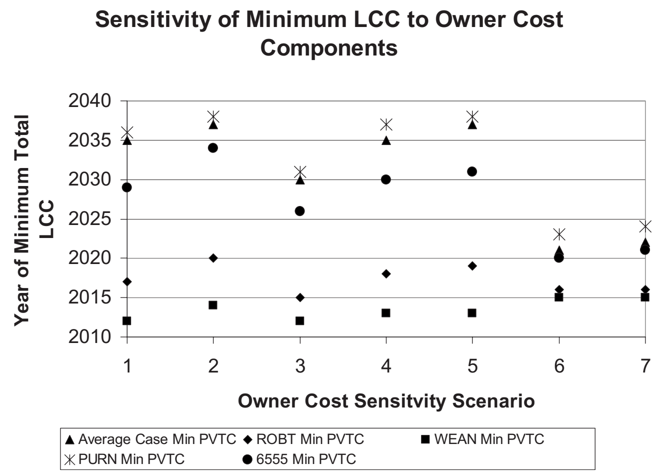

Fig. 3. Variation in minimum cost replacement year for different owner cost scenarios

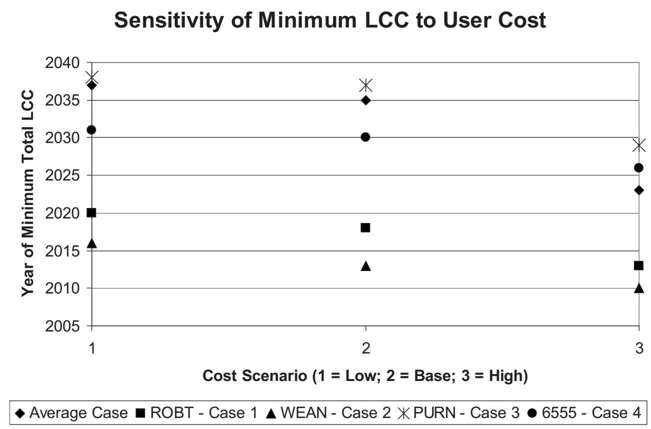

Fig. 4. Variation in minimum cost replacement year for different occupant cost scenarios

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