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Periodic refurbishment and reductions in national costs to sustain dwelling services

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This paper uses a simulation model to make exploratory estimates of current and potential reductions in national costs to sustain dwelling services due to refurbishment. Data and parameters are based on a typical New Zealand dwelling of lightweight timber framed construction. Dwelling service years provided by a dwelling over one year adjusted for depreciation serve as a proxy for benefits. The costs to construct one dwelling and fractions thereof serve as a proxy for the costs of maintenance, refurbishment, replacement, and new construction. Current levels of refurbishment reduce national average costs to sustain dwelling services by a magnitude of 15%. Potential reductions in national costs are modest (5%) should the housing stock be stationary, but are negligible when the expansion rate of the housing stock is as high as 2.0% per year. A decline in the expansion rate of a housing stock has a greater impact on reducing national costs than an increase in the number of cycles of refurbishment.

Keywords: Housing stock, simulation model, periodic refurbishment, dwelling services, national costs

Introduction

Refurbishment extends the service life of dwellings and reduces the annual replacement rate of a housing stock below that which would be required otherwise to sustain a set quantity and quality of dwelling services. National costs to sustain dwelling services subsequently decrease. Social benefits due to refurbishment include an increase in the consumer surplus, a reduction in waste products from demolition, a reduction in pollution from manufacturing and construction processes, and a decrease in the throughput of resources. This paper makes exploratory estimates of current reductions in national costs to sustain dwelling services due to refurbishment, and the potential for further reductions. Data and parameters are based on a typical New Zealand dwelling of lightweight timber framed construction.

Estimates of the benefits and costs of housing stock require the use of a dynamic simulation model. Nauda *et al.* (1979) and Brewer (1989) promote the use of control theory and the Kolmogorov partial differentiation equation, respectively, to model the dynamics of housing stock. However, these models do not provide the same degree of transparency and simplicity of construction as that offered by a simulation model based on classical population dynamics. Johnstone (1998) used such a model to estimate the impact of single-cycle refurbishment. This paper extends Johnstone's model to include periodic 'full' refurbishment as described in the second part of the next main section. Partial refurbishment is not modelled.

Needleman (1965) estimated the maximum costs of modernization of housing as a percentage of the costs of rebuilding for which modernization is cheaper. His simple formula excludes the flow of benefits. Sigsworth and Wilkinson (1967) added a term to Needleman's formula that represents the sum of discounted net benefits over the anticipated life of the house after improvement. Schaaf (1969) further amended Sigsworth and Wilkinson's formula to take into account the value of a demolished dwelling, differences in annual rental

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values of new and rehabilitated dwellings, and the annual rate of economic depreciation of a new dwelling.

Use of Schaaf's (1969) criterion for a dwelling cohort requires adoption of the implicit assumption that there are no dwelling losses from a dwelling cohort over the extended life of the dwelling cohort. A number of empirical studies of the mortality of housing stock confirm that dwelling losses occur at all ages (Gleeson, 1985; Johnstone, 1994; Komatsu *et al.*, 1994). Gleeson (1992) and Johnstone (1997) have developed actuarial models to estimate the maximum expenditure that can be justified undertaking refurbishment for each age at which refurbishment takes place. Gleeson's model does not include economic depreciation of dwelling services nor maintenance costs. Johnstone's (1997) model includes these factors and this model is used to estimate the earliest age at which full refurbishment can be justified.

The model

Description of simulation model

The simulation model can be visualized as a series of multi-deck stacks. The level of each deck represents the effective age of a dwelling cohort. A new dwelling cohort enters the first deck of the first stack at the start of each time interval and previous dwelling cohorts move down the stack to the next deck. Dwelling losses from each deck are determined by a probability of loss schedule that forms the first column of a standard life table as described in texts on population dynamics, e.g. Keyfitz and Beekman (1984).

If no refurbishment takes place, then survivors of each dwelling cohort move progressively down the first stack until all dwellings have departed from each cohort. If periodic refurbishment takes place, then survivors move part way down the first stack and shift over to the top of the second stack. Survivors then move part way down the second stack to the same level as before, shift over to the top of the third stack, and so on.

Dwelling losses from each deck over the same time interval form total dwelling losses of all ages. These losses are continuously replaced by the entry of new construction. If the housing stock is stationary, then new construction consists entirely of replacement construction. If the housing stock undergoes expansion, then new construction consists of both new-build construction, which adds to the size of the housing stock, and replacement construction.

Parameters within the simulation model are set to extreme limits in order to estimate the maximum impact of periodic refurbishment. Entire national dwelling cohorts undergo 'full' and complete refurbishment to the extent that economic depreciation of dwelling services and the probability of loss of dwellings are fully reversed. The effective age of dwellings is zero immediately after undergoing full refurbishment. Figure 1 illustrates the surviving stock schedule of a dwelling cohort that undergoes three cycles of periodic refurbishment with a 40-year interval between cycles. The surviving stock schedule initially follows the same course as that for new dwellings which do not undergo full refurbishment, follows a scaled down course as for new dwellings until the next cycle of full refurbishment, and so on.

The size and quality of dwellings in the simulation model are assumed to be homogeneous. The quantity of dwelling services supplied is expressed in units of 'service year equivalents' (sye), the dwelling services provided by a dwelling over one year adjusted for economic depreciation. Dwelling services include only those services provided by improvements to land, and specifically exclude the services of physical space provided by pure land. Dwelling services and land services are separated in order to avoid confounding separate issues of economic depreciation. The costs of supplying dwelling services are expressed in 'construction units' (cu), the cost to construct one dwelling, and the real costs of all forms of construction work are assumed to remain constant over time. The proxies for benefits and costs can be converted into dollar terms by multiplying by their respective prices.

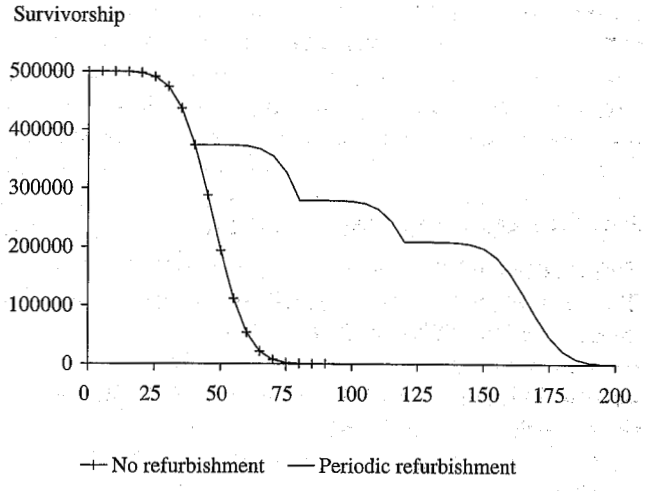

Figure 1 Survivorship of a dwelling cohort which undergoes three cycles of refurbishment with a 40-year interval between cycles: full line, periodic refurbishment; and crosses, no refurbishment

The objective function

The national average costs of providing dwelling services are given by the total costs to sustain the housing stock over any time interval divided by the total dwelling services provided by the housing stock over the same time interval (Johnstone, 1998). The objective function, f, takes the following form (standard notation of classical population dynamics is used throughout this paper).

$$\mathrm{f}(\mathrm{D}(h),h,i,k,L_x,\mathrm{M}(h),q_h,r,\mu_z\omega,x,z) = \frac{C_t}{S_t} = \frac{C_t/P_g}{S_t/P_g} \quad (1)$$

where $\mathrm{D}(h)$ is an economic depreciation function of the effective age h with h the effective age of a dwelling cohort ($h = x - kz$), i is the real discount rate, k is the number of cycles of refurbishment, L_x is the number of dwelling service years provided by a dwelling cohort within an expanding or stationary and stable housing stock over the age interval x to $(x + 1)$, $\mathrm{M}(h)$ is a maintenance function of the effective age h, q_h is the primary probability of loss over the effective age interval h to $(h + 1)$ (see later), r is the annual expansion rate of a housing stock, μ_z is the maximum cost ratio or maximum justifiable expenditure on refurbishment every z years expressed as a proportion of the costs to construct a new dwelling, ω is the service lifespan of the housing stock, x is the actual age of a dwelling cohort at the start of an age interval x to $(x + 1)$, z is the time interval between each cycle of periodic refurbishment, C_t is the total cost of sustaining a housing stock over the time interval t to $(t + 1)$, P_g is the geometric mean size of the housing stock during the time interval t to $(t + 1)$, and S_t is the total dwelling services provided by a housing stock over the same time interval t to $(t + 1)$.

The service loss index, S_t/P_g, is an indicator of the average quality of dwelling services provided by a housing stock expressed in units of dwelling service year equivalents per dwelling per year (sye/dg/yr).

Dwelling services in the objective function

Refurbishment takes place every z years for k cycles. The actual age at which refurbishment takes place is given by $y = kz$. When $k = 0$, the corresponding maximum cost ratio $\mu_z = 0$. The zero cycle represents the case when a dwelling cohort first enters the housing stock and no expenditure on refurbishment can be justified.

Dwelling services in the denominator of the objective function are given by the sum of dwelling service years provided by each dwelling cohort adjusted for economic depreciation. Economic depreciation of dwelling services subsequent to entry is described by the function $\mathrm{D}(h)$.

$$S_t = \sum_{x=0}^{z-1} L_x.\mathrm{D}(x) + \sum_{x=z}^{2z-1} L_x.\mathrm{D}(x-z) + \ldots + \sum_{x=kz}^{\omega} L_x.\mathrm{D}(x-kz) \quad (2)$$

Dwelling service years L_x provided by each dwelling cohort over the time interval t to $(t + 1)$ are given by

$$L_x = l_x - d_x.a_0 \quad (3)$$

where l_x is the number of dwellings from an original dwelling cohort, l_0, which survive to the actual age x, d_x is the number of dwelling losses from a dwelling cohort of actual age x over the age interval x to $(x + 1)$, and a_0 is the average number of dwelling service years provided by dwellings lost over the age interval x to $(x + n)$. The value of $a_0 = \frac{1}{2}$ when $n = 1$ gives sufficiently precise results for the purposes of this paper.

Stock losses (d_x) over each age interval are given by the product of the surviving dwellings at the start of each age interval (l_x), the primary probability of loss at the effective age h (q_h), and a multiplier function. Johnstone (1994) established previously that the mortality of New Zealand housing stock is dynamic in that the mortality is a function not only of age, but also the annual expansion rate of the housing stock.

$$d_x = l_x.q_h(1 + 78.62r)^{0.70} \quad (4)$$

The probability of loss (q_h) is fully reversed after undergoing refurbishment and the effective age $h = 0$. The section on Data and parameters explains the background to the primary probability of loss function (q_h).

Total dwelling losses of all ages which are lost over each time interval t to $(t + 1)$ are replaced by replacement construction. If the housing stock undergoes expansion, then new dwelling entries include not only replacement construction but also new-build construction. Dwelling entries over the time interval t to $(t + 1)$ are given by

$$l_0 = \sum_{x=0}^{\omega} d_x + P_{t+1} - P_t = \sum_{x=0}^{\omega} d_x + (\exp r - 1)P_t = \sum_{x=0}^{\omega} d_x + (\exp r - 1)\sum_{x=0}^{\omega} l_x \quad (5)$$

where P_t is the size of the housing stock at the start of the time interval t to $(t + 1)$ and P_{t+1} is the size of the housing stock at the start of the time interval $(t + 1)$ to $(t + 2)$.

Costs in the objective function

Total costs (C_t) in the numerator of the objective function are the sum of the costs of new-build construction (C_{new}), replacement construction (C_{replace}), refurbishment (C_{refurb}), and annual maintenance (C_{maint}).

The number of new-build entries to the housing stock from Equation 5 gives the costs of new-build construction:

$$C_{\text{new}} = (\exp r - 1)\sum_{x=0}^{\omega} l_x \quad (6)$$

The number of replacement entries to the housing stock from Equation 5 gives the costs of replacement construction:

$$C_{\text{replace}} = \sum_{x=0}^{\omega} d_x \quad (7)$$

The costs of refurbishment are given by

$$C_{\text{replace}} = \mu_z\ (l_z + l_{2z} + \ldots + l_{kz}) = \mu_z \cdot \sum_{k=0}^{k} l_{kz} \quad (8)$$

The costs of annual maintenance are given by the product of the maintenance factor M(h) and L_x, the number of dwelling service years provided by dwellings over the age interval x to (x + 1) for $h = x - kz$. The units of M(h) are in construction units per dwelling service year (cu/sy).

$$C_{\text{maint}} = \sum_{x=0}^{z-1} L_x.\text{M}(x) + \sum_{x=z}^{2z-1} L_x.\text{M}(x-z) + \ldots + \sum_{x=kz}^{\omega} L_x.\text{M}(x-kz) \quad (9)$$

Data and parameters

Primary probability of loss

The mortality regime of New Zealand housing stock established by Johnstone (1994) cannot be used to estimate current and potential reductions in costs due to refurbishment because it based on dwellings that have already undergone refurbishment. It is necessary to use a mortality regime for dwellings which have yet to undergo refurbishment in order to estimate the impact of refurbishment. A housing stock that does not undergo refurbishment is referred to from here on as a 'primary' housing stock. Performance indicators and parameters of a primary housing stock are referred to using the 'primary' prefix.

All dwelling cohorts are subject to a primary probability of loss schedule. A primary probability of loss schedule cannot be estimated using direct data because the majority of dwellings undergo refurbishment before departing from a housing stock. An indirect estimate is made here using the relationship between economic depreciation of dwelling services and probability of loss. The probability of loss is zero and economic depreciation of dwelling services is at a minimum when a dwelling cohort first enters a housing stock. The probability of loss is unity when dwelling services of the last dwelling within the dwelling cohort have fully depreciated.

An estimate of a primary service lifespan requires judgement because a primary dwelling cohort is a hypothetical dwelling cohort. In the author's opinion, it is unlikely that tenants would be prepared to pay rent over and above the use of land for an 80-year-old New Zealand dwelling that has undergone maintenance only, as described later, but has never undergone refurbishment.

The probability of loss schedule which best fitted the mortality of New Zealand housing stock is a transform of a normal distribution stock losses schedule (Johnstone, 1994). The primary probability of loss schedule used in the simulation model is also set to be a transform of a normal distribution stock losses schedule with the primary service lifespan (ω_p) being set to be 80 years when the annual expansion rate of the housing stock is zero. Stock losses (d_x) from a primary dwelling cohort within a stationary and stable primary housing stock is given by

$$d_x = \text{INT}\left[\frac{l_0}{\sigma\sqrt{2\pi}}\, e^{-\frac{1}{2}[(x-\mu)/\sigma]^2}\right] \quad (10)$$

where INT is a function that truncates fractional stock losses to the nearest integer, l_0 is the radix of a life table, or initial dwellings entries at age 0 set to 100 000 dwellings by convention, but set here to be 500 000 dwellings to minimize truncation errors, σ is the standard deviation of stock losses set to be 10.5 years, and μ is the mean age of stock losses set to be 46.5 years.

Dwellings within the simulation model are subject to dynamic mortality, as is the case with New Zealand housing stock. For example, the primary service lifespan (ω_p) is 51 years when the annual expansion rate of the housing stock is 2.0% per year.

A sensitivity analysis of the primary probability of loss is carried out at the end of the Results section.

Economic depreciation of dwelling services

An empirical study of the economic depreciation of New Zealand housing stock has yet to be carried out. Extensive literature surveys of empirical studies of economic depreciation of dwellings by Malpezzi *et al.* (1987) and Baer (1991) do not provide satisfactory guidelines which can be applied with confidence to New Zealand housing stock, as no study estimates the economic depreciation of dwelling services or rent (excluding rent for land) over the full service life of dwellings. The simulation model therefore uses four schedules of reversed 'S', straight-line, convex, and concave curve depreciation as categorized by Baer

(1991). Each schedule of depreciation is adjusted so that the dwelling services of a stationary housing stock fully depreciate by the primary service lifespan of 80 years and by a corresponding shorter primary service lifespan when the housing stock undergoes expansion.

The surviving stock schedule of a primary dwelling cohort describes a reversed 'S' curve. Reversed 'S' curve depreciation is therefore described by the function

$$D(h) = \frac{l_{h+1}}{l_0} \tag{11}$$

where l_{h+1} is the number of dwellings within a dwelling cohort which would survive to the effective age $h + 1$ should no refurbishment take place ($h = x$) and l_0 is the initial dwelling entry of a cohort at age 0 or the radix of a life table which describes the mortality of a dwelling cohort. The units of $D(h)$ are dimensionless and $0 \leq D(h) \leq 1$.

Each schedule of a life table is a mathematical transform of one another. Expected surviving stock l_x and l_{x+1} which survives to the exact ages x and $(x + 1)$ are given by stock losses d_x over the successive age intervals x to $(x + 1)_{as}$ described in Equation 10 for a stationary and stable primary housing stock.

Straight-line depreciation is described by the function

$$D(h) = 1 - \frac{h+1}{\omega_p} \quad \text{when } h < \omega_p$$
$$D(h) = 0 \quad \text{when } h \geq \omega_p \tag{12}$$

where ω_p is the primary service life span of a dwelling cohort. Straight-line depreciation is 1.25% per year when the housing stock is stationary and the primary service lifespan $\omega_p = 80$ years.

Diminishing value depreciation forms a convex curve. Dwelling services depreciate by 99.9% by the primary service lifespan of 80 years when diminishing value depreciation is 8.27% per year. This rate of economic depreciation is unrealistic, but nonetheless diminishing value depreciation is included for the sake of completeness. Convex curve depreciation of a stationary housing stock is described by the function

$$D(h) = (1 - 0.0827)^{h+1} \quad \text{when } h < 80$$
$$D(h) = 0 \quad \text{when } h \geq 80 \tag{13}$$

Concave curve depreciation is described by the function

$$D(h) = \sqrt{1 - \left[\frac{h+1}{\omega_p}\right]^2} \quad \text{when } h < \omega_p$$
$$D(h) = 0 \quad \text{when } h \geq \omega_p \tag{14}$$

The four schedules of economic depreciation are graphed in Figure 2.

Costs of new-build and replacement construction

The costs of new-build and replacement construction are based on the New Zealand Institute of Valuers 1996 National Modal House, a typical New Zealand dwelling of lightweight timber framed construction with a floor area of 100 m^2 (NZIV, 1996). Construction details and costs of the National Modal House are listed in Table 1.

Costs of maintenance

Maintenance includes all work that retains the provision of essential services such as weathertight shelter, security, lighting, heating, water supply, and waste disposal. Replacement or resurfacing of obsolescent or aesthetically unacceptable, but still functional, components is specifically excluded. Because exterior painting provides a protective coating as well as preserving appearance, this work falls under the category of maintenance.

Estimates of the costs of maintenance are based on the maintenance records of 25 New Zealand Housing Corporation dwellings that date back between 24 and 39 years from 1988. The costs of exterior painting are based on the National Modal House primarily because the New Zealand Housing Corporation records do not separate the costs of interior decorating and exterior painting. Maintenance costs are set out in Table 2.

Costs of refurbishment

Refurbishment is defined here as that work which reverses the economic depreciation of dwelling services and extends the service life of a dwelling through replacement or resurfacing of worn, damaged, degraded, or obsolescent building components. Interior decorating is included under refurbishment.

Although building components do not have the same replacement or resurfacing life cycles, a simulation model which accounts for all cycles would be unnecessarily complex for the purpose of making exploratory estimates of the impact of refurbishment. The cycles of refurbishment are therefore simplified. All refurbishment work takes place simultaneously over the same cycle.

The costs of full refurbishment are NZ1997 $45 593.87 (0.479 cu). These costs are applied under all scenarios and cases within scenarios. Detailed costs are listed in Table 3.

Table 1 Costs of 1996 National Modal House. Schedule based on New Zealand Institute of Valuers (NZIV, 1996) pricing based on unpublished priced schedule provided by Rawlinsons Group, (1997).

	June 1997 NZ$	Percentage of construction unit
Preliminaries (profit margin is added to each item)	4 200.00	4.41
Excavation	727.34	0.76
Substructure: Timber piles set in concrete, bearers, joists; 20mm particle board flooring; double sided foil insulation; floor sanding, horizontal baseboards	9 189.66	9.66
External and internal wall framing: lightweight timber framing	5 980.38	6.28
Roof framing: timber trusses, purlins, ceiling battens, soffit framing, fascia, barge boards	7 201.31	7.57
External cladding: cellulose cement weatherboards, eaves and soffit sheeting; building paper; external trim	7 345.20	7.72
Insulation: glass fibre in walls and ceiling	1 887.75	1.98
Internal linings and trim: gypsum plaster board; MDF skirting	7 127.57	7.49
Decks and steps: timber	636.00	0.67
Aluminium exterior windows and doors: supply and fix	7 198.07	7.56
Interior doors: supply and fix prehung doors and linings	2 838.73	2.98
Joinery fittings: supply and fix kitchen and bathroom units, shelving	8 067.38	8.48
Hardware: supply and fix	2 323.16	2.44
Controlled combustion heater: supply and fix; base	3 364.32	3.54
Roof covering: pre-finished corrugated steel roofing	4 049.37	4.26
Spouting and downpipes: PVC	963.55	1.01
Plumbing: polybutylene water pipes, polypropylene traps and wastes, taps and valves, flashings; supply and fix bath, shower base and screen, WC pan and cistern, vanity unit, laundry tub	6 194.32	6.51
Drainage: excavate trench, PVC sanitary and stormwater piping	3 573.92	3.76
Electrical: mains, meter board, wiring, outlets, fittings, stove	5 587.34	5.87
Exterior painting: 3 coat system on wall cladding, trim, and baseboards	2 352.73	2.47
Interior painting: 3 coat system on walls and ceilings	3 302.30	3.47
Subtotal: 1996 National Modal House	94 110.40	98.90
Vinyl flooring (10 m^2) and 3 coats satin polyurethane floor finish (85 m^2)	1 045.00	1.10
Revised 1996 National Modal House	95 155.40	100.00

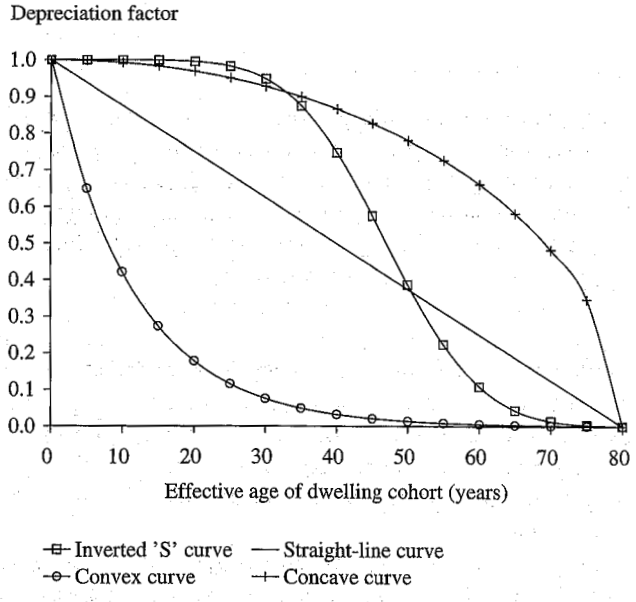

Figure 2 Reversed 'S' (squares), straight line, convex (circles) and concave (crosses) depreciation

Service lifespan of housing stock

The service lifespan of a housing stock is defined here as that age beyond which less than 0.1% of the oldest dwelling cohort still stands and provides dwelling services. This definition based on Shryock and Siegel and Associates (1973) excludes exceptional dwellings, thus enabling sensible comparisons of the service lifespans of different housing stocks. The current service lifespan of New Zealand housing stock is 140 years (Johnstone, 1994).

The service life of dwellings is ultimately limited by the service life of the structural systems used by dwellings. The potential service life of lightweight timber framing is indicated by New Zealand's oldest dwelling, Kemp House, which was constructed in 1821 (Salmond, 1986). Given that few European dwellings were constructed in New Zealand prior to 1860 and that most departures from a housing stock are the end result of an economic process, and not general failure of the structural system, a service life of 180 years for

Table 2 Costs of annual maintenance

	Average annual costs June 1997 NZ$	Percentage of construction unit
Costs based on NZ housing corporation records		
Electric range: repairs	26.20	
Hotwater cylinder: repairs	20.52	
Electrical: outlets, lighting, meter board, minor wiring	27.01	
Taps: washers, replacement	10.58	
Waste pipework: clear blockages, repair soil pipe junctions	13.09	
Water supply	15.90	
Drainage system: clear blockages, repair soil line	23.18	
Spouting and downpipes: clean out, repair	26.24	
Flashings: repair	3.24	
Hardware: door locks, window catches	6.75	
Glazing: repairs to windows	4.08	
Miscellaneous	56.63	
Unspecified due to illegibility or inadequacy of entry on card	36.49	
Subtotal	269.91	0.284
Costs based on 1996 National Modal House (Rawlinsons Group, 1997)		
Preparation and painting of roof averaged over 7 years	159.69	0.168
Preparation and painting wall cladding averaged over 8 years	213.22	0.224
Total	642.82	0.676

lightweight timber framing is not necessarily exceptional. The potential service life of lightweight timber framed construction is substantiated by examples of dwellings of similar construction in other countries. Brand (1994) documents a number of lightweight timber framed dwellings constructed in the United States prior to 1800 that are still standing. The potential service lifespan of housing stock constructed from lightweight timber framing is therefore set to be 200 years.

Constraints and procedure of optimization

Reversed 'S' curve depreciation forms a base scenario against which the remaining three depreciation scenarios are compared. Variations in the service lifespan ω, interval between cycles of full refurbishment z, and annual expansion rate r of the housing stock form different cases within each scenario.

The primary probability of loss schedule, q_h, and the discount rate $i = 0.06$ are fixed. The annual expansion rate r and the service lifespan of the housing stock ω are constrained as follows: $0 \leq r \leq 2.0\%$ per year; $51 \leq \omega \leq 200$ years. The upper limit interval z between each cycle of full refurbishment is constrained as follows: $z \leq 80$ years for $r = 0\%$ per year and $z \leq 51$ for $r = 2.0\%$ per year under all scenarios. The lowest limit interval z is determined by the earliest age at which full refurbishment can be justified.

A stagewise optimization procedure is used to estimate local extrema and stationary values under each scenario and cases within each scenario.

Results

Global extremum under the base scenario

The objective function under the base scenario is optimized when the simulated housing stock is stationary, the interval between each cycle of full refurbishment $z = 38$ years, and the number of cycles of full refurbishment extends the service lifespan of the simulated housing stock from $\omega_p = 80$ years to the maximum constraint of $\omega = 200$ years. National average costs are 24.2% smaller than that for a primary housing stock (0.0245 versus 0.0323 cu/sye). Full results are listed in Table 4.

Alternative economic depreciation scenarios

Table 5 lists the national average costs for a stationary housing stock under the scenarios of reversed 'S' curve (base scenario), straight-line curve, concave curve, and convex curve depreciation.

The objective function is minimized under all scenarios when the simulated housing stock is stationary and $\omega = 200$ years. The optimum interval z between each cycle of full refurbishment declines as the severity of economic depreciation with effective age

Table 3 Cost of full refurbishment. Schedule based on New Zealand Institute of Valuers (NZIV, 1996) pricing based on unpublished priced schedule provided by Rawlinsons Group (1997)

Component replaced or resurfaced	June 1997 NZ$	Average Proportion (%)	June 1997 NZ$	Cycle z (years)	Source of cycle and proportion
Substructure	6 179.15	15	926.87	40	Tucker and Rahilly (1990)
External and internal wall framing	5 980.38	15	897.06	40	Tucker and Rahilly (1990)
External cladding and trim	5 521.82	100	5 521.82	50	Page (1997)
Internal linings and trim	7 127.57	30	2 138.28	40	Tucker and Rahilly (1990)
Aluminium windows and doors	7 253.33	100	7 253.33	40	NBA Construction Consultants (1985)
Joinery fittings: kitchen, bathroom	8 067.38	100	8 067.38	25	NBA Construction Consultants (1985)
Controlled combustion heater	3 364.32	100	3 364.32	15 to 40	NBA Construction Consultants (1985)
Roofing	3 738.65	100	3 738.65	50	Page (1997)
Spouting and downpipes	963.55	100	963.55	20+	NBA Construction Consultants (1985)
Plumbing pipework and traps, flashings	1 769.84	100	1 769.84	20-40	NBA Construction Consultants (1985)
Plumbing fittings	2 640.24	100	2 640.24	25-40	NBA Construction Consultants (1985)
Electrical: wiring	1 971.93	50	985.97	40	Tucker and Rahilly (1990)
Electrical: stove and hotwater cylinder	1 388.20	100	1 388.20	25	NBA Construction Consultants (1985)
Interior painting.	3 575.09	100	3 575.09	8	Tucker and Rahilly (1990)
Floor covering: vinyl sheet	1 338.27	100	310.87	15 to 30	NBA Construction Consultants (1985)
Flooring finish: polyurethane	1 027.40	100	1 027.40	10	NBA Construction Consultants (1985)
Demolition and removal of rubbish	1 025.00	100	1 025.00		
Total			45 593.87		

Table 4 Results of global extremum under the base scenario ($r = 0$)

	Primary housing stock	Global extremum	Percentage difference
Optimum interval between refurbishment	–	38	–
Number of refurbishment cycles	–	4	–
Service lifespan (years)	80	200	150.0
Average service life (years)	47	128.0	172.3
Mean age of housing stock (years)	24.7	81.1	228.3
Service loss index (sye/dg/yr)	0.869	0.962	10.7
Applied cost per refurbishment (cu/dg)	–	0.479	–
Annual replacement costs (cu/dg/yr)	0.0213	0.0078	-63.4
Annual maintenance costs (cu/dg/yr)	0.0068	0.0068	0.0
Annual refurbishment costs (cu/dg/yr)	0.0000	0.0090	–
Annual total costs (cu/dg/yr)	0.0280	0.0235	-15.7
National average costs (cu/sye)	0.0323	0.0245	24.2

Table 5 Results of global extremum under reversed 'S', straight-line, convex, and concave curve depreciation (r = 0, ω = 200 years)

	Reversed 'S' (base scenario)	Straight-line	Convex	Concave
Optimum interval z between refurbishment (years)	38	36	20	38
Service loss index (sye/dg/yr)	0.962	0.759	0.401	0.958
Difference in SLI from base scenario (%)	–	-21.1	-58.3	-0.5
National average costs (cu/sye)	0.0245	0.0311	0.0754	0.0245
Difference in NAC from base scenario (%)	–	26.9	207.8	0.0

increases. National average costs under the two most realistic scenarios, reversed 'S' and concave curve depreciation, are practically the same, whereas national average costs under the straight-line and convex curve depreciation scenarios differ by 26.9% and 207.8%, respectively, from that for the base scenario.

Current reductions in national average costs

There is no single statistic that measures the refurbishment process in New Zealand, and the service loss index of New Zealand housing stock is unknown. Upper and lower limit estimates of current reductions in national average costs are therefore made. The bases of these estimates are listed in Table 6.

The upper limit estimate of 32.5% is based on the minimum known costs of refurbishment between 1921 and 1989. The average annual replacement rate and average expansion rate of the New Zealand housing stock between 1921 and 1981 were 0.39% and 2.3% per year, respectively (Johnstone, 1994). Additions and alterations averaged 14.4% of the value for new construction between 1921 and 1989 (Statistics New Zealand, 1921–1990). Venter (1980) estimated that 28% of the value of additions and alterations carried out over a two-year period from 1977 to 1979 included additions such as garages, decks, and swimming pools. Alterations (refurbishment) during this period constituted 10.4% of new construction by value (0.000 35 cu/dg/yr). The service loss index (0.918 sye/dg/yr) is taken to be the same as that for a primary housing stock.

The lower limit estimate of 15.5% is based on the costs required to undertake full and complete refurbishment (47.9% of the costs to construct a new dwelling), the optimum age at which full refurbishment should take place (z = 27 years when r = 2.3%), and the proportion of dwellings which undergo full refurbishment within the expanding housing (2.46%) when that housing stock is subject to the same mortality as that for New Zealand housing between 1860 and 1980. The service loss index (0.977 sye/dg/yr) is taken to be the same as that for the simulated housing stock which uses a primary mortality regime (z = 27 years).

The potential for further reductions in national average costs

The national average costs of a stationary housing stock decrease by 5.0% (0.0258 to 0.0245 cu/sye, optimum z = 38 years) under the base scenario when additional cycles of full refurbishment extend the service lifespan of the housing stock from 140 years to 200 years, and decrease by 0.4% (0.0473 to 0.0471 cu/sye, optimum z = 27 years) when the expansion rate of the housing stock remains constant at 2.3% per year. If

Table 6 Estimate of reductions in national average costs (r = 2.3%, ω = 140 years)

	Annual maint. (cu/dg/yr)	Annual refurb (cu/dg/yr)	Annual replace (cu/dg/yr)	Annual new-build (cu/dg/yr)	Service loss index (sye/dg/yr)	National average costs (cu/sye)	Reduction in NAC (%)
Primary service life span ω_p = 80 years							
Primary housing stock (no refurbishment)	0.00676	0.00000	0.02077	0.02335	0.918	0.05542	
Upper limit estimate (partial refurbishment)	0.00676	0.00035	0.00388	0.02335	0.918	0.03741	32.5
Lower limit estimate (full refurbishment)	0.00676	0.01178	0.00388	0.02335	0.977	0.04685	15.0
Simulated housing stock (full refurbishment)	0.00676	0.01041	0.00569	0.02335	0.977	0.04730	14.7

the expansion rate of the simulated housing stock declines from 2.3% to 1.0% per year and the service lifespan of the housing stock remains unchanged at 140 years, then national average costs decrease by 23.7% (0.0473 to 0.0361 cu/sye, z held fixed at 27 years). Full results are listed in Table 7.

Sensitivity analysis of lower limit estimate of reductions in national average costs

A lower limit estimate of current reductions in national average costs (r = 2.3%) is 18.3% when the primary service life span ω_p = 60 years and 12.1% when ω_p = 100 years, compared with 15.5% when ω_p = 80 years. A summary of results is listed in Table 8.

Conclusions

Exploratory estimates indicate that refurbishment of New Zealand dwellings has reduced the national average costs to sustain dwelling services by a magnitude of 15%. Each reduction in national costs subsequent to an additional cycle of refurbishment is subject to diminishing returns as there are progressively fewer old dwellings still standing that can take advantage of refurbishment. The potential for further reductions in national costs is therefore modest (5%) should the housing stock be stationary, and is negligible should the expansion rate of the housing stock be as high as 2.0% per year, because an expanding housing stock has relatively fewer old dwellings which can take advan-

Table 7 Estimate of potential reductions in national average costs

	r = 0%		r = 2%		r = 1%
	ω = 140	ω = 200	ω = 140	ω = 200	ω = 140
Optimum interval between refurbishment	38	38	27	27	
Applied interval between refurbishment	38	38	27	27	27
Number of refurbishment cycles	2	4	4	6	4
Average service life (years)	96.8	128.0	94.9	113.2	109.2
Mean age of housing stock (years)	55.9	81.1	31.3	32.9	48.1
Service loss index (sye/dg/yr)	0.939	0.962	0.977	0.978	0.981
Applied cost per refurbishment (cu/dg)	0.479	0.479	0.479	0.479	0.479
Annual replacement costs (cu/dg/yr)	0.0103	0.0078	0.0057	0.0053	0.0060
Annual new-build costs (cu/dg/yr)	0.0000	0.0000	0.0233	0.0233	0.0101
Annual maintenance costs (cu/dg/yr)	0.0068	0.0068	0.0068	0.0068	0.0068
Annual refurbishment costs (cu/dg/yr)	0.0072	0.0090	0.0104	0.0106	0.0126
Annual total costs (cu/dg/yr)	0.0243	0.0235	0.0462	0.0461	0.0354
National average costs (cu/sye)	0.0258	0.0245	0.0473	0.0471	0.0361
Reduction in national average costs (%)	–	5.0	–	0.4	

Table 8 Sensitivity analysis of reductions in national average costs for New Zealand housing stock due to refurbishment (r = 2.3%, ω = 140 years)

	Annual maint. (cu/dg/yr)	Annual refurb (cu/dg/yr)	Annual replace (cu/dg/yr)	Annual new-build (cu/dg/yr)	Service loss index (sye/dg/yr)	National average costs (cu/sye)	Reduction in NAC (%)
Primary service life span w_p = 60 years							
Primary housing stock (no refurbishment)	0.00676	0.00000	0.03098	0.02335	0.908	0.06728	
Lower limit estimate (full refurbishment)	0.00676	0.01777	0.00388	0.02335	0.976	0.05303	21.2
Simulated housing stock (full refurbishment)	0.00676	0.01579	0.00776	0.02335	0.976	0.05498	18.3
Primary service life span ω_p = 100 years							
Primary housing stock (no refurbishment)	0.00676	0.00000	0.01497	0.02335	0.926	0.04868	
Lower limit estimate (full refurbishment)	0.00676	0.00766	0.00388	0.02335	0.973	0.04281	12.1
Simulated housing stock (full refurbishment)	0.00676	0.00640	0.00553	0.02335	0.973	0.04320	11.3

tage of refurbishment. A decline in the expansion rate of a housing stock has a greater impact on reducing national costs to sustain dwelling services than an increase in the number of cycles of refurbishment.

For the sake of simplicity, the simulation model is based on all refurbishment taking place simultaneously, irrespective of the optimum replacement and resurfacing cycles of individual building components. Some building components are therefore replaced more frequently than necessary with each optimum cycle of full refurbishment, and interior decorating, for example, take place less frequently than normal. The simulation model can be modified to include different cycles of refurbishment, but data on the subsequent impact on mortality and economic depreciation of dwelling services would need to be available for such a model to be viable.

Extreme assumptions have been made in this paper where data have been limited or unavailable so as to establish the boundaries of a penumbra within which more precise estimates lie. The results lack precision, but they do establish an order of magnitude and provide an insight into the dynamics of undertaking periodic refurbishment. For example, the results of this paper highlight that permitting widespread use of short-lived structural systems within a housing stock would dramatically increase the national costs to sustain dwelling services.

Although the results of this paper are specific to lightweight timber framing as used in New Zealand, the simulation model can be used for other housing stocks or building stock in general. When lightweight timber framing is used as the structural system, exterior wall cladding and internal linings are fixed to the structural system. With heavyweight construction such as brick, stone, and concrete, the exterior cladding and the structural system can be one and the same. The initial costs of heavyweight construction may be greater than lightweight timber framing (cost structures of alternative structural systems differ in each country), but maintenance and refurbishment costs would be smaller. Heavyweight construction is inherently more durable than lightweight timber framing and the potential service life of heavyweight construction is greater, as the many examples of buildings in Brand (1997) demonstrate. The national average costs to sustain dwelling services using heavyweight construction may be smaller than those using lightweight timber framed construction, but studies are needed to confirm this or otherwise. In making comparisons between different countries it must be appreciated that economic depreciation of dwelling services includes factors of obsolescence, so depreciation is specific for each country, as are standards of dwelling services.

Lightweight timber framing in New Zealand currently undergoes a timber preservative treatment and the service lifespan of these treated timbers may be much greater than the limit of 200 years as used in this paper. The results of this paper indicate that a longer service life alone will not enable significant decreases in the national average costs to sustain dwelling services. Given a set standard of dwelling services, it is a balanced combination of capital costs, maintenance costs, and service life of both structural system and building components that will reduce national costs to sustain dwelling services. Furthermore, the full potential of reductions in national costs due to refurbishment can only be realized when the expansion rate of a housing stock declines.

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Appendix: Introduction to life tables

A life table of a housing stock is a simulation model consisting of a set of nonlinear schedules that are constructed from age-specific loss and survivorship data. Each schedule is a mathematical transform of another as follows (Keyfitz and Beekman, 1984).

Probability of loss (${}_nq_x$) is the proportion of dwellings that are standing at the beginning of an age interval that will be lost from the housing stock before reaching the end of the age interval. Probability of loss is given by

$$ {}_nq_x = \frac{l_x - l_{x+n}}{l_x} \qquad \text{(A1)} $$

where l_x and l_{x+n} are the expected surviving stock which survive to the exact age x and $x + n$ marking the beginning of each respective age interval. By convention, the subscript for the age interval (n) is omitted when $n = 1$.

Stock losses (${}_nd_x$) give the dwelling losses over successive age intervals x to $x + n$. Stock losses are given by

$$ {}_nd_x = l_x - l_{x+n} \qquad \text{(A2)} $$

The stock in age interval (${}_nL_x$) gives the number of dwellings in each age interval within a stationary and stable housing stock. The stock in age interval can also be interpreted as the number of dwelling service years between the start of two adjacent age intervals x and $x + n$ provided by a single dwelling cohort. The stock in age interval is given by

$$ {}_nL_x = nl_x - {}_nd_x \; {}_na_x \qquad \text{(A3)} $$

where ${}_na_x$ is the average number of dwelling service years that are provided by dwellings lost over the age interval.

Total useful life (T_x) gives the number of stationary stock dwellings in an indicated age interval and all subsequent age intervals. Alternatively, total useful life is the total dwelling service years provided by a dwelling cohort after the age of x. Total useful life is given by

$$ T_x = {}_nL_x + {}_nL_{x+n} + {}_nL_{x+2n} + \ldots \sum_{k=0}^{\infty} {}_nL_{x+kn} \qquad \text{(A4)} $$

for $k = 0, 1, 2, \ldots$

Life expectancy at age x (e_x) gives the average number of dwelling service years remaining to be provided by those dwellings which are still standing at the beginning of an age interval from x to $x + n$. Life expectancy at age x, or remaining average service life at age x, is given by

$$ e_x = \frac{T_x}{l_x} \qquad \text{(A5)} $$

The life expectancy upon entry (e_0), or average service life (upon entry), is given by

$$ e_0 = \frac{T_0}{l_0} \qquad \text{(A6)} $$