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Development of a model to estimate the benefit-cost ratio performance of housing

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A simulation model based on classical population dynamics is developed to estimate the benefit-cost ratio performance of different typologies of housing with the purpose of identifying potential reductions in the total costs and hence resources used to sustain housing. A typical New Zealand dwelling constructed of lightweight timber framing is used as an example. Dwellings within the simulation model undergo periodic cycles of refurbishment based on best practices. When the simulated housing stock expands at the rate of 1.5% per year, an annual expenditure equivalent to the costs to construct one dwelling sustains the services provided by 26.7 dwellings after adjustment for economic depreciation. This benefit-cost ratio performance improves by 32.4% when the housing stock is stationary. Further improvements of 5.3% can be achieved by deferring refurbishment and accepting a higher level of economic depreciation of dwelling services. The results of all scenarios indicate that structural systems with a service life of only 50 years should not be used unless the costs of such systems are substantially less than the costs of traditional structural systems and that lightweight timber framed dwellings should not be sustained well beyond a service life of 90 years.

Keywords: sustainability, housing stock, simulation model, benefit-cost ratio

Introduction

The production processes that create, maintain, refurbish, demolish and replace capital stock also pollute the environment (Oka *et al.*, 1993) and there are limits to the levels of pollution that the environment can absorb (Tietenberg, 1992). There are also economic and physical limits to the extent that pollution generated by production processes can be minimized (Georgescu-Roegen, 1976). A fundamental principle of strong sustainability therefore is that a minimum flow of resources should be used to sustain the services provided by capital stock. Abidance by this principle mitigates pollution and conserves stocks of depletable resources for use by future generations.

Housing forms a significant proportion of all capital stock. For example, Philpott (1992) estimates that housing in 1989 formed 23% of the total value of New Zealand's capital stock, including infrastructure, plant and machinery. Throughout the world there is a need to replace existing housing and provide additional housing, a need that involves choices as to which typology of housing to use. These choices in turn largely determine the flow of resources used to sustain housing. This paper develops a simulation model to estimate the benefit-cost ratio performance of different typologies of housing with the purpose of identifying potential reductions in the total costs and hence resources used to sustain housing.

A dynamic stock and flow model is required to estimate the benefit-cost ratio of housing because the annual replacement rate of a housing stock is a function of the distribution of dwelling losses from each dwelling cohort over its service life span, the distribution of dwellings by age and the expansion rate of the housing stock (Johnstone, 2001b). Previous stock and flow models of housing include that by Woodhead and Rahilly (1986), which focuses solely on the flows of new construction, Glenck and Lahner (1996) which estimates the waste management requirements for the

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region of Upper Austria, and Kohler *et al.* (1997), which estimates the energy and mass flows of the German building stock. Johnstone (1998) estimates the optimum timing of a single cycle of full refurbishment of dwellings and Johnstone (2001a) makes exploratory estimates of the current and potential reductions in national costs to sustain housing stock due to periodic cycles of full and complete refurbishment. In this paper, a typical New Zealand dwelling constructed of lightweight timber framing is used as an example to demonstrate use of the simulation model. Dwellings within the simulation model undergo periodic cycles of refurbishment where the refurbishment cycles of components are independent and the durations of the cycles are based on best practices.

Method

Description of simulation model

The simulation model is based on the theories of classical population dynamics (Keyfitz, 1968) and can be visualized as a multi-deck stack where the level of each deck represents the age of a dwelling cohort. A new dwelling cohort enters the first deck of the 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 the Appendix. 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, whereas if the housing stock undergoes expansion, then new construction consists of both replacement construction and new-build construction that adds to the size of the housing stock.

Typology of housing and homogeneity

The simulation model is used to examine and compare the benefit-cost ratio performance of different typologies of housing. A standard dwelling represents each typology of housing and each standard dwelling should have the same floor area to enable a fair comparison. In a simulation model of a particular typology of housing each dwelling is replaced by an identical dwelling. A housing stock consisting of different typologies of dwellings and floor areas can be simulated by combining separate simulation models.

A typical New Zealand dwelling constructed of lightweight timber framing is used as an example for the purposes of demonstrating use of the simulation model. The standard dwelling that represents this particular typology of housing is based on the National Modal House (NZIV, 1996). The standard dwelling is detached and has a floor area of 100 m^2.

Fixed land use density

The density of land use is fixed in the simulation model so an expanding housing stock scenario implies an extension of an urban area. The simulation model can be used to compare the benefit-cost ratio performance of detached, terraced and high-rise apartment dwellings, but a separate spatial model is required to estimate expenditure on transport per dwelling for each land use density.

Costs of services supplied by infrastructure not included

The simulation model does not include the costs of services provided by infrastructure such as heating, cooking, water supply, waste disposal and telecommunications. These costs are best estimated using separate and independent models. It is noted that an expanding housing stock, irrespective of land use density, will require an expanding infrastructure.

Recycling

The simulation model can be used to estimate the impact of recycling at a component level. Recycling is not addressed in this paper due to lack of hard data in New Zealand.

Service life of dwellings

This paper adopts the ISO/DIS 15686-1 (1998) definition of 'service life' as the period of time after installation during which a building or its parts meets or exceed the performance requirements. The service life of a dwelling is that period over which a dwelling provides an acceptable standard of dwelling services.

The service life of a dwelling is ultimately limited by the service life of its structural system, as a dwelling can no longer provide dwelling services when general structural failure occurs. Lightweight timber framed dwellings have a potential service life of at least 180 years under New Zealand's climate as illustrated by Kemp house constructed in 1821 (Salmond, 1986). However, the majority of such dwellings do not realize this potential service life as the average service life and service life span (see Appendix for definitions) of the New Zealand housing stock is 90 years and 140 years respectively (Johnstone, 1994). Early departures from the housing

stock are the end result of an economic process and natural disasters such as fire and earthquake.

Departure of dwellings from the housing stock

Empirical studies of the mortality of housing confirm that dwellings depart from a housing stock at all ages and that the rate of losses from each dwelling cohort is non-linear over its service life span (Gleeson, 1985; Komatsu, 1994; Johnstone, 1994). For example, Gleeson (1985) estimates that of each original dwelling cohort that enters the Indianapolis housing stock, approximately 14% are lost between entry and the age of 70 years with a further 29% being lost between the age of 70 and 95 years. Johnstone (1994) estimates similar rates of losses for New Zealand housing stock and has established that the mortality of New Zealand housing stock is dynamic in that mortality is not only a function of age but also the expansion rate of the housing stock. The proportion of dwellings that depart from the housing stock each year increases when the expansion rate of the housing stock increases and decreases when the expansion rate decreases. The construction of new-build infill housing during expansionary periods enabled by early demolition of existing dwellings provides one explanation of the dynamic nature of the mortality.

The economic life of a dwelling is over when the value of a cleared site for a new use is greater than the value of the property (land and buildings) in its current use plus the costs of demolition and site clearance (Heilbrun and McGuire, 1987). Put in another way, demolition and replacement can be justified when the net increase in value of the property is greater than the costs to bring about that increase. Not all dwellings undergo demolition and replacement or redevelopment upon the end of their economic lives. One reason why is because the use value of the property to the owners is greater than the exchange value offered by developers. An unknown proportion of dwellings continue to be technically efficient by providing dwellings services and net rent (or imputed rent) well after the end of their economic lives. Given that current rates of land use succession do not necessarily result in the minimum national costs to sustain housing, the current schedule of mortality of New Zealand housing stock is adopted under the base scenario to provide realism and the service life span of the simulated housing stock is varied from 30 years to 180 years, the potential service life of lightweight timber framed dwellings. Dwellings depart from each dwelling cohort at all ages and all remaining dwellings within a dwelling cohort depart from the housing stock in the final year of its selected service life span. The schedule of probability of loss used in the simulation model is described in the data and parameter section.

Benefit-cost ratio criterion (BCR)

Investment streams allocated to maintenance, refurbishment, replacement construction and new-build construction need to increase or decrease in any proportion in order to minimize the costs to sustain housing. A benefit-cost ratio (BCR) criterion is therefore used instead of an excess benefits over costs criterion to rank alternative investment streams (Mishan, 1982).

The benefit-cost ratio is simplified when a housing stock expands at a constant growth rate or remains stationary. Under these conditions, the distribution of dwellings by age remains stable and the BCR takes the simple form of the ratio of the sum of the total discounted benefits over each time interval to the sum of the total discounted costs required to sustain those benefits.

$$\mathrm{BCR} = \frac{{}_nB_t \sum_{t=0}^{\infty} v^t e^{nrt}}{{}_nC_t \sum_{t=0}^{\infty} v^t e^{nrt}} = \frac{{}_nB_t}{{}_nC_t} \qquad (1)$$

where ${}_nB_t$ is the benefits over the time interval t to $(t+n)$; ${}_nC_t$ is the costs over the same time interval t to $(t+n)$; v is the real discount factor where $v = 1/(1+i)$; i is the real discount rate; n is the time interval over which benefits are realized and costs are expended; and r is the annual expansion rate of the housing stock. The benefit-cost ratio simplifies to the ratio of benefits over a single time interval to costs over the same time interval.

Expansion rate of the housing stock

Positive net migration currently forms the major source of effective demand to form additional households (Statistics New Zealand, 2003). This is because the fertility of the natural population has declined since the 1960s to the extent that the natural population now barely replaces itself. The average number of persons per household has declined from over 6.0 in 1900 to 2.7 at the last Census in 2001 (Statistics New Zealand, 2003). Further decreases over the next number of decades are likely to be gradual. The annual expansion rate of the simulated housing stock is set to be 0% and 1.5%, the average expansion rate of the housing stock over the past decade.

Proxies for benefits and costs

A benefit-cost ratio criterion does not require benefits and costs to be measured in the same metric in order to correctly rank alternative investment streams (Fisher, 1923). Benefits and costs in this paper are expressed in units of quantities, instead of value, in order to provide a

Table 1 Costs and cycles of refurbishment

Component	Propn (%)	Cost 1997 NZ$	Cycle z (years)	Source of cycle and proportion
Substructure	15	1326.87	40	Tucker and Rahilly (1990)
Wall framing	15	1246.02	40	Tucker and Rahilly (1990)
External cladding & trim	100	5611.42	50	Page (1997)
Internal linings & trim	30	2138.27	40	Tucker and Rahilly (1990)
Aluminium windows & doors	100	7975.61	40	NBA Consultants (1985)
Fittings: kitchen, bathroom	100	8307.88	25	NBA Consultants (1985)
Combustion heater	100	3472.78	40	NBA Consultants (1985)
Roofing	100	4530.88	50	Page (1997)
PVC spouting, downpipes	100	1128.60	20	NBA Consultants (1985)
Plumbing piping & traps	100	1812.82	40	NBA Consultants (1985)
Plumbing fittings	100	2825.88	40	NBA Consultants (1985)
Electrical: wiring	50	1452.42	40	Tucker and Rahilly (1990)
Electrical: stove & HWC	100	1477.80	25	NBA Consultants (1985)
Prep & painting interior	100	3575.09	8	Tucker and Rahilly (1990)
Prep & painting of roof	100	1117.80	7	Page (1997)
Prep & painting of cladding	100	1705.72	9	Page (1997)
Floor covering: vinyl sheet	100	360.00	30	NBA Consultants (1985)
Polyurethane floor finish	100	1027.40	10	NBA Consultants (1985)

more illuminating measurement of performance than a dimensionless index and to enable immediate comparisons of the benefit-cost ratio performance of housing in different countries. Dwelling service year equivalents (sye), the dwelling services provided by a dwelling over one year adjusted for physical depreciation and obsolescence, serve as a proxy for benefits. Dwelling construction units (cu), the costs to construct one dwelling, and fractions thereof, serve as a proxy for the costs of new-build construction, maintenance, refurbishment, demolition and replacement. Both proxies can be converted into dollar value terms by multiplying by their respective prices.

Dwelling services exclude the services of land

Dwelling services in this paper include only those services provided by improvements to land and specifically exclude the services of land for which ground rent or imputed ground rent is paid. Dwelling services and land services are separated in order to avoid confounding economic depreciation of improvements and appreciation of land values.

Maintenance and refurbishment

Maintenance is defined herein as comprising all that work undertaken to retain the provision of essential services such as watertight shelter, security, lighting, heating, water supply and waste disposal.

Refurbishment is defined herein as the resurfacing or replacement of building components that results in a reversal of the economic depreciation of dwelling services. Under a base scenario, the duration between each refurbishment cycle for each component is based on best practices as cited in Table 1. The durations between all refurbishment cycles are varied by ±10% and +20% under alternative scenarios.

In practice, not all dwellings undergo refurbishment when due and dwellings are unlikely to undergo refurbishment as they approach the end of their anticipated service life. Under the base scenario, the proportion of dwellings (P_y) within each cohort that undergo refurbishment when due is set to be the ratio of the dwellings still standing at the end of a refurbishment cycle of duration z to that standing at the start of the cycle (see Appendix):

$$P_y = \frac{l_{y+z}}{l_y} \tag{2}$$

where y is the age at which refurbishment takes place.

Real costs of construction over time

The real costs of all construction activities including maintenance, refurbishment and demolition are assumed to remain constant over time. Under this assumption, the long run supply curve of the construction industry is perfectly elastic and returns to scale are constant. In practice, the scarcity rent of construction materials will increase over time thus increasing the price of construction. Use of cheaper substitutes will mitigate increases in costs. Long-run price increases in construction and subsequent upward shifts in the long-run supply curve will result in corresponding increases in rent (or imputed rent) for housing. The

magnitude of increases in rent depends on the price elasticity of demand for housing. Because the price elasticity of demand for housing is inelastic, long run increases in the price of construction will result in a proportionately smaller contraction in the quantity of demand. Increases in rent for housing will therefore be of a similar magnitude to that of increases in the price of construction and if the benefit-cost ratio based on proxies is converted into a benefit-cost ratio based on value, then there would be a minor reduction in the resultant benefit-cost ratio.

Real costs of construction over the service life of dwellings

The real costs of construction, maintenance, refurbishment and demolition are set to remain constant over the service life of each dwelling under the base scenario. Studies of samples of dwellings in New Zealand (Clark *et al.*, 2000) and Australia (McFallan and Then, 2002) show that maintenance and refurbishment costs of housing increase with age. Real maintenance and refurbishment costs are set to increase exponentially by 0.5% over the service life of a dwelling under an alternative scenario.

The model

Benefits in the numerator of the BCR

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

$$L_x = l_x - d_x \cdot a_0 \tag{3}$$

where l_x is the number of dwellings from an original dwelling cohort, l_0, which survive to the age x, d_x is the number of dwelling losses from a dwelling cohort of 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 $a_0 = ½$ when $n = 1$ gives sufficiently precise results for the purposes of simulating the dynamics of a housing stock.

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) and the probability of loss function $P(x, r)$:

$$d_x = l_x \cdot P(x, r) \tag{4}$$

where r is the annual expansion rate of the housing stock. The probability of loss function $P(x, r)$ is explained in more detail in the Data and parameters section.

New construction entries over the time interval t to $(t+1)$ are given by

$$\begin{aligned} l_0 &= \sum_{x=0}^{\lambda} d_x + P_{t+1} - P_t = \sum_{x=0}^{\lambda} d_x + (\exp r - 1)P_t \\ &= \sum_{x=0}^{\lambda} d_x + (\exp r - 1)\sum_{x=0}^{\lambda} l_x \end{aligned} \tag{5}$$

where λ is the service life span of the housing stock, 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 $(t+2)$. The size of the housing stock at time t (P_t) is simply the sum of all the dwelling cohorts that are standing at time t.

Dwelling services are adjusted for depreciation. The flow of dwelling service year equivalents (S_e) provided by a housing stock over the time interval t to $(t+1)$ is expressed as follows:

$$S_e = \sum_{x=0}^{\lambda} L_x \cdot D(x) \tag{6}$$

where $D(x)$ is an economic depreciation factor that is a function of the age x of dwelling cohorts. The units of $D(x)$ are dimensionless and $0 \le D(x) \le 1$.

The service loss index (SLI) gives 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):

$$\text{SLI} = \frac{S_e}{\sum_{x=0}^{\lambda} L_x} \tag{7}$$

Costs in the denominator of the BCR

The national average costs to sustain housing over the time interval t to $(t+1)$, (C_{total}), is the sum of the costs of new-build construction (C_{new}), annual maintenance (C_{maint}), refurbishment (C_{refurb}), demolition (C_{dem}) and replacement construction (C_{replace}) divided by the sum of dwelling service years provided over the time interval:

$$\begin{aligned} C_{\text{total}} &= \frac{\sum \text{Costs}}{\sum_{x=0}^{\lambda} L_x} \\ &= \frac{C_{\text{new}} + C_{\text{maint}} + C_{\text{refurb}} + C_{\text{dem}} + C_{\text{replace}}}{\sum_{x=0}^{\lambda} L_x} \end{aligned} \tag{8}$$

The units of national average costs to sustain housing are in construction units per dwelling per year (cu/dg/yr).

The costs of new-build construction over the time interval t to $(t+1)$ is given by the number of new-build entries to the housing stock from Equation 5:

$$C_{new} = (\exp r - 1)\sum_{x=0}^{\lambda} l_x \cdot I_{new} \quad (9)$$

where I_{new} is an index of the costs to construct a dwelling in construction units per dwelling (cu/dg).

The costs of maintenance over the time interval t to $(t+1)$ is given by:

$$C_{maint} = \sum_{x=0}^{\lambda} L_x \cdot M(x) \quad (10)$$

where $M(x)$ is a function of maintenance in construction units per dwelling service year (cu/sy).

The costs of refurbishment over the time interval t to $(t+1)$ are given by

$$C_{refurb} = l_\alpha \cdot R_\alpha \cdot P_\alpha + l_\beta \cdot R_\beta \cdot P_\beta + \ldots + l_\theta \cdot R_\theta \cdot P_\theta \quad (11)$$

where $l_\alpha, l_\beta, \ldots, l_\theta$ are the number of surviving dwellings within a dwelling cohort of ages $y = \alpha, \beta, \ldots, \theta$; $R_\alpha, R_\beta, \ldots, R_\alpha, R_\beta, \ldots, R_\theta$ are indexes of the costs to undertake refurbishment at the ages $y = \alpha, \beta, \ldots, \theta$; and $P_\alpha, P_\beta, \ldots, P_\theta$ gives the proportion of dwellings within each dwelling cohort that undergoes refurbishment at the ages of $y = \alpha, \beta, \ldots, \theta$.

The number of departures from the housing stock from equation (4) gives the costs of demolition:

$$C_{dem} = \sum_{x=0}^{\lambda} d_x \cdot I_{dem} \quad (12)$$

where I_{dem} is an index of the costs of demolition in construction units per dwelling (cu/dg).

The number of replacement entries to the housing stock from Equation 4 gives the costs of replacement construction:

$$C_{replace} = \sum_{x=0}^{\lambda} d_x \cdot I_{new} \quad (13)$$

where I_{new} is an index of the costs to replace a dwelling in construction units per dwelling (cu/dg).

The benefit-cost ratio (BCR) of the housing stock is the service life index SLI divided by national average costs C_{total}:

$$BCR = \frac{{}_nB_t}{{}_nC_t} = \frac{S_e}{\sum Costs} = \frac{S_e \Big/ \sum_{x=0}^{\lambda} L_x}{\sum Costs \Big/ \sum_{x=0}^{\lambda} L_x} = \frac{SLI}{C_{total}} \quad (14)$$

Data and parameters

Probability of loss schedule

The best-fit probability of loss schedule $P(x, r)$ for New Zealand housing stock is given by the product of a probability of loss schedule (q_x^S) that applies for a stationary and stable housing stock and a multiplier function of the annual expansion rate r of the housing stock (Johnstone, 2001b):

$$P(x,r) = q_x^S \cdot (1 + 78.62r^{0.70}) = q_x^S \quad \text{for} \quad r = 0. \quad (15)$$

The probability of loss schedule (q_x^S) in the above equation is a transform of the stock losses schedule (d_x^S) that applies for a stationary and stable housing stock where

$$d_x^S = INT\left[\frac{l_0 \cdot b}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}[(x-\mu+0.5)/\sigma]^2}\right] \quad (16)$$

where INT is a function that truncates fractional stock losses to the nearest integer, l_0 is the initial dwellings entries to a life table at age 0 (100,000 initial entries by convention), b is an adjustment factor that ensures the sum of truncated dwelling losses over the service life of a dwelling cohort equals the initial dwelling entries l_0, σ *is* the standard deviation of stock losses from a dwelling cohort within a stationary and stable housing stock, and m is the mean age of stock losses from a dwelling cohort within a stationary and stable housing stock. The values of the standard deviation and mean age of stock losses are 31.08 years and 130 years respectively.

Economic depreciation of dwelling services

No empirical study has been carried out on the economic depreciation of dwelling services (rent or imputed rent excluding rent for land) over the full service life of New Zealand dwellings. According to Baer (1991), a reversed S shaped depreciation schedule (RSS depreciation) forms the most realistic schedule of depreciation of buildings. An RSS depreciation schedule is used under the base scenario. In this paper, the RSS depreciation declines to a threshold value and not to zero because each dwelling within the simulation model either undergoes regular maintenance and refurbishment or departs from the housing stock. Fluctuations in economic depreciation are ignored because rents in practice do not fluctuate with each and every decline in the condition of building components that contribute to dwelling services and subsequent refurbishment of those components.

S-shaped curve depreciation is described by the standard logistic curve

$$Q(x) = \frac{K}{1 + ce^{-rmx}}, \quad c = \frac{K}{Q(0)} - 1 \quad (17)$$

Reversed s-shaped curve depreciation is described by

$$D(x) = \frac{P - Q(x)}{P - Q(0)} \quad \text{for} \quad P \geq Q(x) \quad (18)$$

The current service life span of New Zealand housing stock is 140 years (Johnstone, 1994), so the threshold age is set to 140 years. In the absence of empirical data on the value of a lower limit threshold for economic

Table 2 Results of maximum BCR under base scenario

		A	B	(A-B)/B
		$r = 0\%$	$r = 1.5\%$	(%)
Benefit-cost ratio	(sye/cu)	35.31	26.68	32.4
Average service life	(yr)	70.2	71.4	−1.7
Mean age of housing stock	(yr)	35.1	29.6	18.6
Service life span	(yr)	71	74	−4.0
Service loss index	(sye/dg/yr)	0.946	0.960	−1.5
Annual new-build cost	(cu/dg/yr)	0.00000	0.01517	–
Annual maintenance costs	(cu/dg/yr)	0.00284	0.00284	0.0
Annual refurbishment costs	(cu/dg/yr)	0.00945	0.00992	−4.7
Annual demolition costs	(cu/dg/yr)	0.00025	0.00014	78.6
Annual replacement costs	(cu/dg/yr)	0.01425	0.00788	80.8
Total average costs	(cu/dg/yr)	0.02679	0.03596	−25.5
Annual new-build costs	(%)	0.0	42.2	
Annual maintenance costs	(%)	10.6	7.9	
Annual refurbishment costs	(%)	35.3	27.6	
Annual demolition costs	(%)	1.0	0.4	
Annual replacement costs	(%)	53.2	21.9	

depreciation due to obsolescence, D(140) is set to approach a value of 0.50 with D(70) = 0.75, P = 10,010, and Q(0) = 10 under the base scenario. Thresholds of D(140) = 0.75 and D(140) = 0.25 are used in alternative scenarios.

Costs of construction, maintenance, refurbishment and demolition

The costs to construct the National Modal House are $94,110.40 in June 1997 New Zealand dollars (NZIV, 1996). Vinyl flooring (10 m^2) in the kitchen and a 3-coat polyurethane floor finish to the remaining floor areas brings the total costs to NZ$95 155.40. 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 prior to1988. The average annual costs of maintenance are $269.91.

Table 1 lists the costs of refurbishment including removal and disposal of existing components and making good to collateral damage in the process. The replacement of component costs are based on the schedule of the National Modal House (NZIV, 1996) and pricing data provided by Rawlinsons Group (1997). The costs of demolition and disposal of a dwelling are $1700.

Results

Under a base scenario, the initial mortality of a simulated housing stock is the same as that for the New Zealand housing stock, depreciation of dwelling services follows a reversed S curve declining to a threshold level of D(140) = 0.50, maintenance and refurbishment costs do not increase over the service life of dwellings, and a proportion only of dwellings undergo refurbishment.

Table 2 compares the maximum benefit cost ratios (BCR) under the base scenario for a stationary and expanding ($r = 1.5\%$) housing stock. The stationary housing stock provides 32.4% more dwellings services per construction unit than the expanding housing stock (35.31 sye/cu versus 26.68 sye/cu) after adjustment for economic depreciation of dwelling services. The maximum BCRs occur when the service life span of the stationary and expanding housing stock is 71 years and 74 years respectively.

Figure 1 shows the BCRs over a range of service life spans for the stationary and expanding housing stock

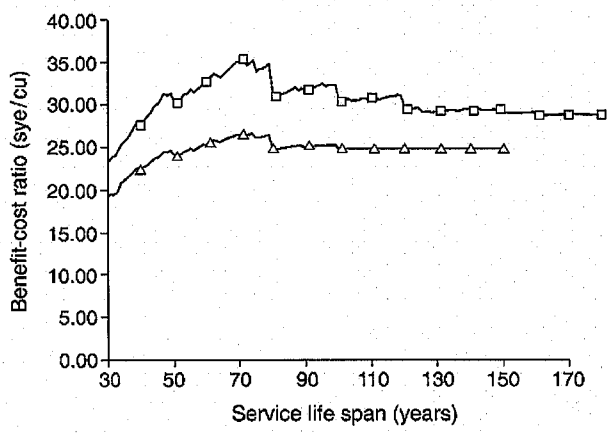

Figure 1 Benefit-cost ratio performance of stationary housing stock (squares) and expanding housing stock with $r = 1.5\%$ (triangles)

Table 3 Results of maximum BCR under alternative scenarios ($r = 0\%$)

	$BCR_{maximum}$			Difference in BCR from $BCR_{maximum}$			
	$\lambda_{optimum}$ (years)	Value (sye/cu)	Diff from base scenario (%)	$\lambda = 50$ (%)	$\lambda_{optimum}$ −5 (%)	$\lambda_{optimum}$ +5 (%)	$\lambda = 180$ (%)
Base scenario	71	35.31	–	−15.9	−3.9	−3.3	−18.7
Depreciation only							
D(140) = 0.75	74	36.35	3.0	−17.9	−1.5	−0.6	−9.2
D(140) = 0.25	71	34.47	−2.4	−14.2	−3.2	−4.1	−29.1
No depreciation	79	37.70	6.8	−20.0	−0.2	−8.1	−1.0
New-build & replacement							
−10% costs	71	37.29	5.6	−15.2	−3.8	−3.5	−20.7
+10% costs	74	33.55	−5.0	−16.6	−0.9	−1.1	−16.8
Maintenance and refurbishment							
Annual increase in costs = 0.5%	71	32.63	−7.7	−13.3	−3.4	−5.0	−31.7
Maintenance only							
−10% costs	71	35.69	1.1	−16.1	−4.0	−3.3	−18.7
+10% costs	71	34.94	−1.1	−15.7	−3.8	−3.3	−18.7
Refurbishment only							
−10% costs	74	36.63	3.7	−16.5	−0.9	−1.1	−16.6
+10% costs	71	34.10	−3.4	−15.4	−3.8	−3.7	−20.5
Early, −10% cycle z	68	33.09	−6.3	−13.8	−1.6	−3.7	−20.0
Deferred, +10% cycle z	78	37.73	6.9	−12.8	−3.5	−4.5	−18.2
Deferred, +20% cycle z	84	39.39	11.6	−14.7	−2.8	−13.7	−16.7
Depreciation and refurbishment							
D(140) = 0.25, +20% cycle z	84	37.48	6.2	−10.8	−1.8	−14.7	−25.5

under the base scenario. The service life span λ of the expanding housing stock is limited to 149 years because it is subject to higher levels of mortality. Both the peak and decline in the BCRs are more pronounced in the stationary housing stock.

Tables 3 and 4 list the results of the maximum BCRs for the stationary and expanding housing stock under alternative scenarios of economic depreciation of dwelling services and costs to sustain dwelling services. The 'no economic depreciation' scenario is unrealistic, but is listed for the sake of completeness. This scenario is not included in the following comparisons.

The $BCR_{maximum}$ under the scenarios of economic depreciation with thresholds of D(140) = 0.75 and D(140) = 0.25 differ less than ±3.0% from that under the base scenario (D(140 = 0.50) for a stationary and expanding housing stock. With the exception of the early and deferred refurbishment scenarios, the optimum service life span for each scenario differ from that for the base scenario by less than ±3 years for both the stationary and expanding housing stocks. In the stationary housing stock the BCRs for $\lambda = \lambda_{optimum} \pm 5$ years differ less than ±5.0% from the $BCR_{maximum}$ whereas in the expanding housing stock the same differ less than ±2.4%. In both the stationary and expanding housing stocks the optimum service life increases by between 4 and 7 years for each 10% increase in the duration of the refurbishment cycle.

The BCRs for $\lambda = 50$ are significantly less than the $BCR_{maximum}$ for the stationary housing stock under all scenarios. The differences in BCRs range from −10.8% to −17.9% whereas the differences in BCRs for the expanding housing stock range from −7.5% to −12.4%. The BCRs for $\lambda = 180$ are significantly less than the $BCR_{maximum}$ for the stationary housing stock under all scenarios. The differences in BCRs range from −9.2% to −31.7% whereas the differences in BCRs for the expanding housing stock ($\lambda = 149$) range from −4.7% to −10.4%.

Discussion

A typical New Zealand dwelling constructed of lightweight timber framing is used as an example to demonstrate use of the simulation model. A simulated housing stock comprised entirely of these detached dwellings undergoes periodic cycles of refurbishment based on best practices. When the housing stock expands at the rate of 1.5% per year, an annual expenditure equivalent to the costs to construct one dwelling sustains the services provided by 26.7 dwellings after adjustment for economic depreciation. This benefit-cost ratio performance improves by 32.4% when the housing stock is stationary. The costs of services provided by infrastructure are not included in the above benefit-cost

Table 4 Results of maximum BCR under alternative scenarios ($r = 1.5\%$)

	$BCR_{maximum}$			Difference in BCR from $BCR_{maximum}$			
	$\lambda_{optimum}$ (years)	Value (sye/cu)	Diff from base scenario (%)	$\lambda = 50$ (%)	$\lambda_{optimum}$ −5 (%)	$\lambda_{optimum}$ +5 (%)	$\lambda = 149$ (%)
Base scenario	74	26.68	–	−11.1	−0.8	−0.8	−6.9
Depreciation only							
D(140) = 0.75	74	27.18	1.9	−12.4	−1.1	−0.4	−4.7
D(140) = 0.25	71	26.23	−1.7	−10.0	−1.9	−1.9	−9.2
No depreciation	79	27.81	4.2	−13.7	0.0	−4.8	−2.8
New-build & replacement							
−10% costs	74	27.28	2.3	−10.1	−0.6	−1.0	−7.6
+10% costs	74	26.11	−2.1	−12.1	−0.9	−0.6	−6.2
Maintenance and refurbishment							
Annual increase in costs = 0.5%	71	25.28	−5.3	−9.5	−2.0	−2.4	−10.4
Maintenance only							
−10% costs	74	26.90	0.8	−11.3	−0.8	−0.8	−6.9
+10% costs	74	26.47	−0.8	−11.0	−0.7	−0.8	−6.8
Refurbishment only							
−10% costs	74	27.44	2.9	−11.6	−0.9	−0.6	−6.0
+10% costs	74	25.97	−2.7	−10.9	−0.7	−1.0	−7.7
Early, −10% cycle z	68	25.36	−5.0	−9.6	−1.3	−1.8	−7.9
Deferred, +10% cycle z	78	27.91	4.6	−8.2	−1.8	−1.7	−6.3
Deferred, +20% cycle z	84	28.83	8.1	−9.6	−1.3	−5.9	−5.5
Depreciation and refurbishment							
D(140) = 0.25, +20% cycle z	84	28.08	5.3	−7.5	−0.8	−6.3	−7.3

ratios and, because the simulation model is not a spatial model, separate estimates of transportation costs per dwelling need to be made when comparing the total benefit-cost ratio performance of low density versus high density housing.

It is a combination and balance of capital costs, ongoing costs and the service lives of both components and dwellings that determine the total costs and hence resources used to sustain housing. The simulation model not only enables comparisons of the benefit-cost ratio performances of different typologies of housing, but also enables exploration of the right balance of the above factors that lead to an improvement in the benefit-cost ratio performance of a particular typology of housing. For example, if the durations of refurbishment cycles based on best practices are deferred by 20% and a lower threshold of depreciation of dwelling services is accepted, then the benefit-cost ratio performance improves by 5.3%. The gap between the average service life of the New Zealand housing stock (90 years) and the optimum service life of the simulated housing stock (84 years) reduces to 6 years in this deferred refurbishment scenario.

Additional uses of the simulation model include forecasting levels of construction activities within the construction industry and estimating the impact of recycling. For example, the simulation model forecasts that annual expenditure on maintenance and refurbishment will shift from 35.5% to 45.9% of total annual expenditure to sustain the housing stock as the expansion rate of the housing stock declines to zero. With minor modifications, the simulation model can be used to estimate the embodied energy and mass flows to sustain housing and the resultant flow of pollutants to the environment as a true flux over time, whereas similar estimates based on an individual building average the flows over the service life of the building. In 1996, non-treated timbers were allowed to be used in New Zealand, a decision that lead to a widely publicized rotting building syndrome a few years later. The longer-term consequences have yet to be estimated. The simulation model enables estimates of the long term impact of premature failure of the structural systems of dwellings by using a hazard function instead of a mortality function as used in this paper.

The results of this paper highlight the issue of short-life versus long-life dwellings. The New Zealand Building Code currently requires components that contribute to structural stability to have a service life of 50 years (Building Industry Authority, 1992). This service life falls well short of the 90-year average service life and 140-year service life span of the New Zealand housing stock (Johnstone, 1994). The benefit-cost ratio performance of a stock of dwellings that satisfies only the minimum requirements of the New Zealand Building Code is significantly inferior to that of lightweight timber framed dwellings should these dwellings have

similar construction, maintenance and refurbishment costs. The benefit cost ratio performance can be inferior by as much as 12.4% when the housing stock expands at the rate of 1.5% and by as much as 17.4% when the housing stock is stationary. The need for New Zealand housing to continue using structural systems with a service life that well exceeds 50 years becomes greater as the expansion rate of the housing stock declines because there are proportionately more older dwellings in a slowly expanding or stationary housing stock that are able to take advantage of refurbishment.

Predictions of the durability of building components based on accelerated ageing tests are fraught with difficulties (Masters, 1987) and, in a recent study of accelerated testing, Rimestad (1998) concludes that field failure data should be used whenever possible to guide the design of accelerated tests. There is a risk that the actual service lives of innovative structural systems fall short of the projected service lives based on accelerated aging tests. The most reliable predictor of durability is a successful history of performance. Structural systems made of traditional materials such as timber, brick, stone and concrete have demonstrated a service life of at least 180 years (Brand, 1997) whereas innovative structural systems using non traditional materials have yet to demonstrate a comparable track record. The results of this paper indicate that it is imprudent to allow use of short-life structural systems with a service life only 50 years unless the costs of such systems are substantially less than that of traditional structural systems. The results also indicate that it is not in the best national interests to sustain lightweight timber framed dwellings well beyond 90 years, especially when the real costs of maintenance and refurbishment increase with age and the expansion rate of the housing stock declines.

The need for additional housing throughout the world is likely to continue for many more decades before replacement construction forms the major proportion of all new housing. The choices of typology of housing in terms of both construction type and density will largely determine the resources required to sustain housing. The right choices need to be made otherwise environmental pollution from manufacturing processes, waste products from demolition, and CO_2 contributions to the atmosphere due to activities by the construction industry will increase by a greater extent than necessary. The true long-term merits of innovative structural systems used by housing should be closely examined, otherwise we risk imposing significant penalties on future generations, and it is imperative that the right choices of housing typology be encouraged and promoted at national level. The development of the simulation model in this paper is a step and contribution in the direction to enable informed choice and decision-making.

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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 non-linear 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

$$ {}_nq_x = \frac{l_x - l_{x+n}}{l_x} \tag{A1} $$

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

$$ {}_nd_x = l_x - l_{x+n}. \tag{A2} $$

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

$$ {}_nL_x = {}_nl_x - {}_nd_x\ {}_na_x \tag{A3} $$

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

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

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 x and $x+n$. Life expectancy at age x, or remaining average service life at age x, is given by

$$ e_x = \frac{T_x}{l_x}. \tag{A5} $$

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

$$ e_0 = \frac{T_0}{l_0}. \tag{A6} $$

The service life span of a housing stock (λ) is defined herein to be that age beyond which less than 0.1% of the oldest dwelling cohort still stands and provides dwelling services. This definition based on Shryock *et al.* (1973) enables sensible comparisons of the service life span of different housing stocks as exceptional dwellings are excluded.