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Stock and Flow Models of Housing

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Title of paper: **Stock and flow models of housing**

Intended category: Sustainable infrastructure and buildings

Abstract

Formulation of sustainable housing policies requires the use of stock and flow models to quantify the dynamic relationships between the benefits of housing in the form of dwelling services and the costs to sustain those services. A number of stock and flow models of New Zealand housing stock have been developed over the past 10 years and a selection of these models and their results are described. These models estimate the average service life of New Zealand housing stock, the maximum expenditure that can be justified on undertaking full refurbishment as opposed to investing in new housing, the energy and mass flows of a standard house, the potential for further reductions in national costs due to refurbishment, and the benefit-cost ratio performance of housing. Recommendations for future research include quantification of the impact of land use succession criteria and taxation schedules on the total costs to sustain buildings in general.

Stock and flow models of housing

Housing in itself is but a means to an end. We are ultimately concerned with the services that housing provides. Government policies and regulations that influence the sustainability of housing should be based on both the level of services provided by housing as well as the costs to sustain those services. Appropriate policies and regulations cannot be formulated when the relationships between the benefits of housing in the form of dwelling services and the costs to sustain those services are uncertain or unknown. It is therefore necessary to establish and quantify these relationships. To do so requires a stock and flow modelling approach due to the dynamic nature of the relationships between benefits and costs over time.

Over the past 10 years the author has developed a number of stock and flow models of the New Zealand housing stock. This paper outlines a selection of these models and addresses issues that affect the sustainability of housing. The selection of models includes a mortality model that estimates the average service life of New Zealand housing stock and an actuarial model that estimates the maximum expenditure that can be justified on undertaking full refurbishment as opposed to investing in new housing. Later models include those that estimate the energy and mass flows of the housing stock, the potential for further reductions in national costs due to refurbishment, and the benefit-cost ratio performance of housing. This paper concludes with recommendations for future research.

Mortality of housing stock

Realistic models of housing stock should be based on empirically established functions of mortality otherwise they will be prone to error. Variations and extensions of the theories and life table models of classical population dynamics have been developed and applied by demographers, statisticians, and ecologists over the past 200 years. There are two basic types of life tables, namely the current, or period life table and the generation, or cohort life table. A current life table is based on age-specific death statistics over a short period and therefore does not represent the mortality experienced by an actual cohort. Instead, it assumes a hypothetical cohort that is subject to age-specific death rates observed over a particular period. A generation life table is based on the mortality actually experienced by cohorts and is therefore useful for studies of shifts in mortality over time and projections of mortality.

A limited number of empirical studies of the mortality of housing stock have been carried out due to severe data difficulties. In the early 1980s Gleeson (1985) carried out a pioneering study of the mortality of a sample of Indianapolis housing stock using a current life table approach. A current life table is based on the implicit assumption that each successive cohort is subject to the same regime of mortality, an assumption which Gleeson (1985) concedes is ‘heroic’ with respect to housing stock. Because there was a scarcity of data for very old dwellings, Gleeson (1985) effectively extrapolated 57% of the sum total of dwelling losses in his life table and estimated the average service life of the housing stock to be 99.6 years. Johnstone (2001a) estimates the true average service life to lie somewhere between 96 and 118 years due to the uncertainty of the true distribution of dwelling losses over the service life of each cohort. The remaining average service life at the start of each successive age interval becomes progressively more indeterminate as the level of uncertainty filters through the life table.

A current life table approach cannot be used to estimate the mortality of New Zealand housing stock due to the lack of data on the age of dwelling demolitions. Statistic New Zealand has periodically published dwelling demolition totals for each year based on notifications received from local authorities and the longest uninterrupted data series covers the period between March 1969 and March 1986. Statistics New Zealand has subsequently ceased collecting and publishing data on dwelling demolitions. Johnstone (1994) therefore developed an indirect modelling approach which uses a linking series of generation life tables. These life tables simulate dwelling losses from each dwelling cohort over successive age intervals when driven by test regimes of mortality. Dwellings losses over the same time interval combine to form a time series of total dwelling losses of all ages. This time series and a snap shot of the distribution of the housing stock by age were compared against field survey data to test the realism and precision of the mortality regimes driving the model. Although an indirect modelling approach does not allow the mortality of housing stock to be estimated to the same precision that a direct current or generation life table approach can, useful results have been obtained.

Johnstone (1994) estimated the average service life of New Zealand housing stock to be 90 years and established that the mortality of New Zealand housing had been dynamic between 1860 and 1980. The probability of loss function $P(x,r)$ for New Zealand housing is given by the product of a base probability of loss (q_x) at age x and a multiplier function:

$$P(x,r) \quad = \quad q_x(1-78.62r)^{0.70}$$

where r is the annual expansion rate of the housing stock. The probability of loss of dwellings from each cohort had simultaneously increased and decreased with each increase and decrease in the expansion rate of the housing stock. Each dwelling cohort had been subject to a different regime of mortality as a result. Figure 1 shows the distribution of dwelling losses from different dwelling cohorts. The initial size of each dwelling cohort is scaled to 100,000 dwellings, the radix or ‘opening ledger’ of a life table.

If the base mortality and multiplier function which applied to the New Zealand housing between 1860 to 1980 remains the same in the future, then the current average service life of 90 years would increase to 130 years should the expansion rate of the New Zealand housing stock decline to zero. The mean age of the housing stock would increase from about 35 years to almost 70 years. The severity of the base mortality may decrease in the future due to increases in the level and number of cycles of refurbishment undertaken within the housing stock. The multiplier function may also decrease in the future due to decreasing opportunities for in-fill housing and housing policies that moderate the scale of demolition and redevelopment during expansionary cycles. Such shifts in mortality would increase the average service life and mean age of the housing stock.

Forecasting replacement housing

There is an inverse relationship between the annual replacement rate and the average service life of a housing stock, a relationship that applies irrespective of the distribution of dwelling losses from a dwelling cohort over its service life span. This relationship known as Little’s law (Sterman, 2000) applies only when the housing stock is stationary and stable. The annual replacement rate of an expanding housing stock is a function of the distribution of dwelling losses from each cohort over its service life span and the expansion rate of the housing stock. Little’s law has frequently been misapplied. For example, in a study of housing in England, Meikle and Connaughton (1994) state that a very low annual replacement rate of 0.1% between 1986 and 1990 implies that houses in England will need to last up to 1000 years on average. This average service life is an over-estimate because the annual replacement rate of a housing stock declines as the expansion rate of the housing stock increases.

A number of forecasts of replacement housing have been based on extrapolation that implicitly assume dwelling losses increase as the size of a housing stock increases; for example see Brown (1975). Extrapolations based on previous rates of dwelling losses can lead to substantial error because, under conditions of dynamic mortality, total dwelling losses of all ages can actually decrease even though the size of the housing stock increases monotonically.

A dynamic stock and flow model is required to forecast replacement levels of the New Zealand housing stock. The expansion rate *r* of New Zealand housing stock has averaged about 1.5% per year over the past decade (Statistics New Zealand, 2003). The annual replacement rate is forecast to be 0.73% should the expansion rate of the housing stock decline to and stay steady at 0.5% per year. This annual replacement rate represents 11,000 dwellings based on the size of the housing stock (1,515,639 occupied and unoccupied dwellings) at the last Census in 2001.

Maximum justified expenditure on refurbishment

Investment in new construction provides immediate additional housing, but investment in refurbishment also provides additional housing in the long run by extending the remaining life expectancy of dwellings. Gleeson (1992) developed a maximum cost ratio model based on reliability theory to estimate the maximum expenditure or budget that can be justified fully refurbishing existing dwellings. Gleeson (1992) implicitly assumed there is no decline in the value of dwelling services with age. In practice, the value of dwelling services declines with age, the causes of which include obsolescence and physical depreciation. Johnstone (1995) developed a similar maximum cost ratio model that used assumed straight-line and diminishing value depreciation schedules. The use of assumed depreciation schedules was necessary because empirical studies of the depreciation of dwelling services of New Zealand housing stock over a full service life span have yet to be carried out. Johnstone demonstrated that greater maximum cost ratios are justified when the benefits of dwelling services undergo depreciation with age. Johnstone (1997) later extended and generalised his maximum cost ratio model to demonstrate the dynamics of maximum cost ratios under different maintenance regimes. Greater expenditure on the refurbishment of public housing can be justified when discount rates decline. In the extreme, demolition and replacement can be justified as real discount rates decline, especially should increases in annual maintenance costs with age be substantial. These relationships are shown in Figure 2. A maximum cost ratio of 1.0 or greater implies demolition and replacement.

Energy and mass flow of housing stock

Benefits and costs are normally expressed using a monetary numeraire. By doing so, disparate costs and benefits can be added or compared. Nonetheless, the expression of costs in physical units can provide alternative and illuminating perspectives of costs. A prime example is Leach's (1976) study of the energy costs of food production which estimates the full extent to which we effectively 'eat' oil. By modelling the energy and mass flows of resources used to sustain housing we are able to highlight the need for and facilitate forward planning of the use of these resources.

Macdiarmid (1978) estimated the embodied energy content of a 100 m^2 lightweight timber framed 'Neil' house in New Zealand to be 2.6 GJ/m^2. Macdiarmid (1978, p. 92) concluded

> It would appear that capital energy costs are rather more significant than previously thought, while still not being as great as operational energy costs. However if houses become more energy efficient, we will soon reach a point where further increases in

operational energy efficiency are more than offset by the increased capital energy costs.

Baird and Aun (1983) estimated the embodied energy content of the New Zealand Institute of Valuers 1972 National Modal House to be 3.6 GJ/m^2. Johnstone (2001b) updated Baird and Aun's (1983) estimate to 2.75 GJ/m^2 for a 1996 National Modal House using the embodied energy coefficients of building materials tabulated by Alcorn (1998). Johnstone (2001b) then used a dynamic stock and flow model to estimate the life cycle energy and mass flows (construction, maintenance, refurbishment, demolition, and replacement) of a housing stock comprised entirely of dwellings based on the 1996 National Modal house. Johnstone (2001b) estimated that after adjustment for depreciation it requires 8,325 MJ and 10,074 MJ to sustain each year of dwelling services provided by a stationary housing stock and an expanding housing stock ($r = 1.5\%$) respectively.

Johnstone (2001b) then estimated the ratio of annual operational energy flow at source to the annual energy required to sustain dwelling services to be 5.1:1 for an expanding housing stock ($r = 1.5\%$). This estimate is based on the energy consumption at the meter for a typical all-electric New Zealand household in 1971-1972 (Statistics New Zealand, 1973) and a multiplier factor of 1.53MJ/MJ (Baines and Peet, 1995) to take into account electricity generation and distribution. A report by the Ministry of Commerce (1991) claims that homeowners are able to reduce their energy consumption by as much as 60% by using energy more efficiently. A reduction of 60% in the above annual operational energy flow and a corresponding increase of, say, 10% in the annual energy flow required to sustain dwelling services would reduce the above energy ratio from 5.1:1 to 1.9:1. A decrease of this magnitude in the energy ratio substantially modifies the relative importance of the two energy flows.

Johnstone (2001b) estimated that timber weatherboards require almost 30% less energy to sustain than fibre cement planks. However, such results should not be used to modify or redirect the use of resources because the economic value of energy used to create and sustain a capital good is not fully captured by a purely physical numeraire. Georgescu-Roegen (1982) rebutted Costanza's (1980) claim of equivalence between embodied energy and economic value and Böhm-Bawerk (1932) laid a similar claim of Marx's labour theory of value to rest almost a century ago. Investment decisions should be based on a comparison of the economic value in dollar terms of both benefits and costs, including opportunity costs. The annual equivalent costs of using fibre cement planks are 53% less than that of timber weatherboards when the discount rate is 8% (Page, 1997). This estimate does not take into account the subsequent value of a property that uses one form of cladding rather than another. Use of more expensive timber weatherboards instead of fibre cement planks would be justified should the difference in value of the property match or exceed the difference in costs expressed in present value terms. Use of an expensive cladding system in a low land-value neighbourhood would result in over capitalisation whereas use of an inexpensive cladding system in a high land-value neighbourhood would result in under capitalisation.

Potential reductions in national costs due to refurbishment

Johnstone (2001c) used a dynamic stock and flow model to estimate current and potential reductions in national costs to sustain dwelling services due to refurbishment. Data and parameters were based on a typical New Zealand dwelling of lightweight timber framed construction. 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. Johnstone (2001c) estimated that current levels of refurbishment reduce national average costs to sustain dwelling services by a magnitude of 15% and that 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. This is because an expanding housing stock has relatively fewer old dwellings that can take advantage of refurbishment. A decline in the expansion rate of a housing stock has a greater impact on reducing national costs to sustain housing than an increase in the number of cycles of refurbishment.

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 minimise 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.

Benefit-cost ratio performance of housing

The potential service life of building components is limited by durability and the timing and sequencing of maintenance and refurbishment affect the rate of degradation. The decision to undertake maintenance and refurbishment is an economic decision. An owner may choose not to undertake refurbishment should the costs of doing so be greater than the subsequent increase in the value of the property. There may be a subsequent downward spiral in the condition of the building and the value of the services it provides. The service life of the structural system of a dwelling forms an upper limit to the potential service life of the dwelling. However, few dwellings realise their potential service life because the majority of demolitions and replacements of dwellings are the end result of an economic process based largely on land values. Under the standard land use succession criterion, 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 & 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. Johnstone (2003) has demonstrated that the standard land use succession criterion as applied to a stationary housing stock with static land values is anomalous due to the criterion being a function of the potential service life of dwellings. If a developer or property owner assumes that dwellings have a long service life, then the criterion justifies demolition and replacement at an age shorter than the assumed potential service life. However, if a developer or property owner assumes that dwellings have a short service life, then the criterion justifies that assumption as a self-fulfilling prophecy, as shown in Table 1. The timing of land use succession is also influenced by the discount rate. The standard land use succession criterion was therefore not adopted in the following model.

Johnstone (forthcoming) developed a model to estimate the benefit-cost ratio performance of different typologies of housing. A typical New Zealand dwelling constructed of lightweight timber framing is used as an example and dwellings within the simulation model undergo periodic cycles of refurbishment based on best practices. The service life span of the housing stock is varied and the maximum benefit-cost ratio occurs when the service life span of the housing stock is about 72 years as shown in Figure 3. The corresponding benefit cost ratio for an expanding housing stock ($r = 1.5\%$) is such that an annual expenditure equivalent to the costs to construct one dwelling sustains the services provided by 26.7 dwellings after adjustment for depreciation of dwelling services. 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 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.

Deferral of refurbishment does not necessarily have a negative impact provided selective deferral is adopted (Lee, 1987). Given this, further improvements of 5.3% in the benefit-cost ratio can be achieved by deferring refurbishment by 10% and accepting a higher level of economic depreciation of dwelling services.

The New Zealand Building Code 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). A sensitivity analysis of the above model that varies the levels of maintenance and refurbishment and the depreciation of dwellings services indicates 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. Furthermore, there is no national benefit-cost ratio advantage to be gained by sustaining all lightweight timber framed dwellings beyond a service life of 90 years.

Future research

The standard land use succession criterion based on discounting has a major impact on the timing of land use succession and hence on the total costs to sustain dwellings and especially commercial buildings where the use value is less frequently greater than the exchange value. The criterion is anomalous in that the timing of land use succession is affected by assumptions as to the service life of buildings, assumptions that become self-fulfilling prophecies. Price (1993) provides a trenchant critique of the very process of discounting upon which the standard land use succession criterion is based, and recommends the allocation of investment funds be based on the cash opportunity cost of funds, a technique developed by Eckstein (1957), Marglin (1963, 1967), and Feldstein (1964). There is a need to better understand and quantify the impact of using land use succession criteria on the sustainability of buildings.

In principle, depreciation rates for capital assets are based on customary usage and obsolescence under normal circumstances but, in practice, the rates for buildings do not necessarily reflect a true average service life. For example, the straight-line depreciation rate for New Zealand buildings with reinforced concrete framing, steel framing, or timber framing is 3% (Inland Revenue Department, 1993). Full depreciation occurs in the 33rd year of service life as compared to the 90 year average service life of New Zealand dwellings. High depreciation rates are a common fiscal instrument used to encourage redevelopment. The subsequent increase in the value of potential buildings waiting in the wing to succeed existing buildings is greater than any increase in value of existing buildings. Earlier demolition and replacement than would be the case otherwise is subsequently justified under the standard land use succession criterion. Early demolition and replacement of buildings is not necessarily in the best long term national interests. There is a need to establish the impact of taxation schedules on the sustainability of buildings.

An empirical study of the depreciation of New Zealand housing stock has yet to be carried out. Extensive literature surveys of empirical studies of the depreciation of dwellings by Malpezzi, Ozanne and Thibodeau (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 depreciation of dwelling services or rent (excluding rent for land) over the full service life of dwellings. There is a need for better understanding and quantification of the depreciation of dwellings services over the full service life of dwellings. One step in this direction is to include data on the value of improvements and land in surveys of the condition of the housing stock carried out by the Building Research Association of New Zealand (1999).

Johnstone's (1994) study of the mortality of New Zealand housing stock was based on the compiled data contained in the National Housing Commission study of the New Zealand housing stock as at August 1978 (Nana, 1981) that was provided by Valuation New Zealand. Valuation New Zealand provided Johnstone with a 1991 update, but the level of uncertainty in the data prevented any sensible comparison of shifts in mortality between 1978 and 1991. A large number of dwellings in the 1978 study had undergone major renovations or additions, so Valuation New Zealand overwrote the original age with a 'mixed age' category to the extent that the uncertainties as to the decade within which pre 1960 dwellings were constructed had almost doubled over a period of 13 years. Fortunately, the original age of dwellings has been retained in other database fields which were not included in the Nana (1981) study. An update on estimates of the mortality of New Zealand housing stock requires access to data from Quotable Value New Zealand. Data on house sales between 1986 and 1996 held by the University of Auckland Department of Property covers almost 50% of the New Zealand housing stock, but full access to data on the entire housing stock is beyond the financial resources of an individual academic (Private correspondence with Quotable Value New Zealand). An update of the National Housing Commission study of the New Zealand housing stock as at 1978 is now well overdue and such a study requires government agency support.

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Table 1

Age at which demolition and replacement is justified for a stationary housing stock with static land values (Ω is assumed potential service life)

	Discount rate (%)									
Ω	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
50	50	50	50	50	50	50	50	50	50	50
60	60	60	60	60	60	60	60	60	60	60
70	70	70	70	70	70	70	70	70	70	70
80	72	80	80	80	80	80	80	80	80	80
90	60	67	70	90	90	90	90	90	90	90
100	40	60	66	69	72	79	80	100	100	100
110	40	59	63	69	72	79	110	110	110	110
120	39	58	63	68	72	75	80	120	120	120
130	39	50	62	68	71	75	80	130	130	130
140	38	50	62	67	70	75	80	100	119	120
150	38	50	62	67	70	75	80	100	119	150
160	38	50	62	67	70	75	80	100	119	160
170	38	49	61	67	70	75	80	100	119	170
180	37	49	61	67	70	75	80	100	119	180

Figure 1

Distribution of dwellings losses from New Zealand dwelling cohorts scaled to 100,000 dwelling entries

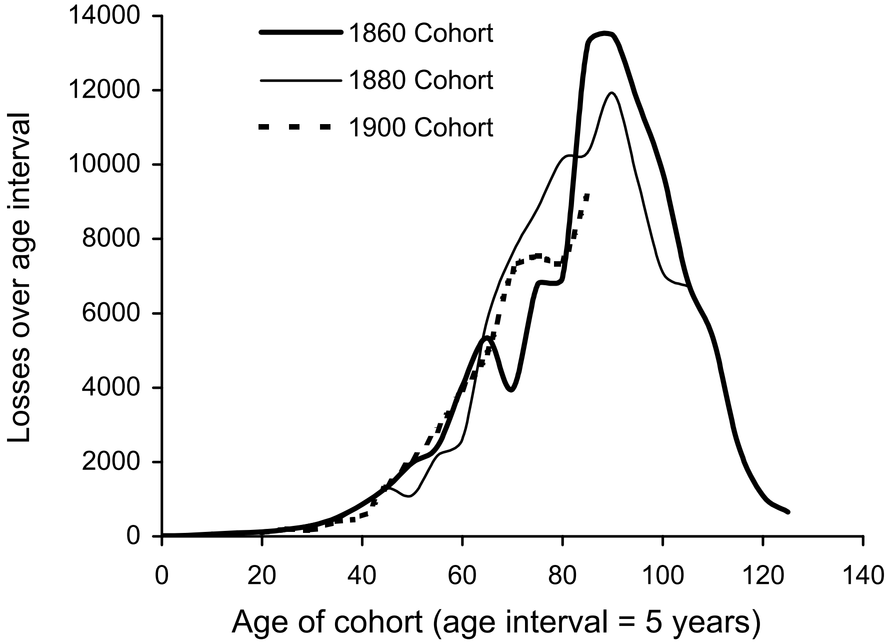

Figure 2

Maximum cost ratio for scenario of diminishing value depreciation of dwelling services and increasing maintenance costs

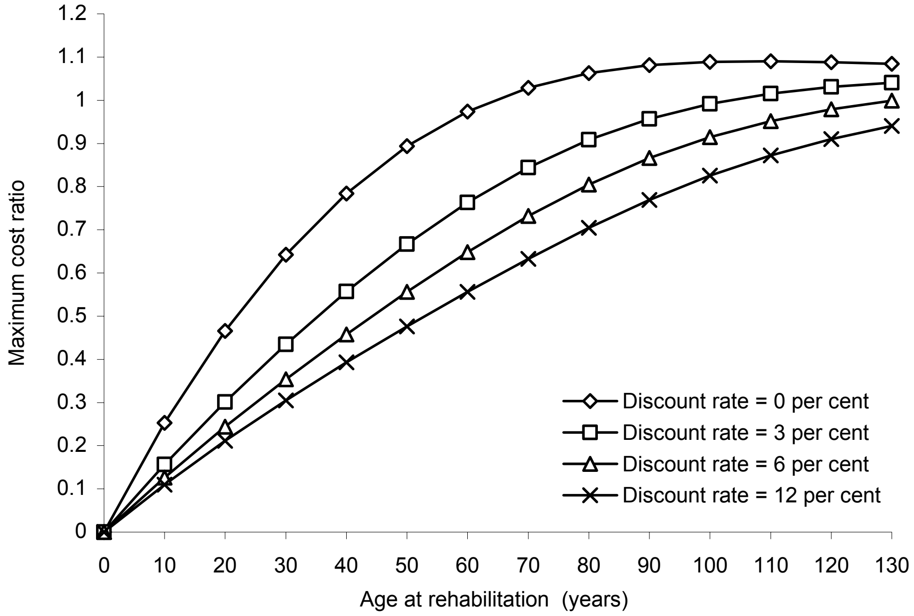

Figure 3

Benefit-cost ratio performance of stationary housing stock (squares) and expanding housing stock with r = 1.5% (triangles) in units of service year equivalents per construction unit.