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Modelling the annual replacement rate of housing stock

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Summary

This paper examines a number of models used to estimate the annual replacement rate of housing stock. These models range from simplistic extrapolation of past patterns of dwelling losses to dynamic models based on classical population dynamics. The explicit assumptions and, in particular, the implicit assumptions which are built into each model limit the usefulness of each model to forecast realistic dwelling losses. The writer's model of the dynamics of New Zealand housing stock shows that dwelling losses are not only a function of age but also the expansion rate of the housing stock. As a result of fluctuations in the expansion rate, each cohort of dwellings has been exposed to different regimes of mortality. Future regimes of mortality, therefore, cannot be assumed to be the same as past regimes. Because the economic process of departures from housing stock is dynamic, models which forecast annual replacement rates of housing stock should also be dynamic and these models should be driven by mortality regimes which are based on empirically established patterns of dwelling losses.

Definitions

Dwelling losses: All possible departures from housing stock — dwelling related demolition as the result of obsolescence; land use related demolition necessary to allow sub-division to proceed; demolition to allow public works to proceed; change in use from residential to commercial; consolidation of multi-units into single dwellings; and natural disaster, such as fire and earthquake.

Dwelling cohort: A group of dwellings which make an entry to housing stock over the same time interval.

Average economic life of a dwelling cohort: The average number of remaining service years which are provided by a dwelling cohort upon entry. Equivalent to average life expectancy or life expectancy upon entry in population dynamics terminology.

Economic life span: The time period during which the longest surviving dwelling of an original dwelling cohort provides a flow of housing services.

Stock profile: The distribution of housing stock by age of construction.

Introduction

Seip, a distinguished Norwegian economist and former Minister of Housing has argued that:

> 'Future policies must be based on the optimum use of resources, and one of the greatest real resources is the existing housing stock. ...It is now widely acknowledged that housing in the past has concentrated too much on new development to the neglect of the considerable value embodied in existing buildings...'[1]

In a recent perpetual inventory study, Philpott estimated that owner-occupied dwellings in 1990 formed about 23% of New Zealand's total capital stock of buildings, infrastructure, plant, and equipment with a value of $50,468 million in 1983/1984 prices.[2] The national costs of maintaining and replacing New Zealand's housing stock is therefore not without some significance. The writer has estimated that should the expansion rate of New Zealand housing stock decline to 1.0% per year, an expansion rate which currently represents an increase in the formation of about 13,000 households, replacement construction would form about 40% of total new construction.[3] It is in the interests of the

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[1] Seip, H. 'Building in Economic Terms', *Building Research and Practice*, March/April 1979, p. 90.

[2] Philpott, B. *Provisional Estimates of New Zealand Real Capital Stock by SNA Production Groups 1950-1990*, PEP Internal Paper 233a, Victoria University of Wellington, 1992, p. 23.

[3] Johnstone, I.M. *The Mortality of New Zealand Housing Stock*, PhD Dissertation, University of Auckland, UMI Dissertation Services No. 9322214, 1993, Table VIII-1, p. 211.

property and building industry to better understand the dynamics of replacement and maintenance of housing stock. Over the years a number of models have been developed to forecast the annual replacement rate of housing stock. This paper examines some of these models and demonstrates that the explicit and implicit assumptions which form the basis of these models limits their usefulness to forecast dwelling losses. The writer argues that annual replacement forecasts should be modelled by dynamic simulation models which are driven by empirically established patterns of dwelling losses.

Extrapolation Based On The Residual Method

The New Zealand Department of Statistics (NZDS) has periodically published annual dwelling demolition totals based on notifications received from local authorities. The longest uninterrupted series of notified dwelling losses covers the period between March 1969 and March 1986 and these annual totals do not necessarily include all demolitions or departures from the housing stock.[4] Statistics on dwelling departures due to change in use from residential to commercial, or consolidation of multi-unit flats into single dwellings, have not been compiled at any stage. Researchers of New Zealand housing stock have therefore estimated dwelling losses using a residual method which makes use of annual data series of new dwelling completions and quinquennial censi statistics on the stock of dwellings.

Brown used a residual method to estimate the annual rate of dwelling losses as a percentage of New Zealand's total housing stock.[5] By projecting the annual rate of dwelling losses between 1951-1971, Brown forecast the annual rate of dwelling losses between 1975-1981 to be about 0.60%. A National Housing Commission (NHC) study[6] concurred with Brown's estimate while a study by Burtt forecast the annual rate of dwelling losses between 1979-1989 to be 0.4% in line with an estimated long term average.[7]

At the 1991 Census New Zealand's total housing stock numbered approximately 1.3 million dwellings[8] and over recent years annual dwelling permits have fluctuated between about 18,000 to 21,000 dwellings per year.[9] Dwelling completions based on past statistics would number at least 95% of dwelling permits.[10] An annual replacement rate of 0.60% applied to New Zealand's current housing stock equates to about 7,800 dwellings per year or about 40% of 20,000 dwelling completions.

Coyte has criticised the residual method on the grounds that completion statistics are understated due to a large number of dwellings which are included in the inter-census increases not being included in the completions statistics.[11] Investigations by NZDS have found that notifications of completions have been unreliable in certain cases.[12] Merrett has pointed out that uncertainties in the data series are amplified in the residual.[13] This has been demonstrated by the writer who has estimated that when the order of uncertainties in New Zealand dwelling permits[14] and inter-census net gains data are about 5% and 0% respectively, the uncertainties in the estimated dwelling losses residual is about ± 40%.[15] The residual method does not allow accurate calculations to be made of past demolition or retirement rates. More accurate estimates of dwelling losses using this method cannot be made unless the expansion rate of the housing stock declines and the corresponding ratio of replacement construction to total construction increases.

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[4] New Zealand Department of Statistics, *Population and Buildings Series 1923-1953, Population Migration, and Building Series 1953-1971, Building and Construction Statistics Series 1971-1979, Building Statistics Series 1979-1986,* Department of Statistics, Wellington.

[5] Brown, S.E. *Projection of Housing Needs*. National Housing Commission Research Paper 75/1, Wellington, 1975.

[6] National Housing Commission. *A Forecast of New Zealand's Permanent Private Housing Requirements: 1976-1986.* National Housing Commission Research Paper 76/1, Wellington, 1987.

[7] Burtt, D.J. *The Demand for Housing in New Zealand: Part II.* National Housing Commission Research Paper 79/5, Wellington, 1979.

[8] New Zealand Department of Statistics, *1991 New Zealand Census of Population and Dwellings, Provisional Local Authority Population and Dwellings*, Department of Statistics, Wellington, 1991.

[9] New Zealand Department of Statistics. *Building Statistics Series 1988-1993,* Department of Statistics, Wellington.

[10] Johnstone, *op cit*, pp. 99-103.

[11] Coyte, C.A. *A projection of New Zealand's housing requirements to 1980 and the effect upon the building industry.* Unpublished MComm dissertation, Auckland University, 1965.

[12] New Zealand Department of Statistics, *Building and Construction Statistics 1977-78 and 1978-79*, Department of Statistics, Wellington, p. 6.

[13] Merrett, S. 'The Required Rate of New Dwelling Construction', *Environment and Planning A*, v.18, 1986, pp. 1531-35.

[14] The writer has used dwelling permits rather than dwelling completions statistics in order to extend the annual series to between 1920-1980.

[15] Johnstone, *op cit*, pp. 104-11.

As will be seen later in this paper, total dwelling losses over successive time intervals do not necessarily increase monotonically when housing stock undergoes expansion. Extrapolation of past patterns of total dwelling losses does not take into account the dynamics of dwelling losses.

Life Span Method

Coyte estimated the annual replacement rate of New Zealand housing stock to be between 0.95% and 1.09% on the unsupported assumption that dwellings are replaced every 65 years.[16] Coyte argued that because there were 66,136 pre 1901 dwellings still standing in 1956, those pre 1901 dwellings would be replaced in the 10 year interval between 1956 to 1966. By doing so, Coyte implicitly assumed that no dwelling losses take place over the first half of a dwelling cohort's economic life span. The annual replacement rate of 1.09% and 0.95% of the housing stock in 1956 and 1961 respectively follows through from an estimated average of 6,614 dwelling losses per year between 1956 to 1966.

An annual replacement rate of 1.0% applied to New Zealand's current housing stock equates to about 13,000 dwellings per year, or about 65% of current levels of annual dwelling completions.

It takes a period of one economic life span to replace all dwellings constructed before a certain date. In 1992 a number of pre 1860 dwellings were still standing. In 1956 there would have been a greater number of pre 1860 dwellings still standing of an age of at least 95 years. The first European dwelling in New Zealand was constructed in 1792 and New Zealand oldest surviving dwelling, Kemp House at Keriki, was constructed in 1821.[17] Although Kemp House no longer provides a flow of housing services, but is instead open to the public and protected against demolition under the New Zealand Historic Places Trust Act 1980, there are definitely 20, and perhaps as many as 150, pre 1860 dwellings still standing and yielding housing services as at December 1992.[18] The economic life span of New Zealand dwellings is therefore at least 130 years and perhaps as long as 150 years. Coyte under-estimated the period required to replace all dwellings and, within the context of his model, over-estimated the annual replacement rate. Coyte's model also does not take into account the dynamics of dwellings losses.

Mathematical Models Of Normal Life And Economic Life Span

Needleman developed a simple mathematical model to estimate the 'normal' life of a dwelling under dynamic conditions, the normal life of a dwelling being taken to be the number of years that elapse before half the dwellings built in a particular year has been demolished.[19] Needleman's model was based on the assumption that it is the oldest dwellings in the stock that are demolished each year and the implicit assumption that all dwellings are exposed to the same regime of mortality. Needleman derived his model as follows:

> 'Let:
> the normal length of life of a dwelling be n,
> the annual rate of growth of the stock be r,
> the annual rate of demolition be d, and
> the stock of dwellings at the beginning of the year nought, y_0 be 1.
> Gross investment in y_0 will be $r - d$. Between the beginning of and the beginning of y_n all the dwellings in existence at the beginning of y_0 and half the gross investment in y_0 itself, will have been demolished. That is, the total demolitions to have taken place by the beginning y_n will be
>
> $$1 + \frac{r + d}{2}$$
>
> The sum of demolitions will also be equal to
>
> $$d + d(1 + r) + d(1 + r)^2 + \ldots d(1 + r)^{n-1}$$
>
> ...'[20]

The following equation is arrived at after equating the above two expressions:

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[16] Coyte, *op cit*, p. 71.

[17] Salmond, J. *Old New Zealand Houses 1800-1940*. Auckland, Heinemann Reed, 1986.

[18] Estimate of pre 1860 dwellings was provided in December 1992 by Mr J.M. Stacpoole, historian of New Zealand buildings.

[19] Needleman, L. *The Economics of Housing*. London, Staples Press, 1965.

[20] *Ibid*, p. 41.

$$n = \frac{\log(1 + \frac{r}{d} + \frac{r^2 + rd}{2d})}{\log(1 + r)}$$

That n represents the normal life of dwellings is based on half the gross investment in y_0 itself being demolished by the beginning of year y_n. Needleman made no reference as to the composition of the stock at year y_0. Because annual demolitions and gross investments must be unitary and take place each successive year, the size of the housing stock at year is therefore one unit, not one dwelling, and the dwellings within the unit range in age from *0* up to *n* years. The actual number of dwellings within the unit is immaterial for the purpose of the model.

Let us now adapt the above model to estimate the economic life span of dwellings. Let m represent the economic life span of dwellings and assume that both annual gross investments and demolitions occur instantaneously at the start of each year. The gross investment of $r + d$ for year y_0 occurs at the beginning of year y_1 and demolitions of d for year y_0 occur at the beginning of year y_1. Net investment for year at the beginning of year y_1 is therefore r, as required. All dwellings in existence at the beginning of year are demolished after a period of m years between the beginning of years y_0 and y_n. The gross investment of $r + d$ at the beginning of year y_1 is still standing at year y_m because by then these dwellings are of age y_{m-1}. The sum of demolitions to have taken place by the beginning of year y_m is therefore equal to *1*. The sum of demolitions to have taken place by the beginning of year y_m is equal to

$$d + d(1 + r) + d(1 + r)^2 + \ldots d(1 + r)^{m-1}$$

The above geometric series represents a snapshot of an expanding housing stock taken at year y_0 with the first term representing the oldest and smallest dwelling cohort. The following equation is arrived at after equating the two equal expressions:

$$m = \frac{\log(1 + \frac{r}{d})}{\log(1 + r)}$$

Needleman estimated the normal life of British housing stock in 1965 to be 141.7 years basing this estimation on an average expansion rate of 1.3% per annum over the previous 160 years and an average replacement rate of 0.25% per annum between 1881 and 1961.[21] The economic life span of British housing is estimated to be 141.3 years using the same average expansion rate and replacement rate. The difference of about half a year between the normal life and economic life span is due entirely to different arbitrary decisions as to how demolitions are distributed over the final year of a dwelling cohort's life span. The normal life, economic life span, and average economic life of dwellings in Needleman's model are, for all practical purposes, one and the same.

The precision of the above mathematical models can be easily tested. The economic life span of dwellings is simply the age of the oldest dwellings within a housing stock. A few small British dwellings and cottages of traditional construction have remained in use after 400 years and many dwellings are older than 200 years.[22] The life span of British housing stock is therefore much greater than 142 years. Needleman's model of mortality lacks precision due to the assumption that it is the oldest dwellings only that are demolished. Dwelling losses from a housing stock are not necessarily restricted to the oldest dwellings. A pioneering empirical study of the mortality of housing stock by Gleeson has established that dwelling losses occur at all ages.[23] For example, Gleeson estimated that about 15% of dwelling entries over each time interval are lost from a sample of Indianapolis housing stock between entry and the age of 70 years with about a further 35% being lost between the age of 70 and 100 years.[24]

Needleman advised that if Britain wishes to raise housing standards in the future, given that age is a guide to condition, then it is important to reduce the normal life of dwellings by increasing the rate of replacement.[25] When dwelling losses take place at all ages, the normal life of a dwelling is not a good indicator of housing standards because two housing stocks of the same size, and which are expanding at the same rate. can have the same normal life

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[21] *Ibid*, p. 40.

[22] NBA Construction Consultants Limited. *Maintenance Cycles and Life Expectancies of Building Components and Materials: A Guide to Data and Sources*, London, 1985.

[23] Gleeson, M.E. 'Estimating Housing Mortality from Loss Records', *Environment and Planning*, v.17, 1985, pp. 647-59.

[24] *Ibid*, Table 2, p. 652.

[25] Needleman, *op cit*, pp. 40-4.

but different average economic life times and life spans.[26] The average economic life of dwellings, in conjunction with economic life span, forms a better indicator of housing standards in terms of the age distribution of housing stock.

Conceptual Model Of Housing Stock Dynamics

In the late 1970s Wyatt developed a conceptual model of Britain's housing stock.[27] Wyatt's model is based on a multi-deck stack where each deck represents an equal period of time. Dwellings pass down the stack at a rate determined by decay curves. These decay curves are based on a conceptualisation of decay in building components. Decisions are made at each deck as to whether maintenance should take place or not. Dwellings that undergo maintenance return up the stack, the re-entry point being dependent on which upgrading strategy has been adopted. Each dwelling ultimately reaches the bottom of the stack where demolition takes place. Wyatt took the decay characteristics of housing stock to be physically determined in that each construction form has either a long, medium, or short life span. Like Needleman, Wyatt assumed that for each construction form it is the oldest dwellings that are demolished.

Wyatt's dynamic stack model is more realistic than Needleman's simple mathematical model and allows the dynamic characteristics of a housing stock to be examined. However, simulated dwelling losses generated by Wyatt's model have not been validated against appropriate field survey data. The precision with which those simulated dwelling losses follow the true patterns of dwelling losses for British housing stock is therefore unknown.

Validation of Dynamic Housing Stock Models

The ability of a dynamic housing stock model to replicate the total size of a housing stock at regular intervals is trivial. A more exacting validation test is the ability to replicate stock profiles at various snapshot points in time. However, stock profiles of housing stocks which are subject to different regimes of mortality tend to merge as the expansion rate of the housing stocks increase.[28] The ultimate validation test is the ability to replicate true dwelling losses as well as true stock profiles otherwise the model may exhibit realism but lack precision.

The need for precision is demonstrated as follows. When a housing stock expands at a constant rate and the average life expectancy is held constant, different distributions of dwelling losses over the life span of dwelling cohorts result in different replacement rates. This is because early dwelling losses from younger, and hence larger, cohorts tend to predominate. Total dwelling losses of all ages over each interval are greater when a larger proportion of dwelling losses from each cohort occur early during its life span.

For example, consider two housing stocks of the same size which have different patterns of dwelling losses but the same average economic life of 75 years. Let the pattern of dwelling losses from each cohort of the first housing stock be constant over the life span of each cohort while the pattern of dwelling losses from each cohort of the second housing stock follow that of a normal distribution curve. If both housing stocks expand at a rate of 2.0% per year over a period sufficiently long enough for each respective stock profile to be proportionately stable, then total dwelling losses over each interval from the first housing stock, compared to the second, are in the ratio of 1.5:1.[29] This ratio increases to 2.8:1 when the expansion rate of each housing stock increases to 4.0% per year. It is only when a housing stock is stationary and the distribution of dwellings by age is stable that the replacement rate for any given economic life is independent of the pattern of dwelling losses.

Dynamic Population Models

Variations and extensions of the theories and life table models of classical population dynamics have been developed and applied by actuaries, demographers, statisticians, and ecologists over the past 200 years.[30] Control theory[31] and the Kolmogorov partial differentiation equation[32] can also be used to model population dynamics, however these alternative approaches do not offer the same simplicity of model construction. There are two basic types of life tables, namely the current, or period life table, and the generation, or cohort life table.[33] A current life table is based on age-

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[26] Johnstone, *op cit*, pp. 41-3.

[27] Wyatt, D.P. 'Housing Stock Management, Its Performance and Life Cycle', *Housing Science*, v.19, No. 4, 1984, pp. 337-47.

[28] Johnstone, *op cit*, pp. 41-2.

[29] Johnstone, *op cit*, pp. 42-3.

[30] Key modern researchers include N. Keyfitz (demography), H.S. Shryock and J.S. Siegel (demography), A.J. Lokta (ecology), and E.F. Spurgeon (actuarial science).

[31] Nauda et al, 'A Control Theory Approach to Modelling the Housing Sector', *Applied Mathematical Modelling*, v.3, 1979, pp. 309-11.

[32] Brewer, J.W. 'The age-dependent eigenfunctions of certain Kolmogorov equations of engineering, economics, and biology', *Applied Mathematical Modelling*, v.13, 1989, pp. 47-57.

[33] Keyfitz, N. and J.A. Beekman. *Demography Through Problems*. New York, Springer-Verlag, 1984.

specific death statistics over a short period so 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 current life table can be regarded as a 'snapshot' summary of mortality at an instant of time. A generation life table is based on the mortality experienced by a particular cohort, and is therefore useful for projections of mortality and studies of mortality trends. A generation life table approach requires time series data on age-specific losses and survivorship which are unlikely to be available for housing stock.

Current Life Table Model

In the early 1980s Gleeson demonstrated that life table models of classical population dynamics can also be applied to housing stock.[34] Gleeson adopted a current life table approach to estimate the mortality of a sample of Indianapolis housing stock using demolition statistics as a measure of dwelling losses. The use of demolition statistics minimises potential double-counting, but excludes dwelling losses due to mergers or changes in use. The year of construction was unavailable for 12% of the sample of 175,174 dwellings. Gleeson allocated these 'age unknown' dwellings to cohorts in the proportion of the distribution of dwellings with known age and used grouping methods to minimise the effects of data errors and idiosyncratic fluctuations due to the small size of the sample of dwellings. Data on dwelling losses collected for the two separate years of 1979 and 1980 were averaged and dwelling constructed over the interval 1905 to 1914 were grouped together. Gleeson conceded that the method he used to smooth out fluctuations caused by data errors and small samples was crude but, in his opinion, use of more elaborate and sophisticated methods in estimating housing mortality was best deferred for more refine studies that use improved data.

Because there was a scarcity of data for very old dwellings, Gleeson fitted a Gompertz curve tail to the survivorship schedule at the ages 75 to 95 years to estimate survivorship for dwellings older than 95 years. By doing so, about 57% of the sum total of dwellings losses were extrapolated. Gleeson estimated the average life expectancy of Indianapolis housing stock to be 99.6 years. The writer has estimated that due to the uncertainty as to the true pattern of dwelling losses which filters throughout the life table, the true average life expectancy lies somewhere between 96 and 118 years.[35] The remaining life expectancy at each successive age interval becomes progressively more indeterminate.

Indirect Mortality Model

In a recently completed PhD dissertation the writer estimated the mortality of New Zealand housing stock using an indirect modelling approach based on the theoretical framework of classical population dynamics. Use of an indirect model was necessary due to the unavailability of age-specific data on New Zealand dwelling losses. The indirect mortality model makes use of the following field survey data:

1. National Housing Commission data on survivorship of New Zealand urban housing stock as at August 1978.[36]
2. Statistics on New Zealand total housing stock compiled at each five year census since 1858.
3. Annual new dwelling permit series starting in 1921 for urban dwellings and 1938 for rural dwellings.

The National Housing Commission study on the survivorship of New Zealand urban housing stock was based on the Valuation New Zealand (VNZ) computerised database of land use records. The age of each dwelling is recorded in an age field in the VNZ database by category of the decade within which the dwelling was constructed. Each time there is a valuation update, the age of dwellings which have undergone a major renovation or addition are recorded as a mixed age category for the reasons '...the original erection date ceases to describe the structural quality'. [37] The original age of such dwellings have not been preserved in a separate age field.

The mixed age category in the August 1978 NHC study comprised 46,979 dwellings of age unknown, or 5.8% of the sample of 803,288 urban dwellings. VNZ provided the writer with a December 1991 update of its land use database. Over the intervening period of 13 years the percentage of pre 1960 age unknown dwellings has almost doubled.[38] As a result of the order of uncertainty in the 1978 and 1991 data, possible shifts in the mortality of New Zealand housing stock between 1978 and 1991 cannot be detected. Furthermore, the mortality of New Zealand housing stock cannot be estimated by making use of the most recent data.

Description Of Indirect Mortality Model

The deterministic mortality model is driven externally by a predetermined exogenous series of net gain variables based on census data and internally by selected schedules of endogenous probability of loss variables which form the

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[34] Gleeson, *op cit*, pp. 647-59.

[35] Johnstone, *op cit*, pp. 63-5.

[36] Nana, N. *Urban Housing Stock in New Zealand, Volume 10: New Zealand Totals*. National Housing Commission Research Paper 81/6, Wellington, 1981.

[37] Nana, *op cit*, p. 13.

[38] Johnstone, *op cit*, pp. 119-23.

mortality regimes of each dwelling cohort. When the mortality model is driven under dynamic mortality conditions, the probability of loss variables are amplified by a function of the expansion rate of the housing stock.

The mortality model simulates patterns of dwelling losses from individual surviving dwelling cohorts over each time interval, the sum total of which form total dwelling losses of all ages. The total dwelling losses and predetermined net gains over each time interval form the gross gains entries of new dwelling cohorts. The dwelling cohorts still standing at the start of each time interval in turn form the state variables of a housing stock profile.

Dwelling cohorts at 1860 form the initial state variables of the mortality model. Because the distribution of housing stock by age of construction at the 1858 Census is unknown, the writer estimated the initial state variables at 1860 by assuming the housing stock at 1860 to be in a stationary and stable state.

The writer has adopted a total population and total mortality approach. Patterns of dwellings losses from sub-populations of dwellings, such as multi-unit dwellings and detached dwellings, are merged and no differentiation has been made as to the sources and causes of dwelling losses.

Limitations Of Indirect Mortality Model

The mortality model does not take into account non zero-age dwelling entries such as the conversion of a single dwelling into two or more multi-units. The mortality model can be modified to account for these entries, but to do so would require statistics on the age of the source of dwelling entries. Such data is unavailable in New Zealand. Additional dwelling units created by conversions formed up to 3% of New Zealand housing total dwelling completions during a peak expansionary period between 1969 and 1973. An accumulation of non-zero age dwelling entries within certain dwelling cohorts would have some effect upon the findings of a study which attempts to establish a definitive pattern of dwelling losses from housing stock. Given the order of uncertainty in the New Zealand field survey data, the writer has assumed that non-zero dwelling entries have a negligible effect upon the findings on New Zealand housing stock.

Hypotheses Of Mortality

The writer tested three hypotheses of static, variable, and dynamic mortality:

1. Under conditions of static mortality, the writer assumed dwelling cohorts to have been exposed to the same regime of mortality resulting in each dwelling cohort having the same average economic life. This hypothesis is the same as the implicit and subsequently untested assumption which forms the basis of Gleeson's study of a sample of Indianapolis housing stock.
2. Under conditions of variable mortality, the writer assumed dwelling cohorts to have been exposed to regimes of mortality which change over time resulting in dwelling cohorts having different average economic lives.
3. Under conditions of dynamic mortality, the writer assumed dwelling cohorts to have been exposed to regimes of mortality which vary simultaneously over time.

Validation Of Indirect Mortality Model

The writer validated each mortality model by testing simulated total dwellings losses and a stock profile against corresponding field survey data. The high levels of uncertainty in the field survey data precluded using statistical tests of significance. Upper and lower boundaries of uncertainty for the field survey data were estimated and used to formulate criteria and descriptive tests for a realistic and useful mortality model. Figure 1 shows the envelope of uncertainty for total dwelling losses over five year intervals between 1920 to 1980 while Figure 2 shows the envelope of uncertainty for the stock profile, as at August 1978.

The inter-linkage of each series of model simulated total dwelling losses and corresponding stock profile mutually restrict zones that the other may lie within. Given the order of uncertainty in the New Zealand field survey data, a definitive pattern of dwelling losses cannot be estimated, but potentially useful mortality models can be decisively eliminated.

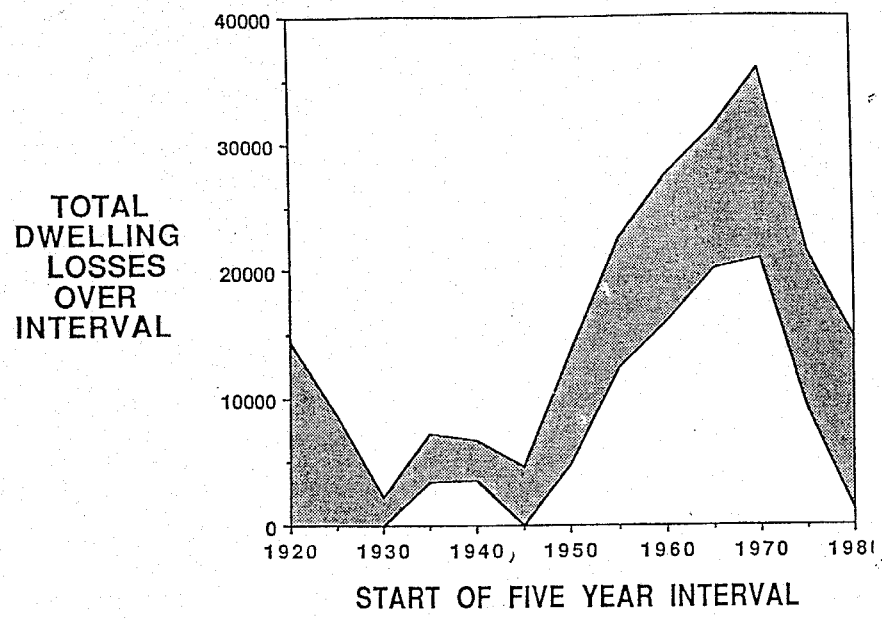

Figure 1 Envelope of uncertainty for total dwelling losses over five year intervals

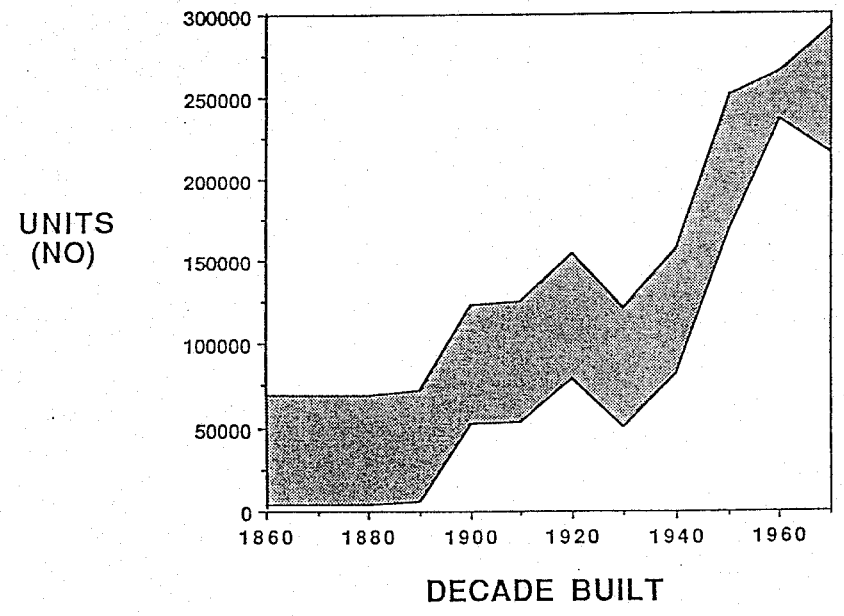

Figure 2 Envelope of uncertainty of stock profile as at August 1978

Results Of Indirect Mortality Model

If a housing stock is exposed to a regime of static mortality, total dwelling losses over successive time intervals increase monotonically when the housing stock expands monotonically.[39] New Zealand housing stock has expanded monotonically since 1860, but total dwellings over successive time intervals between 1920-1979 have increased and decreased. On these grounds alone the hypothesis of static mortality has been refuted.

Total dwelling losses from the best fit static mortality model fell short of the lower boundary of uncertainty by as much as 40% and exceeded the upper boundary by as much as 30%. The best fit static mortality model over-estimated the sum of gross gains between 1920-1979 by 5.4% when set to generate the best stock profile. An inferior model based on straight-line survivorship, or depreciation, over-estimated the same by 29.2%

The elimination of static mortality tells us that the mortality of New Zealand housing stock in the future cannot be assumed to be the same as that in the past and that past mortality has not been a function of age alone. The variable

[39] Johnstone, *op cit*, pp. 111-12.

mortality models were less realistic than the static mortality models. The elimination of variable mortality further tells us that the mortality of New Zealand housing stock has not been a function of age and date of entry alone.

The most useful mortality model to date is compatible with the hypothesis of dynamic mortality. In other words, the mortality of New Zealand dwelling cohorts between 1860-1979 has been a function of age and the expansion rate of the housing stock. Apart from a period of severe housing shortage between 1945-1949, total dwelling losses have increased and decreased simultaneously with increases and decreases in the expansion rate. Total dwelling losses simulated by the best fit dynamic mortality model fall short of the lower boundary of uncertainty by 6.5% and exceed the upper boundary by 6.4%.

The average normal life of New Zealand housing stock, or the period over which 50% of dwellings are lost from each dwelling cohort, is estimated to be about 90 years. The economic life span of New Zealand housing stock is estimated to be about 130 years. By reading directly from Gleeson's housing stock life table, the normal life and economic life span of a sample Indianapolis housing stock are estimated to be 100 years and 150 years respectively.[40] The writer's findings on New Zealand housing stock support Gleeson's study that the distribution of dwelling losses over an economic life span follows the general shape of a normal curve with a skew to the left. Figure 3 shows the distribution of dwellings losses from a typical New Zealand dwelling cohort over its economic life span superimposed over the distribution of dwelling losses from a dwelling cohort within a stationary and stable state housing stock. The size of each dwelling cohort has been scaled to 100,000 dwellings.

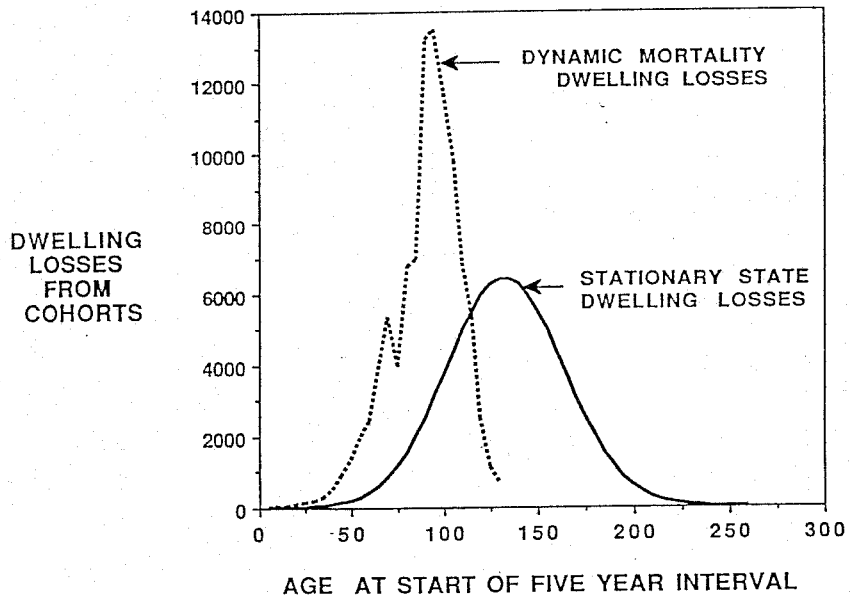

Figure 3 Distribution of dwelling losses from typical New Zealand dwelling cohort

Forecasting Potential Of Indirect Mortality Model

The forecasting potential of a housing stock model is reflected by its ability to replicate patterns of past dwelling losses to an acceptable degree of realism and precision. Although the indirect mortality model is able to replicate useful patterns of dwelling losses, the degree of precision of the model is limited by the level of uncertainty in the field survey data — in particular the stock profile of New Zealand housing stock. A more precise mortality model can be developed only when more precise filed data is available to validate the model.[41] The indirect mortality model in its present form is suitable for projecting medium (10 years) to long term scenarios of the dynamics of New Zealand housing stock.

A forecast of New Zealand dwelling losses requires assumptions to be made as to future expansion rates of the housing stock. There are many factors which will determine future expansion rates. These include increases in the natural population, the age distribution of the population, rural-urban population drift, immigration levels, housing stock occupancy and vacancy ratios, mortgage interest rates, affordability of housing, house prices, and government policies which, in combination, will influence future effective demands to form additional households. These factors need to be

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[40] Gleeson, *op cit*, p. 652.

[41] One method of reducing the uncertainty with the Valuation New Zealand land use database would entail establishing a statistical distribution of the mixed age category of dwellings by first random sampling the VNZ database and then using archive records to re-establish the original of the mixed age category dwellings within the random sample.

taken into account in order to forecast a useful set of scenarios. A useful forecast of dwelling losses from New Zealand housing stock is therefore dependent not only on the realism and precision of the housing stock model itself, but also on the realism of assumed future expansion rates which drives the model.

The writer has set up the indirect mortality model to simulate alternative scenarios of a constantly expanding and a stationary housing stock. In each expanding housing stock scenarios the mortality regime is the same as that experienced by New Zealand housing stock between 1860 to 1980, whereas in each stationary housing stock scenario the mortality regimes have been varied using the same family of mortality functions. The results of each scenario are tabulated in Table 1 and Table 2 located at the end of this paper. Figure 4 graphs the replacement: gross gains ratio versus the annual expansion rate.

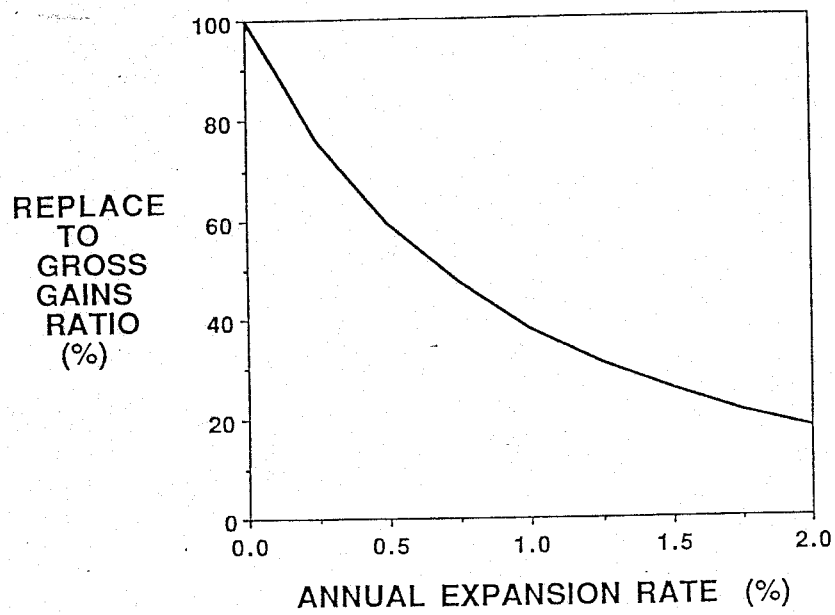

Figure 4 Replacement: gross gains ratio versus annual expansion rate

The stock profiles in both the expanding and stationary housing stock scenarios are stable in that the proportion of dwellings within each cohort remains constant over time, whereas the stock profile of New Zealand housing stock between 1860-1980 has been unstable due to fluctuations in the expansion rate. Under the conditions of constant expansion rate it takes at least one economic life span for a stock profile to stabilise. The extent of differences between the dynamics of a stable and unstable housing stock profile is illustrated by the following example. Over the 1985-1989 five year interval the average expansion rate of New Zealand housing stock was 1.70% resulting in an annual replacement rate of 0.37%. The writer estimates the annual replacement rate of a constantly expanding and proportionately stable housing stock with the same expansion rate to be about 0.47%, a difference of 21% .

An annual replacement rate of 0.37% applied to a housing stock of 1.3 million dwellings, as at the 1991 Census, represents about 4,800 dwellings per year. Table 2 shows us that a minimum replacement rate of 0.77%, or about 10,000 dwellings per year, is required to sustain a stationary and stable housing stock of the same size at a mean age of about 69 years. The mean age of New Zealand's housing stock is currently about 32 years. An annual replacement rate of 1.67%, or about 21,700 new dwellings per year, would be required to maintain a stationary and stable housing stock of the same size and at the same mean age. Figure 5 shows the annual replacement rate for an expanding and a stationary and stable housing stock versus the mean age of the housing stock.

Should the expansion rate of New Zealand's housing stock decline to zero overnight, then the mean age of the housing stock would increase unless a minimum of about 20,000 new dwellings per year were constructed to replace existing dwellings, allowing a 10% margin for error. Conversely, should New Zealand's housing stock continue to expand, then a construction level below 20,000 new dwellings per year over a prolonged period would result in an accelerated increase in the mean age of New Zealand's housing stock.

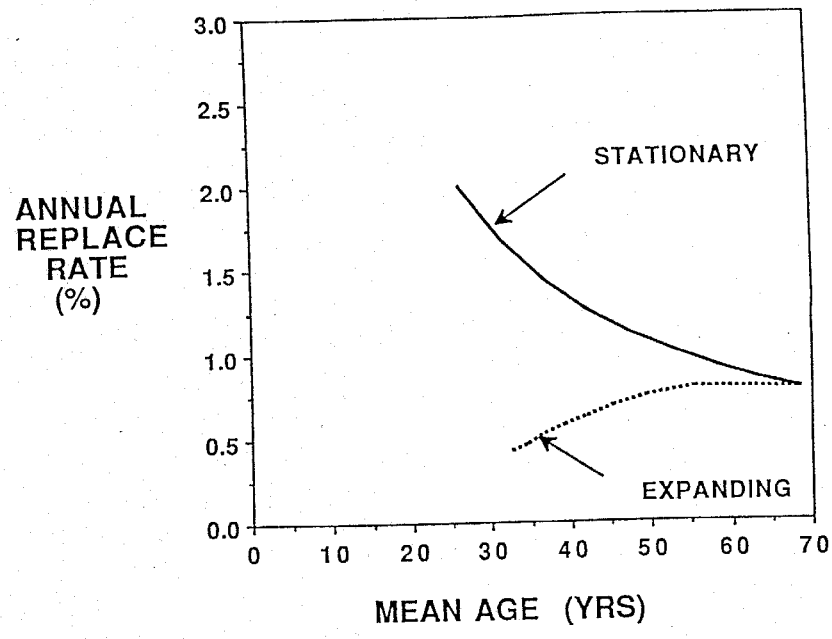

Figure 5 Annual replacement rate for an expanding and stationary housing stock versus mean age

Conclusions

This paper has examined a number of models used to estimate the annual replacement rate of housing stock, ranging from simplistic extrapolation of past dwelling losses to more sophisticated dynamic housing stock models which have been validated against field survey data. Estimates of dwelling losses based on the residual method have been demonstrated to be an inaccurate base upon which to extrapolate from in the first instance. Secondly, extrapolation of past dwelling losses do not take into account the dynamics of dwelling losses.

A realistic model of the dynamics of dwelling losses cannot easily be solved by analytical methods as the problem is non-trivial and involves several non-linear equations. The dynamics of housing stock is best approached by the use of simulation models. Simulation models based on unsubstantiated assumptions of economic life span, average economic life, and distributions of dwelling losses can also lead to erroneous forecasts, the order of error being greater at high expansion rates of housing stock. Empirically established patterns of dwellings losses should be used to drive simulation models of housing stock.

The ideal housing stock model would be a linking series of generation life table models based on age-specific dwelling losses statistics. Such a model would offer the greater precision enabled by direct measurements of mortality and would allow detection of shifts in mortality. However, it is unlikely that any country has compiled a series of statistics on age-specific dwelling losses. Until such data series are available, researchers of housing stock will need to resort to either a current life table approach, as adopted by Gleeson, or develop an alternative indirect mortality model which is peculiar to the data difficulties encountered in that country. A current life table model offers the potential for precision in estimating the mortality of housing stock provided the housing stock is not subject to dynamic regimes of mortality. A current mortality model cannot detect shifts in mortality over time, as can the indirect mortality model developed by the writer, and is not in itself a dynamic housing stock model which can be used to forecast dwelling losses. The indirect mortality model both replicates and forecasts dwelling losses, but lacks the potential to estimate the mortality of housing stock to the same precision as the direct current life table modelling approach. The current life table model and the indirect mortality model are therefore complementary.

As New Zealand's housing stock ages over the next number of decades, the proportionate costs of maintaining the older stock of dwellings will undoubtedly increase. There is a balance between an appropriate annual replacement rate to maintain a suitable mean age of housing stock versus the increased costs of maintaining an older housing stock. The writer contends that as the expansion rate of housing stock declines and annual replacements form a greater proportion of total new construction, there will greater incentive and need for the property and building industry to develop realistic and more precise simulation models of housing stock. Appropriate housing policies to assist in minimising the national costs of sustaining housing stock require a better understanding of the dynamics and trade-offs of replacement versus rehabilitation. Simulation models of housing stock are necessary to bring this about.

Table 1 Dynamics of an expanding housing stock

CONSTANTLY EXPANDING AND PROPORTIONATELY STABLE HOUSING STOCK									
	ANNUAL EXPANSION RATE								
	0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Annual replacement rate (%)	0.77	0.78	0.73	0.67	0.61	0.56	0.51	0.46	0.42
Annual gross gains rate (%)	0.77	1.03	1.23	1.42	1.61	1.81	2.01	2.21	2.42
Replacement: Gross gains ratio	100.0	75.7	59.3	47.2	37.9	30.9	25.4	20.8	17.4
Average economic life (yrs)	130.0	109.7	103.3	99.3	96.4	94.1	92.3	90.7	89.3
Mean age (yrs)	68.7	55.5	49.6	45.4	42.1	39.2	36.8	34.6	32.6
Economic life span (yrs)	260	200	180	170	165	160	155	150	145

Table 2 Dynamics of a stationary housing stock

STATIONARY AND STABLE HOUSING STOCK									
	AVERAGE ECONOMIC LIFE								
	130	120	110	100	90	80	70	60	50
Annual replacement rate (%)	0.77	0.83	0.91	1.00	1.11	1.25	1.43	1.67	2.00
Mean age (yrs)	68.7	63.4	58.1	52.8	47.5	42.2	36.9	31.6	26.3
Economic life span (yrs)	260	240	220	200	180	160	140	120	100