MODELLING THE DYNAMICS OF THE ENERGY AND MASS FLOWS REQUIRED TO SUSTAIN HOUSING STOCK

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Abstract: In order to optimise the energy and mass flows required to sustain housing stock, it is necessary to model the dynamics of the benefits and cost trade-offs between maintenance and rehabilitation versus demolition and replacement. This paper presents an overview of dynamic housing stock models which can be converted into dynamic energy and mass flow models.

1.0 INTRODUCTION

Appropriate and internally consistent housing policies cannot be formulated until the interacting dynamics between the benefits provided by housing stock in the form of dwelling services and the contributing costs of sustaining housing stock — ongoing maintenance, periodic rehabilitation, replacement construction, and newbuild construction which adds to the size of the housing stock — have been established and quantified. Benefits and costs are normally expressed using a monetary numeraire. The advantage of doing so is that 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 study of the energy costs of food production [1]. Forecasts of the CO_2 contribution to the atmosphere by the building industry rely on estimates of the direct and indirect energy required to sustain building stock. Estimates of the direct mass flows of building materials or the embodied mass flows of minerals, metals, and fresh water highlight the need for and facilitate forward planning of the use of scarce resources.

Preliminary work necessary to develop dynamic energy or mass flow models of housing stock has already been completed. Numerous estimates of the embodied energy of building materials and dwellings have been carried out during the 1970s and 1980s [2]. In recent years, dynamic housing stock models have been developed which can be converted into energy and mass flow models. Dynamic housing stock models are based on models of mortality, a statistical concept which pertains to probability of loss, survivorship, and life expectation. Empirical studies of the mortality of housing stock have been carried out by Gleeson [3], Komatsu *et al.* [4] and Johnstone [5]. Gleeson [6] and Johnstone [7] have developed maximum cost ratio models to estimate the maximum expenditure that can be justified fully rehabilitating dwellings as opposed to constructing new dwellings instead. Johnstone has estimated the maximum impact and optimum timing of rehabilitation upon the average dwelling services per unit total cost required to sustain those services [8]. This paper presents an overview of these models.

2.0 MODELLING THE MORTALITY OF HOUSING STOCK

A life table is a simulation model which makes use of age-specific data on losses and survivorship to simulate the mortality of a stationary and stable population or an individual cohort within that population. Variations and extensions of the theories and life table models of classical population dynamics have been developed and applied by actuaries [9], demographers [10], ecologists, and engineers over the past 200 years. Within the context of housing stock, most losses or departures take the form of either demolition, change in use, or abandonment. These departures, including abandonment, are the end result of an economic process. The economic life of a dwelling is that period over which that dwelling provides dwelling services. This period is generally much shorter than the potential physical life of the dwelling. The average economic life of a dwelling is the average number of years of dwelling services which are provided by a dwelling cohort. The life span of a population can be defined as that age beyond which less than 0.1% of an original cohort survives [11]. Adoption of this definition enables sensible comparisons of different housing stock as potential blurring caused by a minority of exceptional dwellings is thereby avoided.

Gleeson carried out a pioneering study of the mortality of a sample of Indianapolis housing stock over a decade ago [3]. More recently Komatsu *et al.* estimated the mortality of timber dwellings in Japan [4] and Johnstone estimated the mortality of New Zealand housing stock [5]. Both Gleeson and Komatsu *et al.* used a current life table approach based on cross-sectional data on age-specific dwelling losses and survivorship. Johnstone adopted an indirect modelling approach because age-specific data on dwelling losses are unavailable in New Zealand. The resulting mortality model is comprised of a series of linked life tables and was validated against alternative longitudinal data. Johnstone established that the mortality experienced by New Zealand housing stock between 1860 to 1980 had been dynamic and not static. The probability of loss of dwellings from each cohort had 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 of fluctuations in the expansion rate of the housing stock. The distribution of dwelling losses from each cohort over its economic life span generally followed that of a negatively skewed normal distribution. The average economic life of current dwelling cohorts is in the order of 90 years, provided the expansion rate of the housing remains constant at 2% per year. The current economic life span of the housing stock is 130 years.

3.0 MODELLING THE DYNAMICS OF HOUSING STOCK

The optimum energy or mass flows required to sustain housing stock cannot be estimated by simply summing the contributing flows for individual dwellings over a full life cycle. This is because the costs to sustain an individual dwelling have an impact upon the total costs of sustaining the entire housing stock. For example, maintenance and rehabilitation can reduce the level of annual replacement construction within a housing stock below that which would be needed otherwise to sustain a given flow of dwelling services. The interacting dynamics of maintenance, rehabilitation, replacement, and newbuild construction can only be modelled within the framework of the total housing stock.

A life table model of mortality is restricted to modelling replacement construction only within a stationary and stable housing stock whereas a dynamic housing stock model can, in addition, simulate the flows of both replacement and newbuild construction within an expanding housing stock. Nauda *et al.* [12] and Brewer [13] have promoted the use of Control Theory and the Kolmogorov partial differentiation equation respectively to model the dynamics of housing stock. These models, however, do not provide the same degree of transparency and simplicity of model construction as that offered by models based on classical population dynamics.

The mortality model developed by Johnstone doubles up as dynamic housing stock model [5]. Use of the model enables different scenarios to be forecast. For example, if the expansion rate of New Zealand housing stock were to decline to a constant rate of 1% per year, a rate which represents a doubling in the size of the housing stock every 70 years, then replacement construction would form a sizeable 40% of all new construction. If the housing stock were in a stationary and stable state, then the mean age of the housing stock would be 69 years as opposed to the current mean age of 32 years. A reduction in the expansion rate in the future would result in a shift in emphasis away from newbuild construction towards maintenance, rehabilitation, and replacement construction.

4.0 MODELLING THE BENEFITS OF HOUSING STOCK

Housing, in itself, forms but a means to an end. We are ultimately concerned with the flow of dwelling services that housing can provide. Efficient use of scarce resources involves providing the maximum flow of dwelling services of a given quality for the least cost. A number of empirical studies reviewed by Malpezzi *et al.* [14] and Baer [15] have established that the value of dwellings and dwelling services (rent and imputed rent) generally decline with age. Studies of the optimum use of energy and mass flows of housing should therefore take into account not only the benefits of dwelling services but also the dynamics of the economic depreciation of those services. The following example illustrates why. Assume that dwellings within two housing stocks, one in a stationary and stable state and the other undergoing expansion, are exposed to the same regime of mortality and undergo the same economic depreciation of dwelling services. The mean age of the stationary housing stock would be greater and hence, ceteris paribus, greater depreciation of dwelling services would have taken place within the older housing stock. The younger and expanding housing stock would provide a greater quantity of dwelling service year equivalents per dwelling over each time interval.

5.0 MODELLING REHABILITATION VERSUS NEW CONSTRUCTION

Investment in new construction provides immediate housing, but investment in rehabilitation also provides additional housing in the long term by extending the remaining life expectancy of dwellings. Johnstone developed an actuarial model to estimate the maximum expenditure or budget that can be justified fully rehabilitating existing dwellings for each age at which rehabilitation takes place [7]. This budget is expressed as a ratio of the costs to construct a new dwelling of similar size and quality. Gleeson developed a prior maximum cost ratio model based on reliability theory and the assumption there is no decline in the value of dwelling services with age [6]. In practice, the value of dwelling services does decline with age as a result of obsolescence, the causes of which include physical depreciation [15, 16].

Although a number of empirical studies have quantified rates of depreciation over the early life of dwellings, none to date do so over a full economic life span. In order to increase the realism of the maximum cost ratio model and to establish the impact and dynamics of depreciation of dwelling services, Johnstone's model assumed two commonly used schedules of depreciation in addition to Gleeson's hypothetical schedule of no depreciation with age. A straight line depreciation rate of 0.8 % per year was selected so that dwelling services depreciate to a value of zero by the age of 125 years, an age which approximates the economic life span of New Zealand housing stock. A corresponding diminishing value depreciation rate of 1.0 % per year was selected. Both costs and benefits were discounted back to present values.

When all other variables are held constant, maximum cost ratios increase with the age at which full rehabilitation takes place, increase with the expansion rate of the housing stock, and decrease with each increase in the discount rate. Under conditions of no depreciation, it is impossible to fully rehabilitate a 50 year dwelling within the maximum justifiable budget of 5% of the costs to construct a new dwelling of similar size and quality (annual discount rate of 12%). Greater maximum cost ratios are justified when the benefits of dwelling services undergo depreciation with age. The maximum justifiable budget for the previous example increases to 46% of the costs to construct a new dwelling under conditions of straight line depreciation and 42% under conditions of diminishing value depreciation.

6.0 MODELLING THE IMPACT OF REHABILITATION

Johnstone modelled the maximum impact and optimum timing of rehabilitation upon the quantity of dwelling service year equivalents provided per unit total cost required to sustain those services [8]. All dwellings within a cohort were assumed to undergo full rehabilitation at the maximum cost which could be justified on an actuarial benefit-cost ratio basis. The costs of maintenance per dwelling were assumed to be a constant 1% of the costs to construct a new dwelling, regardless of the age of the dwelling. This estimate was based on maintenance records of a random sample of 25 New Zealand Housing Corporation dwellings located in Auckland over a 40 year period.

Optimum timing of rehabilitation occurs at the age of 40 years under the above conditions. When entire dwelling cohorts undergo full rehabilitation at this age, the average economic life increases by a maximum of 60%, the level of replacement construction decreases, and the average quantity of dwelling services per unit total cost increases by a maximum of 17%. Should a proportion only of dwelling cohorts undergo full rehabilitation, then the impact of full rehabilitation would be scaled down accordingly. Changes in the expansion rate of a housing stock have a greater impact upon the benefits and total costs than does optimal timing of full rehabilitation. When the timing of full rehabilitation is optimum, a stationary housing stock can provide 53% more dwelling services per unit total cost over each time interval than a housing stock which is expanding at a constant rate of 2% per year.

7.0 CONVERSION TO ENERGY AND MASS FLOW MODELS

Dwelling service years have been used as a proxy for monetary benefits in the above models. The same proxy for benefits can be used in energy or mass flow models. The value of benefits is fully captured in the non-physical numeraire because the units of dwelling service years can be directly converted into monetary units, if so desired, by multiplying the quantity of dwelling service years by the dollar rental rate per period (excluding land).

Dwelling construction units, the costs to construct a new dwelling, have been used as a proxy for costs. This proxy for costs can also be expressed in monetary costs by multiplying the quantity of dwelling construction units by the dollar cost to construct one dwelling. Dwelling construction units can be converted directly into units of embodied energy or mass. In doing so, the economic value of the resulting embodied energy or mass is not fully captured within the physical numeraire despite the claims by a number of energy analysis researchers, including Costanza, that the economic value of capital stock can be fully captured in terms of embodied energy [17]. Costanza's claim of an equivalence between embodied energy and economic value [17] was rebutted by Georgescu-Roegen [18]. Böhm-Bawerk laid a similar claim to rest, Marx's labour theory of value, almost a century ago [19]. The value of capital is a function of the expected net benefits (rent or imputed rent in the case of dwellings) over the anticipated life of capital [20]. These net benefits consist of a flow of abstract services defined by Fisher as psychic income [20] and aptly described by Georgescu-Roegen as the mysterious flux of enjoyment of life [21]. The value of psychic income, by virtue of its nature of belonging to the inner mental world, cannot be fully captured using a physical numeraire, but can be fully captured by non-physical monetary units.

Whether to discount or not is a non issue when total benefits are compared to total costs over a single time interval. However, when benefits occur in the future, these benefits do not have the same value as present benefits and should be discounted accordingly. When the units of costs are in physical units, as opposed to monetary units, future costs do not represent future value. It is meaningless to discount a physical metric. That this is so can be clearly seen by considering the consequences of attempting to carry out the inverse of discounting a physical metric — in other words, to attempt to compound a physical metric. Abstract debts may be subject to the laws of perpetual exponential growth, but the physical world of energy and resources is not.

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