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Energy and mass flows of housing: a model and example

Ivan M. Johnstone

Department of Property, The University of Auckland, 26 Symonds Street, Auckland, New Zealand

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Abstract

The energy and mass flows required to sustain dwelling services can be established and quantified only within the framework of a stock and flow model of the total housing stock. This paper develops such a model to estimate the energy flows of a typical sub-population of New Zealand housing stock. The energy and mass flows of key building materials are estimated and the energy flows of alternative cladding systems are compared. The stock and flow model is driven by empirical schedules of mortality. A guide to estimating the mortality of housing stock is set out in the companion paper (Johnstone IM. Energy and mass flows of housing: estimating mortality. Building and Environment 2000;36(1):43–51). © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The costs and benefits of housing 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 an alternative and illuminating perspective of costs. A prime example is Leach's [1] study of the energy costs of food production which estimates the full extent to which we effectively 'eat' oil. Energy and mass flows of housing are expressed in units such as megajoules of energy, tonnes of concrete, cubic metres of timber, and tonnes of glass per year. 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. At the same time, we are able to identify those strategies that can best reduce undesirable externalities. For example, forecasts of the CO_2 contribution to the atmosphere by the building industry rely on estimates of the direct and indirect energy used to sustain housing.

Preliminary work necessary to develop an energy and mass flow model of housing has already been completed. Estimates of the embodied energy coefficients of building materials were made during the 1970s and early 1980s [2] and these estimates have recently been updated [3]. Extensive databases of embodied energy coefficients are now in existence. For example, Davis Langdon and Everest, a firm of chartered surveyors in London, has compiled a database of 5000 items [4].

Studies of the initial gross energy requirement of buildings were carried out in the 1970s and early 1980s, summarised in and including Baird & Aun [2]. These studies did not include the energy requirement of maintenance, rehabilitation, and demolition over the full life cycle of a building, though Baird and Aun [2] did examine an example of single-cycle renovation. Bekker [5] addressed issues of resources used by an individual building over its full life cycle and presented a simple formula to quantify and illustrate critical influences.

Various organisations have compiled databases on maintenance cycles and the expected service life of building materials and components. The more comprehensive of these databases include NBA Construction Consultants Limited [6], RICS/BRE [7], and HAPM [8]. Data on maintenance cycles and the service life of components enable and facilitate not only conventional life cycle studies of buildings, such as that by Tucker and Rahilly [9], but also studies of life cycle energy.

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The Society of Environmental Toxicology and Chemistry (SETAC) has organised a number of workshops since the late 1970s to identify the state of the art in life cycle assessments and to identify the research needed to enhance the development and use of life cycle assessment methods. These workshops culminated in the publication "A technical framework for life-cycle assessments" [10]. Methods for estimating the life cycle energy and environmental impact of buildings have been developed [11] and the International Standards Organisation (ISO) is in the process of developing standards concerning service life prediction methods, auditing systems, and life cycle costing and maintenance of buildings [12].

Recent studies of the gross energy requirement of buildings by Oka et al [13], Buchanan and Honey [14], and Cole and Kernan [15] include estimates of pollutants in response to concerns regarding global warming, ozone depletion, and environmental degradation. Studies by Cole and Kernan [15], Adalberth [16, 17], and Suzuki and Oka [18] include the life cycle energy requirement of buildings. The state of the art has progressed to the stage where the energy requirements, CO_2 emissions, and mass of materials and components in a building can be directly calculated from 3D CAD drawings [19], thus significantly reducing the drudgery of estimates.

The above studies are of individual buildings and the results are expressed in units of initial energy requirements and pollutants per floor area or, in the case of life cycle studies, as an average over the service life of the building in question. Studies of individual buildings can be used to estimate energy and mass flows of the total building stock, the results of which are expressed as a flux. Some energy and mass flow studies of the total building stock have already been undertaken. Woodhead and Rahilly [20] have developed a procedure to estimate the resources required for a proposed housing program on a regional basis. One component of the model estimates the number and sizes of different dwelling forms to house a forecast population demand. Another component quantifies the building elements comprising the dwellings, such as walls and roof. Materials and labour input per unit of building element are estimated and the results are combined to produce estimates of overall resource requirements.

Woodhead and Rahilly's study focuses solely on the mass flows of new construction. Glenck and Lahner [21] have adopted a materials accounting method to estimate the waste management requirements for the region of Upper Austria. A combination of 12 different methods is used to assess both material stocks and flows of buildings, infrastructure, and industrial processes. Kohler et al. [22] have developed a macroeconomic (aggregated top down) and process oriented (disaggregated bottom up) approach to estimate the energy and mass flows of the German building stock. Statistical data and input-output tables for the German economy are used for the calculation of the overall flows which are compared against the aggregate of detailed flows created by new construction, refurbishment, demolition, and utilisation of buildings.

The timing and distribution of the resources used to sustain individual dwellings have an impact upon the total housing stock. For example, maintenance retards the rate of departure of dwellings from a housing stock and rehabilitation reverses the rate of departure. Each additional cycle of rehabilitation extends the life expectancy of dwellings and, by doing so, reduces the level of annual replacement construction below that which would be required otherwise to sustain a set quantity of dwelling services. The interacting dynamics of benefits in the form of dwelling services and the costs of sustaining those services — new-build construction which adds to the size of a housing stock, maintenance, rehabilitation, demolition, and replacement construction — therefore can be established and quantified only within the framework of a stock and flow model of the total housing stock.

Regimes of mortality form the primary drivers of a stock and flow model. Gleeson [23], Komatsu et al. [24], and Johnstone [25] have carried out empirical studies of the mortality of housing stock. A guide to estimating the mortality of housing stock is set out in the companion paper [26].

This paper converts Johnstone's [27] stock and flow model of rehabilitation into an energy and mass flow model of housing. The energy flows of a typical subpopulation of New Zealand housing stock are estimated to illustrate use of the model. Energy and mass flows of key building materials are also estimated and the energy flows of alternative cladding systems are compared.

2. Description of model

2.1. Multi- deck stack representation of housing stock

The simulated housing stock can be visualised 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 progressively down to the next deck. Dwellings are lost from each dwelling cohort over each time interval, the level of which is determined by a probability of loss function. Different dwelling cohorts may be subject to different regimes of mortality. New dwelling cohorts continuously replace total dwelling losses of all ages. If the housing stock is stationary, then each new dwelling cohort comprises replacement construction only. If the housing stock undergoes expansion, then each new dwelling cohort comprises both new-build construction and replacement construction.

2.2. Dwelling services

Housing stock, in itself, is but a means to an end. We are ultimately concerned with the magnitude and quality of the flow of dwelling services that housing stock can provide. The model in this paper therefore includes the flow of dwelling services provided by housing stock to enable estimates of the average flow of resources required to sustain each unit of dwelling services. Dwelling services include only those services rendered by improvements to land. The services of land are excluded in order to avoid confounding separate issues of economic depreciation.

2.3. Homogeneity of dwellings

The size and quality of dwellings are set to be homogeneous for the sake of model simplicity. Heterogeneity can be taken into account by constructing separate models for distinct classes of dwellings and combining the results of the sub-populations.

2.4. Maintenance and rehabilitation

All dwellings are set to undergo the same regime of annual maintenance, the level of which may remain constant or vary with age. Rehabilitation may take place at irregular intervals and the scale and content of each event of rehabilitation may differ over the service life of a dwelling cohort.

The proportions of survivors that undergo rehabilitation at each successive cycle are unknown. To assume that all survivors undergo rehabilitation at each successive cycle would be to overstate the energy and mass flows of rehabilitation that occur in practice. Homeowners are less likely to undertake rehabilitation as their expectations of demolishing and replacing their dwellings in the near future increase. A reasonable assumption of the proportion of survivors that undergo each successive cycle of rehabilitation is given by the probability of survivorship for each age at which rehabilitation may take place. For example, if the probability of survivorship of any one dwelling within a dwelling cohort over the next 10 years is 0.95, then 95% of the dwelling cohort is set to undergo rehabilitation. The probability of survivorship decreases as a dwelling cohort ages, so a diminishing proportion of survivors within each dwelling cohort undergoes rehabilitation with age.

Expenditure on rehabilitation does not guarantee an extension of dwelling services. Situations exist where dwellings undergo extensive rehabilitation and are demolished shortly afterwards so as to enable replacement or redevelopment. Demolition and replacement of existing dwellings that provide adequate services may appear to be wasteful of resources, but the alternative of foregoing opportunities that generate greater value is more wasteful.

2.7. Real costs of construction and embodied energy coefficients of building materials

The real costs of all forms of construction and demolition work are assumed to remain constant over time. The long run supply curve of the construction industry is perfectly elastic and returns to scale are constant. The embodied energy coefficients of building materials are also assumed to remain constant over time. These assumptions can be relaxed.

2.8. Infrastructure

The energy and mass flows required to establish and support an expanding infrastructure to accommodate an expanding housing stock are not taken into account.

3. Output of dwelling services

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:

$$S_e = \sum_{x=0}^{\alpha-1} L_x \cdot \mathrm{D}(x) + \sum_{x=\alpha}^{\beta-1} L_x \cdot \mathrm{D}(x) + \ldots + \sum_{x=\theta}^{\omega} L_x \cdot \mathrm{D}(x) \tag{1}$$

where: L_x is the number of dwelling service years provided by a dwelling cohort within an expanding or stationary housing stock over the age interval x to $(x+1)$; $\mathrm{D}(x)$ is an economic depreciation factor that is a function of the age x of dwelling cohorts; α, β, $\ldots\theta$ are the ages at which rehabilitation takes place; and ω is the service life span of the housing stock.

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):

$$\mathrm{SLI} = \frac{S_e}{T_t} \tag{2}$$

where T_t is the number of dwellings in the housing stock providing dwelling services over the time interval t to $(t+1)$.

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

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

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 $a_0 = 1/2$ when $n=1$ gives sufficiently precise results for the purposes of an energy and mass flow model of 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 $\mathrm{P}(x, r)$:

$$d_x = l_x \cdot \mathrm{P}(x, r) = l_x \cdot q_x(1 + 78.62r)^{0.70} \tag{4}$$

where r is the annual expansion rate of the housing stock. The probability of loss function is explained in more detail in the companion paper [26].

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

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

where P_t is the size of the housing stock at the start of the time interval t to $(t+1)$ and $P_{t'+1}$ is the size of the housing stock at the start of the time interval $(t+1)$ to $(t+2)$.

The size of the housing stock at time t (P_t) is simply the sum of all the dwelling cohorts which are standing at time t. The proportion of dwelling entries (l_0) which are lost during the time interval of entry is negligible and is therefore ignored.

4. Inputs of energy and materials

4.1. Resources for new-build construction

The flows of resources used for new-build construction $(\mathbf{I}_{new})$ over the time interval t to $(t+1)$ are given by the product of the number of new-build entries to the housing stock from Eq. (5) and the row vector of resources $\mathbf{R}_{\mathbf{new}}$:

$$\mathbf{I}_{\mathbf{new}} = \exp\ r - 1\sum_{x=0}^{\omega} l_x \cdot \mathbf{R}_{\mathbf{new}} \tag{6}$$

4.2. Resources for utility services

The flows of resources used to provide utility services $(\mathbf{I}_{\mathbf{utilities}})$ such as heating, cooking, water supply, and sewage disposal over the time interval t to $(t+1)$ are given by the product of the total dwelling service years provided by the housing stock and the row vector of resources $\mathbf{R}_{\mathbf{utilities}}$:

$$\mathbf{I}_{\mathbf{utilities}} = \sum_{x=0}^{\omega} L_x \cdot \mathbf{R}_{\mathbf{utilities}} \tag{7}$$

4.3. Resources for annual maintenance

The flows of resources used for annual maintenance $(\mathbf{I}_{\mathbf{maint}})$ over the time interval t to $(t+1)$ are given by the sum of the products of the number of dwelling service years provided by dwelling cohorts over the age interval x to $(x+1)$, the maintenance factor $\mathrm{M}(x)$, and the row vector of resources $\mathbf{R}_{\mathbf{maint}}$:

$$\mathbf{I}_{\mathbf{maint}} = \left[\sum_{x=0}^{\alpha-1} L_x \cdot \mathrm{M}(x) + \sum_{x=\alpha}^{\beta-1} L_x \cdot \mathrm{M}(x) + \ldots + \sum_{x=\theta}^{\omega} L_x \cdot \mathrm{M}(x)\right] \cdot \mathbf{R}_{\mathbf{maint}} \tag{8}$$

4.4. Resources for rehabilitation

If all survivors within a dwelling cohort undergo rehabilitation, then the flows of resources used for rehabilitation $(\mathbf{I}_{\mathbf{rehab}})$ over the time interval t to $(t+1)$ are given by

$$\mathbf{I}_{\mathbf{rehab}} = l_\alpha \cdot \mathbf{R}_{\mathbf{rehab}\alpha} + l_\beta \cdot \mathbf{R}_{\mathbf{rehab}\beta} + \ldots + L_\theta \cdot \mathbf{R}_{\mathbf{rehab}\theta} \tag{9}$$

where: $l_\alpha, l_\beta, \ldots, l_\theta$ are the number of dwellings within dwelling cohorts that undergo rehabilitation at the ages $x = \alpha, \beta, \ldots, \theta$; and $\mathbf{R}_{\mathbf{rehab}\alpha}, \mathbf{R}_{\mathbf{rehab}\beta}, \ldots, \mathbf{R}_{\mathbf{rehab}\theta}$ are row vectors of resources used for rehabilitation at the ages $x = \alpha, \beta, \ldots, \theta$.

The proportion of dwellings that undergo an event of rehabilitation at the age y is given by the probability of survival (np_y) through n years:

$$ {}_{n}p_{y} = (1 - q_{y})(1 - q_{y+1})\ldots(1 - q_{y+n-1}) \tag{10} $$

where $y = \alpha, \beta, \ldots, \theta$.

4.5. Resources for demolition

The flows of resources used for demolition ($\mathbf{I}_{\mathbf{demolish}}$) over the time interval t to $(t + 1)$ are given by the product of the number of replacement entries to the housing stock from Eq. (5) and the row vector of resources $\mathbf{R}_{\mathbf{demolish}}$:

$$ \mathbf{I}_{\mathbf{demolish}} = \sum_{x=0}^{\omega} d_{x} \cdot \mathbf{R}_{\mathbf{demolish}} \tag{11} $$

4.6. Resources for replacement construction

The flows of resources used for replacement construction ($\mathbf{I}_{\mathbf{replace}}$) over the time interval t to $(t + 1)$ are given by the product of the number of replacement entries to the housing stock from Eq. (5) and the row vector of resources $\mathbf{R}_{\mathbf{replace}}$:

$$ \mathbf{I}_{\mathbf{replace}} = \sum_{x=0}^{\omega} d_{x} \cdot \mathbf{R}_{\mathbf{replace}} \tag{12} $$

5. Outputs of solid waste, emissions to air, releases to water

5.1. Waste due to new-build construction

The flows of waste due to new-build construction ($\mathbf{O}_{\mathbf{new}}$) over the time interval t to $(t + 1)$ are given by the product of the number of new-build entries to the housing stock and the row vector of waste $\mathbf{W}_{\mathbf{new}}$:

$$ \mathbf{O}_{\mathbf{new}} = (\exp\ r - 1)\sum_{x=0}^{\omega} l_{x} \cdot \mathbf{W}_{\mathbf{new}} \tag{13} $$

5.2. Waste due to utility services

The flows of waste due to providing utility services ($\mathbf{O}_{\mathbf{utilities}}$) over the time interval t to $(t + 1)$ are given by the product of the total dwelling service years provided by the housing stock and the row vector of waste $\mathbf{W}_{\mathbf{utilities}}$:

$$ \mathbf{O}_{\mathbf{utilities}} = \sum_{x=0}^{w} L_{x} \cdot \mathbf{W}_{\mathbf{utilities}} \tag{14} $$

5.3. Waste due to annual maintenance

The flows of waste due to annual maintenance ($\mathbf{O}_{\mathbf{maint}}$) over the time interval t to $(t + 1)$ are given by the sum of the products of the dwelling service years provided by dwellings (L_{x}), the maintenance factor $\mathrm{M}(x)$, and the row vector of waste $\mathbf{W}_{\mathbf{maint}}$:

$$ \mathbf{O}_{\mathbf{maint}} = \left[\sum_{x=0}^{\alpha-1} L_{x} \cdot \mathrm{M}(x) + \sum_{x=\alpha}^{\beta-1} L_{x} \cdot \mathrm{M}(x) + \ldots + \sum_{x=\theta}^{\omega} L_{x} \cdot \mathrm{M}(x) \right] \cdot \mathbf{W}_{\mathbf{maint}} \tag{15} $$

5.4. Waste due to rehabilitation

If all survivors within a dwelling cohort undergo rehabilitation, then the flows of waste due to rehabilitation ($\mathbf{O}_{\mathbf{rehab}}$) over the time interval t to $(t + 1)$ are given by

$$ \mathbf{O}_{\mathbf{rehab}} = l_{\alpha} \cdot \mathbf{W}_{\mathbf{rehab}\alpha} + l_{\beta} \cdot \mathbf{W}_{\mathbf{rehab}\beta} + \ldots + l_{\theta} \cdot \mathbf{W}_{\mathbf{rehab}\theta} \tag{16} $$

where: $l_{\alpha}, l_{\beta}, \ldots, l_{\theta}$ are the number of dwellings within dwelling cohorts that undergo rehabilitation at the ages $x = \alpha, \beta, \ldots, \theta$; and $\mathbf{W}_{\mathbf{rehab}\alpha}, \mathbf{W}_{\mathbf{rehab}\beta}, \ldots, \mathbf{W}_{\mathbf{rehab}\theta}$ are row vectors of waste due to rehabilitation at the ages $x = \alpha, \beta, \ldots, \theta$.

The proportion of dwellings that undergo an event of rehabilitation at the age y is given by the probability of survival (${}_{n}p_{y}$) through n years as given by Eq. (10).

5.5. Waste due to demolition

The flows of waste due to demolition ($\mathbf{O}_{\mathbf{demolish}}$) over the time interval t to $(t + 1)$ are given by the product of the number of replacement entries to the housing stock from Eq. (5) and the row vector of waste $\mathbf{W}_{\mathbf{demolish}}$:

$$ \mathbf{O}_{\mathbf{demolish}} = \sum_{x=0}^{\omega} d_{x} \cdot \mathbf{W}_{\mathbf{demolish}} \tag{17} $$

5.6. Waste due to replacement construction

The flows of waste due to replacement construction ($\mathbf{O}_{\mathbf{replace}}$) over the time interval t to $(t + 1)$ are given by the product of the number of replacement entries to the housing stock and the row vector of waste $\mathbf{W}_{\mathbf{replace}}$:

Table 1
Summary of quantities of materials and gross energy requirements (GER) of revised Modal House

Material/work	Baird and Aun [2] study				Updated energy coefficients[a]				Revised materials[b]		
	Units	Gross quantity	Rate (MJ/Unit)	GER (MJ)	Rate (MJ/Unit)	GER (MJ)	IFIAS level	Year	Gross quantity	GER (MJ)	Proportion of total (%)
Preliminaries	$	–	–	1185	–	1185	4	1983	1	1185	0.5
Administration	$	–	–	904	–	904	4	1983	1	904	0.4
Earthworks	m^3	119	100	11900	–	11900	1	1983	85.9	8586	3.4
Timber, milled	m^3	23.36	4692	109586	1380	32231	1	1994	0	0	0.0
Timber, formwork	m^3	3.11	283	881	165	514	1	1995	0	0	0.0
Timber, hardboard	m^3	0.32	20626	6648	13310	4290	1	1994	0	0	0.0
Timber, framing	m^3	–	–	–	1380	–	1	1994	14.7	20286	8.0
Timber, mouldings	m^3	–	–	–	1710	–	1	1995	1.88	3206	1.3
Timber, particle board	kg	–	–	–	8	–	1	1994	1305	10440	4.1
Timber, MDF	m^3	–	–	–	8330	–	4	1994	0.56	4665	1.8
Wallpaper	m^2	165.39	14.9	2468	16	2646	3	1988	167.6	2682	1.1
Building paper	m^2	98.11	7.5	732	4.97	488	2	1995	101.5	505	0.2
Concrete, precast	m^3	0.23	4780	1104	4700	1086	3	1994	0	0	0.0
Concrete, insitu	m^3	6.94	3840	26653	2350	16311	3	1994	1.15	2710	1.1
Structural clay	kg	886.9	6.9	6120	6.3	5587	3	1994	85	536	0.2
Plaster, solid	kg	104.16	6.7	698	2	208	2	1994	0	0	0.0
Plaster, fibrous	kg	504	6.7	3377	6.1	3074	3	1995	0	0	0.0
Gypsum board	m^3	1.98	5000	9900	6460	12791	?	1991	3.22	20821	8.2
Asbestos cement	kg	287.5	8.2	2358	–	2358	4	1983	0	0	0.0
Fibre cement	m^3	–	–	–	13550	–	4	1994	1.05	14241	5.6
Bitumen felt	kg	12.88	38.0	489	44.1	568	4	1995	1.28	56	0.0
Glass	kg	115.03	31.5	3623	15.9	1829	2	1994	115.0	1829	0.7
Steel, general	kg	451.63	35.0	15807	32	14452	2	1994	217.9	6973	2.7
Steel, rods	kg	215.16	35.0	7531	12.5	2690	4	1994	0	0	0.0
Galvanised iron	kg	1865.4	37.0	69021	34.8	64917	2	1994	1605.5	55870	21.9
Steel, pipes	kg	53.43	57.0	3045	–	3045	4	1983	0	0	0.0
Copper	kg	307.06	45.9	14094	70.6	21678	3	1994	139.1	9818	3.8
Lead	kg	45.9	25.2	1157	35.1	1611	3	1995	45.9	1611	0.6
Aluminium, recycled	kg	–	–	–	34.3	–	3	1995	243	8335	3.3
PVC	kg	8	96	768	70	560	2	1992	193.5	13544	5.3
Polybutylene[c]	kg	–	–	–	103	–		1994	8.56	882	0.3
Paints, general	m^2	628.6	15	9429	6.5	4086	4	1994	0	0	0.0
Paints, water based	m^2	118.8	10	1188	7.4	879	4	1994	1013.1	7497	2.9
Paints, solvent based	m^2	150.8	12	1810	6.1	920	4	1994	637.8	3891	1.5
Electrical work	$	–	–	395	–	395	4	1983	1	395	0.2
Electric range	No.	1	6456	6456	–	6456	4	1983	1	6456	2.5
Rubber, synthetic	kg	12.1	148	1791	110	1331	2	1994	12.1	1331	0.5
Insulation, fibre	kg	10.5	23	242	23	242	4	1991	10.5	242	0.1
Insulation, fibreglass	m^3	–	–	–	970	–	4	1991	14.3	13832	5.4
Aluminium foil	kg	–	–	–	204	–	3	1995	10.0	2036	0.8
Brass	kg	0.2	49.3	10	62	12	4	1994	0.2	12	0.0
Site power	$	–	–	3000	–	3000	1	1983	1	3000	1.2

Transport, road, 30 km	kg	19000	0.114	2166	–	2166	1	1983	19	2166	0.8
Transport road, 50 km	kg	20200	0.190	3838	–	3838	1	1983	20.2	3838	1.5
Transport, general	$	–	–	700	–	700	1	1983	1	700	0.3
Carpet	kg	–	–	–	106	–	4	1994	132.4	14029	5.5
Felt underlay	kg	–	–	–	18.6	–	4	1992	66.2	1230	0.5
Vinyl flooring	m^3	–	–	–	105990	–	2	1991	0.045	4770	1.9
Total		–	–	331071	–	230948	–	–	–	255109	–

[a] Based on Alcorn [3].

[b] Based on the New Zealand Institute of Valuers National Modal House 1996 Revision [31].

[c] The Embodied Energy Coefficient for high-density polyethylene is used for polybutylene.

$$\mathbf{O}_{\mathbf{replace}} = \sum_{x=0}^{\omega} d_x \cdot \mathbf{W}_{\mathbf{replace}} \tag{18}$$

6. Data used in model

6.1. Depreciation of dwelling services

An empirical study of the depreciation of New Zealand housing stock has yet to be carried out. Extensive literature surveys of empirical studies of depreciation of dwellings by Malpezzi et al. [28] and Baer [29] do not provide satisfactory guidelines which can be applied with confidence to New Zealand housing stock. No study estimates the depreciation of dwelling services or rent (excluding rent for land) over the full service life span of dwellings. The depreciation function D(x) is therefore assumed. Depreciation of dwelling services is based on a reversed 'S' curve as described by Baer. The surviving stock schedule of a dwelling cohort describes a reversed 'S' curve, so reversed 'S' curve depreciation is described by the function

$$\mathrm{D}(x) = \frac{l_x}{l_0} \tag{19}$$

where the units of the depreciation function D(x) are dimensionless ($0 \leq \mathrm{D}(x) \leq 1$), l_x is the number of dwellings within a dwelling cohort which would survive to the age x, l_0 is the original number of dwellings in a dwelling cohort which enter the housing stock at age zero.

Dwelling services fully depreciate by the service life span of 143 years when the housing stock undergoes expansion at the rate of 2.0% per year.

6.2. Energy requirement of new-build and replacement construction

Estimates of the energy requirements of new-build and replacement construction are based on an update and revision of Baird and Aun's [2] study of the New Zealand Institute of Valuers (NZIV) 1972 National Modal House [30]. The floor area of the 1972 Modal House is 92.9 m^2.

The first set of columns in Table 1 summarises the quantities of materials and gross energy requirements in Baird and Aun's original study. The second set of columns updates the embodied energy coefficients using estimates by Alcorn [3]. The update results in a 30.2% decrease in the original gross energy requirement of the 1972 Modal House (from 331,071 MJ to 230,948 MJ or 3.6 GJ/m^2 to 2.5 GJ/m^2). A decrease in the embodied energy coefficient for milled timber alone (from 4692 MJ/m^3 to 1380 MJ/m^3) reduces the original gross energy requirements of the 1972 Modal House by 23.4%.

The final set of columns in Table 1 revises the original quantities and types of materials to that of the NZIV 1996 National Modal House [31]. The floor area of the 1996 Modal House has increased to 100 m^2 but the original floor area and floor plan of the 1972 Modal House has been retained in this paper to enable direct comparisons of changes in materials and corresponding changes in energy requirements over time.

Table 2 lists the changes in construction and buildings materials from the 1972 Modal House to that of the revised Modal House. The main changes in construction include use of timber piles instead of a concrete foundation wall and the deletion of the chimney and fireplace. A concrete porch and steps have been replaced with timber deck and steps. Main changes in building materials include fibre cement planks in lieu of timber weatherboards, factory painted aluminium window frames in lieu of timber window frames, and medium density particleboard floors in lieu of tongue and groove floorboards. Galvanised steel spouting and downpipes, structural clay drainage pipes, and copper waste and water pipes are replaced with PVC. Additional building materials include fibreglass insulation in the walls and ceiling space and perforated aluminium foil insulation under the suspended floor. Revision of the 1972 Modal House by way of changes in construction, substitute building materials, and the addition of insulation increase the updated gross energy requirement by 1.8% (from 230,948 MJ to 235,080 MJ). If virgin aluminium with an embodied energy coefficient of 218 MJ/kg [3] were to be used for the window frames, then the updated gross energy requirement would increase by 21.1% (from 230,948 MJ to 279,719 MJ). This paper includes floor coverings which increase the final gross energy requirement of new-build and replacement construction of a revised Modal House to 255,109 MJ or 2.75 GJ/m^2.

6.3. Energy requirement of annual maintenance

The energy requirement of annual maintenance is based on the maintenance records of 25 New Zealand Housing Corporation dwellings that date back to the early 1940s. Table 3 lists the average annual maintenance costs of those items which are not included under rehabilitation in this paper. The sum of these costs total 0.14% of the costs to construct a new dwelling. The energy requirement of annual maintenance is estimated as 357 MJ/year based on the average energy intensity per dollar to construct a new dwelling.

6.4. Life cycle and energy requirements of the revised Modal House

Table 4 lists the life cycle and energy requirements of rehabilitation for the revised Modal House. The life cycle for each process is based on either a projected

Table 2
Summary of changes in construction and materials of revised Modal House

Baird and Aun [2] study based on NZIV 1972 Modal House	Revision based on NZIV 1996 Modal House
Floor area: 92.9 m^2	Floor area: 92.9 m^2
Concrete foundation walls, plastered	Timber piles embedded in concrete foundation, timber base boards
Suspended lightweight timber sub-floor structure	Suspended lightweight timber sub-floor structure
Chimney and fire place	Deletion of chimney and fireplace, make good
Concrete porch and steps	Timber deck and steps
Tongue and groove timber floor boards	Medium density particle board sheet flooring, 20 mm
Lightweight timber framing walls	Lightweight timber framing walls
Lightweight timber roof framing	Lightweight timber roof trusses
Timber weatherboards, painted	Fibre cement planks, 7.5 mm, painted
Asbestos cement soffits	Fibre cement sheeting soffits, 4.5 mm
Galvanised steel roofing, painted	Galvanised steel roofing, painted
Timber framed windows	Aluminium framed windows, factory painted
Gypsum board and some hardboard wall linings	Gypsum board wall linings, 9.5 mm
Fibrous plaster and some hardboard ceiling linings	Gypsum board ceiling linings, 9.5 mm
No insulation in walls and ceiling space	Fibreglass insulation in walls (75 mm) and ceiling space (100 mm)
No insulation sub-floor	Perforated aluminium foil sub-floor
Galvanised steel spouting and downpipes, cast iron vent pipe	PVC spouting, downpipes, and vent pipe
Structural clay drainage pipes and gully traps	PVC drainage pipes and gully traps
Copper waste pipes and water pipes	PVC waste pipes and polybutylene water pipes
Cast iron bath and concrete laundry tub	Pressed steel bath (factory painted) and stainless steel laundry tub
Solid timber kitchen joinery fittings	Medium density fibreboard joinery fittings, melamine finish
No floor coverings	Wool carpet and vinyl floor coverings

Table 3
Average annual expenditure on maintenance

Category	Costs (1988 NZ$)	Proportion (%)
Hot water cylinder: repairs, replacement	16.55	17.9
Electrical: outlets, lighting, meter board	21.78	23.5
Taps: washers, replacement	8.53	9.2
Waste pipework: repairs, replacement, clear blockages	10.56	11.4
Water supply	12.82	13.8
Drainage system: clear WC blockages, repair drainage lines	18.69	20.2
Flashings: repair, replace	2.61	2.8
Fittings: cupboards, shelving	1.12	1.2
Total	92.66	100.0

Average annual maintenance expenditure = 0.14% of cost to construct a new dwelling

service life span [6], economic life [32], or database of components in use [9].

6.5. Energy requirement of demolition

The energy requirement of demolition of 13,378 MJ (144 MJ/m^2) is based on Adalberth's [17] estimate of 40 kWh/m^2.

7. Results and discussion

7.1. Energy flows of housing stock

Fig. 1 graphs the energy flows of a sub-population of housing stock that is comprised solely of dwellings based on the revised Modal House. This sub-population is referred to from here on as being the housing stock.

The annual expansion rate of the housing stock is varied from zero to 2.0% per year. At each expansion rate the housing stock is stable in that the size of each

Table 4
Summary of life cycle and energy requirements of revised Modal House

Process	Energy requirement (MJ)	Cycle (yr)	Average proportion (%)	Source of cycle and proportion
New-build and replacement construction	255109	Mortality	100	Johnstone [25]
Annual maintenance[a]	357	1	100	
Rehabilitation				
External				
Repaint roofing	2240	7	100	Page [32]
Repaint cladding, doors	1667	8	100	Page [32]
Replace door and frames, prime	542	20	50	Tucker and Rahilly [9]
Replace spouting & downpipes, PVC	3119	25	100	NBA Construction Consultants [6]
Replace substructure and wall framing	1950	40	15	Tucker and Rahilly [9]
Replace aluminium windows	9761	40	100	NBA Construction Consultants [6]
Replace galvanised steel roofing, prime	54143	50	100	Page [32]
Replace fibre cement planks, prime	13629	50	100	Page [32]
Internal				
Repaint doors, trim, ceiling	2118	8	100	Tucker and Rahilly [9]
Replace wall papering	2685	8	100	Tucker and Rahilly [9]
Replace wool carpeting	14029	10	100	Tucker and Rahilly [9]
Replace vinyl flooring	4785	10	100	Tucker and Rahilly [9]
Replace sanitary fixtures	1605	20	50	Tucker and Rahilly [9]
Kitchen upgrade	13479	25	100	NBA Construction Consultants [6]
Replace internal wall linings	3837	40	30	Tucker and Rahilly [9]
Replace electrical wiring	2242	40	50	Tucker and Rahilly [9]
Replace hardware	4788	60	100	NBA Construction Consultants [6]
Demolition[b]	13378	Mortality	100	Johnstone [25]

[a] Gross energy requirement of annual maintenance is based on the average energy intensity per dollar to construct a dwelling.
[b] Gross energy requirement of demolition is based on Adalberth [16].

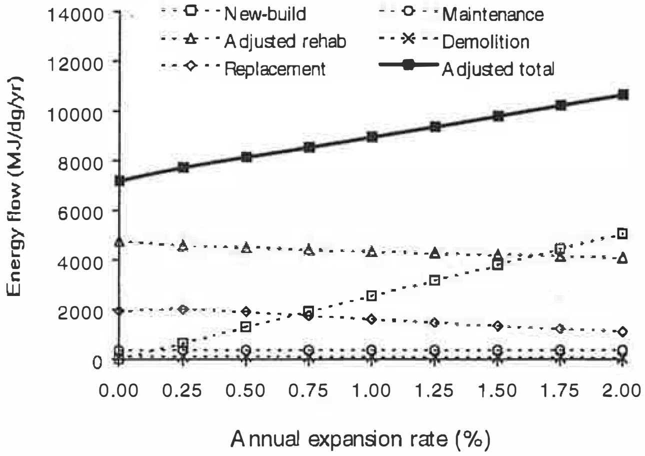

Fig. 1. Energy flows of housing stock under different annual expansion rates.

dwelling cohort as a ratio of the size of the total housing stock remains constant. Under conditions of dynamic mortality the average service life and service life span of the housing stock increases from 90 years and 143 years to 130 years and 226 years, respectively, when the annual expansion rate of the housing stock declines from 2.0% to 0% per year. The average service life and service life span which apply for a particular annual expansion rate take time to change to that for another due to lags inherent in the dynamics of housing stock. The same applies for energy and mass flows. Full results are listed in Table 5.

Energy flows are expressed in megajoules per dwelling per year (MJ/dg/yr) to enable energy flows under different expansion rates to be compared. The product of the energy flows per dwelling and the number of dwellings in the housing stock during the year under consideration gives the energy flows of the total housing stock. Energy flows referred to from here on are energy flows per dwelling unless specified otherwise.

The new-build energy flow is zero when the housing stock is stationary and this energy flow increases with each increase in the annual expansion rate. The maintenance energy flow is constant with each increase in the expansion rate. The adjusted rehabilitation energy flow takes into account the proportion of dwellings within each dwelling cohort that undergo each successive event of rehabilitation. This energy flow decreases with each increase in the annual expansion rate because there are proportionately fewer older dwellings that can take advantage of rehabilitation. Demolition and replacement energy flows decrease with each increase in the expansion rate because older dwellings which contribute the major proportion of total dwelling losses of all ages form a smaller proportion of the total size of the housing stock. The adjusted total energy flow, or sum of the fore-mentioned energy flows, increases with each increase in the annual expansion rate.

The adjusted total energy flow required to sustain dwelling services is 33% less when the housing stock is stationary compared to when it undergoes expansion at the rate of 2.0% per year (7187 MJ/dg/yr vs 10,669 MJ/dg/yr or 77.4 MJ/m^2/yr vs 114.8 MJ/m^2/yr). A stationary housing stock requires less energy to sustain dwelling services regardless of whether the housing stock is subject to dynamic or static mortality. If the housing stock should be subject to the same mortality when stationary as that when undergoing expansion

Table 5
Results of energy flows and dynamics of housing stock based on the revised Modal House

	Annual expansion rate of housing stock (%)								
	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
New-build energy flow (MJ/dg/yr)	0	640	1277	1913	2546	3178	3808	4436	5062
Maintenance energy flow (MJ/dg/yr)	357	357	357	357	357	357	357	357	357
Rehabilitation energy flow (MJ/dg/yr)	5223	5069	4960	4858	4757	4659	4563	4469	4376
Demolition energy flow(MJ/dg/yr)	103	106	100	92	85	77	70	64	58
Replacement energy flow (MJ/dg/yr)	1962	2025	1901	1757	1612	1473	1343	1222	1111
Total energy flow (MJ/dg/yr)	7645	8197	8595	8977	9358	9745	10142	10548	10965
Adjusted rehab energy flow (MJ/dg/yr)	4764	4583	4493	4417	4347	4279	4213	4147	4081
Adjusted total energy flow (MJ/dg/yr)	7187	7711	8128	8536	8947	9365	9792	10226	10669
Service loss index (sye/dg/yr)	0.863	0.886	0.900	0.912	0.921	0.930	0.937	0.944	0.949
Total energy flow to dwelling services ratio (MJ/sye)	8856	9249	9548	9847	10158	10483	10823	11179	11550
Adjusted total energy flow to dwelling services ratio (MJ/sye)	8325	8700	9029	9364	9712	10074	10450	10838	11238
Average service life of housing stock (years)	130.0	110.3	104.0	100.1	97.2	95.0	93.1	91.5	90.2
Service life span of housing stock (years)	226.0	183.0	170.0	162.0	156.0	152.0	149.0	146.0	143.0
Mean age of housing stock (years)	68.7	54.8	49.0	44.9	41.6	38.7	36.3	34.1	32.2
Annual replacement as % of size of housing stock (%)	0.77	0.79	0.75	0.69	0.63	0.58	0.53	0.48	0.44
Annual new-build as % of size of housing stock (%)	0.000	0.25	0.50	0.76	1.01	1.26	1.52	1.77	2.02

under dynamic mortality (r = 2.0%), then it requires 28% less energy (7670 MJ/dg/yr vs 10,669 MJ/dg/yr). Increases in mortality under conditions of dynamic mortality account for only a small proportion of the larger energy flows required to establish and sustain an expanding housing stock.

The energy required to undertake rehabilitation within a housing stock forms a substantial proportion of the total. The adjusted rehabilitation energy flow forms 66% of the adjusted total energy flow when the housing stock is stationary and 38% when the annual expansion rate is 2.0% per year.

The mean age of the housing stock is 32 years when the annual expansion rate is 2.0% per year and 69 years when the housing stock is stationary. Depreciation of dwelling services is less when the housing stock is younger. The service loss index, a measure of the average depreciation of dwelling services provided by a housing stock, is 0.949 when the expansion rate of the housing stock is 2.0% per year and 0.863 when the housing stock is stationary.

The adjusted total energy flows to dwellings services ratio is a measure of the total average energy flows required to sustain one year of dwelling services expressed in units of megajoules per dwelling service year equivalent (MJ/sye). This ratio is 8325 MJ/sye when the housing stock is stationary and 11,238 MJ/sye when the housing stock undergoes expansion at the rate of 2.0% per year. In other words, the housing stock requires 26% less energy on average to sustain each year of dwelling services when stationary.

7.2. Operational energy flow versus adjusted total energy flow

The average annual expansion rate of the New Zealand housing stock between each quinquennial census has fluctuated from 8.1% to 0.9% per year over the past century and has averaged 1.5% per year over the past decade [33]. Further expansion is largely contingent on future immigration policies because positive net migration currently forms the major source of effective demand to form additional households [33]. The fertility of the natural population has declined since the 1960s to the extent that the natural population now barely replaces itself and the average number of persons per household (pph) has declined from over 6 pph at the turn of the century to 2.9 pph at the last census in 1996 [33]. Further decreases over the next number of decades are likely to be gradual. An annual expansion rate of 1.5% per year is therefore selected for the purposes of illustrating use of the energy and mass flow model. The corresponding adjusted total energy flow is 9792 MJ/dg/yr (105.4 MJ/m^2/yr).

Table 6
Energy flows of key materials used by the revised Modal House (r = 1.5%)

	Timber framing	Gypsum board lining	Fibre cement cladding	Galvanised steel roof	PVC	Paint
New-build and replacement (MJ/dg)	20286	20821	14241	53128	13544	11388
New-build energy flow (MJ/dg/yr)	303	311	213	793	202	170
Rehabilitation energy flow (MJ/dg/yr)	32	63	148	614	108	778
Replacement energy flow (MJ/dg/yr)	107	110	75	280	71	60
Total energy flow (MJ/dg/yr)	442	484	435	1686	382	1008
Adjusted rehabilitation energy flow (MJ/dg/yr)	29	57	131	547	100	727
Adjusted total energy flow (MJ/dg/yr)	439	478	419	1619	373	957

Table 7
Mass flows of key materials used by the revised Modal House (r = 1.5%)

	Timber framing (m^3)	Gypsum board lining (m^3)	Fibre cement cladding (m^3)	Galvanised steel roof (kg)	PVC (kg)	Paint[a] (l)
New-build and replacement (unit/dg)	14.700	3.223	1.051	1526.7	193.5	110.1
New-build mass flow (unit/dg/yr)	0.219	0.048	0.016	22.8	2.9	1.6
Rehabilitation mass flow (unit/dg/yr)	0.023	0.010	0.011	17.6	1.6	7.3
Replacement mass flow (unit/dg/yr)	0.077	0.017	0.006	8.0	1.0	0.6
Total mass flow (unit/dg/yr)	0.320	0.075	0.032	48.4	5.5	9.6
Adjusted rehabilitation mass flow (unit/dg/yr)	0.021	0.009	0.010	15.7	1.4	6.9
Adjusted total mass flow (unit/dg/yr)	0.318	0.074	0.031	46.5	5.3	9.1

[a] Based on coverage of 15 m^2 per litre.

The Energy Efficiency Conservation Authority in New Zealand (EECA) has completed the second full year of the Household Energy End Use Project (HEEP) [34]. One end purpose of HEEP is to update and expand existing energy end-use databases, the majority of which are still based on the 1971–72 Household Electricity Survey [35]. The sample size of 29 dwellings in the HEEP study will be expanded to 400 dwellings in future studies to provide reliable data on the two largest energy uses of space heating and hot water heating. In the meantime, the 1971–72 survey provides sufficiently accurate data for illustration purposes.

The annual operational energy flow of space heating, hot water heating, cooking, and lighting for a typical all-electric New Zealand household in 1971–1972 was 32,868 MJ/dg/yr (9130 kWh/dg/yr) at the meter [35]. A multiplier factor of 1.53 MJ/MJ takes into account electricity generation and distribution [36], so the ratio of the operational energy flow at source to the adjusted total energy flow is therefore 5.1:1 when the annual expansion rate of the housing stock is held constant at 1.5% per year.

A report by the Ministry of Commerce [37] claims that homeowners are able to reduce their energy consumption by as much as 60% by using energy more efficiently. Insulation of New Zealand dwellings was not compulsory until the introduction of a residential insulation standard in 1978 [38] and it is possible that less than 30% of current dwellings meet the present standard [39]. High-grade energy used for the low-grade energy tasks of space heating and hot water heating forms as much as 60% of the total operational energy flow at source [34]. The need to use high-grade energy for low-grade energy tasks can be significantly reduced by increasing insulation levels, using solar collectors and heat pumps, and adopting solar energy design principles. A reduction of 60% in the above operational energy flow and a corresponding increase of, say, 10% in the energy flow required to sustain dwelling services would reduce the operational energy flow ratio from 5.1:1 to 1.9:1. The combined total of the operational energy flow and the energy flow required to sustain dwelling services would decrease by 49% from about 60,000 MJ/dg/yr to 31,000 MJ/dg/yr (646 $MJ/m^2/yr$ to 334 $MJ/m^2/yr$).

7.3. Energy and mass flows of key building materials ($r = 1.5\%$)

The following building materials contribute 52.4% to the total gross energy requirement of new-build and replacement construction: timber framing (8.0%), gypsum board linings (8.2%), fibre cement cladding (5.6%), galvanised steel roofing (20.8%), PVC (5.3%), and paint (4.5%). Table 6 lists the energy flows of these materials while Table 7 lists the mass flows

Galvanised steel roofing has the highest initial energy requirement of 53,128 MJ/dg and the highest adjusted total energy flow of 1619 MJ/dg/yr. Paint has the lowest initial energy requirement of 11,388 MJ/dg yet has the second highest adjusted total energy flow of 957 MJ/dg/yr due to the shorter intervals between each cycle of painting and hence greater frequency of painting over the service life span of a dwelling cohort.

Timber framing has the highest initial mass requirement of 14.7 m^3/dg and the highest adjusted total mass flow of 0.318 m^3/dg/yr in terms of volume. Paint has an initial mass requirement of 110.1 litres and an adjusted total mass flow of 9.1 l/dg/yr.

Under conditions of dynamic mortality one has to make assumptions as to what the future expansion rate of the housing stock will be in order to estimate the average volume of materials which will be used by a dwelling over its full service life [26]. The average expected volume of paint to be used by a dwelling over its service life is given by the product of the average service life of a dwelling cohort and the adjusted total litres of paint per dwelling per year used by a dwelling cohort. The average mass flow for a dwelling cohort within an expanding housing stock will be less than that for the total housing stock which includes

Table 8
Comparison of energy flows of fibre cement planks and timber weatherboards (r = 1.5%)

	Replacement cycle (years)					
	Fibre cement planks			Timber weatherboards		
	45	50	55	63	70	77
New-build and replacement (MJ/dg)	14995	14995	14995	9910	9910	9910
New-build energy flow (MJ/dg/yr)	224	224	224	148	148	148
Rehabilitation energy flow (MJ/dg/yr)	277	247	222	239	229	220
Replacement energy flow (MJ/dg/yr)	79	79	79	52	52	52
Total energy flow (MJ/dg/yr)	580	549	525	439	429	420
Adjusted rehab energy flow (MJ/dg/yr)	252	224	202	221	210	200
Adjusted total energy flow (MJ/dg/yr)	555	526	505	421	410	401

the mass flows for new-build construction. Given an expansion rate of 1.5% per year, the average service life of a dwelling cohort is 93.1 years (from Table 5), the average adjusted total mass flow is 7.9 l/dg/year, and the average expected volume of paint to be used by a dwelling over its service life is 736 l.

7.4. Comparison of the energy flows of alternative cladding systems ($r = 1.5\%$)

Table 8 compares the energy flows of fibre cement planks and timber weatherboards. The life cycle of both wall claddings are varied by ±10% to establish the sensitivity to changes in the life cycle. Timber weatherboards are replaced every 70 ± 7 years and the adjusted total energy flow ranges from 401 to 421 MJ/dg/yr. Fibre cement planks are replaced every 50 ± 5 years and the total adjusted energy flow ranges from 505 to 555 MJ/dg/yr. Use of timber weatherboards therefore requires almost 30% less energy. In dollar terms, the annual equivalent costs of using fibre cement planks are 53% less than that of timber weatherboards (NZ\$4.67/m^2 vs NZ\$10.30/m^2, 1995/96 base year) when the discount rate is 8% [32].

8. Conclusions

The energy and mass flows required to sustain dwelling services are dependent on the building materials used for housing, the durability and economic life of building components, the mortality of the housing stock, the proportion of surviving dwellings which undergo rehabilitation at each successive event of rehabilitation, and the expansion rate of the housing stock. A hypothetical housing stock comprised totally of lightweight timber framed dwellings in New Zealand has been used to illustrate use of the energy and mass flow model developed in this paper. The total energy flow required to sustain such a housing stock ranges from 7200 MJ/dg/yr to 10,900 MJ/dg/yr (80 MJ/m^2/yr to 120 MJ/m^2/yr) depending on the annual expansion rate of the housing stock and the proportion of dwellings which undergo rehabilitation. The assumption as to the proportion of surviving dwellings that undergo each event of rehabilitation needs to be validated and the schedule of building components that undergo rehabilitation needs to be extended as the schedule used in this paper is not exhaustive.

The energy flow of rehabilitation forms a major proportion of the total required to sustain dwelling services. Estimates of energy and mass flows should be based on empirical schedules of mortality because to do otherwise is to run the risk of under-estimating the average service life of dwellings and subsequently under-estimating the energy and mass flows of rehabilitation.

Energy and mass flows can be reduced by increasing the proportion of dwellings within each dwelling cohort that undergoes each event of rehabilitation and by increasing the number of cycles of rehabilitation. The durability of the structural system used by dwellings, however, ultimately limits the service life of dwellings and hence the potential for further reductions. Potential reductions in energy and mass flows are subject to diminishing returns because there are progressively fewer dwellings remaining in each dwelling cohort that can take advantage of rehabilitation as each dwelling cohort ages.

A decrease in the expansion rate of a housing stock has a greater impact on reducing the energy and mass flows required to sustain dwelling services than an increase in the extent of rehabilitation or changes in the distribution and use of building materials over time. A decrease in the expansion rate therefore has a corresponding greater impact on reducing the magnitude of the flows of CO_2 and other pollutants to the atmosphere due to activities by homeowners and the construction industry.

The ratio of costs to benefits over a single time interval is numerically the same as the ratio of the sum of future discounted costs to the sum of future discounted benefits when both costs and benefits increase by the same proportion over successive time intervals. The expression of energy and mass flows as a ratio of the resources required to sustain one unit of dwelling services also does not involve discounting but for a different reason. It is meaningless to discount a physical unit. If a physical unit can be discounted, then the inverse process of compounding can also be carried out. As Daly [40] has pointed out, abstract debts may be subject to the laws of perpetual exponential growth, but the physical world of energy and resources is not.

The results of an energy and mass flow study of housing must not be used to optimise the use of resources. Optimisation requires a comparison of the economic value of benefits in the form of dwelling services and the economic value of the costs of providing those services. The economic value of energy and mass used to create a capital good is not fully captured by a purely physical numeraire. Georgescu-Roegen [41] rebutted Costanza's [42] claim of equivalence between embodied energy and economic value and Böhm-Bawerk [43] laid a similar claim of Marx's labour theory of value to rest almost a century ago.

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