Auckland Region Dynamic Ecological-Economic Model: Technical Report NZCEE Research Monograph Series-No. 13

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Auckland Region Dynamic Ecological-Economic Model: Technical Report

NZCEE Research Monograph Series – No. 13

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Preface

In this technical report, the development of a system dynamics model of Auckland Region's environment-economy interactions is detailed. The model, known as the Auckland Region Dynamic Environment-Economy Model (ARDEEM), builds on the static monetary and physical flow models developed by McDonald and Patterson (1999), McDonald, Le Heron and Patterson (1999) and McDonald (2004a, 2004b, 2005). The model is characterised by positive and negative non-linear feedbacks between its component modules. The purpose of the model is not to predict Auckland Region's economic future, but instead to highlight possible physical and economic consequences under various scenarios. A key reason for the adoption of a system dynamics modelling framework is that it allows a great deal of flexibility in setting the scenarios that may be investigated. The scenarios themselves are designed to capture not only the 'business as usual' situation, but also the dynamic physical and economic consequences resulting from more extreme change.

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1 Structure of ARDEEM

ARDEEM is a novel system dynamics model designed to simulate the combined environmental and economic implications of change in the Auckland Region between 1998 and 2051. The focus of ARDEEM is therefore on the medium- to long-term (i.e. 30–70 years) consequences of change in the Auckland Region. ARDEEM cannot therefore be expected to capture short-term fluctuations in economic activity such as those arising from cyclical commodity price fluctuations.[1] The ARDEEM model consists of the following integrated modules:

- *Population module*. Simulates population growth by age-sex cohort. The population module provides inputs directly for the labour force, economic flow, and physical flow modules, and indirectly for the growth module. It is also used in the generation of several key indicators, including resource use per capita, GRP per capita and so on.
- *Labour force module*. Takes outputs from the population module by age-sex cohort and generates estimates of total labour force, employment and unemployment by industry.
- *Growth module*. Generates estimates of economic output by industry. The cornerstone of the growth module is a production function with constant returns to scale. The production function has the following factor inputs: employment (as generated by the labour force module); commodity imports and use (from the economic flow module); and manufactured capital stocks. The production function is augmented with indices representing technological change and natural capital depletion/degradation. The output estimates generated by this module feed into the economic flow and economic physical flow modules.
- *Economic flow module*. Describes the financial flow of commodities within the Auckland Region economy, and includes commodity supply, use, imports and exports. The module provides inputs for the growth and economic physical flow modules and generates key economic aggregates including value

[1] Other modelling frameworks such as Computable General Equilibrium (CGE), optimisation models (e.g., MARKAL), and some econometric models are better suited for this purpose.

added (regional GRP), balance of trade, labour productivity, capital productivity and so on.

- *Economic physical flow module*. Describes the Auckland Region economy in physical (mass) flow terms, including commodity supply, use, imports, and exports, and is closely related to the economic flow module. The focus of the module is on the within economy physical flows. Monetary estimates of commodity supply and use from the economic flow module are converted into physical equivalents based on price ($ per tonne) and indices of improvements in physical productivity.
- *Environment-economy physical flow module*. Describes the physical flow of raw materials and residuals associated with economic activity in the Auckland Region. The focal point of this module is the physical flow of ecological commodities not conventionally measured in economic markets. The module draws on the output by industry estimates of the growth module, exogenous estimates of raw material use/residual generation per $ output, and indices of improvements in physical productivity to generate its estimates of the physical flow of raw materials and residuals.

The links between the various modules are described in Figure 1. Sections 3 to 8 fully describe ARDEEM. Verification and validation of the model is conducted in Section 9. In Section 10 three scenarios are developed and simulated: (1) 'business as usual'; (2) 'cornucopian growth'; and (3) 'prudent pessimism'. The final Section of this Report outlines the major limitations of ARDEEM model including the identification of key areas for future development.

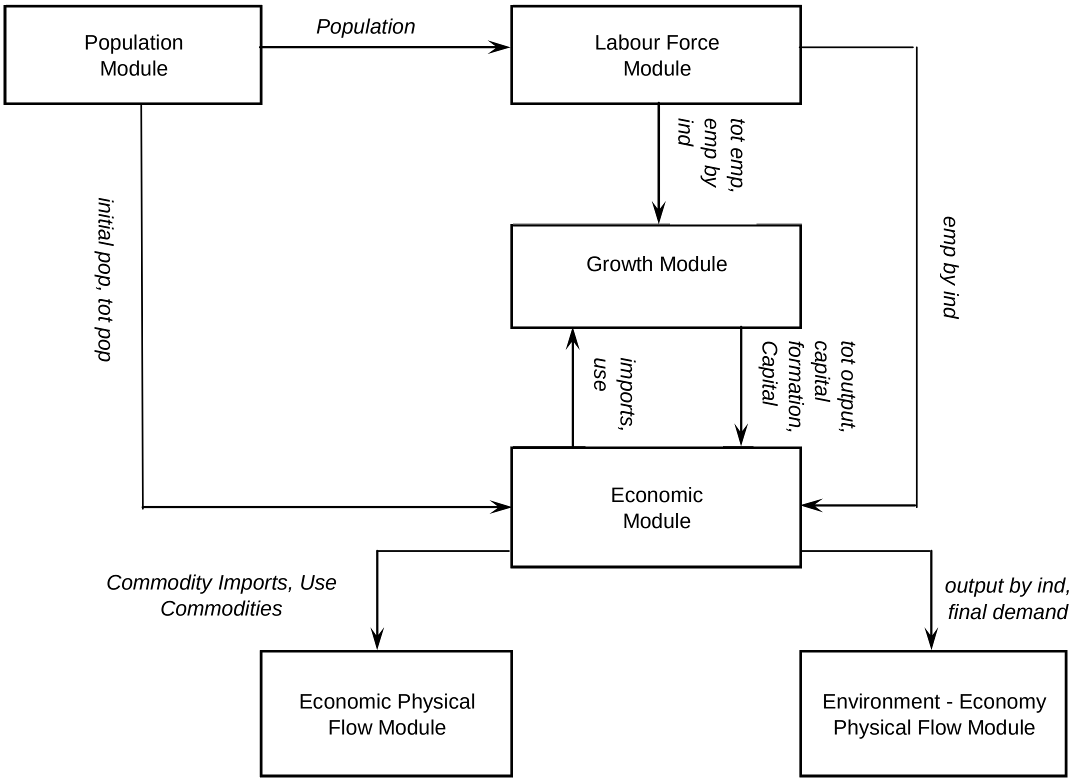

Figure 1 ARDEEM Module Linkages.

Note: The italicised key variables pass information between the modules.

2. Brief Description of ARDEEM's Mathematical Nomenclature

This Section provides a brief description of ARDEEM's mathematical nomenclature and naming conventions, specifically including:

Upper case stocks. All stocks begin with a capital letter.

Lower case flows and converters. All flows and converters begin with a lower case letter.

Subscripted arrays. Variables with multiple dimensions are arrayed. A population stock, for example, may have two dimensions – age and sex. In ARDEEM variables with arrayed dimensions are denoted by variable names with suffix subscripts. Vensim's® array functionality substantially reduces (1) the visual clutter of influence diagrams, and (2) the time required to program equations.

Full variable names. To help comprehend/understand how Vensim® system dynamics influence diagrams and mathematical formulae, variables names are presented in full.

A complete list of ARDEEM arrays and their elements is presented below:

Age-group	*a*	= 0-4 yrs, 5-9 yrs, 10-14 yrs, 15-9 yrs, 20-24 yrs, 25-29 yrs, 30-34 yrs, 35-39 yrs, 40-44 yrs, 45-49 yrs, 50-54 yrs, 55-59 yrs, 60-64 yrs, 65-69 yrs, 70-74 yrs, 75-79 yrs, 80 yrs and over
Commodity	*c*	= Com01, Com02, Com03
Final demand	*f*	= HhldCons, OFD, IntRegExp, IntNatExp
Industry	*i*	= Ind01, Ind02, Ind03
Imports	*imp*	= Interregional, International
Age-group (for population pyramid)	*p*	= 0-9 yrs, 10-19 yrs, 20-29 yrs, 30-39 yrs, 40-49 yrs 50-59 yrs, 60-69 yrs, 70-79 yrs, 80+ yrs
Sex	*s*	= male, female
Raw materials	*rm*	= Rm01, Rm02, Rm03, Rm04, Rm05
Residuals	*r*	= Res01, Res02, Res03, Res04, Res05, Res06
	n	total number of elements in the relevant array

3. Population Module

In this Section, a population module is developed that disaggregates Auckland Region's population by sex and five year age cohorts (i.e. 0–4 years, 5–9 years … 75–79 years, and 80 years and over). Sub-national population projections from Statistics New Zealand (2004) suggest that Auckland Region will grow from a 2001 base population of 1,216,900 to between 1,624,400 (low projection series) and 1,926,500 (high projection series) by 2026. This represents total population growth of between 33.5 percent (low) and 58.3 percent (high) over the 25 year period. Over two-thirds of New Zealand's total population growth between 2001 and 2026 is projected to be in the Auckland Region (Statistics New Zealand, 2004). By 2026 Auckland Region is projected to be home to more than 37 percent of New Zealand's total usually resident population, compared with 31 percent as at the 2001 Census. The implications of this growth cannot be understated:

- *Changes in the types of infrastructure required*. Although Aucklanders are relatively young, when compared with other New Zealanders, the average age has been steadily rising (Statistics New Zealand, 1998). Changes in the age structure of Aucklanders could potentially affect birth rates, housing requirements, health and education requirements, consumption patterns, and the nature of the labour force.
- *Pressure on existing infrastructure*. Much of Auckland Region's infrastructure is at capacity or the end of its life, or needs to meet higher environmental standards (Auckland Regional Council, 1999). Of particular concern is the pressure being placed on transportation networks, water supply services, wastewater treatment, and energy generation infrastructure.[2]

[2] The pressure of population growth on Auckland Region's infrastructure may arguably be seen through a number of local crises and associated policy responses including: the 1994 energy blackouts (resulting from a poorly maintained and ageing energy supply network), 1998 water shortage (resulting in the construction of the so-called 'Waikato pipeline'), and ongoing traffic congestion (leading to substantial local and central government expenditure on roading projects).

- *Demand for new infrastructure*. This includes demands for power stations, transportation networks[3], social and community services (i.e. hospitals, schools, libraries, museums, recreational facilities), open space (i.e. neighbourhood reserves, parklands and sports grounds) and additional housing.[4,5]
- *Structural mix of the economy*. Community, social and personal services play a more significant role in the Auckland Region economy than elsewhere in New Zealand. It can be argued that this role may be exacerbated through growth in population based services such as health and education. Export education, for example, has over recent years become a substantial industry in the Auckland Region economy.

In Figure 2, the ARDEEM population module is shown as a Vensim® system dynamics influence diagram. Note how the age-sex cohort structure of the model is captured using Vensim's® array functionality, rather than by building multiple population stocks with inflows and outflows for each age-sex cohort.

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[3] Household trends in car ownership and energy consumption during the 1990s have exacerbated these demands by growing at rates substantially higher than the population growth rate (Auckland Regional Council, 1999).

[4] The average home occupancy rate in Auckland Region has been steadily rising (Statistics New Zealand, 1998; Auckland Region Council, 1999) Although this trend may to some extent dampen the demand for additional housing, it is insufficient to offset the likelihood of substantial future housing requirements. By contrast, the New Zealand home occupancy rate has been steadily declining.

[5] Over the last two decades Auckland Region territorial local authorities, supported by the Auckland Regional Council, have through initiatives such as the Auckland Regional Growth Forum advocated a more compact urban form, resulting in greater numbers of apartments, terraced housing and infill housing. Although trends for traditional housing have persisted, there has been a significant increase in higher density living.

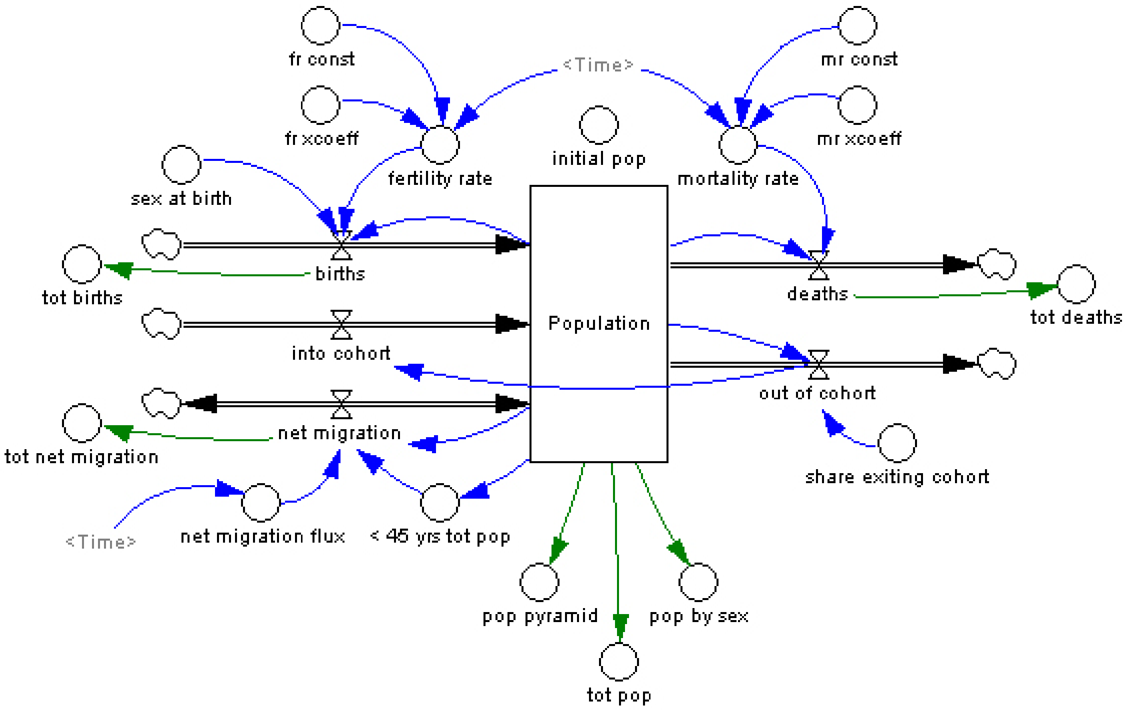

Figure 2 Population Module Influence Diagram

The population module may be described using the following mathematical equations:[6]

Stocks

$Population_{a,s}(t + dt)$ $= Population_{a,s}(t) + (births_{a,s} + net\ migration_{a,s} + into\ cohort_{a,s} - deaths_{a,s} - out\ of\ cohort_{a,s}) \times dt.$ As measured in number of people.

where:

Initial $Population_{a,s}$ $= initial\ pop_{a,s}$ for the 1998 base year (no. people).

<u>Inflows</u>

$births_{a,s}$ $= \sum_{a,s}((Population_{a,s}(t) \times fertility\ rate_{a,s} / 1000) \times sex\ at\ birth_{s})$[7] As measured in number of people.

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[6] It is important to note that variables are defined only once, at first use, to avoid unnecessary duplication.

where:

fertility rate$_{a,s}$ = ($fr\ xcoeff_{a,s} \times$ LN((t) – 1971)) + $fr\ const_{a,s}$. Fertility rate per thousand population in the age-sex cohort. All male cohorts are set to zero.

fr const$_{a,s}$ = the constant of a logarithmic time series regression equation describing the Auckland Region fertility rate of a particular age-sex cohort between 1971 and 2000.[8] If s = male then $fr\ const_{a,s}$ is set to zero. Similarly, *fr* const$_{a,s}$ for females a<9 and a>=50 is set to zero.

fr xcoeff$_{a,s}$ = the 'x' coefficient of a logarithmic time series regression equation describing the Auckland Region fertility rate of a particular age-sex cohort between 1971 and 2000. Once again, if s = male, or s = female and a < 10 or a >= 50 years, then $fr\ xcoeff_{a,s}$ is set to zero.

sex at birth$_s$ = shares of sex at birth. It is assumed that likelihood of a male or female being born is the same, i.e. 0.5.

net migration$_{a,s}$ = *net migration flux* $\times$($Population_{a,s}(t)$ / *< 45 yrs tot pop*)

where:

net migration flux = a time series of annual net migration into/from Auckland Region. These estimates are taken directly from Statistics New Zealand's (2004) sub-national population projections (medium series).

<45 yrs tot pop = $\sum_{a=0 \text{ to } 4 \text{ yrs}}^{40 \text{ to } 44 \text{ yrs}} \sum_{s=f,m} (Population_{a,s}\ (t))$. Total population under 45 years of age.

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[7] Double summations, such as $\sum_{a} \sum_{s=f,m} (Population_{a,s}(t))$, are summarised here as $\sum_{a,s} (Population_{a,s}(t))$.

[8] Linear and logarithmic time series regressions are utilised throughout this Report to account for the changing nature of exogenous variables. The pros and cons of using time series regression in this way are given in the Appendices.

into $cohort_{a,s}$ = *out of* $cohort_{a,s}$. If *a* represents the 5 to 9 age cohort then it is assumed that one fifth of the 0 to 4 age cohort moves into the 5 to 9 age cohort each year. A similar pattern applies to other age cohorts. As measured in number of people.

Outflows

$deaths_{a,s}$ = $Population_{a,s}(t) \times (mortality\ rate_{a,s} / 1000)$. As measured in number of people.

where:

mortality $rate_{a,s}$ = $(mr\ xcoeff_{a,s} \times \mathrm{LN}((t) - 1971)) + mr\ const_{a,s}$. Mortality rate per thousand by age-sex cohort.

mr $const_{a,s}$ = the constant of a linear or logarithmic time series regression equation describing the mortality rate of a particular age-sex cohort between 1971 and 1995.

mr $xcoeff_{a,s}$ = the 'x' coefficient of a linear or logarithmic time series regression equation describing the mortality rate of a particular age-sex cohort between 1971 and 1995.

out of $cohort_{a,s}$ = $Population_{a,s}(t) \times$ *share exiting cohort.* As measured in number of people.

where:

share exiting cohort = the share of population in each age-sex cohort exiting the cohort in each full time step. It is assumed that the number of people in each year of age in a cohort is the same i.e. one fifth of the age cohort moves into the next cohort each year.

Reporting variables

pop by sex$_s$ = $\sum_a (Population_{a,s}(t))$. Total population by sex (no. of people).

tot births = $\sum_{a,s} (births_{a,s})$. Total births (no. of people).

tot deaths = $\sum_{a,s} (deaths_{a,s})$. Total deaths (no. of people).

tot net migration = $\sum_{a,s} (net\ migration_{a,s}))$. Total net migration (no. of people).

tot pop = $\sum_{a,s} (Population_{a,s}(t))$. Total population (no. of people).

pop pyramid$_{0\ to\ 9,s}$ = $Population_{0\ to\ 4,s} + Population_{5\ to\ 9,s}$. Total population for the 0 to 9 age cohort by sex for reporting in a population pyramid. Other population pyramid age-sex cohorts were calculated in an analogous manner (no. of people).

The reliance on time series regression to determine fertility and mortality rates represents an attempt to use statistical techniques to capture trends in these rates over the last thirty years. Modellers such as Boumans *et al.* (2002), Jollands *et al.* (2005), and Jollands *et al.* (2007) have also used this approach in their modelling.[9] It is *very* important to note, however, that time series regression cannot predict the future. Fertility and mortality rates, for example, may change due to unforeseen factors such as a tightening of immigration policy, political instability, economic depression, the spread of disease, natural disasters, one-off health care advancements, war and so on. Being able to directly change exogenous variables such as fertility rates is therefore essential for simulation of Auckland Region's environment-economy system.

[9] 'Curve fitting' approaches have also been extensively used by the Resource Futures Group at the CSIRO in Canberra. This group, led by Dr Barney Foran, has developed the Australian Stocks and Flows Model (ASFM) to simulate the resource requirements necessary to sustain the Australian economy to 2100 under particular policy driven scenarios.

4. Labour Force Module

In this Section the labour force dynamics of the ARDEEM model are developed. The labour force module consists of no stocks or flows, but only of converters which transform the population module estimates into total available labour force (> 15 years of age), adjust these estimates for unemployment to derive FTE employment and, in turn, distribute this employment to economic industries. The employment by industry estimates are a critical factor input into the economic growth module of Section 5. The Vensim® system dynamics influence diagram for the labour force module is depicted in Figure 3. The mathematics of the module is given below:

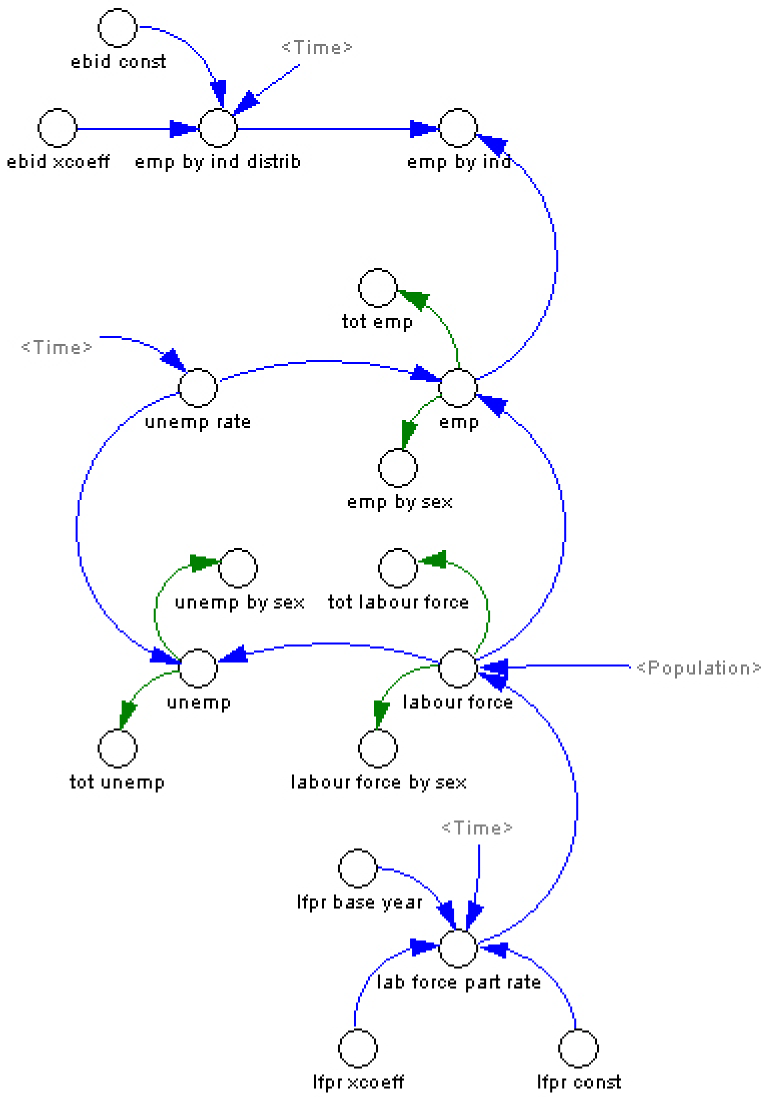

Figure 3 Labour Force Module Influence Diagram

Converters

lab force part rate$_{a,s}$ = (*lfpr xcoeff*$_{a,s}$ × LN((*t*) – *lfpr base year*$_{a,s}$)) + *lfpr const*$_{a,s}$. Labour force participation rates for those under 15 years of age are set to zero. Units are people/people.

where:

lfpr base year$_{a,s}$ = the base year of a logarithmic time series regression equation describing labour force participation of a particular age-sex cohort. A 1986 base year was used for $a < 60$, and a 1993 base year for $a >= 60$.

lfpr const$_{a,s}$ = the constant of a logarithmic time series regression equation describing labour force participation of a particular age-sex cohort from the base year.

lfpr xcoeff$_{a,s}$ = the 'x' coefficient of a logarithmic time series regression equation describing labour force participation of a particular age-sex cohort from the base year.

labour force$_{a,s}$ = *Population*$_{a,s}$(*t*) × *lab force part rate*$_{a,s}$. Available labour force (subset of population), measured in full-time equivalents (FTEs).

emp$_{a,s}$ = *labour force*$_{a,s}$ × (1 – *unemp rate*$_{a,s}$). As measured in FTEs.

where:

unemp rate$_{a,s}$ = a time-series of annual unemployment rates for New Zealand as taken from Statistics New Zealand. It is assumed that Auckland Region unemployment rates in each age-sex cohort are similar to those of the nation. Post-2005 unemployment rates for each age-sex cohort were derived using a moving average of the preceding 6 years.

unemp$_{a,s}$ = *labour force*$_{a,s}$ × *unemp rate*$_{a,s}$. As measured in FTEs.

emp by ind$_i$ = $\sum_{a=0 \text{ to } 4 \text{ yrs}}^{80 \text{ yrs and over}} \sum_{s=f,m} (emp_{a,s}) \times emp\ by\ ind\ distrib_i$. As measured in FTEs.

where:

emp by ind distrib$_i$ = ($ebid\ xcoeff_i \times \text{LN}((t) - 1987)) + ebid\ const_i$

ebid const$_i$ = the constant of a logarithmic time series regression equation describing the distribution of employment (FTEs) across economic industries between 1987 and 2003.

ebid xcoeff$_i$ = the 'x' coefficient of a logarithmic time series regression equation describing the distribution of employment (FTEs) across economic industries between 1987 and 2003.

Reporting variables

labour force by sex$_s$ = $\sum_{a=15 \text{ to } 19 \text{ yrs}}^{80 \text{ yrs and over}} (labour\ force_{a,s})$. Total labour force by sex (FTEs).

tot unemp = $\sum_{a=15 \text{ to } 19 \text{ yrs}}^{80 \text{ yrs and over}} \sum_{s=f,m} (unemp_{a,s})$. Total unemployment (FTEs).

unemp by sex$_s$ = $\sum_{a=15 \text{ to } 19 \text{ yrs}}^{80 \text{ yrs and over}} (unemp_{a,s})$. Total unemployment by sex (FTEs).

tot labour force = $\sum_{a=15 \text{ to } 19 \text{ yrs}}^{80 \text{ yrs and over}} \sum_{s=f,m} (tot\ labour\ force_{a,s})$. Total labour force (FTEs).

emp by sex$_s$ = $\sum_{a=15 \text{ to } 19 \text{ yrs}}^{80 \text{ yrs and over}} (emp_{a,s})$. Total employment by sex (FTEs).

tot emp = $\sum_{a=15 \text{ to } 19 \text{ yrs}}^{80 \text{ yrs and over}} \sum_{s=f,m} (emp_{a,s})$. Total employment (FTEs).

5. Growth Module

In this Section a growth model for ARDEEM is developed. The model builds on the economic growth theories critiqued in McDonald (2005). Although several alternative growth models were operationalised and tested using hypothetical data, a severe paucity of actual data,[10] along with time constraints, prohibited fuller implementations. One or two of these alternatives could arguably be considered to be more conceptually appealing than the actual model implemented below. One such alternative, an endogenous growth model, is depicted in Appendix A using a Vensim® system dynamics influence diagram.

At the core of the ARDEEM growth model is a production function controlling the estimation of future output by industry within the Auckland Region economy (Figure 4). The production function comprises factor inputs (manufactured capital, natural capital, labour, domestic commodity use, commodity imports, and technological change), which are determined through a number of dynamic feedback loops. The factor inputs and their loops are considered further below:

- *Capital*. This represents the stock of manufactured capital (covering intangible assets, plant and machinery, transport equipment, other construction, non-residential buildings, and residential buildings) utilised in producing economic output in the economy. Capital stock estimates for the base year were derived by scaling down national estimates to the Auckland Region based on FTE employment.[11] The national estimates were obtained from Statistics New Zealand (2000). Capital formation depends on economic output and an exogenously set investment rate, while capital depreciation depends on the size of the capital stock and an exogenously set depreciation rate. Capital investment and depreciation rates were developed by applying

[10] An alternative engine based on endogenous growth theory, for example, required estimates of knowledge stocks, knowledge creation/duplication rates, and so on for the modelling of the 'stepping on toes' and 'standing on the shoulders of giants' technological spillover effects. A further complication, relevant to this example, was the necessity to build not only dynamics for knowledge creation occurring within the Auckland Region, but also for the rest of the world.

[11] It is assumed that the mix of capital used by each worker is spatially invariant across New Zealand. Comment on validity of this assumption.

regression analysis to national time series obtained from Statistics New Zealand's INFOS database (http://www.stats.govt.nz/products-and-services/infos/default.htm). Again, future patterns of investment and depreciation may not follow past trends. Furthermore, capital investment and the production of economic output are interdependent activities. The economic output of an industry includes wage, salary, and dividend payments made to employees, which in turn, provides the fuel for further investment. Data constraints prohibited the explicit modelling of this feedback.[12]

- *Labour*. Labour inputs are included in ARDEEM through the estimation of the number of human hours worked annually in each industry. These estimates were generated by multiplying for each industry employment estimates by occupation (FTEs), by the number of hours typically worked in each week within each occupation (hours), and then scaling these to produce annual estimates. Measurement in human-hours accounts for productivity changes brought about by working more hours per day. Labour factor payments (i.e. wages and salaries) also play a critical role in ARDEEM, through namely: (1) investment in the formation of capital – as discussed above; and (2) commodity consumption – as captured in the positive feedback between the Economic and Growth modules involving the use_i variable.
- *Commodity use*. The criticality of minor factor inputs in generating an industry's output along with path dependencies are captured in the model by consideration of commodities used in intermediate consumption. Currently commodity inputs in ARDEEM are only considered in aggregate; it is envisaged that future versions of the model will consider more carefully the role played at a detailed commodity level.
- *Commodity imports*. Commodity imports are essential to the Auckland Region economy (refer to McDonald (2004a, 2005, 2008) for further details).[13] Auckland Region's traditional role in import substitution has been

[12] Separation of domestic and foreign capital investment at a disaggregated sectoral level was the main constraint.
[13] This critical dependence has been further investigated by the author and Professor Le Heron of the School of Geography and Environmental Science at University of Auckland. Based on an analysis of changes in Auckland Region value added and employment multipliers between 1987 and 2003 it was found that economic interdependencies between industries had substantially weakened, while a compensatory growth in trade, particularly with neighbouring

identified elsewhere, as was the increasing trade openness of the economy; particularly for light manufacturing industries. If local supply is unable to satisfy local demand for a particular commodity it is likely that the market response will be to import this commodity. Furthermore, if a locally provided non-renewable resource becomes scarce, and cannot easily be substituted for, then importation of the resource will be critical for continued economic activity. Allowing for the possible simulation of substitution of domestic commodities for imported equivalents is therefore considered paramount. It is envisaged that in future versions of ARDEEM consideration will also be given to the demand for exports occurring elsewhere.

- *Technology index*. This stock represents technological change over time via the positive feedback loop between the *Technology Index*$_i$ stock and the *technology formation*$_i$ flow. The formation rate is controlled by the exogenously determined *technology rate*$_i$. The technology rate for each industry was set equal to the 1998–2002 geometric annual average total factor productivity (TFP) rate as obtained from Black *et al.* (2003). Since the TFP covers all factor inputs the technology index must augment the entire production function. It should be noted that if each industry's TFP is set to zero then the reporting variables *output per worker*$_i$ and *capital per worker*$_i$ will tend toward a steady-state over the long term i.e. there will be no productivity growth and the growth rate of the Auckland Region economy will simply mirror the population growth rate. Again, it is important to note that future trends in TFP may not reflect historical trends.
- *Elasticities*[14] *of output with respect to factor inputs* (a_i, b_i, g_i, and d_i). These elasticities were estimated by taking a 1987 to 2003 time series of the logs of the factor inputs (i.e. *Capital*$_i$, *emp by ind*$_i$, *use*$_i$, and *imports*$_i$) and performing a constrained regression such that the coefficients of the dependent variables of the regression equation (i.e. a_i, b_i, g_i, and d_i) summed to 1, i.e. exhibited constant returns to scale. This approach is commonly used by economists to derive the elasticities of factor inputs with respect to output. It is important to

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regions and Australia, had eventuated. Given the globalisation of international markets this is perhaps not surprising.

[14] Elasticities measure the responsiveness of ouput to a change in a factor of production. Coefficients a_i, b_i, g_i, and d_i can be interpreted as the percentage point change in output from a one percentage point change in the relevant factor of production.

note that the regression analysis is used only to establish the initial values of a_i, b_i, g_i, and d_i, i.e. it does not in any way mean that these elasticities will remain the same over the next 30–70 years. Furthermore, no assumptions have been made as to how one factor input may substitute for another; instead these may be tested explicitly under various simulations.

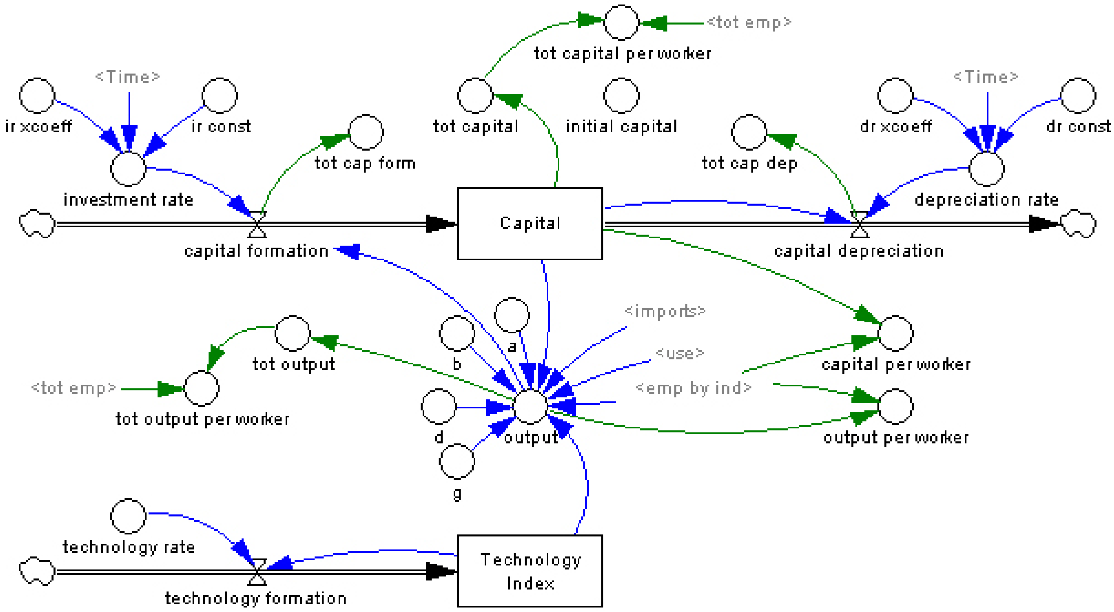


Figure 4 Growth Module Influence Diagram

Capital Stock

Capital$_i$ $(t + dt)$ = *Capital$_i$*(t) + (*capital formation$_i$* – *capital depreciation$_i$*) $\times$ *dt.* The total available manufactured capital stock ($ mil)[15] utilised by industry *i*.

where:

Initial *Capital$_i$* = *initial capital$_i$* ($ mil) for the 1998 base year.

<u>Inflows</u>

capital formation$_i$ = *output$_i$* $\times$ *investment rate$_i$*. As measured in $ mil.

where:

[15] All financial values are in $1995 unless stated otherwise.

investment rate$_i$	$= (ir\ xcoeff_i \times \mathrm{LN}((t) - 1987)) + ir\ const_i$
where:	
ir xoceff$_i$	= the 'x' coefficient of a linear or logarithmic time series regression equation describing the rate of capital investment by industry *i* between 1987 and 2003.
ir const$_i$	= the constant of a linear or logarithmic time series regression equation describing the rate of capital investment by industry *i* between 1987 and 2003.
output$_i$	=. $(Technology\ Index_i(t) \times Capital_i(t)^{a_i} \times emp\ by\ ind_i)^{b_i} \times \sum_{imp=1}^{n} \left(imports_{imp,i}\right)^{g_i} \times \sum_{c=1}^{n} \left(use_{c,i}\right)^{d_i}$. A production function estimating total output ($ mil) in each industry *i*. The production function assumes constant returns to scale (i.e. $a_i + b_i + g_i + d_i = 1$).
where:	
a_i	= the elasticity of output with respect to capital utilised by industry *i*.
b_i	= the elasticity of output with respect to employment utilised by industry *i*.
g_i	= the elasticity of output with respect to total imports utilised by industry *i*.
d_i	= the elasticity of output with respect to total intermediate commodity use by industry *i*.
$imports_{imp,i}$	= total imports ($ mil) used by industry *i*.
$use_{c,i}$	= total commodities ($ mil) used by industry *i*.

<u>Outflows</u>

capital depreciation$_i$	$= Capital_i(t) \times depreciation\ rate_i$. As measured in $ mil.
where:	
depreciation rate$_i$	$= dr\ xcoeff_i \times \mathrm{LN}((t) - 1972) + dr\ const_i$
where:	

dr $xcoeff_i$	= the 'x' coefficient of a linear or logarithmic time series regression equation describing the rate of capital depreciation by industry *i* between 1972 and 2003.
dr $const_i$	= the constant of a linear or logarithmic time series regression equation describing the rate of capital depreciation by industry *i* between 1972 and 2003.

Technology Index Stock

$Technology\ Index_i\ (t + dt) = Technology\ Index_i(t) + (technology\ formation_i) \times dt$

where:

Initial *Technology Index* = 1 for the 1998 base year.

<u>Inflows</u>

$technology\ formation_i = Technology\ Index_i(t) \times technology\ rate_i$

where:

$technology\ rate_i$	= the geometric rate of annual technological change for industry *i*. Black *et al.* (2003) have estimated total factor productivity by industry in the New Zealand economy over the period 1988 to 2002. These estimates are used here as a proxy for the rate of technological change in the Auckland Region economy.

Reporting variables

tot cap form	= $\sum_{i=1}^{n}(capital\ formation_i)$. Total capital formation ($ mil).
tot cap dep	= $\sum_{i=1}^{n}(capital\ depreciation_i)$. Total capital depreciation ($ mil).

tot capital	$= \sum_{i=1}^{n} (Capital_i(t))$. Total capital ($ mil).
tot capital per worker	= *tot capital* / *tot emp* (as long as *tot emp* is non-zero, otherwise 0). As measured in $ mil.
tot output per worker	= *tot output* / *tot emp* (as long as *tot emp* is non-zero, otherwise 0). As measured in $ mil.
tot output	$= \sum_{i=1}^{n} (output_i)$. Total output ($ mil).
$capital\ per\ worker_i$	$= Capital_i(t) / emp\ by\ ind_i$ (as long as $emp\ by\ ind_i$ is non-zero, otherwise 0). Total capital ($ mil) by industry i.
$output\ per\ worker_i$	$= output_i / emp\ by\ ind_i$ (as long as $emp\ by\ ind_i$ is non-zero, otherwise 0). Total output ($ mil) by industry i.

6. Economic Module

The economic module consists of a commodity-by-industry input-output economic system. This module describes the circular flow of commodities supplied both domestically and internationally, and their corresponding use and final consumption (Figure 5). The module is linked with the growth module through a number of positive (reinforcing) feedbacks. On the one hand, it provides key inputs into the growth module by generating estimates of (1) commodity imports required to satisfy both intermediate and final demand, and (2) intermediate demand commodity use. On the other hand, it utilises estimates of output and capital formation in the calculation of the interregional exports, international exports and other final demands (capital formation).

There are several key features of the economic module. First, utilising the input-output model allows the interrelationships between economic industries to be simulated over time. If, for example, households consume more dairy products, then the model would simulate not only a resultant increase in dairy product manufacture, but also an increase in dairy cattle farming.[16] Second, the input-output model is created in a commodity-by-industry format which records joint production. Although data constraints will typically restrict the simulation to less than 50 industries, the number of commodities will be far less restricted; the supply and use of hundreds of commodities could be simulated without difficulty. Third, this detailed consideration of industries and their commodities potentially enables the unique role played by manufacturing in capital formation to be directly incorporated in the growth module production function. It also permits consideration of minor, but limiting or critical commodity factor inputs, to be incorporated in the production function. Fourth, the adoption of a financial commodity-by-industry framework ensures comparability and the straightforward translation into physical equivalents (see Section 7 below).

[16] These relationships are evaluated at each time step within the model. It should be noted, however, that the input mix of commodities (i.e. purchase pattern) utilised by each industry is assumed to remain constant over time. A more complete implementation of the model would allow this mix to change over time. Duchin and Szyld (1985) and Leontief and Duchin (1986) have, for example, performed time series regression on input-output technical coefficients to assess the future impact of automation on workers. This approach, while beyond the scope of this report, provides a possible pathway for the future development of the economic module.

Finally, the commodity-by-industry format permits the computation of economic and ecological multipliers (and by corollary ecological footprints) at each time step. Overall, the economic module combines the detailed commodity-by-industry input-output data with the flexibility of dynamic simulation.

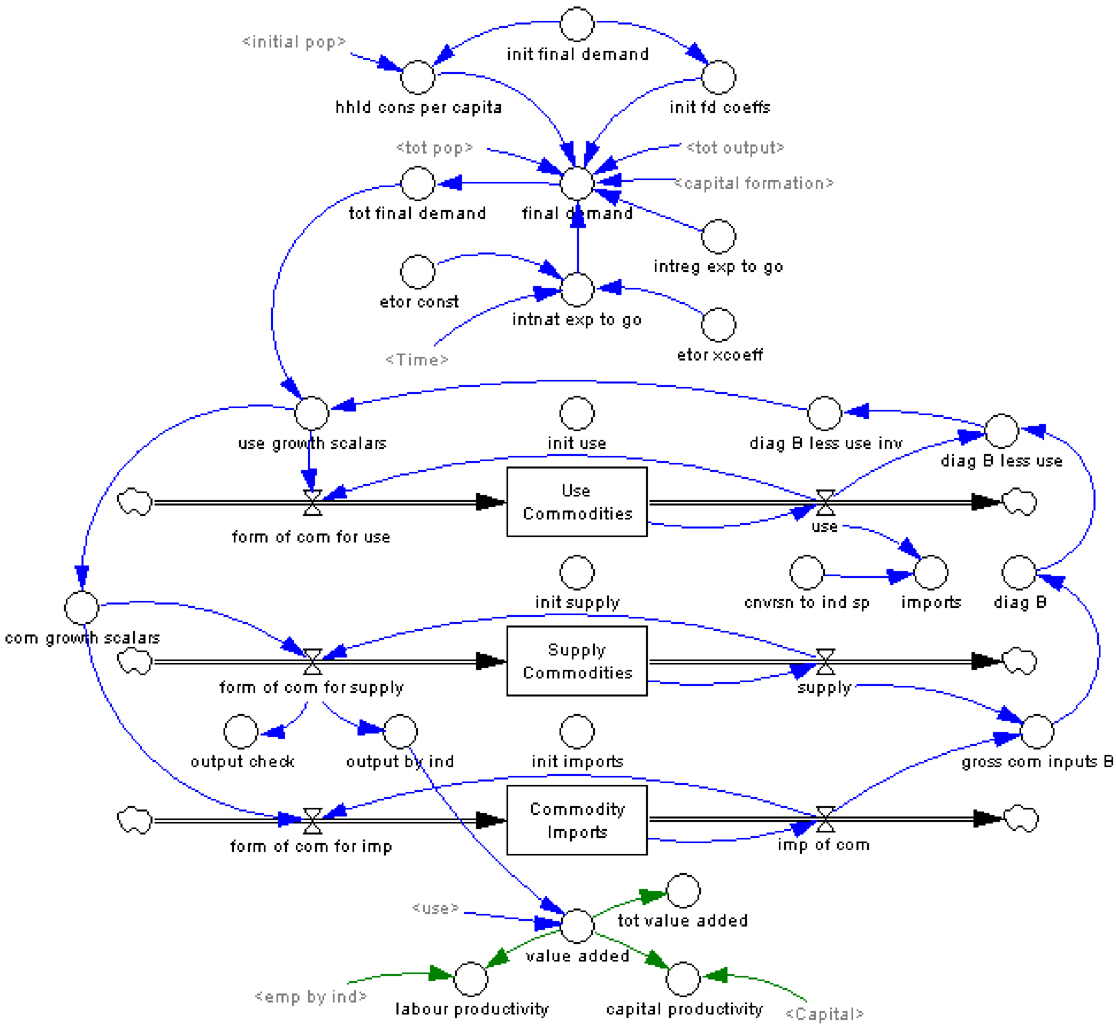


Figure 5 Economic Module Influence Diagram

Use Commodities Stock

$Use\ Commodities_{c,i}\ (t + dt)\ = Use\ Commodities_{c,i}(t) + (form\ of\ com\ for\ use_{c,i} - use_{c,i}) \times dt$. As measured in \$ mil.

where:

Initial $Use\ Commodities_{c,i}$ $= init\ use_{c,i}$ (\$ mil) for the 1998 base year.

Inflow

form of com for use$_{c,i}$	= *use*$_{c,i}$ × *use growth scalars*$_{i.}$ As measured in \$ mil.
where:	
use growth scalars$_c$	$= \sum_i diag\ B\ less\ use\ inv_{c,i} \times tot\ final\ demand_{k,i}$
diag B less use inv$_{c,i}$	= INVERT MATRIX(*diag B less use*$_{c,i}$,3)
diag B less use$_{c,i}$	= *diag B*$_{c,i}$ – *use*$_{c,i}$
diag B$_{c,i}$	= *gross com inputs*$_c$. As measured in \$ mil.
gross com inputs B$_c$	$= \sum_{i=1}^{n}(supply_{i,c}) + \sum_{imp=1}^{n}(imp\ of\ com_{imp,c})$. Total gross commodity inputs (\$ mil).
tot final demand$_c$	$= \sum_{f=1}^{n}(final\ demand_{c,f})$. Total final demand (\$ mil) by commodity *c*.
final demand$_{c,HhldCons}$	= *hhld cons per capita*$_c$ × *tot pop*. As measured in \$ mil.
final demand$_{c,OFD}$	$= init\ fd\ coeffs_{c,OFD} \times \sum_{i=1}^{n}(capital\ formation_i)$. As measured in \$ mil.
final demand$_{c,IntRegExp}$	= *init fd coeffs*$_{c,IntRegExp}$ × *tot output* × *intreg exp to go*. As measured in \$ mil.
final demand$_{c,IntNatExp}$	= *init fd coeffs*$_{c,IntNatExp}$ × *tot output* × *intnat exp to go*. As measured in \$ mil.
intnat exp to go	= (*etor xcoeff* × LN((*t*) – 1987)) + *etor const*
etor const	= the constant of a logarithmic time series regression equation describing the ratio of international exports to gross output between 1987 and 2003.
etor xcoeff	= the ‘x’ coefficient of a logarithmic time series regression equation describing the ratio of international exports to gross output between 1987 and 2003.
intreg exp to go	= the ratio of interregional exports to gross output for the 1998 year.

init fd coeffs$_{c,f}$ = $init\ final\ demand_{c,f}\ /\ \sum_{c=1}^{n}(init\ final\ demand_{c,f})$

init final demand$_{c,f}$ = final demand consumption by commodity *c* across final demand *f* for the 1998 base year ($ mil).

hhlds cons per capita$_c$ = $init\ final\ demand_{c,HhldCons}\ /\ \sum_{a,s}(initial\ pop_{a,s})$. As measured in $ mil.

<u>Outflow</u>

use$_{c,i}$ = *Use Commodities*$_{c,\,i}(t)$. As measured in $ mil.

imports$_{imps,i}$ $= \sum_{c=1}^{n} cnvrsn\ to\ ind\ sp_{imp,c} \times use_{c,i}$

cnvsrn to ind sp$_{imps,c}$ = a matrix for converting imports from commodity to industry space for the 1998 base year. This matrix was derived from the Market Economics Ltd Auckland Region input-output model (for technical details refer to McDonald (2008)).

Supply Commodities Stock

$Supply\ Commodities_{i,c}\ (t + dt) = Supply\ Commodities_{i,c}(t) + (form\ of\ com\ for\ supply_{i,c} – supply_{i,c}) \times dt$. As measured in $ mil.

where:

Initial *Supply Commodities*$_{i,c}$ = *init supply*$_{i,c}$ for the 1998 base year ($ mil).

<u>Inflow</u>

form of com for supply$_{i,c}$ = $supply_{i,c} \times com\ growth\ scalars_c$. As measured in $ mil.

where:

com growth scalars$_c$ = *use growth scalars*$_i$

<u>Outflow</u>

supply$_{i,c}$ = *Supply Commodities*$_{i,c}(t)$. As measured in $ mil.

Commodity Imports Stock

$Commodity\ Imports_{imp,c}\ (t + dt)$ = $Commodity\ Imports_{imp,c}(t) + (form\ of\ com\ for\ imp_{imp,c} - imp\ of\ com_{imp,c}) \times dt$. As measured in \$ mil.

where:

Initial $Commodity\ Imports_{imp,c}$ = $init\ imports_{imp,c}$ for the 1998 base year (\$ mil).

<u>Inflow</u>

$form\ of\ com\ for\ imp_{imp,c}$ = $imp\ of\ com_{imp,c} \times com\ growth\ scalars_c$. As measured in \$ mil.

<u>Outflow</u>

$imp\ of\ com_{imp,c}$ = $Commodity\ Imports_{imp,c}(t)$. As measured in \$ mil.

Reporting variables

$output\ check$ = $\sum_{i,c}(form\ of\ com\ for\ supply_{i,c})$. Total output check (\$ mil).

$output\ by\ ind_i$ = $\sum_{c=1}^{n}(form\ of\ com\ for\ supply_{i,c})$. Total output by industry i (\$ mil).

$value\ added_i$ = $output\ by\ ind_i - \sum_{c=1}^{n}(use_{c,i})$. Total value added by industry i (\$ mil).

$tot\ value\ added$ = $\sum_{i=1}^{n}(value\ added_i)$. Total value added (\$ mil).

$labour\ productivity_i$ = $value\ added_i\ /\ emp\ by\ ind_i$ (as long as $emp\ by\ ind_i$ is non-zero, otherwise 0). Labour productivity as measured in \$ mil.

$capital\ productivity_i$ = $value\ added_i$ / $Capital_i(t)$ (as long as $Capital_i(t)$ is non-zero, otherwise 0). Capital productivity as measured in $ mil.

7. Economic Physical Flow Module

The economic physical flow module is the physical equivalent of the economic flow module. It describes the Auckland Region economy in physical (mass) flow terms, including commodity supply, use, imports and exports (Figure 6). The module focuses purely on the within economy physical flows. Financial estimates of commodity supply, use, imports, and exports are converted to physical equivalents based on price ($ per tonne) and physical productivity indices that allow for technological improvements.[17] The module utilises within economy data from Market Economics Ltd's financial and physical input-output models (for technical details refer to McDonald (2008)).

[17] It is assumed that these technological improvements occur at a constant compounding rate. This simplifying assumption has been adopted to demonstrate how technological change might be incorporated within ARDEEM, but is considered questionable given long-run thermodynamic constraints.

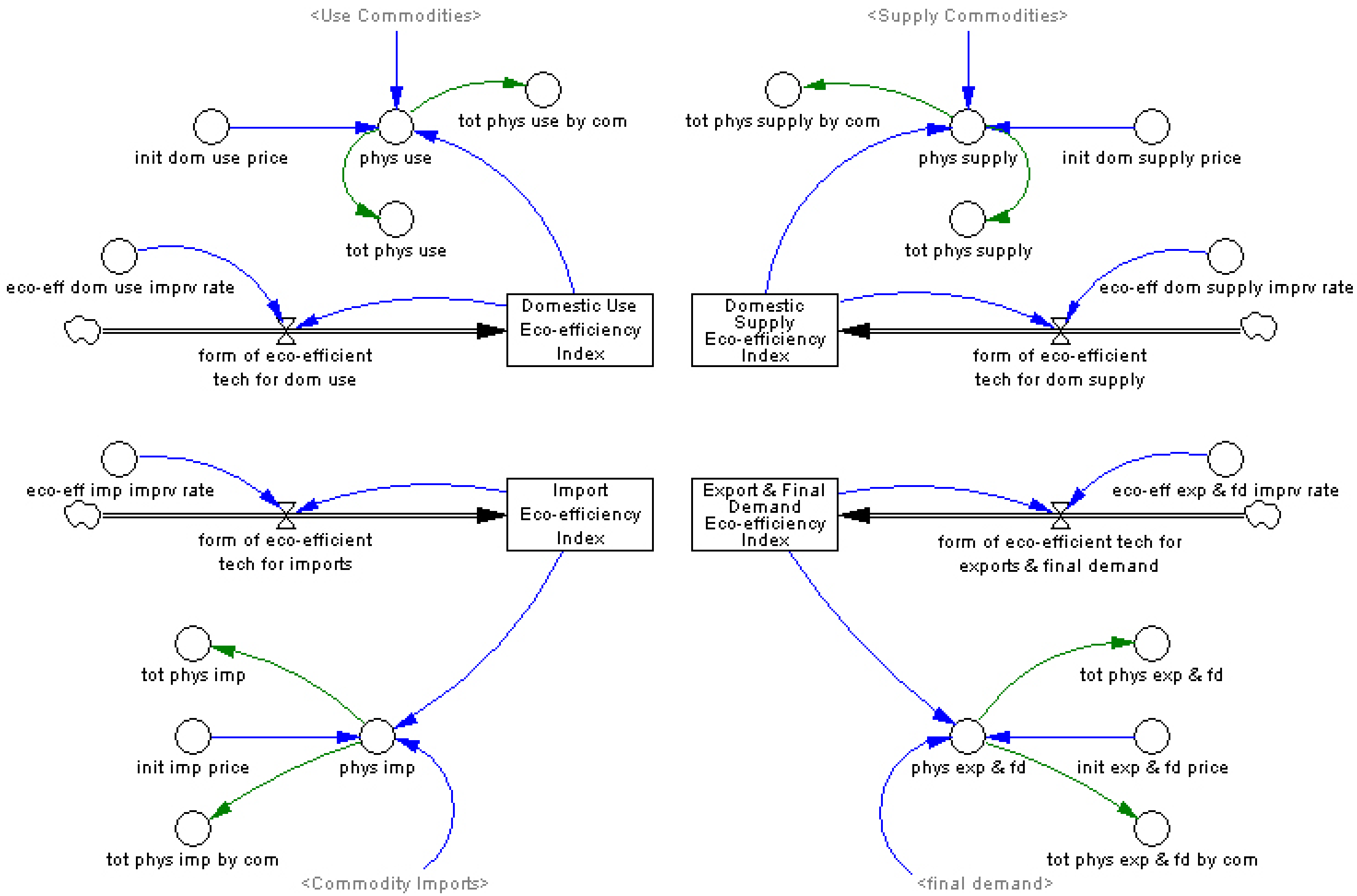


Figure 6 **Economic Physical Flow Influence Diagram**

Domestic Use Physical productivity Index Stock

Domestic Use Physical productivity Index$_{c,i}$ (t + dt) = *Domestic Use Physical productivity Index*$_{c,i}$(t) + (*form of eco-efficient tech for dom use*$_{c,i}$) × dt

where:

Initial *Domestic Use Physical productivity Index*$_{c,i}$ = 1 for the 1998 base year.

<u>Inflow</u>

form of eco-efficient tech for dom use$_{c,i}$ = *Domestic Use Physical productivity Index*$_{c,i}$(t) × *eco-eff dom use imprv rate*$_{c,i}$

eco-eff dom use imprv rate$_{c,i}$ = the rate of physical productivity improvements in domestic use of commodity *c* by industry *i*. This rate is assumed to compound over time through technological change.[18]

phys use$_{c,i}$ = ((*Use Commodities*$_{c,i}$(t) × 1000000) / *init dom use price*$_{c,i}$) × *Domestic Use Physical productivity Index*$_{c,i}$(t)) (as long as *init dom use price*$_{c,I}$ is non-zero, otherwise 0). As measured in tonnes.

init dom use price$_{c,i}$ = the 1998 \$ per tonne price used to convert the domestic use of commodity *c* by industry *i*, as recorded in financial terms, into a physical equivalent.

[18] This simplifying assumption has been adopted to demonstrate how eco-efficiency improvements might be included within ARDEEM, but is considered questionable given long-run thermodynamic limits to technological change. This assumption also applies to the following variables within this module: *eco-eff dom supply imprv rate*$_{i,c}$, *eco-eff imp imprv rate*$_{imp,c}$, and *eco-eff exp & fd imprv rate*$_{c,f}$.

Domestic Supply Physical productivity Index Stock

Domestic Supply Physical productivity Index$_{i,c}$ (t + dt) = *Domestic Supply Physical productivity Index*$_{i,c}$(t) + (*form of eco-efficient tech for dom supply*$_{i,c}$) × dt

Initial Domestic Supply Physical productivity Index$_{i,c}$ = 1 for the 1998 base year.

<u>Inflow</u>

form of eco-efficient tech for dom supply$_{i,c}$ = *Domestic Supply Physical productivity Index*$_{i,c}$(t) × *eco-eff dom supply imprv rate*$_{i,c}$

eco-eff dom supply imprv rate$_{i,c}$ = the rate of physical productivity improvements in domestic supply of commodity c by industry i.

phys supply$_{i,c}$ = ((*Supply Commodities*$_{i,c}$(t) × 1000000) / *init dom supply price*$_{i,c}$) × *Domestic Supply Physical productivity Index*$_{i,c}$(t)) (as long as *init dom supply price*$_{i,c}$ is non-zero, otherwise 0). As measured in tonnes.

init dom supply price$_{i,c}$ = the 1998 \$ per tonne price used to convert the domestic supply of commodity c by industry i, as recorded in financial terms, into a physical equivalent.

Import Physical productivity Index Stock

Import *Physical productivity Index*$_{imp,c}$ $(t + dt)$ = *Import Physical productivity Index*$_{imp,c}(t)$ + (*form of eco-efficient tech for imports*$_{imp,c}$) $\times$ *dt*

Initial *Import Physical productivity Index*$_{imp,c}$ = 1 for the 1998 base year.

<u>Inflow</u>

form of eco-efficient tech for imports$_{imp,c}$ = *Import Physical productivity Index*$_{imp,c}(t)$ $\times$ *eco-eff imp imprv rate*$_{imp,c}$

eco-eff imp imprv rate$_{imp,c}$ = the rate of physical productivity improvements in imported commodity *c*.

phys imp$_{imp,c}$ = ((*Commodity Imports*$_{imp,c}(t)$ $\times$ 1000000) / *init imp price*$_{imp,c}$) $\times$ *Import Eco-efficiecy Index*$_{imp,c}(t)$) (as long as *init imp price*$_{imp,c}$ is non-zero, otherwise 0). As measured in tonnes.

init imp price$_{imp,c}$ = the 1998 \$ per tonne price used to convert the commodity *c* imports by industry *i*, as recorded in financial terms, into a physical equivalent.

Export & Final Demand Physical productivity Index Stock

Export & Final Demand Physical productivity Index$_{c,f}$ (t + dt) = *Export & Final Demand Physical productivity Index*$_{c,f}$(t) + (*form of eco-efficient tech for exports & final demand*$_{c,f}$) × dt

Initial Export & Final Demand Physical productivity Index$_{c,f}$ = 1 for the 1998 base year.

<u>Inflow</u>

form of eco-efficient tech for exports & final demand$_{c,f}$ = *Export & Final Demand Physical productivity Index*$_{c,f}$(t) × *eco-eff exp & fd imprv rate*$_{c,f}$

eco-eff exp & fd imprv rate$_{c,f}$ = the rate of physical productivity improvements in commodity *c* destined for final demand category *f*.

phys exp & fd$_{c,f}$ = IF THEN ELSE(*init exp & fd price*$_{c,f}$ = 0, 0, ((*final demand*$_{c,f}$ × 1000000) / *init exp & fd price*$_{c,f}$) × *Export & Final Demand Physical productivity Index*$_{c,f}$(t)). As measured in tonnes.

init exp & fd price$_{c,f}$ = the 1998 $ per tonne price used to convert the commodity *c* used by final demand category *f*, as recorded in financial terms, into a physical equivalent.

Reporting variables

tot phys use	= $\sum_{c,i}(phys\ use_{c,i})$. The total physical use of commodities within the economy (tonnes).
tot phys use by com_c	= $\sum_{i=1}^{n}(phys\ use_{c,i})$. The total physical use of commodity *c* within the economy (tonnes).
tot phys supply	= $\sum_{i,c}(phys\ supply_{i,c})$. The total physical supply of commodities within the economy (tonnes).
tot phys supply by com_c	= $\sum_{i=1}^{n}(phys\ supply_{i,c})$. The total physical supply of commodity *c* within the economy (tonnes).
tot phys imp	= $\sum_{imp,c}(phys\ imp_{imp,c})$. The total physical imports from other economies (tonnes).
tot phys imp by com_c	= $\sum_{imp=1}^{n}(phys\ imp_{imp,c})$. The total physical import of commodity *c* from other economies (tonnes).
tot phys exp & fd	= $\sum_{c,f}(phys\ exp\ \&\ fd_{c,f})$. The total physical exports to other economies plus domestic final consumption (tonnes).
tot phys exp & fd by com_c	= $\sum_{f=1}^{n}(phys\ exp\ \&\ fd_{c,f})$. The total physical export and final consumption of commodity *c* (tonnes).

8. Environment-Economy Physical Flow Module

This module describes the physical flow of raw materials and residuals associated with economic activity in the Auckland Region (Figure 7). The module focuses on the physical flow of ecological commodities crossing the environment-economy system boundary. This is largely made up of physical flows of commodities not conventionally measured in economic markets. This module, like the economic physical flow module, draws on estimates of output by industry generated by the growth module, exogenous estimates of raw material use/residual generation per $ output (as generated from Market Economics Ltd's physical input-output table), and indices of improvements in physical productivity[19] to establish the physical flow of raw material and residuals.

[19] It is assumed that these technological improvements occur at a constant compounding rate. This simplifying assumption has been adopted to demonstrate how technological change might be incorporated within ARDEEM, but is considered questionable given long-run thermodynamic constraints.

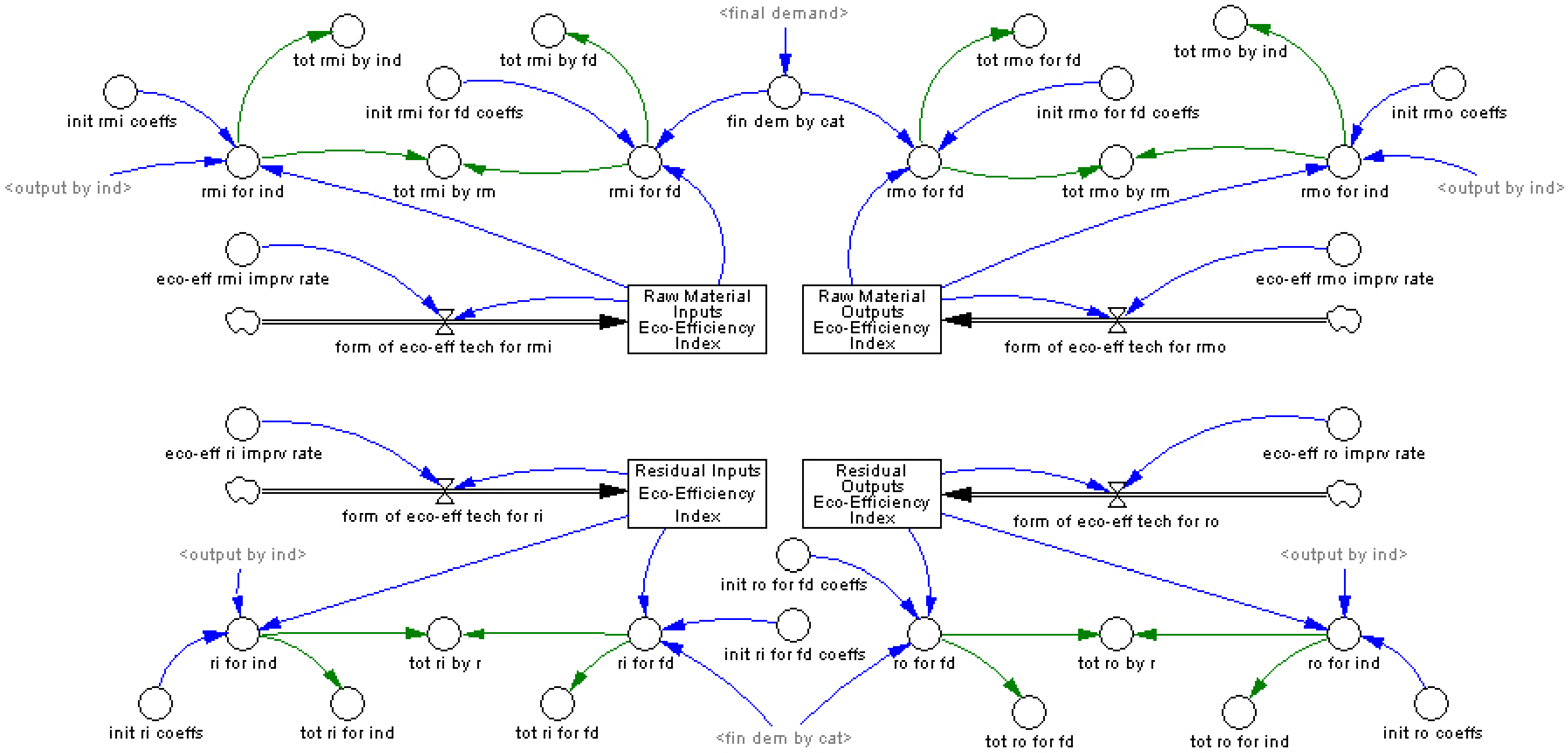


Figure 7 Environment-Economy Physical Flow Influence Diagram

Raw Material Inputs Physical productivity Index Stock

$$Raw\ Material\ Inputs\ Physical\ productivity\ Index_{rm}\ (t + dt) = Raw\ Material\ Inputs\ Physical\ productivity\ Index_{rm}(t) + (form\ of\ eco\text{-}eff\ tech\ for\ rmi_{rm}) \times dt$$

where:

Initial *Raw Material Inputs Physical productivity Index*$_{rm}$ = 1 for the 1998 base year.

<u>Inflow</u>

form of eco-eff tech for rmi$_{rm}$	= *Raw Material Inputs Physical productivity Index*$_{rm}(t) \times$ *eco-eff rmi imprv rate*$_{rm}$
eco-eff rmi imprv rate$_{rm}$	= the rate of physical productivity improvements in the use of raw material input *rm*. This rate is assumed to compound over time through technological change.[20]
rmi for ind$_{rm,i}$	= *init rmi coeffs*$_{rm,i} \times$ *output by ind*$_i \times$ *Raw Material Inputs Physical productivity Index*$_{rm}(t)$. As measured in tonnes.
init rmi coeffs$_{rm,i}$	= the 1998 physical input of raw material *rm* (tonnes) required to produce $ of output in industry *i*.
rmi for fd$_{rm,f}$	= *init rmi for fd coeffs*$_{rm,f} \times$ *fin dem by cat*$_f \times$ *Raw Material Inputs Physical productivity Index*$_{rm}(t)$. As measured in tonnes.
init rmi for fd coeffs$_{rm,f}$	= the 1998 physical input of raw material *rm* (tonnes) required for consumption of $ of output in final demand category *f*.

[20] This simplifying assumption has been adopted to demonstrate how eco-efficiency improvements might be included within ARDEEM, but is considered questionable given long-run thermodynamic limits to technological change. This assumption also applies to the following variables within this module: *eco-eff rmo imprv rate*$_{rm}$, *form of eco-eff tech for ri*$_r$ and *eco-eff ro imprv rate*$_r$.

fin dem by cat$_f$ = $\sum_{c=1}^{n}$(*final demand*$_{c,f}$). Total final demand by category *f* ($ mil).

Raw Material Outputs Physical productivity Index Stock

Raw Material Outputs Physical productivity Index$_{rm}$ (t + dt) = *Raw Material Outputs Physical productivity Index*$_{rm}$(t) + (*form of eco-eff tech for rmo*$_{rm}$) × *dt*

where:

Initial Material Outputs Physical productivity Index$_{\mathrm{rm}}$ = 1 for the 1998 base year.

<u>Inflow</u>

form of eco-eff tech for rmo$_{rm}$ = *Raw Material Outputs Physical productivity Index*$_{rm}$ × *eco-eff rmo imprv rate*$_{rm}$(t)

eco-eff rmo imprv rate$_{rm}$ = the rate of physical productivity improvements in the supply of raw material output *rm*.

rmo for ind$_{i,rm}$ = *init rmo coeffs*$_{i,rm}$ × *output by ind*$_i$ × *Raw Material Outputs Physical productivity Index*$_{rm}$(t). As measured in tonnes.

init rmo coeffs$_{i,rm}$ = the 1998 physical output of raw material *rm* (tonnes) generated in producing $ of output in industry *i*.

rmo for fd$_{f,rm}$ = *init rmo for fd coeffs*$_{f,rm}$ × *fin dem by cat*$_f$ × *Raw Material Outputs Physical productivity Index*$_{rm}$(t). As measured in tonnes.

init rmo for fd coeffs$_{f,rm}$ = the 1998 physical output of raw material *rm* (tonnes) generated in consuming \$ of output in final demand category *f*.

Residual Inputs Physical productivity Index Stock

Residual Inputs Physical productivity Index$_r$ (t + dt) = *Residual Inputs Physical productivity Index*$_r$(t) + (*form of eco-eff tech for ri*$_r$) $\times$ dt

where:

Initial *Residual Inputs Physical productivity Index*$_r$ = 1 for the 1998 base year.

<u>Inflow</u>

form of eco-eff tech for ri$_r$ = *Residual Inputs Physical productivity Index*$_r$(t) $\times$ *eco-eff ri imprv rate*$_r$

eco-eff ri imprv rate$_r$ = the rate of physical productivity improvements in the use of residual input *r*.

ri for ind$_{r,i}$ = *init ri coeffs*$_{r,i}$ $\times$ *output by ind*$_i$ $\times$ *Residual Inputs Physical productivity Index*$_r$(t). As measured in \$ mil.

init ri coeffs$_{r,i}$ = the 1998 physical input of residual *r* (tonnes) required to produce \$ of output in industry *i*.

ri for fd$_{r,f}$ = *init ri for fd coeffs*$_{r,f}$ $\times$ *fin dem by cat*$_f$ $\times$ *Residual Inputs Physical productivity Index*$_r$(t). As measured in tonnes.

init ri for fd coeffs$_{r,f}$ = the 1998 physical input of residual *r* (tonnes) required for consumption of \$ of output in final demand category *f*.

Residual Outputs Physical productivity Index Stock

$Residual\ Outputs\ Physical\ productivity\ Index_r\ (t + dt) = Residual\ Outputs\ Physical\ productivity\ Index_r(t) + (form\ of\ eco\text{-}eff\ tech\ for\ ro_r) \times dt$

where:

Initial Residual Outputs Physical productivity $Index_r$ = 1 for the 1998 base year.

Inflow

$form\ of\ eco\text{-}eff\ tech\ for\ ro_r$ = $Residual\ Outputs\ Physical\ productivity\ Index_r(t) \times eco\text{-}eff\ ro\ imprv\ rate_r$

$eco\text{-}eff\ ro\ imprv\ rate_r$ = the rate of physical productivity improvements in the supply of residual output *r*.

$ro\ for\ ind_{i,r}$ = $init\ ro\ coeffs_{i,r} \times output\ by\ ind_i \times Residual\ Outputs\ Physical\ productivity\ Index_r(t)$. As measured in tonnes.

$init\ ro\ coeffs_{i,r}$ = the 1998 physical output of residual *r* (tonnes) generated in producing $ of output in industry *i*.

$ro\ for\ fd_{f,r}$ = $init\ ro\ for\ fd\ coeffs_{f,r} \times fin\ dem\ by\ cat_f \times Residual\ Outputs\ Physical\ productivity\ Index_r(t)$. As measured in tonnes.

$init\ ro\ for\ fd\ coeffs_{f,r}$ = the 1998 physical output of residual *r* (tonnes) generated in consuming $ of output in final demand category *f*.

Reporting variables

tot rmi by rm_{rm} $= \sum_{f=1}^{n} (rmi\ for\ fd_{rm,f}) + \sum_{i=1}^{n} (rmi\ for\ ind_{rm,i})$. Total physical input of raw material *rm* (tonnes) into the economy.

tot rmo by rm_{rm} $= \sum_{f=1}^{n} (rmo\ for\ fd_{f,rm}) + \sum_{i=1}^{n} (rmo\ for\ ind_{i,rm})$. Total physical output of raw material *rm* (tonnes) from the economy.

tot ri by r_{r} $= \sum_{f=1}^{n} (ri\ for\ fd_{r,f}) + \sum_{i=1}^{n} (ri\ for\ ind_{r,i})$. Total physical input of residual *r* (tonnes) into the economy.

tot ro by r_{r} $= \sum_{f=1}^{n} (ro\ for\ fd_{f,r}) + \sum_{i=1}^{n} (ro\ for\ ind_{i,r})$. Total physical output of residual *r* (tonnes) from the economy.

tot rmi by ind_{i} $= \sum_{rm=1}^{n} (rmi\ for\ ind_{rm,i})$. Total physical input of raw materials into industry *i* (tonnes).

tot rmi by fd_{f} $= \sum_{rm=1}^{n} (rmi\ for\ fd_{f,rm})$. Total physical input of raw materials into final demand category *f* (tonnes).

tot rmo for fd_{f} $= \sum_{rm=1}^{n} (rmo\ for\ fd_{f,rm})$. Total physical output of raw materials from final demand category *f* (tonnes).

tot rmo by ind_{i} $= \sum_{rm=1}^{n} (rmo\ for\ ind_{i,rm})$. Total physical output of raw materials from industry *i* (tonnes).

tot ri for ind_i = $\sum_{r=1}^{n}(ri\ for\ ind_{r,i})$. Total physical input of residuals into industry *i* (tonnes).

tot ri for fd_f = $\sum_{r=1}^{n}(ri\ for\ fd_{r,f})$. Total physical input of residuals into final demand category *f* (tonnes).

tot ro for fd_f = $\sum_{r=1}^{n}(ro\ for\ fd_{f,r})$. Total physical output of residuals from final demand category *f* (tonnes).

tot ro for ind_i = $\sum_{r=1}^{n}(ro\ for\ ind_{i,r})$. Total physical output of residuals from industry *i* (tonnes).

9. Validation and Verification of ARDEEM

Several steps were undertaken during the modelling process to ensure that the results generated by ARDEEM were as valid as possible. These are considered below in terms of structural and predictive validity.

9.1 Structural Validity of ARDEEM

Structural validity refers to the logic, consistency and accuracy of the model's internal structure i.e. its equations, interrelationships, and units of measurement. The structural validity of ARDEEM was evaluated by:

- *Creation of 1998 reference mode*. Simulation results generated for the 1998 base year were compared with actuals or estimates generated independently in Microsoft Excel®; particular emphasis was placed on the validity of endogenous variables.
- *Independent peer review*. The relationships within the model were independently peer reviewed by Professor Murray Patterson (School of People, Environment and Planning, Massey University), Professor Richard Le Heron (School of Geography and Environmental Science, University of Auckland), Dr Doug Fairgray (Economist, Market Economics Ltd) and Mr Geoff Butcher (Economist, Butcher Partners Ltd). In light of these peer reviews several changes were made to the conceptualisation of ARDEEM.

9.2 Predictive Validity of ARDEEM

Predictive validity refers to the model's ability to adequately imitate the behaviour of the real system. Predictive validity is however of only limited usefulness as a model may produce results which provide an extremely good historical data fit, but may in no way reflect future outcomes. The predictive ability of ARDEEM was evaluated by:

- *Backcasting*. The model was backcast[21] so as to produce results for the period 1980–1998. Graphs of key variables (*Population*, *Capital*, *Commodity Use*, *Commodity Supply*, capital investment, labour force participation, employment and so on) were plotted against actuals. Given the use of time series regression to 'curve fit' historical trends, it is perhaps not surprising that the results generated reflected actuals.
- *Comparison with Statistics New Zealand projections*. In the case of the Population, births, deaths, net migration and labour force variables it was possible to compare ARDEEM simulation results, under a Business as Usual Scenario, with SNZ projections.

Overall, it is important to remember that complete validation of a model by comparison with the real world is not possible, as ARDEEM only captures a selected number of components and behaves purely in response to its internal relationships.

[21] Several simulations were required for this purpose; with appropriate corrections to the conceptualisation of ARDEEM being made following each simulation.

10. Scenario Analysis

There are several reasons why policy and decision makers need to look into the future. This includes planning for possible futures, deciding between competing alternatives, making provisions for new infrastructure, and so on. Underpinning all of these reasons is arguably a desire to manage complexity and minimise risk (Shearer, 1994). While it is impossible for us to predict the future, it is, however, useful for us to understand what 'might' happen in the future. This forces us to consider the implications of our proposed trajectories; reducing uncertainty and avoiding possible pitfalls. Scenario modelling is one approach that may be used to help us simulate possible futures and their implications.[22]

Scenarios have been defined by Kahn and Wiener (1967) as "a hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision points". Armstrong and Harmon (1975), Boshier *et al*. (1986) and Schnaars (1987) have identified several key advantages of the scenario approach, including: (1) suitable for long-run projections where uncertainty is high and historical relationships have been characterised by dynamic feedbacks, non-linearities, time lags and the like; (2) help us to see the future in totality, rather than piecemeal; (3) allows us to trace people's behaviour in the face of perturbation; and (4) may provide common ground for communication between diverse interest groups or backgrounds.

Scenario development has several important methodological considerations, including: (1) how many scenarios? Despite the lack of agreement within the literature, there seems to be a consensus for three scenarios (Linneman and Klein, 1979). Two scenarios are likely to be categorised as 'good and bad', while the simulation of more than three scenarios often becomes uncontrollable; (2) what time horizon? Most analysts agree that scenario analysis is best suited for long-run simulation (Schnaars 1987; Linneman and Klein, 1979; Van der Heijden, 1996) and (3) what is the process for constructing and writing scenarios? The development of

[22] Forecasting is the major alternative approach. It is typically quantitative, relying on historical trends in key system variables to project futures. It is often undertaken with only limited understanding of how a system operates; particularly the consequences of dynamic feedbacks between key system variables. For this reason forecasting is better suited to projecting short-or-medium term futures.

consistent and comprehensive scenarios typically involves the following steps (Van der Heijden, 1996):

- *Step 1: Selection of scenario themes*. This will involve consideration of possible future changes in cause and effect, development of internal consistency, avoidance of contradictory sub-themes, and relevance to the issues facing the client or stakeholders most interested in the simulation.
- *Step 2: Carefully detailed, plausible and informative story lines*. The story line should ideally be formulated in the form of a qualitative and contextual narrative, and be underpinned by careful documented assumptions that ensure diversity and generate plausible and rich scenarios. A central tenet of story writing is the development of a 'gestalt' or integrated narrative, rather than a disintegrated or piecemeal one.
- *Step 3: Setting of initial driver values*. All initial values should be carefully specified as it is these values which are the main determinants of each scenario.
- *Step 4: Simulation and generation of indicator variables for each scenario*. These indicators should encompass variables that may be used to assess (1) the validity of the model's structures and behaviours (refer to Section 9), and (2) the modelling results. Under ideal circumstances interest and stakeholder groups should be involved in assessing the modelling results. Their opinions, views and inputs are useful in evaluating model results. Refinements may include rewriting of the narrative, resetting of driver values, development or redevelopment of indicators, and improvements to the model's internal structure.
- *Step 5: Reporting of results*. This includes presenting results to clients and stakeholder groups, and also often analysing the possible policy/investment implications of each scenario. Comparison of the scenarios is critical as this provides insight into the strengths, weaknesses and tradeoffs of each scenario. This will aid decision makers in selecting the best, or most appropriate, actions given the scenario results.

10.1 ARDEEM Scenarios

Three scenarios are developed for ARDEEM below. These scenarios are developed to demonstrate the usefulness of ARDEEM, but require signficiant further work – in particular, further peer review and, in turn, redevelopment.[23]

- *Scenario 1: Business As Usual (BAU).* The 'business as usual' scenario assumes that the trends experienced over the last 10–20 years will continue to prevail over the next 50 years. These trends are captured in the regression equations used throughout this Report to initialise ARDEEM's exogenous variables. Given that these trends are discussed in depth in earlier sections of this Report, no further discussion is presented here.
- *Scenario 2: Cornucopian Growth (CG).* Under the cornucopian growth scenario market orthodoxy holds sway. This is a world where the ideology of economic rationalism, liberalism and consumption hold a monopoly of power. Key features of the scenario are (1) an increased instensification of economic interdependence with other economies, and (2) a desire for increased levels of material wealth. Resource constraints are disputed because technological substitutes are readily available.
- *Scenario 3: Prudent Pessimism (PP).* Aucklanders adopt a communal philosophy of self-sufficiency. Global geopolitical instability and cultural social change override the incentives of economic globalisation. Aucklanders develop a strong and mutual sense of purpose including a shared national desire for sustainable living. Underpinning this desire is the belief that current material consumption cannot be sustained without future implications i.e. conservation and maintenance of critical natural capital for future generations is seen as paramount.

[23] To this end, a series of workshops is scheduled under the Sustainable Pathways FRST contract. These workshops will focus on 'what makes Auckland tick' from the viewpoint of key actors within the Auckland Region, namely: central and local government politicians, central and local government policy makers, infrastructure provides, developers, iwi, business and the public at large. These workshops will be jointly prepared and presented by the author and Professor Richard Le Heron of the School of Geography and Environmental Science, University of Auckland.

The key exogenous drivers of change in the 'Cornucopian Growth' and 'Prudent Pessimism' scenarios are specified in full in Table 1 below.

Table 1 Summary of Drivers under Each Scenario

	Cornucopian Growth	Prudent Pessimism
Fertility rate	Woman defer having children until their mid 30's, focusing instead on gaining material wealth. Fertility rates for under 29 year olds are 0.03 percent below the BAU scenario, while fertility rates for over 30's increase marginally at 0.01 percent above the BAU scenario.	Past fertility trends prevail for woman under 30 years of age. A marginal decrease in fertility rates (0.01 percent below the equivalent BAU rate) occurs for woman over 30; a consequence of lower material wealth.
Mortality rates	Reflect past trends.	Reflect past trends.
Net migration	Growth in the economy necessitates skilled and semi-skilled employment opportunities which cannot be fullfilled locally. A more open immigration policy is therefore pursued to avoid possible skill shortages. Net migration numbers grow at 12.5 percent above the BAU scenario.	A very tight immigration policy is adopted in an attempt to avoid overexploitation of the nation's natural resources. Immigrants are selected that have skills which will make New Zealand more self-sufficient. Overall, the number of immigrants drops at a rate 5 percent below the BAU scenario.
Labour force participation	Reflect past trends, except for those aged over 60 who engage at a rate 2.5 percent above the BAU scenario; a consequence of a desire for higher levels of material wealth.	Reflect past trends, except for those over 60 who engage at a rate 0.5 percent above the BAU scenario. This is a result of a desire to retain skilled labour as long as possible in the workforce.
Unemployment rates	Reflect past trends.	Reflect past trends.
Employment distribution by industry	The distribution of employment in the primary and secondary industries reflects past trends. More people are however involved in services; in particular retailing and wholesaling. Services thus grow at a rate 1 percent above the BAU scenario.	A trend toward a more self-sufficient economy requires that more people are employed in primary and secondary industries; at a rate 1.5 percent above the BAU scenario.
Investment rates	The desire for greater material wealth results in increased investment in manufacturing and service industries at a rate 1.5 percent above the BAU scenario.	Primary industry investment rates increase with the desire to be self-sufficient; this occurs at a rate 1 percent above the BAU scenario.
Depreciation rates	Reflect past trends.	Incentives are introduced by government to maintain high quality capital stocks for longer periods within the economy. This results in a depreciation rate 1 percent lower than the BAU scenario.
Technology rates	Technological solutions result in substantial increasing returns in all industries within the economy; at a rate 5 percent above the BAU scenario. Technology continues to offset environmental degradation.	Technological change is felt most in the primary industry at a rate of 5 percent above the BAU scenario, the secondary and tertiary industries however experience less technological innovation and cannot completely offset environmental degradation (growing at a rate 2.5 percent below the BAU scenario).
Substitution effects	Although the use of domestically supplied commodities reflects past trends, the desire for more luxurious commodities results in the substitution of domestically produced commodities for imported commodities. This occurs at a rate 2.5 percent above the BAU scenario.	Domestically supplied commodities are substituted for imported goods, respectively growing at 2 percent above and -3.5 percent below the BAU scenario. This is a response to a desire to minimise transportation costs to the environment to encourage local production of commonly consumed commodities.
International exports	All sectors grow exports at rate 1 percent above the BAU scenario.	There is movement away from international export as a result of the environmental implications of transportation; at a rate 1.5 percent below the BAU scenario.
Interregional exports	All sectors grow exports at rate 1 percent above the BAU scenario.	Interregional exports grow at a rate of 2 percent above the BAU scenario.
Eco-efficiency improvements	Little regard is given to improving the eco-efficiency of commodities. Consequently, eco-efficiency improvements decline at a rate 1 percent below the BAU scenario.	Conservation and maintenance of natural capital is pursued both in relation to commodities consumed within the economy, extracted directly from the environment or released back into the environment after use. Overall, eco-efficiency rates vary between 1 and 3 percent above the BAU scenario.

Note: All rates are annualised geometric averages for the 2001–2051 period.

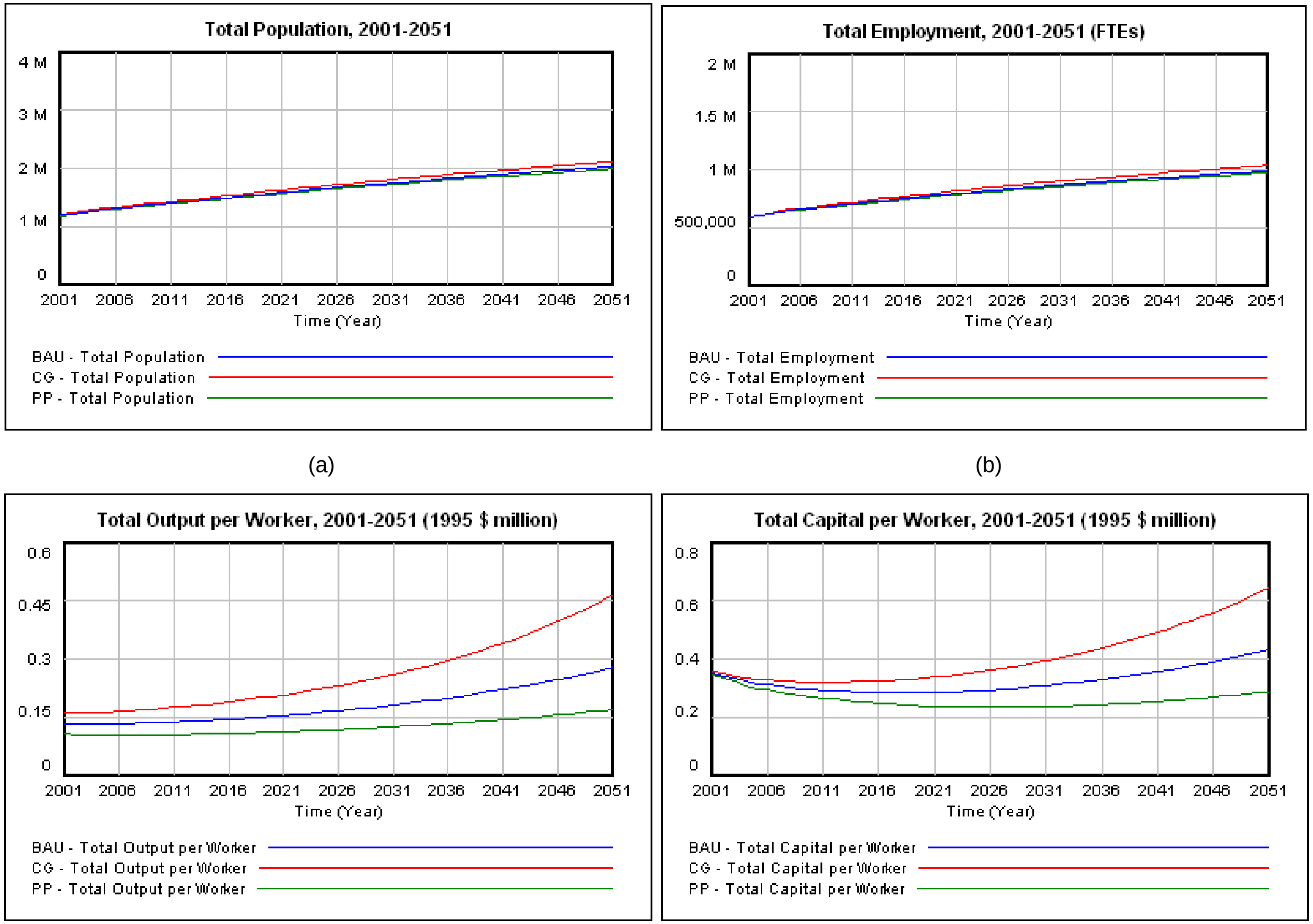
10.2 Simulation Results

The results presented in this Section are preliminary and are meant only to illustrate the potential value of ARDEEM.

There is very little difference between the three scenarios for growth in total population (Figure 8a) and total employment (Figure 8b) between 2001 and 2051. Under the Cornucopian Growth (CG) scenario, population is projected to grow to only 100,000 or so higher than under the Business As Usual (BAU) and Prudent Pessimism (PP) scenarios. There is overall steady population growth from around 1.2 million in 2001 to about 2 million by 2051 for all three scenarios. Total employment (FTEs) mirrors population growth, with minor differences between the three scenarios. Overall growth in total employment is projected at about 400,000 FTEs between 2001 and 2051. Productivity gains are evident however in projected total output per worker (Figure 8c), with output tripling under the CG to $450,000 in 2051, one and a half times more than under the BAU, and three times more than under PP. PP shows only a 40 percent growth in total output per worker over 50 years, while CG indicates a 200 percent growth over the same period. Total capital per worker (Figure 8d) shows an initial decline under all three scenarios. This decline occurs because capital investment rates were being outstripped by capital depreciation rates. Under CG, total capital per worker begins an upward trend around 2013 while under PP this only occurs 30 years later, around 2033. Under CG this variable grows rapidly to $650,000 per worker (an 85 percent increase between 2001 and 2051), while BAU shows a growth of about 25 percent. There is an overall decrease of about 20 percent under PP over the study period with the variable not recovering its 2001 level by 2051.

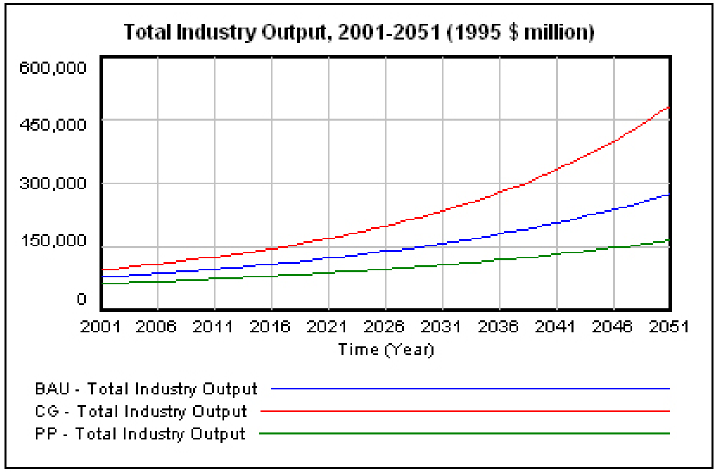
Under CG, total industry output (Figure 8e) escalates fairly rapidly to nearly five times its 2001 value over the study period, with a difference of about $200,000 million between CG and BAU at 2051. Under PP, total industry output grows relatively modestly, doubling over the 50 year study period. Total industry GDP (Figure 8f) mirrors total industry output, with CG 50 percent higher at $150,000 million, and PP 30 percent lower at $70,000 million, than BAU of $100,000 million at 2051. BAU total physical supply (Figure 8g) grows by 200 million t over the study period, while growth of $380 million t under CG makes it double that under PP at 2051. Similarly, total physical use (Figure 8h) grows by three and a half times under CG, but only doubles under PP in 50 years.

Under CG, total physical imports (Figure 8i) rapidly increases nearly threefold to 75 million t over the 50 year period, 35 million t and 45 million t higher than under BAU and PP respectively. Under all three scenarios, total physical exports and final demand (Figure 8j) shows relatively slower growth from about 70 million t in 2001 to between 120 million t (PP) and 170 million t (CG), i.e. a 70 to 140 percent increase. Similarly to total physical imports, CG shows total physical exports and final demand to be 35 million t higher than BAU at 2051. Under CG, total raw material inputs (Figure 8k) quadrupled, a requirement nearly 60 percent greater than BAU. In comparison, this variable under PP doubled over the 50 years. Similarly, total residual outputs under CG almost triples, while under PP it doubles from 2001 to 2051. Under CG, the economy produces nearly 40 percent more residual outputs (370,000 t) than BAU, and nearly 70 percent more than PP (220,000 t) by 2051.



(c) (d)

Figure 8 **ARDEEM Scenario Analysis: Business As Usual, Cornucopian Growth and Prudent Pessimism**



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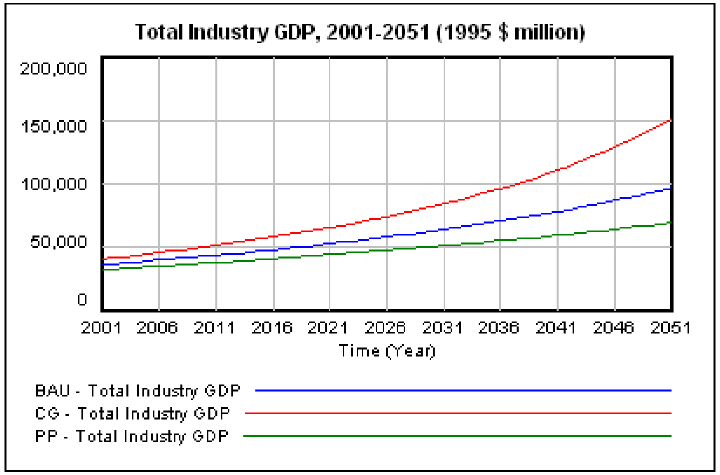

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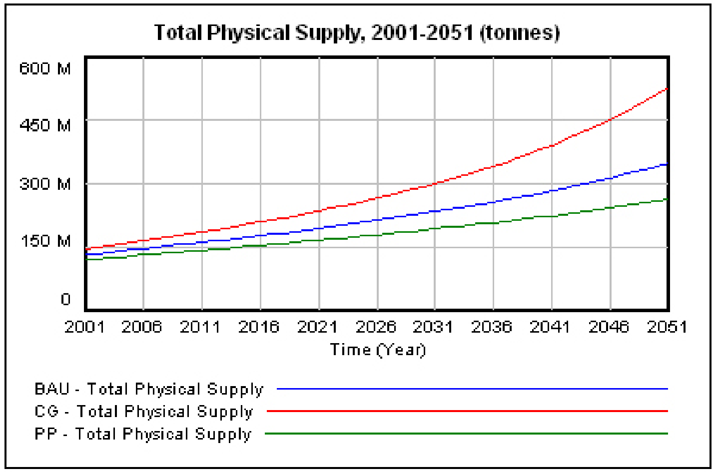

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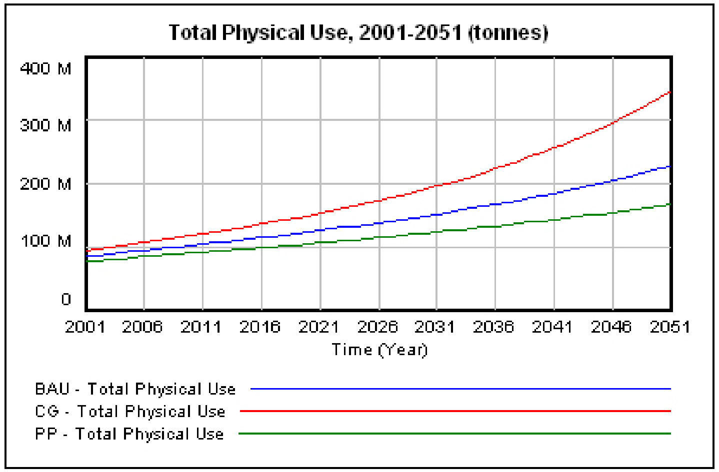
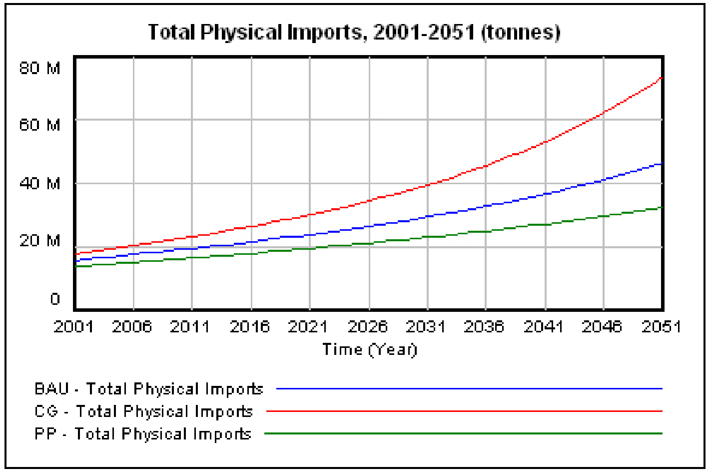


(h)

Figure 8 ARDEEM Scenario Analysis: Business As Usual, Cornucopian Growth and Prudent Pessimism (Continued)



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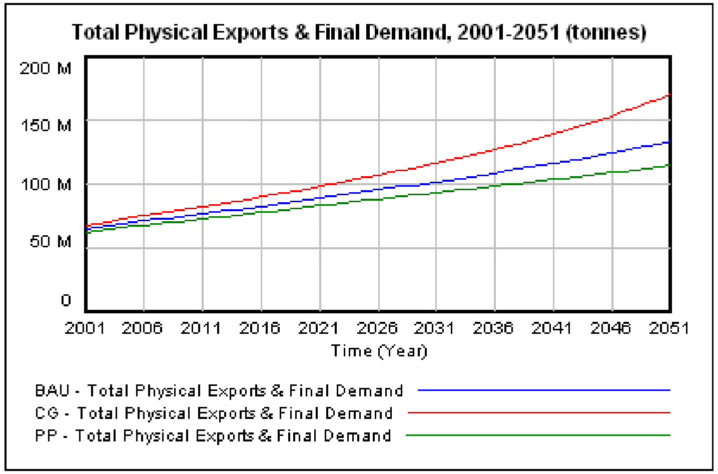

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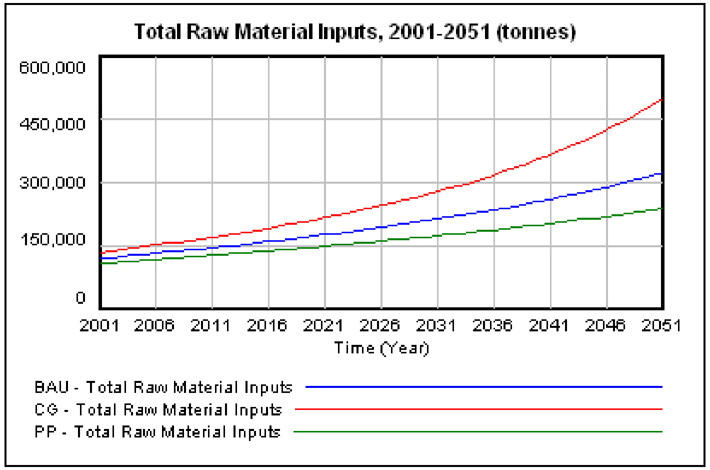

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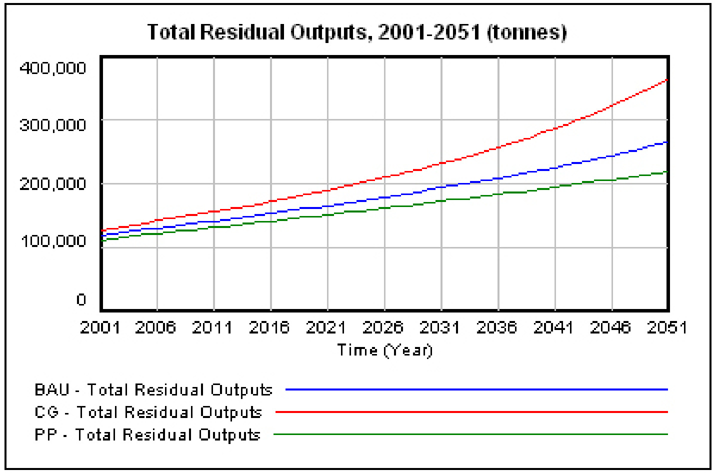

(l)

Figure 8 ARDEEM Scenario Analysis: Business As Usual, Cornucopian Growth and Prudent Pessimism (Continued)

11. Limitations of the ARDEEM

The ARDEEM, like all other mathematical models, is underpinned by a number of assumptions. Often the degree of influence of these assumptions depends on the worldview or belief system of the user analysing the modelling results. It is therefore possible that ARDEEM simulations may, in the eyes of different users, produce results ranging from totally plausible and likely, to completely implausible and unlikely. The purpose of ARDEEM is not however to predict futures, but instead through simulation to investigate the possible dynamic implications of change in the Auckland Region environment-economy system. ARDEEM's major limitations include:

- *Neglect of critical environmental processes*. A significant weakness of the model is that the critical life supporting biogeochemical processes of the environment are simply neglected. Such processes provide humans with resources, waste assimilation, opportunities for spiritual fulfilment, scientific learning and so on. It may therefore be argued that any environmental-economic model which does not consider their influence is incomplete.
- *Price and substitution effects*. The ARDEEM, like the *Limits to Growth* model, may be criticised for the lack of consideration of price effects which might lead to substitution between factor inputs. It is argued that if we know the price elasticity of a commodity then changes in the commodity's supply and demand may be predicted. The ARDEEM, like other simulation models, may only be used to investigate scenarios i.e. it cannot predict the future. It is however possible to test out a scenario with price change and substitution.
- *Number of industries and commodities*. The ARDEEM is currently only a prototype covering three industries and three commodities – a result of time constraints imposed on the completion of this report. Only minimal additional system dynamics modelling is required to extend ARDEEM to, say, 20 or 30 industries, and in the case of commodities to, say, 200 plus commodities. Data constraints will, however, impose restrictions on industry/commodity coverage in future versions of ARDEEM.
- *Spatial dynamics*. Many of the sustainability issues facing Auckland Region are localised or spatially specific in nature and thus not suitable for simulation

in ARDEEM. Consideration of the spatial dynamics is however beyond the scope of this report. With further research it may however be possible to interface ARDEEM with static spatial models already in existence, e.g., Auckland Regional Council's Auckland Strategic Planning (ASP) and Auckland Regional Transport (ART) models.[24]

[24] This possibility is currently being explored under the Sustainable Pathways (MAUX) FoRST contract. Moreover, the final two years of this contract (i.e. 2008 and 2009) will be directed at developing a spatially explicit version of ARDEEM.

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Appendix A: System Dynamics Model of Endogenous Growth

This Appendix presents a Vensim® system dynamics influence diagram, Figure A.1, of an alternative growth engine to the one developed above. Data paucity, and to a lesser degree time constraints, prohibited development of a full implementation of this growth engine.[25] The engine builds on the work of Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992), and Jones (1995, 1998, 2000). The major focus of the engine is on the causal mechanisms underpinning technological progress i.e. how ideas are formulated that lead to the development of new or enhanced technologies. Salient features of the model include:

- *Driven by the potential of profits from designs*. The model endogenises technological progress by assuming that the people engaged in prospecting for new ideas (*people discovering new ideas*) are driven to do so by the potential profits they may generate from selling their designs.
- *Generation of new ideas.* The rate at which new ideas are generated depends on (1) the stock of ideas generated to date (*Ideas*), the productivity of the ideas already discovered[26] (*productivity of research*), and whether the ideas are original or simply duplicates[27] (*duplication factor*).
- *Number of people.* In the current version of the model a larger population generates more ideas, and because ideas are non-rivalrous, everyone in the economy benefits. This is arguably optimistic. Skill levels and education of the population, along with other possible restrictions, are not, however, taken into consideration.

Of particular concern is the omission of natural capital as a critical factor of production. It is envisaged that future versions would overcome this limitation by incorporating:

[25] Popp (2005) has recently suggested a novel method for measuring technological change in environmental models using patents.
[26] This includes both knowledge spillovers (i.e. the 'standing on the shoulders of giants' effect) and the possibility that the discovery of new ideas becomes harder over time (i.e. the 'fishing out' effect).
[27] The so-called 'stepping on toes' effect.

- *Raw materials and residuals*. Although ideas are the key human factor driving technological change (i.e. positive feedback leading to economic growth), the transformation of these designs into commodities (including manufactured capital) will always involve materials/energy, and in turn, the generation of residuals. For this reason critical natural capital, in particular non-renewable and renewable resource stocks, would be incorporated within the model.
- *A race between increasing and diminishing returns*. Given that at least some raw materials and energy will be drawn from non-renewable resource stocks, and that some residuals are not easily assimilated by environmental processes, it may be argued that a race will exist between the increasing returns of technological innovation, and the diminishing returns of non-renewable resource stocks.

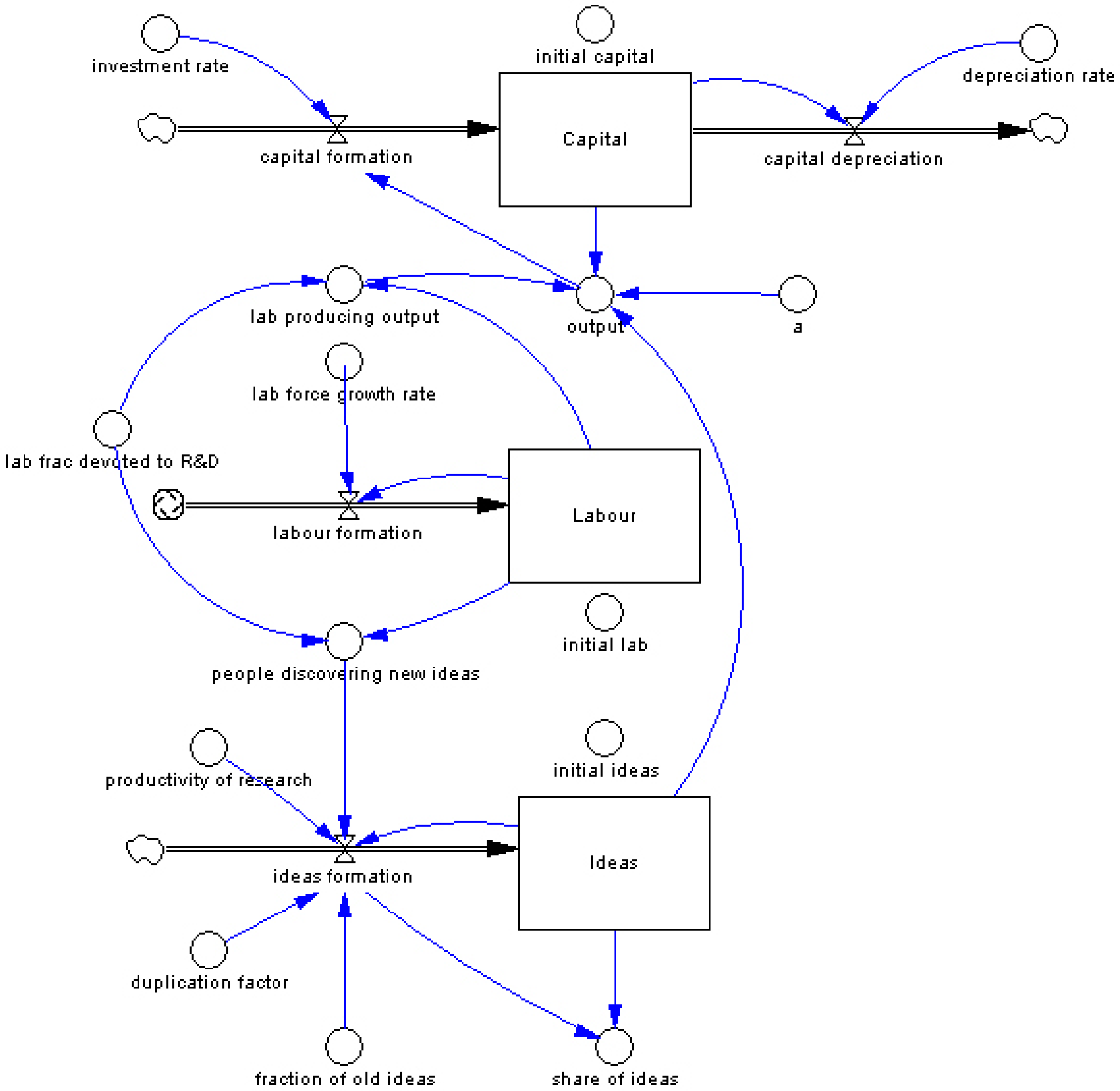

Figure A.1 An Alternative Endogenous Growth Engine

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