Chapter 5
Modelling Manufactured Capital Stocks and Material Flows in the Australian Stocks and Flows Framework

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Introduction

Manufactured capital stocks and their relationships to physical flows of materials and energy are of interest in the fields of industrial ecology and input-output analysis. Manufactured capital stocks embody technologies, which may be characterised by input-output (IO) relations. The rate and nature of technological and structural change in an economy are therefore related to the dynamics of these stocks. Certain capital stocks also act as substantial long-lived stores of materials in the anthroposphere. Additions to and scrapping of these stocks directly generate flows of new and used materials and wastes. This chapter is concerned with two relationships between manufactured capital stocks and material flows, and in particular, how they may be modelled in the field of industrial ecology. Examples are drawn from scenarios developed using the Australia Stocks and Flows Framework (ASFF) (Foran and Poldy 2002).

Section two of this chapter deals with methodological and practical issues encountered in accounting for and modelling manufactured capital stocks. Both commonalities and differences between economic and physical perspectives on capital stocks are discussed. An example is given of historical and projected vehicle stocks in Australia. Section three deals with input-output modelling of technologies embodied in capital stocks, focussing particularly on the 'bottom-up' or 'process modelling' approach employed in ASFF. An example of process-based IO models for steel production in Australia is provided. Section four is concerned with dynamic models of stocks and flows in Industrial Ecology. A dynamic physical IO model (Lennox et al. 2004) within ASFF is described and an example of material

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flows associated with electricity generation capacity is given. Section 5 concludes the chapter, providing a brief discussion of key issues in modelling capital stocks in terms of material stores and/or embodied technologies within the field of industrial ecology.

Manufactured Capital Stocks

Economic and Physical Capital Accounting in Theory

Manufactured capital stocks have structural and functional dimensions – capital *qua* capital and capital *qua* productive capacity.[1] They can also be viewed from economic and physical perspectives. In economic terms, capital *qua* capital has a cost in terms of investment flows and depreciation. Capital *qua* productive capacity produces a stream of economic value over its lifetime. From a physical perspective, commodities are used in the processes of capital formation and maintenance, while capital stocks are employed in the transformation of commodities and the provision of services. The economic value of capital stocks can usually be observed via market prices for new and used capital goods. Equally, it is possible in principle to measure the physical size of capital stocks by some suitable metric (e.g. floor space of a building). However, capital *qua* productive capacity is in practice unobservable in either economic or physical terms. All that can be observed is the actual output of this capital, which may be less than its potential output.

Intrinsic characteristics of productive assets and the way in which they are employed in production may vary with age and time. From 1 year to the next, the technologies embodied in new capital assets may change. For example, the fuel efficiency of car engines has increased, while the average weight and power of cars has also increased. *Embodied technological change* within an asset stock results from the in-built technological differences between assets manufactured in different years. The year in which an asset was manufactured is known as its 'vintage'. Embodied technological changes are likely to be more significant the more broadly each 'technology' is defined (i.e. with increasing aggregation). The intrinsic productivity of individual assets generally decreases monotonically with age and amount and type of use; however, this decay can be alleviated by maintenance and repair. The net result of these effects is known as e*fficiency decay*.[2]

The realised physical productivity of assets may also change because of improved methods of use. This is known as *disembodied technological change*, as it is independent of the built-in or embodied technology of tangible capital. Disembodied technological change may occur at various levels. At a micro level, improved

[1] The terms 'production' and 'productive capacity' are used very generally, to refer to production of market and non-market goods by in all sectors of the economy.

[2] Note that in SNA93, improvements to or extensions of capital must be classified as additions to stocks, whereas 'normal' maintenance activities must not be. In practice, such a distinction may be difficult to make.

practices may be developed for an individual capital asset, while at a higher level, generic techniques such as statistical quality control may be applied to almost any type of plant. The *potential productivity of capital* is then the product of embodied technological change, efficiency decay and disembodied technological change. The first and second of these are generally assumed to be functions of asset stock vintage, while disembodied technological change is assumed to apply proportionally to all vintages. Many types of capital are systematically used at less than full capacity, since a buffer of unused capacity is needed to allow for the relatively faster dynamics of requirements for output of goods and services. *Capacity utilisation* factors can be used to relate the potential productivity of capital to the realised productivity. These factors represent the result of a trade-off between flexibility and opportunity costs. Marginal and fixed costs of production are generally affected by technological as well as economic characteristics of capital stocks, and therefore will be a function of vintage. Again, the importance of vintage is likely to increase with the level of technology aggregation.

In theory, the multiplicative factors for capacity utilisation, efficiency decay, disembodied and embodied technological change relate capital stocks to the services derived from them in a simple and straightforward manner. In applied economics, they are difficult to define precisely, and impossible to estimate from the data sets usually employed in national accounting and macroeconomic analysis (Hulton 1999). The effects of specific innovations (e.g. statistical quality control) may be estimated in productivity studies and the effects of efficiency decay may be partially observable via markets in used equipment (US BEA 1999); however, systematic direct estimation of these factors and their dependence on time and vintage for all classes of tangible fixed capital appears to be impossible. Similar difficulties are encountered at corresponding scales of physical analysis. Specific items of new equipment often have nominal capacity ratings (generally less than maximal capacity). However, such data are impractical to collect and aggregate in large-scale studies. The physical productivity of capital can, by definition, be observed only in terms of throughput or similar measures of usage levels.

It is interesting to note that the value of stocks at the end of their productive lives is generally considered insignificant in economic terms (OECD 2001); however, end-of-life capital goods are often very important from an environmental perspective. Materials or components from end-of-life goods are either recycled or disposed of. End-of-life capital goods from capital stocks can therefore be seen as a material resource or an environmental burden. Furthermore, additional material and energy flows are mobilised in the processes of recycling or disposing of end-of-life goods. Recently, these issues have been dealt with in SEEA (UN 2003), so accounting practices in this area may improve in the future.

Capital Accounting in Practice

Actual stocks of manufactured capital can be estimated directly or indirectly. Census or sampling approaches may be applied to extant stocks, yielding direct estimates of stock sizes. Alternatively, additions to and deletions from stocks can be measured over time; again using census or sampling methods. Integrating these time series yields the cumulative net additions to stocks. Current stocks are then the sum of the initial stocks and the net accumulation to stocks. In the context of national accounting, the second approach has predominated. Investment flows are measured in monetary terms by all OECD countries, as they are an important element of national accounts.[3] Recent standards for measurement and accounting of economic capital are described by the OECD (2001).

Updating stock estimates based only on the current year's transactions appears very efficient. The major practical problem is that deletions from stocks are often unmeasured, or the available measurements are inappropriate to the task of capital stock estimation. Consequently, deletions from stocks are often estimated using the perpetual inventory method (PIM). While widely applied in capital accounting, the functional form and parameterisation of life-expectancy distributions used in the PIM are often of questionable accuracy (US BEA 1999). A further problem is that if net additions to stocks are relatively small in absolute value, the estimates of current stocks will be sensitive to the initial stock estimates. Reacting to the shortcomings of standard capital estimation methods, several countries have begun to make wider use of direct observation in national accounting, including observations of physical measures (Frenken 1992).

To aggregate individual assets into a capital stock, one must choose a common measure for both nominal and functional amounts of capital. Numeraires for nominal manufactured capital include number, mass and area. Discrete measures are more appropriate for relatively homogenous types of capital, while continuous measures are more appropriate for capital that may be added in essentially arbitrary quantities. Vehicles are often accounted for by number, with sub-classes distinguished according to the number of doors or seats, the engine size, or other characteristics. Floor area is a common measure of building stock size. The functional amount of capital may be expressed in terms of its potential output. In the case of industrial production, this may be the effective maximum output rate for the principle product. For capital items with multiple functions and/or functions that cannot be measured quantitatively, it is difficult to distinguish functional from nominal capital.[4] In Australia, systematic collection and publication of physical data is undertaken for only a few types of capital[5] by the Australian Bureau of Statistics (ABS) or other organisations.

Current practice in compilation of physical input-output tables (PIOT) treats manufactured capital stocks summarily or not at all. The Danish PIOTs (Gravgård

[3] It should be noted that the number of sectors and commodities that are distinguished by different countries in relation to investment flows varies dramatically.

[4] It is worth noting the connection between physical accounting measures, and what is known as 'hedonic pricing' in economics. Hedonic prices are those inferred from observable characteristics of goods that are assumed to give them value (e.g. in a computer, one might value primarily speed, memory, hard disk space and screen size).

[5] These include but are not limited to houses, vehicles and power plants.

1999) include ‘net additions to stocks’ as an element of final demand, however there are no capital stock accounts associated with these tables. Even when physical capital stocks are accounted for, their functional dimension is not considered in either the Eurostat MFA methodology (EUROSTAT 2001) or in SEEA. This is presumed to be adequately captured by the economic accounts, with which physical accounts should ideally be harmonised. Indeed the Eurostat guide states that PIOT: should ‘show the physical accumulation of materials in the economy, but not the stocks of man-made or natural capital’ (EUROSTAT 2001).

Example: Motor Vehicle Stocks in Australia

In industrialised countries motor vehicle stocks significantly contribute to a range of environmental and resource problems. Australia is particularly reliant on both cars for personal mobility and on trucks for road freight transport. Both the number of vehicles and the kilometres travelled are very high by world standards, reflecting both the large size of Australia and the relatively low population densities of its cities and towns. Use of motor vehicles contributes to depletion of fossil energy resources and to atmospheric pollution. Motor vehicles also contribute significantly to societal stocks of steel and other metals. Finally, motor vehicle stocks are used in conjunction with major infrastructure stocks such as roads and parking facilities.

This section draws on modelling and scenarios developed in the Australian Stocks and Flows Framework (ASFF) (Foran and Poldy 2002) to illustrate the role of the motor vehicle stocks as a store of metals in society. Motor vehicle stocks are represented using a vintage model. In each period, a set proportion of each vintage survives and the residual stock is scrapped. The vintage model is driven by the quantity of motor vehicles demanded, which is derived from the population size and an assumed numbers of cars per household. In each period, the difference between the required and actual stock size must be made up with new vehicles. The model was calibrated to fit historical time series and other data. Within a scenario, variables controlling motor vehicle stocks are projected into the future. On this basis, vehicle stocks and additions to and deletions from them are projected. Several categories of motor vehicles are modelled in ASFF, but the following examples will focus on passenger cars. In the model, different sizes of car are not distinguished; however, parameters specify the average material intensity and composition of new cars in each vintage.

Figure 5.1 shows the historical and projected future growth in total car stocks under the ‘base case’ scenario from Foran and Poldy (2002). This stock trajectory is driven by population-related variables and a number of exogenous parameters. The corresponding additions to and deletions from stocks, shown in Fig. 5.2 below, are a function of the changing size and age distribution of the car fleet and the parameters determining the life-expectancies of cars of different vintages, which themselves

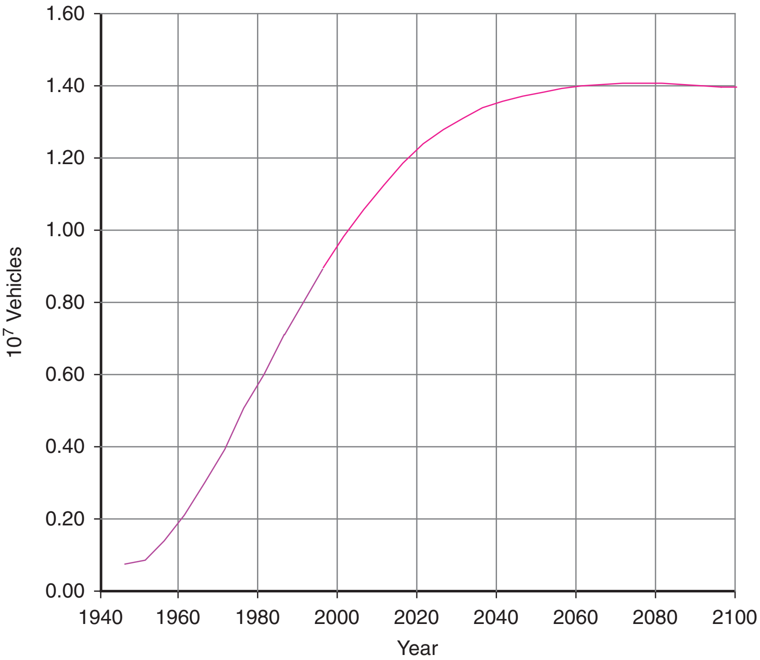

Fig. 5.1 History and Default Scenario Projections for Australian Car Stocks

change over time. The assumptions underlying the future projections shown above include (Foran and Poldy 2002):

- Cars will be manufactured for increased durability, causing the average age of privately owned cars to rise from 10.5 to 13.8 years by 2050.
- The number of cars per household has been increasing, but at a diminishing rate. It is assumed to saturate at 1.21 cars per household.

Under the base case scenario, the overall shape of the curve in Fig. 5.1 is similar to that of the projected population, but the modulating parameters associated with household size and cars per household make it steeper prior to saturation. The number of vehicles would peak around 40% above the present number. The number of new cars required per year would plateau much sooner, meaning that the domestic market would become relatively stable within a decade. By contrast, the number of scrapped vehicles will react much more slowly. It should be noted that subsequent data on new car registrations shows that the conditions for this scenario to be played out in Australia have not yet been met. The number of new passenger vehicle registrations increased by an average of 1.9% per year from 1997 to 2002 (Australian Bureau 2002). This compares to a 1.1% per annum increase from 1996 to 2001 in the base case scenario.

Historically, mass per vehicle rose until the oil crises of the 1970s and has since been falling with the introduction of smaller cars to the market. Design improvements and increasing use of plastics, aluminium and other light-weight materials

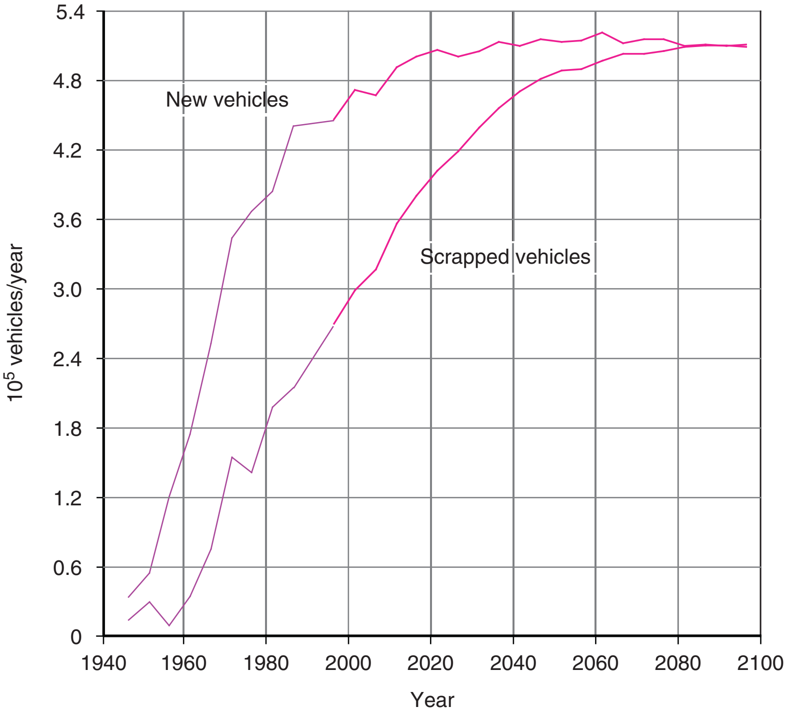

Fig. 5.2 Corresponding Numbers of New and Scrapped Cars (Right)

have also made vehicles lighter and should continue to do so for some time yet. It is assumed in the scenario that these factors outweigh counter-veiling trends towards the purchase of larger vehicles; although it is acknowledged that increased fuel efficiency might actually create a rebound effect by increasing the affordability of larger vehicles (Foran and Poldy 2002). The average vehicle weight is assumed to decrease until it plateaus at 1.2 t. The rapid decrease in average weight per vehicle partially cancels out the still rapid rise in vehicle numbers during the first decade of the twenty-first century. Consequently the masses of new and scrapped vehicles (Fig. 5.3) equilibrate more rapidly than do their numbers.

Modelling Technologies

One way of representing the technologies of production or consumption embodied in manufactured capital stocks is in terms of input-output relations. Input-output relations can be determined through a bottom-up modelling approach, in which an industry is seen as a system comprising a finite number of processes, each having its own input-output characteristics. Process analysis focuses on functional relationships between inputs and outputs that are determined by physical laws,

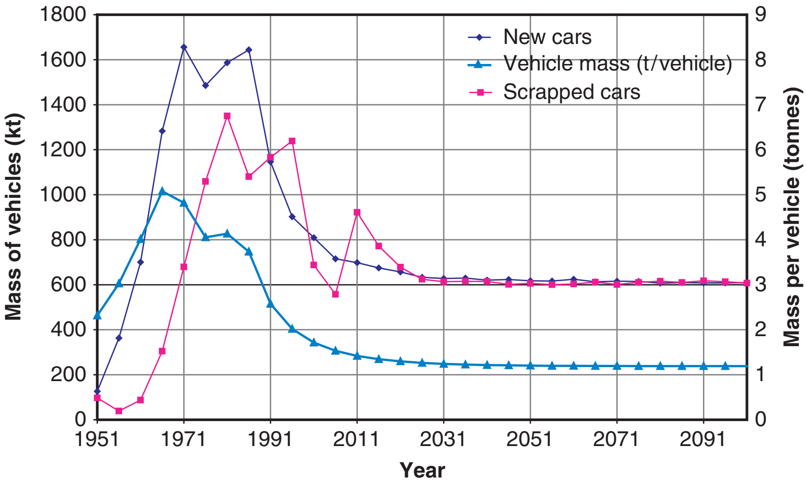

Fig. 5.3 Flows of Materials Associated with the Australian Vehicle Stocks

and/or are based on empirical engineering knowledge. Such relationships, which are frequently non-linear and multivariate, may be simplified for the purpose of constructing linear input-output relations. In the context of IO analysis, the possibility of describing 'generic' technologies is particularly appealing, since behind the IO coefficients will be clear physical interpretations. In principle then, each industry model (set of IO coefficients) can be seen as the composition of generic process models. In practice, inhomogeneity of nominally equivalent processes, as well as the existence of many auxiliary processes within industries (e.g. production of oxygen gas for own use by producers of metals) makes construction of economy-wide or even broad sector IO models a difficult and time-consuming task.

Process Analysis and Activity Analysis

Generic process descriptions can be built from both empirical and theoretical data. Observations of process inputs and outputs may be used directly to construct a model relating the two. Alternatively, descriptions of these relationships can often be found in the technical and scientific literature. Whichever of these methods is used, the validity of the resulting model must be assessed. Remaining within the bottom-up modelling paradigm, the representativeness of source data can be assessed qualitatively. For example, it would be inappropriate to use a model of clinker production by the 'wet process' to describe an industry where the 'dry process' was predominantly used. Quantitative validation requires the use of available 'top-down' statistical data. The latter can be used to validate process models individually and/or to validate a higher level model involving multiple process models. Cross-entropy techniques can be particularly useful for problems of this sort (Golan et al. 1996).

Box 5.1 Input-Output Tables in Australia

The Australian Bureau of Statistics has produced input-output tables for Australia since 1962–1963. In various periods, tables have been compiled annually, biennially or triennially. Since 1994–1995 tables have been compiled biennially with tables for 1998–1999 being published in 2004 (ABS 5209.0.55.001). This publication includes make and use tables for 106 industry sectors (see below) as well as input-output tables for both direct and indirect allocation of competing imports. A separate publication provides total domestic supply and trade data for detailed product items (ABS 5215.0.55.001).

Various State and other regional input-output tables have also been compiled by State Government agencies or researchers. For example the Queensland Office of Economic Statistics and Research has published State and regional input-output tables for Queensland. There is currently no official framework for the production and maintenance of regional input-output tables in Australia.

Input-Output Categories in the 1998–1999 Publication

0101	Sheep
0102	Grains
0103	Beef cattle
0104	Dairy cattle
0105	Pigs
0106	Poultry
0107	Other agriculture
0200	Services to agriculture; hunting and trapping
0300	Forestry and logging
0400	Commercial fishing
1100	Coal; oil and gas
1301	Iron ores
1302	Non-ferrous metal ores
1400	Other mining
1500	Services to mining
2101	Meat and meat products
2102	Dairy products
2103	Fruit and vegetable products
2104	Oils and fats
2105	Flour mill products and cereal foods
2106	Bakery products
2107	Confectionery
2108	Other food products
2109	Soft drinks, cordials and syrups
2110	Beer and malt
2111	Wine and spirits
2112	Tobacco products
2201	Textile fibres, yarns and woven fabrics

(continued)

Box 5.1 (continued)

2202	Textile products
2203	Knitting mill products
2204	Clothing
2205	Footwear
2206	Leather and leather products
2301	Sawmill products
2302	Other wood products
2303	Pulp, paper and paperboard
2304	Paper containers and products
2401	Printing and services to printing
2402	Publishing; recorded media, etc.
2501	Petroleum and coal products
2502	Basic chemicals
2503	Paints
2504	Medicinal and pharmaceutical products, pesticides
2505	Soap and detergents
2506	Cosmetics and toiletry preparations
2507	Other chemical products
2508	Rubber products
2509	Plastic products
2601	Glass and glass products
2602	Ceramic products
2603	Cement, lime and concrete slurry
2604	Plaster and other concrete products
2605	Other non-metallic mineral products
2701	Iron and steel
2702	Basic non-ferrous metal and products
2703	Structural metal products
2704	Sheet metal products
2705	Fabricated metal products
2801	Motor vehicles and parts; other transport equipment
2802	Ships and boats
2803	Railway equipment
2804	Aircraft
2805	Photographic and scientific equipment
2806	Electronic equipment
2807	Household appliances
2808	Other electrical equipment
2809	Agricultural, mining, etc. machinery
2810	Other machinery and equipment
2901	Prefabricated buildings
2902	Furniture
2903	Other manufacturing
3601	Electricity supply
3602	Gas supply

3701	Water supply; sewerage and drainage services
4101	Residential building
4102	Other construction
4501	Wholesale trade
5101	Retail trade
5401	Mechanical repairs
5402	Other repairs
5701	Accommodation, cafes and restaurants
6101	Road transport
6201	Rail, pipeline and other transport
6301	Water transport
6401	Air and space transport
6601	Services to transport; storage
7101	Communication services
7301	Banking
7302	Non-bank finance
7401	Insurance
7501	Services to finance, investment and insurance
7701	Ownership of dwellings
7702	Other property services
7801	Scientific research, technical and computer services
7802	Legal, accounting, marketing and business management services
7803	Other business services
8101	Government administration
8201	Defense
8401	Education
8601	Health services
8701	Community services
9101	Motion picture, radio and television services
9201	Libraries, museums and the arts
9301	Sport, gambling and recreational services
9501	Personal services
9601	Other services

Attempts to systematically describe large suites of generic industrial technologies are reviewed by Gault et al. (1985). Most such efforts have related to energy analysis (Boustead and Handcock 1979) and greenhouse gas emissions modelling (Gielen et al. 1998), which is to be expected, given the intensity of research in these areas over several decades. Gault et al. developed the 'Design Approach' methodology for modelling socio-economic systems. The Design Approach views socio-economic systems form a hierarchical multilevel perspective. It relies heavily on the use of process analysis method, as described by Gault (Gault et al. 1987). The Design Approach has been adopted in the CSIRO's 'Australian Stocks and Flows Framework' (Foran and Poldy 2002; Poldy et al. 2000).

Bottom-up approaches to modelling input-output functions are now frequently applied in the field of IO analysis. However, historically, bottom-up approaches were more widely employed in the related field of activity analysis. Activity analysis was developed by Koopmans and his colleagues in the 1950s ‘to study and appraise criteria, rules and practices for the allocation of resources’ (Koopmans 1953). ‘Methods of production’ and ‘the elementary activity, the conceptual atom of technology’ (Koopmans 1951, 1953) defined technologies at a finer scale than that permitted by Leontief’s input-output analysis. An additional differentiating feature of activity analysis was the use of linear (and later, non-linear) programming techniques to find optimal configurations of technologies. The Design Approach adopts on the one hand the detailed technological representation of activity analysis but on the other, the deliberative approach to modelling and the emphasis on economic planning espoused by Leontief.

More recently, the concept of activities has been employed in an input-output context by Konijn and Steenge (Konijn 1994; Konijin et al. 1995). Their method for disaggregating industries and commodities in make and use tables to generate ‘activity-by-activity’ input-output tables has been adopted by Statistics Netherlands (Algera 1999). In this method, bottom-up information can be used to complement top-down information (make and use tables) in the process of disaggregating frequently inhomogeneous ‘industries’ into more homogeneous ‘activities’. In particular, secondary activities common to a number of different industries are distinguished (e.g. consulting services provided by manufacturing companies).

Example: Technological Change in the Australian Steel Industry

In this section, a study of energy use in the Australian iron and steel industry will illustrate how top-down and bottom-up information can be combined to extract information with the aid of generalised cross-entropy techniques (Golan et al. 1996). For the Australian iron and steel sector, production data exist for iron and steel in total and also with subtotals for the basic oxygen furnace (BOF) versus the electric arc furnace (EAF) route and for ingot casting (IC) versus continuous casting (CC) (Fig. 5.4).

It can be seen that continuous casting replaces (less efficient) ingot casting and that the share of EAF production increases, but is quite small. The energy used by Australia’s iron and steel sector is also known (Fig. 5.5). Note that these data include consumption of self-produced energy (coke and thermal energy). The consumption data constrain the energy input coefficients for individual process steps. Specifically, consumption of each energy type by each process must add up to the total consumption of each energy type. Better estimates of input coefficients would be obtained if data for the total energy used by each process were also available; however, they are not. It was expected that efficiency improvements had occurred in the industry, due both to shut-down of old units and to new units brought on-line in later years. This

Table 5.1 Prior Estimates (Bracket) and Calibrated Energy Input Coefficients for 96/97 (GJ/t)

	Coal	Coke	Liq HC	Nat gas	Electric	Other	COG/BFG
Coke	35.1	0	0(1.285)	0.88	0.10	0.18(0)	5.68
Ovens (coke)	(38.5)			(0.1)	(0.095)		(4.18)
Sinter +	2.44	8.67	0.15	1.87	0.42	0.03(0)	5.67
BF (iron)	(3.05)	(10.8)	(0.23)	(0.14)	(0.43)		(2.26)
EAF	0.08	0	0.12	0.28	4.59	0.06(0)	0
(steel)	(0.085)		(0.12)	(0.25)	(1.53)		
BOF (hot steel)	0.01	4.49	0.04	0.23	0.17	0.01(0)	0.31
	(0.025)	(6.98)	(0.038)	(0.038)	(0.16)		(0.085)
Contin	0	0	0.00	0.01	0.09	0	0.01
Cast (crude steel)	(0.005)		(0.005)	(0.005)	(0.09)	(0.005)	
Ingot Cast	1.27	0	0.01	0.20	0.56	0	0.01
(crude steel)	(1.26)		(0.007)	(0.13)	(0.49)	(0.005)	
Rolling,	1.11	0	0.01	0.99	1.23	0	0.02
finishing, misc.	(1.38)		(0.008)	(0.14)	(0.35)	(0.006)	
(finished steel)							

COG = coke oven gas, BFG = blast furnace gas.

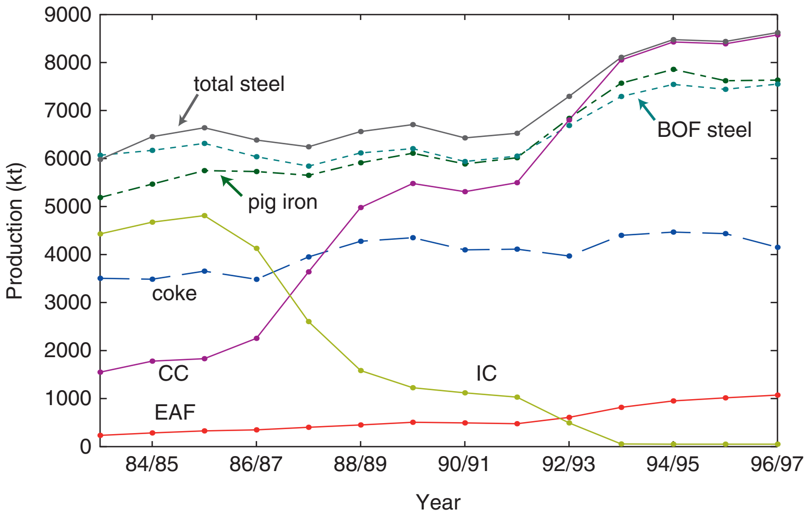

Fig. 5.4 Production of Iron and Steel with Breakdown of Key Processes (Ferber 2002)

is because the Australian industry suffered from world over-capacity in the early 1980s, but more recently has invested several billion Australian dollars in capital works.

Energy input coefficients for the iron and steel industry were calibrated using the cross-entropy methodology for each year from 1981/92 through 1996/97. Prior upper and lower bounds and prior coefficient estimates were specified for each coefficient based mainly on information in (European Integrated Pollution

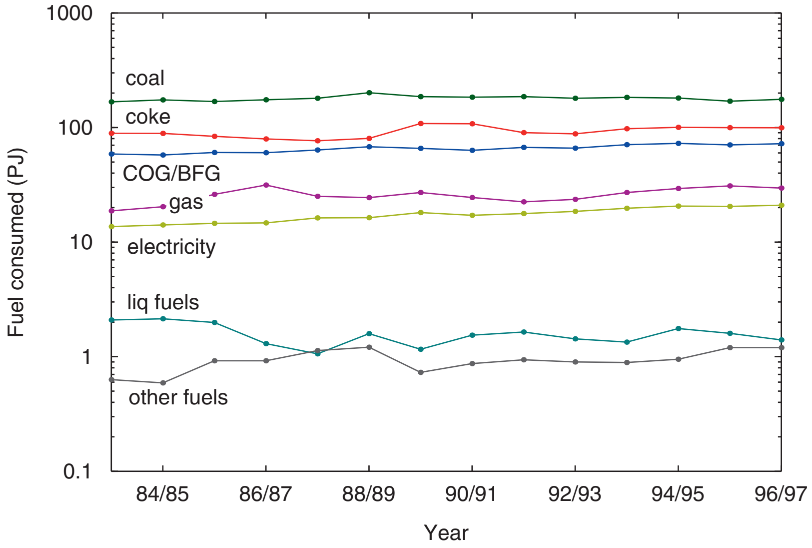

Fig. 5.5 Total Consumption of Fuels and Electricity by the Iron and Steel Sector

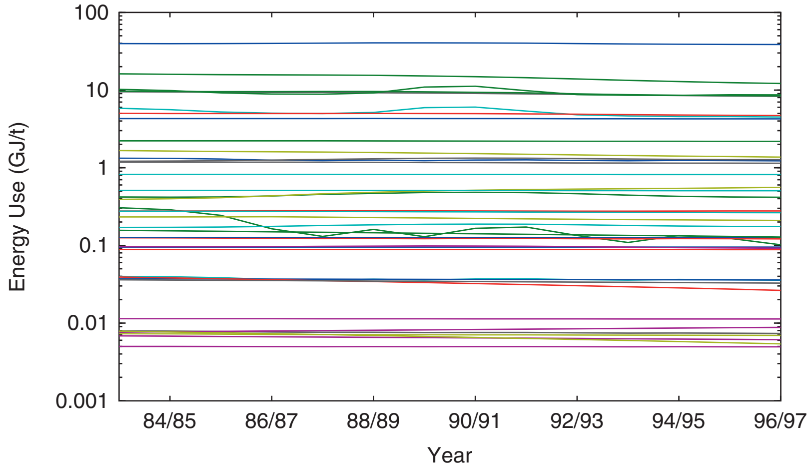

Fig. 5.6 Input Coefficient Trajectories by Process and Energy Type

Prevention and Control Bureau 2001). As an example, the 1996/97 coefficients, along with the prior estimates (which were the same for all years) are shown in Table 5.1 Inputs are given per tonne product of each process (for lack of statistical data, sintering and BF were aggregated and coefficients are per ton pig iron). The shaded coefficients were assumed to be identically zero.

The trajectories of the 40 non-zero coefficients are plotted in Fig. 5.6.

Coefficients for coal and coke use decline slightly over time, but for coke, the decline is interrupted by a large peak from 1989–1992. The peak matches features in overall production and use data, so is not an artefact, but is otherwise hard to explain. Coefficients for COG/BFG use also tend to decline, although it should be noted that the production of COG/BFG increases over time as a proportion of total consumption, indicating improving efficiency. Coefficients for natural gas fluctuate while those for electricity tend to go up until the 1990s, when they begin to decline. Total (gross) energy input to each process declines in most cases – for the aggregated sintering/blast furnace operations, from 23.8 to 20.7 GJ/t. No strong trends were distinguished for less energy-intensive processes, and an increasing trend was observed for the EAF process. This might have been caused by decreasing quality of feed material. In all cases, results such as these cannot be treated as conclusive, since the process of cross-entropy minimization ought to be seen as something between interpolation and regression. The more data are used, the more reliable the results. It is also a characteristic of this method that large changes tend to accrue to large coefficients. This results in conservative, but not necessarily accurate values for the smallest coefficients.

Relating Capital Stocks and Material Flows

Dynamic Input-Output and Process Models

Tying together models of capital stocks and technologies requires the construction of dynamic models. In the IO literature, dynamic IO models make capital investments a function of expected future demands (Leontief 1970a; Sonis and Hewings 1998; Duchin and Szyld 1985). Thus they consider the capacity of each industry and the commodities required to maintain and form new capacity. A few authors have also linked capital investments to technological change within industries via marginal IO coefficients (Tilanus 1967; Azid 2004). In the MFA literature on the other hand, the function of manufactured capital stocks is not usually considered at all. The focus is purely on capital stocks as reservoirs of bulk materials or specific substances of interest.

Environmentally extended input-output models can be traced back to Leontief's work on air pollutants in the 1970s (Leontief 1970b, 1972). Subsequently, similar extended input-output models (i.e. static ones) have been widely applied to environmental and resource issues. Environmental extensions of dynamic IO models have been far less common (consistent with the limited applications of dynamic IO models more generally). Physical input-output models have appeared in recent years, derived from the physical input-output tables (PIOT) now available for a number of European countries and static IO models have been derived from these by various authors. However, as yet there does not appear to be sufficient empirical data to support the construction of dynamic input-output models based only on physical flows statistics. The highly aggregate representation of capital stocks in current PIOTs may also be a barrier to creating dynamic physical models (see above).

Konijn, de Boer and Lange (1997) present a hybrid-unit IO model that includes consumption of selected materials for capital formation. They estimate materials embodied in exports, consumption and fixed capital formation. Duchin, Lange and co-workers (1994) built on the original multi-regional World Model (Leontief et al. 1977) to examine 'relationships among increasing affluence, pollution and technological choices' (Duchin et al. 1994). In particular, they assess the feasibility of 'sustainable development' as envisaged in the Brundtland Report (World Commission 1987). Their dynamic IO model includes capital stock dynamics and exogenous technological change. The latter is derived from extensive bottom-up data and analysis. The model is used to simulate an 'Our Common Future' scenario with technological change and a reference scenario with no technological change post 1990. Idenburg and Wilting (2000; Idenburg 1998) use a dynamic IO model to study the technological change and eco-efficiency in The Netherlands. A multi-sectoral equilibrium model for Norway, extended to describe total material inputs and specific waste flows was developed by Bruvoll and Ibenholt (1997). They use the model to assess the links between material and energy intensities of production and waste flows.

Process analysis has been widely used to construct bottom-up multi-sectoral models in the energy and climate policy fields.[6] These models are often used within an economic optimisation framework to identify solutions achieving policy objectives whilst minimising costs, subject to technological and other constraints (Löschel 2002). Technological change can be modelled in terms of substitution between different technologies and/or changes in individual technologies. Input substitution possibilities are generally reduced as one moves from more generic to more specific and detailed representations of technologies.

Capital vintages are frequently distinguished in bottom-up models. The possibility of substituting intermediate inputs for labor and (less commonly) of substitution between intermediate inputs may differ for new capital and existing capital stocks. The most extreme assumptions are often referred to as 'clay' (non-substitutability) and 'putty' (full substitutability), leading to three basic types of model (Kónya 1994)[7]:

Clay–clay
Putty–clay
Putty–putty

Assumptions of limited substitutability are also possible (e.g. putty–semi-clay) (Ruth et al. 2004). Clay models assume that technological change is entirely embodied in capital stocks, whilst putty models assume that technological change is entirely disembodied. The theoretical appropriateness of these assumptions depends

[6] Top-down approaches based on macro-economic modeling have also been widely used, and have often produced very different results (IEA 1998).

[7] The fourth possibility of clay–putty does not have a logical interpretation, since substitutability *ex post* is not likely to be greater than *ex ante*.

on the level of technological aggregation (Ruth et al. 2004; Davidsdottir 2002). In practice, it may be difficult to identify the many parameter values required in more 'realistic' but complicated models.

Dynamic IO Modelling in ASFF

In ASFF, hierarchically linked sectoral/thematic modules describe different parts of the economy and employ various model structures. One such module, the 'materials model' describes flows of material and energy, as well as capital stocks within 'basic industries' using a dynamic IO structure (Lennox et al. 2003). 'Basic industries' are defined as those transforming raw materials (ores, concentrates, harvested materials, etc.) into bulk industrial materials and energy forms (cement, steel, electricity, etc.) (Lennox et al. 2003). The model is driven by the requirements for processed materials and energy in all other parts of the economy – i.e. those modelled in the other modules of ASFF. Adjustments to these requirements are made to account for materials recycling and international trade in processed materials.

The materials model consists of a set of process-based input-output relations, each of which is associated with a capital stock. Input-output coefficients are exogenously specified for each process and may vary over time. Technological change of individual processes is therefore modelled as being entirely disembodied. On the other hand, multiple processes may produce the same product and the existing capital stocks of each process partly determine the combination of technologies employed. In this respect, technologies are represented as embodied and technological change can be modelled in terms of substituting alternative processes.

Evolution of capital stocks is modelled using vintages and life tables that determine the proportion of each vintage that survives from one period to the next. Physical depreciation of productive capital and capital maintenance are assumed to be factored into life tables. Additions to capital stocks are determined as a function of output requirements, stock scrapping and several decision variables. There is no forecasting of outputs for future years as in Duchin and Syzld's model (1985), partly because the ASFF model deals with longer time steps of 5 years. Processes of capital stock formation and scrapping are associated with material flows through material embodiment parameters. These describe the mass of materials that compose a functional unit of capital. It must be said that flows associated with production equipment are generally small when compared both with either production throughput or materials embodied buildings and civil works. Thus in ASFF, the bulk of industrial capital stocks are industrial buildings or civil works such dams.

Example: Electricity Generation in Australia

The representation of capital stocks and associated material flows in ASFF is illustrated with reference to the electricity generation industry. A number of different

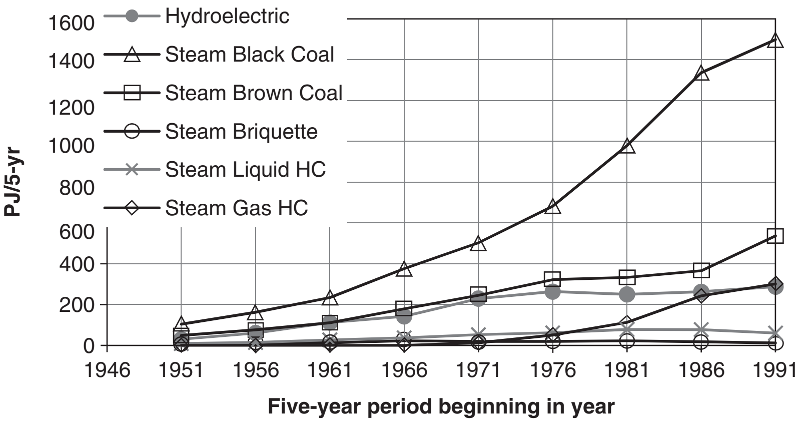

Fig. 5.7 Electricity Production by Process

Table 5.2 Material Composition Coefficients

t/MW nominal capacity	Concrete	Steel
Hydroelectricity	4,100	36
Steam-fired	370	73
t/MW nominal capacity	74	11

generation processes are represented in ASFF including different types of coal, oil and gas firing, as well as hydroelectric generation. Figure 5.7 shows the historical output for each of these processes over historical time. Note that the values shown are in PJ/5-year and are summations over spatial regions represented in the model.

The process models used for electricity generation activities are simpler than those for steel-making (above). As a first approximation it is assumed that the only inputs to generating processes are electricity (for self-use and internal losses) plus the fuel consumed in thermal generation processes. However, in additional to these direct inputs, there are the indirect inputs of materials required for the construction of new capital. By mass, the main constituents of these stocks are steel and concrete. Embodied materials coefficients for hydroelectric, steam and gas turbine generation process capital stocks are shown in Table 5.2 (CISS 2001). Note that hydro-electric works vary greatly in their materials requirements, so these values should be treated with caution.

Using these coefficients, the corresponding endogenous requirements for steel and concrete are computed and are shown in Fig. 5.8. To put the requirements for steel and concrete in perspective, the total supply of steel is illustrated on a second axis in Fig. 5.8, the majority of which is used domestically.

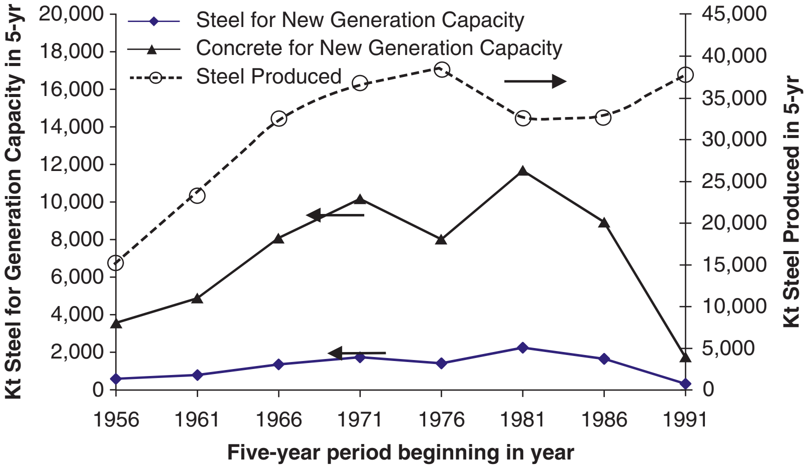

Fig. 5.8 Steel and Concrete for Endogenous Growth of Electricity Supply (Left Axis) and Steel Production (Right Axis)

Discussion and Conclusions

In the IO literature, manufactured capital stocks have primarily been considered as a component of final demand. Few models of the technologies embodied in these stocks have been developed. While technological change is frequently considered in this literature, it is usually implemented in terms of exogenous changes to IO parameters. On the other hand, there are many examples of bottom-up multi-industry and multi-sectoral models that represent embodied technologies. Clay–clay, putty–clay and putty–semi-clay vintage models make an explicit link between capital stocks and technological characteristics. The dynamic physical IO model of industries within ASFF includes vintaged stocks, but does not link these to IO coefficients, which are exogenously specified. The field of activity analysis provides an obvious link between general bottom-up or process-based modelling approaches and the field of IO analysis, which is dominated by top-down approaches.

In the material flow analysis (MFA) literature, capital stocks have mainly been considered as stores of materials/substances and hence, as temporary sinks and sources of material/substance flows. ‘Bulk MFA’ studies in particular, are rarely concerned with process and are essentially descriptive. ASFF shares the aim of describing physical flows into and out of an economy; however, the bottom-up approach taken with ASFF leads to a much more detailed description of the physical economy and a strong interest in process. Physical IO models generally provide more detail than does MFA, but much less than do bottom-up models or some economic IO models. Physical IO modelling still faces a considerable constraint in terms of data availability. The most promising route forward then appears to be with the various possibilities for ‘hybrid’ input-output modelling, whereby top-down and bottom-up methods and/or physical and economic components are combined.

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