# List of figures

1.1 Typology of ecosystems  
1.2 The elements of industrial ecology seen as operating at different levels  
1.3 Industrial ecology conceptualized in terms of its system-oriented and application-oriented elements  
5.1 Conceptual diagram of an aluminum *kombinat*  
5.2 Lignite-burning power plant modified via PYREG  
5.3 Systems integrated with ENECHEM with additional plant for xylite processing  
5.4 Hypothetical process–product flows for COALPLEX  
6.1 Evolution in international governance systems  
8.1 Economy-wide material flows  
9.1 A substance life cycle for copper in the Netherlands, 1990  
11.1 A conceptual framework for a process analysis approach to industrial ecology  
11.2 The process flowsheet for the production of benzene through the hydodealkylation of toluene  
11.3 ASPEN representation of the HDA process  
11.4 A generalized multi-objective optimization framework  
11.5 Approximate Pareto set for the HDA process multi-objective optimization (case 1: diphenyl as a pollutant)  
11.6 Approximate Pareto set for the HDA process multi-objective optimization (case 2: diphenyl as a by-product)  
11.7 Probabilistic distribution functions for stochastic modeling  
11.8 The multi-objective optimization under uncertainty framework  
11.9 Uncertainty quantification in environmental impacts indices for the case study  
11.10 Approximation of Pareto set for the uncertainty case  
11.11 Relative effects of uncertainties on different objectives  
12.1 Technical framework for life cycle assessment  
12.2 Two ways of defining system boundaries between physical economy and environment in LCA  
12.3 Allocation of environmental burdens in multiple processes  
13.1 An impact evaluation combining scenarios for technique, environment and human attitudes  
13.2 Different types of characterization models  
13.3 Relations between emissions and impacts may vary owing to location and other circumstances  
13.4 The aggregated impact value is linearly dependent on all input data  
13.5 Conceptual data model of impact evaluation
List of figures

14.1 Material flow accounting 168
14.2 SEEA: flow and stock accounts with environmental assets 169
14.3 Annual TMR per capita for the USA, the Netherlands, Germany, Japan and Poland 173
14.4 Environmentally adjusted net capital formation in per cent of NDP 175
16.1 The Salter cycle growth engine 188
16.2 The ratio $f$ plotted together with $B$, total exergy and $W$, waste exergy – USA, 1900–98 194
16.3 Fuel exergy used for different purposes – USA, 1900–98 195
16.4 Breakdown of total exergy inputs – USA, 1900–98 196
16.5 Index of total electricity production by electric utilities (1900 = 1) and average energy conversion efficiency over time – USA, 1900–98 197
16.6 Exergy intensity ($E/Y$) plotted against $f$ and the Solow residual, $A(t)$ – USA, 1900–98 198
16.7 Cobb–Douglas production function, USA, 1900–98 200
16.8 Technical progress function with best fit $A$: USA, 1900–98 201
17.1 Materials group indices of intensity of use 208
18.1 Three-year moving averages of prices of zinc relative to the consumer price index in the USA 211
18.2 The ‘intensity of use’ hypothesis and the influence of technological change 213
18.3 Developments in aggregated throughput 215
18.4 Developments in the throughput index 216
18.5 Steel intensities in the UK, 1960–95 218
18.6 Energy intensities in the UK, 1960–97 219
18.7 Steel intensities in the Netherlands, 1960–95 220
18.8 Energy intensities in the Netherlands, 1970–96 221
20.1 Trends in production, energy consumption and CO$_2$ discharge in the Japanese manufacturing industry, 1955–94 237
20.2 Trends in factors and their magnitude contributing to change in CO$_2$ emissions in the Japanese manufacturing industry, 1970–94 239
20.3 Trends in technology knowledge stock of energy R&D and non-energy R&D in the Japanese manufacturing industry, 1965–94 241
20.4 Factors contributing to change in energy efficiency in the Japanese manufacturing industry, 1970–94 243
20.5 Factors contributing to change in energy R&D expenditure in the Japanese manufacturing industry, 1974–94 245
21.1 Global carbon cycle 251
21.2 Global nitrogen cycle 253
21.3 Global sulfur cycle 256
21.4 Global phosphorus cycle 258
22.1 The materials cycle 261
22.2 Processed flows for physical goods in the USA, 1900–96 268
22.3 Processed flows for physical goods in the USA, 1900–96 (log scale) 269
22.4 Physical goods derived from metals and minerals in the USA, 1900–96 270
22.5 Physical goods derived from renewable organic forest and agricultural sources in the USA, 1900–96 271
List of figures

22.6 Physical goods derived from non-renewable organic sources in the USA, 1900–96 272
22.7 Plastic and non-renewable organic physical goods in the USA, 1900–96 273
22.8 World use of materials for processed physical goods, 1970–96 276
23.1 Composition of TMR in the European Union, selected member states and other countries 293
23.2 Trend of GDP and DMI in member states of the European Union, 1988–95 295
23.3 Temporal trends of selected per capita material output flows in Germany (West Germany 1975–90, reunited Germany 1991–96) 296
24.1 Frameworks of environmentally extended physical input–output tables 305
24.2 Materials balance for Japan, 1990 308
26.1 A physical net balance of foreign trade activities for the UK economy for the period 1937–97 329
27.1 Industrial ecology operating at three levels 334
27.2 Industrial symbiosis at Kalundborg, Denmark 336
28.1 World mineral production and total ‘hidden flows’ for the 12 commodities producing the largest total materials flows at the global level 354
29.1 Stocks and flows in the metal model for iron/steel and MedAlloy 367
29.2 Model relationships within the metal model 368
29.3 Intensity of use hypothesis 369
29.4 IU curve for iron/steel and MedAlloy use in 13 global regions 371
29.5 Model results, 1900–2100: (a) consumption; (b) secondary production fraction; (c) price; (d) ore grade; (e) energy consumption 372
30.1 Emissions of heavy metals in the Netherlands, 1990, and steady state 386
30.2 Human toxicity risk ratios for cadmium, copper, lead and zinc in the Netherlands, 1990, and steady state 387
30.3 Aquatic ecotoxicity risk ratios for cadmium, copper, lead and zinc in the Netherlands, 1990, and steady state 388
30.4 Terrestrial ecotoxicity risk ratios for cadmium, copper, lead and zinc in the Netherlands, 1990, and steady state 388
31.1 Metal abundance in the Earth’s crust and in society 396
32.1 The Sherwood Plot 407
32.2 Flow of industrial hazardous waste in treatment operations 408
32.3 Concentration distribution of copper in industrial hazardous waste streams 409
32.4 Concentration distribution of zinc in industrial hazardous waste streams 410
32.5 Optimal supply network for waste re-use in the Bayport Industrial Complex 414
32.6 Direct chlorination and oxychlorination of ethylene in tandem 415
32.7 Chlorine flows in combined vinyl chloride and isocyanate manufacturing 417
32.8 A summary of chlorine flows in the European chemical industry 419
33.1 Development of cadmium input and soil content, leaching and offtake rates in the conventional arable farming system 425
33.2 Development of copper input and soil content, leaching and offtake rates in the conventional arable farming system 426
34.1 The automotive technology system: a schematic diagram 433
34.2 The life cycle of the motor car, and the processes that occur during that cycle 435
List of figures

34.3 The life cycle of the automotive infrastructure, and the processes that occur during that cycle 436
34.4 The results of the SLCA assessments for each of four cars from different epochs over the five life stages, and the overall assessments 439
34.5 Target plots for the environmental assessments of the four cars 440
34.6 A portion of a conceptual transit network for a transmodal system: a web of tram routes serves the urban core 443
35.1 Information service provider environmental life cycle 448
36.1 Product life cycle 458
37.1 Risk analysis and the extended supply chain 468
40.1 A closed-loop supply chain for cartridge re-use 498
40.2 A closed-loop supply chain for single-use cameras 499
40.3 A closed-loop supply chain for photocopiers 501
40.4 A closed-loop supply chain for cellular telephones 503
41.1 The supply chain with forward and backward flows 511
41.2 Material flow, single recovery 514
41.3 Material flow, multiple recovery cycles 515
41.4 Forward and reverse product flows for HP ink-jet printers 518
43.1 Possible adoption patterns of LCA according to institutionalization theory; positioning of 36 surveyed companies by 1998 535
43.2 Possible life cycle-based management toolkit and communication flows 540
44.1 US municipal solid waste flows, 1995 546
45.1 The climate assessment model meta-IMAGE 2.1 555
45.2 Global anthropogenic CO₂ emissions and CO₂ concentrations for the Baseline-A scenario according to the meta-IMAGE model for the carbon balancing experiments 562
45.3 Global anthropogenic CO₂ emissions and CO₂ concentration pathway from the reference case according to the meta-IMAGE model 563
45.4 The global mean surface temperature increase for the Baseline-A scenario for the model uncertainties in the carbon cycle and climate models, and the combined effect of both 564