Index

A, *see* Arrivals
Abstraction in modelling, 20-22, 217
Accumulated time in system (W), 42
Accuracy of models, 14, 16, *see also* Separable models, robustness
Active customer (memory constrained system), 185
ADEPT (tool for modelling proposed systems), 329-32
Aggregate (hierarchical modelling), 152-58, *see also* Flow equivalent service center
Aggregate performance measures for multiple class models, 62-63
Algorithms
  asymptotic bounds, 79
  balanced system bounds, 93
  disk I/O
    non-RPS, 228
    RPS, 232
    multipathing, 239
  hierarchical decomposition, 161
  mean value analysis
    single class exact, 115
    single class approximate, 118
    multiple class exact, 141
    multiple class approximate, 143
    multiple class mixed exact, 146
  memory constraints
    single class, 188
    multiple class, independent, 193-94
    multiple class, shared, 195-96
  open models
    single class, 111
    multiple class, 137
  priority scheduling, 259
  swapping
    dedicated device, 199
    shared device, 200
  variable overhead, 307
Amdahl (case studies) *see* IBM
  IMS capacity, 106-9
  using modelling software, 360-69
  using RMF, 376-94
Appropriateness of queueing networks, 14
Approximate solution techniques
  for separable models, *see* Mean value analysis, approximate
  for non-separable models, *see* Disk I/O; Memory; Processors
Approximation transformations (modelling software), 356
Arrival instant queue length in separable models, 112, 114, 139-40
Arrival instant theorem for separable models, 114, 140
  and balanced system bounds, 126
Arrival rate (λ), 41
Arrivals (A), 40
Assumptions, testing of, 33-36, *see also* Validation
Assumptions of separable models, *see* Separable models, assumptions
Asymptotic bounds, 72-87, *see also* Bounds on performance
  Algorithm 5.1, 79

B, *see* Busy time
Balanced system bounds, 86-93, *see also* Bounds on performance
  Algorithm 5.2, 93
Balanced systems, utilizations in, 90
Baseline model, *see* Existing systems
Basic observable quantities, 40-42
Batch workload, 58, *see also* Closed models
Benchmarking, 3, 30-31
Block size (I/O), 290-91
Books on performance, 18-19
Bottleneck, 72-73
  effect of removing (example using asymptotic bounds), 82-84
  secondary, 82-83
Bounds on performance (Chapter 5), 70-97
  advantages, 70-71, 94
  asymptotic bounds, 72-87
    Algorithm 5.1, 79
    examples and case studies, 77-87

Bounds on performance (*cont'd.*)
balanced system bounds, 86-93
Algorithm 5.2, 93
and arrival instant theorem, 126
optimistic and pessimistic bounds, 71
Busy time (B), 41

C, *see* Completions; Customer classes
Cached I/O devices, 244-45
CAD/CAM system (performance projection of proposed system), 329-32
Capacity planning, *see* Evolving systems
Capture ratio (measurement), 285
Carrier sense multiple access with collision detection (CSMA-CD), 340
Case studies and examples
Amdahl
IMS capacity, 106-9
using modelling software, 360-69
using RMF, 376-92
asymptotic bounds, 78-87
bottleneck removal (asymptotic bounds), 82-84
CAD/CAM system (proposed), 329-32
capacity planning
Amdahl 470, IMS, 106-9
PDP-10, 132-33
communication network (proposed), 324-27
concurrency control (database), 343-47
CPU replacement, 27-29, 33-36
CTSS, 102-3
Cyber 173, 133-34
database concurrency control, 343-47
disk I/O
non-RPS, 227-29
RPS, 232-33
disk load balancing
asymptotic bounds, 85-87
Univac 1100, 312-13
Ethernet, 339-41
evolving systems, 309-15
FCFS scheduling
class-dependent service times, 263-64
highly variable service times, 266-67
FESC for memory constrained system, 189-90
forced flow law, 48-50
global balance, 163-69
hierarchical modelling, 163-66
hierarchical workload characterization (instructional computing acquisition, Prime, VAX), 30-34, 51-52

Case studies and examples (*cont'd.*)
IBM
early virtual memory system, 206-9
processing complex (workload balancing), 24-27
360, 104-6
3790, 8130, 8140 (insurance company), 35-37, 78-82
IMS (Amdahl 470, capacity planning), 106-9
instructional computing acquisition (Prime, VAX), 30-34, 51-52
insurance company (IBM 3790, 8130, 8140), 35-37, 78-82
Little's law
and forced flow law, 48-50
and memory constrained systems, 49-50, 55-56
at various levels, 44-46
loosely-coupled multiprocessor (Cyber 173), 133-34
memory, 206-17
memory constrained system
FESC, 189-90
Little's law, 49-50
modelling software, use of (Amdahl 470), 360-69
modification analysis, 309-15
asymptotic bounds, 85-87
IBM processing complex, 24-27
IBM 360, 104-6
multiple class models, 129-34
multiple class solution techniques, 137-38, 142, 144-45, 147
multiprogramming level variability, 182-84
MVS
Amdahl 470 (using RMF), 376-92
IBM processing complex, 24-27
SRM, 347-50
non-RPS disks, 227-29
paging, 202-5
PDP-10, 132-33
Prime (instructional computing acquisition), 30-34
priority scheduling, 259-61
proposed systems, 324-27, 329-32
RMF usage (Amdahl 470), 376-92
RPS disks, 232-33
single class models, 102-9
of heterogeneous workloads, 130-31
single class solution techniques, 112-13, 116-17, 119
single service center, 5-8

Case studies and examples (*cont'd.*)
SNA flow control, 336-39
software resources, 342-43
swapping
moving from drum to disk (Univac 1100), 314-15
to a shared device, 200-201
tightly-coupled multiprocessor (Univac 1100), 310-11
Univac 1100, 309-15
upgrade from single to dual processor (Univac 1100), 310-11
variation in multiprogramming level, 182-84
VAX
instructional computing acquisition, 30-34, 51-52
memory modelling, 209-17
virtual memory, 202-5
workload balancing (IBM processing complex), 24-27
Center description, 59
for models of existing systems, 283
from RMF, 385-86
Central subsystem, 45, 58, 185-86
Channel Activity Report (RMF), 379-80
Channel contention (I/O)
non-RPS, 225-30
RPS, 230-33
Channel holding time (I/O), 227
Classes, *see* Customer classes; Customer description
Closed classes in mixed models, 144-48
Closed models, 58, 62, 112-19, 139-45
Communication networks, *see* Computer communication networks
Complementary network (hierarchical modelling), 152-55
Completions (C), 40, 47
Components of modelling software, 354-60
Composite queueing (FESCs), 157
Computational algorithms, *see* Algorithms
Computer communication networks (case studies)
Ethernet, 339-41
projecting performance of proposed system, 324-27
SNA, 336-39
Concurrency control (database) (example), 343-47
Conducting a modelling study (Chapter 2), 20-39
list of specific points, 38-39
Conferences on performance, 17-18
Contention time (I/O), 224
Controller (I/O), 234-35
Core computational routine for separable models, *see* Mean value analysis
evolution, 369-70
in modelling software, 354
CPU, *see* Processors
CPU Activity Report (RMF), 378-79
CPU replacement, parameterization to reflect, 301
case study, 27-29, 33-36
CRYSTAL (tool for modelling proposed systems), 327-28
CSMA-CD, 340
CTSS (case study), 102-3
Customer classes (C), 62
Customer description, 57-58
for models of existing systems, 279-82
from RMF, 383-85
Cyber 173 (case study), 133-34

D, *see* Service demand
DASD, *see* Disk I/O
Database modelling
approaches, 343-47
high-level front ends, 359-60
Decomposition, *see* Flow equivalent service center; Hierarchical modelling
Definition of models, 9-12
Delay service center, 59
Derived observable quantities, 40-42
Device homogeneity, 120, 147
Direct Access Device Activity Report (RMF), 379, 381
Disk I/O (Chapter 10), 222-52, *see also* Algorithms, disk I/O
alternate modelling approaches, 248-49
inferring parameter values from measurement data, 245-47, 249
load balancing
asymptotic bounds example, 85-87
Univac 1100 case study, 312-13
non-RPS example, 227-29
representation using modelling software, 247, 367-68
RPS example, 232-33
service time, components of, 224
Domains, 191-96
in MVS, 378
representation using modelling software, 363
Dynamic reconnection (I/O), 237

Effective disk service time, 224
End effects in measurement, 43-44, 277
Ethernet, 339-41
Evaluation of models, 13-14
  closed and mixed, *see* Mean value analysis
  open, *see* Open models
Event monitor, 276
Evolution of core computational algorithms for separable models, 369-70
Evolving systems (Chapter 13), 296-319, *see also* Parameterization
  case studies and examples
    simple example, 24-27
    using asymptotic bounds, 85-87
    IBM 360, 104-6
    Univac 1100, 309-15
    using modelling software, 365-69
  primary and secondary effects, 296-97
Examples, *see* Case studies and examples
Execution graphs (for workload characterization), 329-30
Existing systems (Chapter 12), 274-95, *see also* Parameterization
  RMF example, 376-94
Experimentation, 3
External arrival homogeneity, 120, 149

FCFS, *see* First-come-first-served
FESC, *see* Flow equivalent service center
File placement
  techniques for modelling, 303-4
  Univac 1100 case study, 312-13
First-come-first-served scheduling, 128
  class-dependent service times, 262-64
  highly variable service times, 263-66
Flow balance assumption, 51-52
Flow control (SNA case study), 336-39
Flow equivalent service center (FESC), 152-75, *see also* Load dependent service center
  and separability, 159-60, 191-92
  and transaction workloads, 157
  applications
    Ethernet, 339-41
    memory constrained system, 185-96
    SNA flow control, 336-39
    tightly-coupled multiprocessor, 254-56
  cost of evaluating a model containing, 157, 159, 191-92
  desired characteristics, 155-58
  evaluating high-level models, 159-60
  obtaining parameters, 158-59
Flow equivalence and hierarchical modelling (Chapter 8), 152-175, *see also* Flow equivalent service center; Hierarchical modelling; Load dependent service center
Forced flow law, 47-50
Front ends for modelling software, 358-60
Fundamental laws (Chapter 3), 40-56
  table of, 53

Global balance, 162-69
  cost, 162-63
  details, 166-69
  to evaluate model of SNA, 336-39
  to model priority scheduling, 163-66
Goal-oriented scheduling, 262

Hardware modifications, *see* Evolving systems
  parameterization to reflect, 300-303
  representation using modelling software, 366-68
Heads of string (I/O), 235-36
Hierarchical modelling, 152-75, *see also* Flow equivalent service center; Hybrid modelling
  Algorithm 8.1, 161
  applications
    Ethernet, 339-41
    memory constrained systems, 185-96
    SNA flow control, 336-39
  detailed example, 163-66
Hierarchical workload characterization, 30-34
Homogeneity assumptions, 120, 147-49
  and memory modelling, 179-80, 191-92
Hybrid modelling, 16, 170-73
  of MVS SRM, 347-49

IBM (case studies), *see* Amdahl
  early virtual memory system, 206-9
  processing complex (workload balancing), 24-27
  360, 104-6
  3790, 8130, 8140 (insurance company), 35-37, 78-82
IMS (Amdahl 470 capacity planning case study), 106-9
Inflation of service demands, *see* Load concealment

Inputs and outputs of models (Chapter 4), 4-14, 49, 57-68, 99-101, *see also* Parameterization
Insight, sources of, 35-37
Installation Performance Specification (IPS) (MVS), 377-78
Instructional computing acquisition (case study, Prime, VAX), 30-34
Insurance company case study (IBM 3790, 8130, 8140), 35-37, 78-82
I/O subsystem, *see* Disk I/O
I/O subsystem modifications, parameterization to reflect, 302-3
IPS (IBM MVS Installation Performance Specification), 377-78
Iterative solution techniques
  for separable models, *see* Mean value analysis, approximate
  for non-separable models, *see* Disk I/O; Memory; Processors

Journals on performance, 17-18

K, *see* Number of centers

Last-come-first-served (LCFS) scheduling, 129
Latency time (I/O), 224
LCFS, 129
Little's law, 40, 42-46
  and flow balance assumption, 51-52
  and forced flow law, 48-50
  and mean value analysis, 112, 139
  and memory constrained systems, 49-50, 55-56
  application at various levels, 44-46
  used to derive asymptotic bounds on performance, 76-77
Load concealment
  in evaluating mixed models, 145
  in modelling shared disks, 243
Load dependent service center (Chapter 20), 120-21, 149, 156-58, 403-8 *see also* Flow equivalent service center
  evaluating models containing, 159-60, 403-8
  MVA algorithms for, 403-8
  use in modelling tightly-coupled multiprocessor, 254-56, 310-11
Load independent service center, 120-21, 149, *see also* Queueing service center
Local area networks, 339-41
Logical I/O operation, 287-91
Loosely-coupled multiprocessor, 237, 242-43, 253
  Cyber 173 case study, 133-34

M, *see* Memory constraint
MAP (queueing network modelling software package), 360-69
Mean value analysis (MVA), 108-19, 134-48, *see also* Algorithms, mean value analysis; Evaluation of models; Open models
  approximate, 117-19, 142-45
  calculating outputs from, 116, 142
  exact, 112-17, 139-42
  implementations, 395-402
  key equations, 112, 139
  load dependent centers, 403-8
  mixed models, 144-48
  population precedence, 115-16, 140-41
  residence time equation, 112, 139
Measurement, 21
  choice of interval, 43-44
  event recording, 276
  sampling, 276
  to parameterize FESCs, 158
  useful data items, 275-79
  using RMF, 376-94
Measurement data, inadequacy of, 34-36
Measurement interval duration (T), 40
Memory (Chapter 9), 179-221, *see also* Memory constraint; Multiprogramming level; Paging
  admission policies, hybrid modelling of, 172-73
  assumptions made in separable models, 179-80
  case studies
    early IBM virtual memory system, 206-9
    VAX/VMS, 209-17
  robustness of separable models, 180
Memory constraint (M), 184-96, *see also* Algorithms, memory constraints
  Little's law used to evaluate, 49-50, 55-56
  representation using modelling software, 363
Memory expansion, parameterization to reflect, 209-17, 301-2
Method of stages (global balance), 268-69

Mixed models, 62, 144-48
  Algorithm 7.4, 146
Modelling, alternatives to, 4
Modelling cycle, 22-27
Modelling methodology, *see* Conducting a modelling study
Modification analysis, 12-13, *see also* Evolving systems
Multipathing I/O, 237-41
  Algorithm 10.3, 239
Multiple class models (Chapter 7), 127-51, *see also* Algorithms
  advantages, 127
  case studies illustrating use, 129-34
  contrast with single class models, 130-31
  disadvantages, 127-28
  examples illustrating evaluation, 137-38, 142, 144-45, 147
  inputs and outputs, 62-64
  scheduling disciplines in, 128-29
Multiprocessor, *see* Loosely-coupled multiprocessor; Tightly-coupled multiprocessor
Multiprogramming level
  non-integer, in mean value analysis, 144
  variability (case study), 181-84
MVS (case studies), *see* SRM
  Amdahl 470 (using modelling software), 360-69
  Amdahl 470 (using RMF), 376-92
  IBM processing complex (workload balancing), 24-27

N, *see* Number in system
Non-integer multiprogramming level in mean value analysis, 144
Non-RPS disks, 225-30, *see also* Disk I/O
  Algorithm 10.1, 228
Non-separable models, *see* Disk I/O; Memory; Processors
  approaches to evaluating, 162, 177-78
  need for, 65-67
Notation, table of, 53
Number in system (N as input, Q as output), 60-61, *see also* Little's law
Number of centers (K), 58, 63

Objectives of modelling study, importance of understanding, 27-30
Observation interval, 43-44
One step behavior, 120, 147
Open classes in mixed models, 144-48
Open models, 58, 62, *see also* Algorithms, open models
  evaluation, 109-13, 134-38
Operating systems
  modelling detailed algorithms, 347-49
  modelling upgrades, 305-6
Operational analysis, xii-xiii, 123, 150
Optimistic bounds on performance, 71
Outputs of models, *see* Inputs and outputs of models
Overhead
  Algorithm 13.1, 307
  attribution of, 285-87
    using RMF, 386, 388-91
  modelling changes in, 306-8
  of paging activity, 202-5

Packages, queueing network modelling, *see* Queueing network modelling software
Paging, 201-5
Parameterization, 12-13, *see also* Evolving Systems; Existing systems; Inputs and outputs of models; Proposed systems
  RMF example, 376-94
  software assistance, 358-60
  types and sources of information, 275-79
Path (I/O), 222-23, 231
Path busy, estimating probability of (I/O), 240-41
Path elements, estimating utilizations of (I/O), 238, 240
Path selection (I/O), 237
PDP-10 (case study), 132-33
Performance database, 279
Performance group (MVS), 377
Performance measures, 22, *see also* Inputs and outputs of models
  from RMF, 388, 391-92
Performance-oriented design, *see* Proposed systems
Performance period (MVS), 377
Performance projection, *see* Evolving systems; Proposed systems
  simple example, 24-27
Pessimistic bounds on performance, 71
Physical I/O operations, 287-91
Population, *see* Number in system; Little's law
Population precedence (MVA), 115-16, 140-41

Primary and secondary effects of modifications, 12-13, 20-21, 248, 296-97
Prime (case study, instructional computing acquisition), 30-34
Priority scheduling, 256-62
  Algorithm 11.1, 259
  representation using modelling software, 362-63
  an approach using global balance, 163-66
Processing capacity, *see* Bounds on performance
  of open models, 109, 134-35
Processor sharing scheduling, 129
Processors (Chapter 11), 253-71, *see also* CPU replacement; Multiprocessor; Scheduling discipline
Program listings
  single class exact MVA, 395-97
  multiple class exact MVA, 398-402
Projecting performance, *see* Evolving systems; Proposed systems
Projection phase (modelling cycle), 22-27
Proposed systems (Chapter 14), 320-34
  case studies, 324-27, 329-32

Q, *see* Number in system; Queue length
Queue length (Q), 60-61, *see also* Little's law
  at channel (I/O), 227
  in open models, 111, 136
Queue length distribution, 62
  for load dependent centers, 405-7
Queueing network modelling software (Chapter 16), 354-73
  approximation transformations, 356
  core computational routine, 354
  example use, 360-69
  high-level front ends, 358-60
  user interface, 356-58
Queueing service center, 59
Queueing theory, 16

R, *see* Residence time; Response time
Ready customer (memory constrained system), 185
Reconnect (I/O), 230
  algorithms, 237
  failure, estimating probability of, 241
Relationships among observed quantities, table of, 54
Remote terminal emulation, 27, *see also* Benchmarking
Residence time (R), 42, 61, *see also* Mean value analysis; Open models; Response time
Residence time equation (MVA), 112, 139, *see also* Mean value analysis
  for load dependent centers, 405-7
  modifications
    for biased processor sharing, 261-62
    for FCFS with class-dependent service times, 262-63
    for FCFS with highly variable service times, 265
    for priority scheduling, 258
Residual service time, 265
Resource Measurement Facility (RMF) (IBM), use of, 376-94
Response time (R), 42, 61, *see also* Mean value analysis; Open models; Residence time
Response time law, 46
  to estimate think times, 282
  to evaluate memory constrained system, 207
Retry (I/O), 230
RMF (IBM Resource Measurement Facility), use of, 376-94
Rotation time (I/O), 230
Rotational position sensing (RPS), 230-33, *see also* Disk I/O
  Algorithm 10.2, 232
Routing homogeneity, 120, 147
RPS, *see* Rotational position sensing

S, *see* Service time per visit
Sampling monitor, 276
Saturated system, 72, 109, 134-35
Scheduling discipline, *see* First-come-first-served; Last-come-first-served; Priority; Processors; Separable models, scheduling disciplines in
Secondary bottleneck, 82-83
Secondary effects of modifications, 12-13, 296-97, 306-9
Seek time (I/O), 224
Sensitivity analysis, 33-36
Separable models, 15
  advantages, 121-22
  arrival instant theorem, 114
  assumptions, 20-22, 62, 147, 149
  inputs and outputs, 57-68
  limitations, 64-66, 121
  robustness, 121, 180, 222-25, 248, 261, 264

Separable models (*cont'd.*)
scheduling disciplines in, 59, 62, 128-29, 253-54
theoretical foundations, 119-21, 147, 149
Service center, 4-8, *see also* Center description
Service center flow balance, 120, 147
Service center types, 59
Service demand (D), 48-49, 59-60
estimation of
for models of existing systems, 283-91
CPU, 285-87
I/O, 287-91
difficulties, 284
using RMF, 386, 388-91
inflation, *see* Load concealment
Service objective (MVS), 377
Service rate (μ) (FESC), 156-58, *see also* Flow equivalent service center; Load dependent service center
Service rate of tightly-coupled multiprocessor, 255-56
Service time per visit (S), 41
Service time homogeneity, 120, 149
Shadow CPU technique (priority scheduling), 258-61
Shared disks, 242-43
Simulation, 15-16
in hybrid modelling, 170-73
to parameterize FESCs, 158
Simultaneous resource possession, 185
Single class models (Chapter 6), 98-126, *see also* Algorithms
advantages, 98, 122, 127-28
case studies illustrating use, 102-9
examples illustrating evaluation, 112-13, 116-17, 119
inaccuracy when workload is heterogeneous, 130-31
inputs and outputs, 57-62
limitations, 98-99
Single server queue, 4-8
SNA (IBM System Network Architecture), 336-39
Software modifications, parameterization to reflect, 303-6
Software resources, 342-43
Software specifications, refinement of (modelling proposed systems), 324-36
Solution of models, *see* Evaluation of models
SRM (IBM MVS System Resources Manager)
description, 377-78
hybrid model of, 346-49
State, *see* Global balance, details of
States of a customer (memory constrained system), 185
Static reconnection (I/O), 237
Stochastic analysis, xii-xiii, 123, 150
Swapping, 196-201
moving from drum to disk (Univac 1100 case study), 314-15
to a dedicated device, 197-99
Algorithm 9.4, 199
to a shared device, 198-201
Algorithm 9.5, 200
System Network Architecture (SNA) (IBM), 336-39
System Resources Manager (IBM MVS) *see* SRM

T, *see* Measurement interval duration
Tape I/O, 290-91, 386, 387, 391
Terminal workload, 58
Think time (Z), 46
estimating, 282, 384
Thrashing, 202-5
Throughput (X), 41, 61
bounds on, 72-73, 76-77
in memory constrained systems, 187-88
in open models, 109, 134-35
versus multiprogramming level, 181-84
Tightly-coupled multiprocessor, 253, 254-56
upgrading from single to dual processor (Univac 1100 case study), 310-11
Tolerances, in validation, 292
Transaction (database), 344-46
Transaction workload, 58, *see also* Open models
calculating utilization, 51-52
Transfer time (I/O), 224
TSO (IBM Time Sharing Option) (case studies), 24-27, 360-69, 376-94

U, *see* Utilization
Unattributed busy time, apportioning, 285-91
Univac 1100 case studies, 309-15
User interface for modelling software, 356-58

Utilization (U), 41, 61
Utilization law, 41-42, 45
  and flow balance assumption, 51-52

V, *see* Visit count
Validation, 22-27, 291-92
Validation phase (modelling cycle), 22-27
Variability in multiprogramming level, 181-84
Variance in service time, 265-66
VAX (case studies)
  instructional computing acquisition, 30-34, 51-52
  memory modelling, 209-17
Verification phase (modelling cycle), 22-27
Virtual memory, 201-5
Visit count (V), 47-50

W, *see* Accumulated time in system
Waiting customer (memory constrained system), 185
Workload Activity Report (RMF), 379-80, 382
Workload balancing (IBM processing complex case study), 24-27
Workload characterization
  hierarchical, 30-33
  in modelling proposed systems, 323-34
  using RMF, 376-94
Workload components
  identification, 279-81
  modifications, parameterization to reflect, 399-400
Workload intensity, 57-58, 62, 63, 100-101
  determining for existing systems, 281-82
  from RMF, 383-85
Workload measures, 22
Workload modifications
  parameterization to reflect, 297-300
  PDP-10 case study, 132-33
  representation using modelling software, 365
Workload representation in single class models, 99-101
Workload types, 57-58
  selecting for models of existing systems, 279-81
  from RMF, 383-85

X, *see* Throughput

Z, *see* Think time

λ, *see* Arrival rate

μ, *see* Service rate