Contents

Pro	eface .	• • • • • • •	•••••••••••••••••••••••••••••••••••••••	VII
Lis	t of Fi	igures	Σ	сШ
Lis	t of Ta	ables .		XV
Lis	t of Sy	ymbols	X	VII
1	An	Outline	of Network Economics	1
2	Fundamentals of Networks			
	2.1	The Ir	nportance of Networks to the Economy	7
		2.1.1	Markets for Network Services	7
		2.1.2	Network Technologies	15
		2.1.3	Construction of Networks	28
		2.1.4	Pricing of Network Services	31
		2.1.5	Solution Methods	36
	2.2	Linear	and Non-linear Programming	37
		2.2.1	Duality in Linear Programming	37
		2.2.2	Convex Analysis	42
		2.2.3	Convex Analysis Applied to Linear Programming	51
			2.2.3.1 Perturbations of the Right Hand Side	51
			2.2.3.2 Feasible Perturbations of the Right Hand Side	53
		2.2.4	Basic Differentiation Rules	54
	2.3	Trans	port Networks	55
		2.3.1	Elementary Features of Transport Networks	55
		2.3.2	Flow Conservation (Kirchhoff's Law)	63
		2.3.3	Undirected Capacitated Networks	65
		2.3.4	Basic Problems for Transport Networks	67
		2.3.5	Decomposition of Transportation Network Planning	70
			2.3.5.1 Sequential Procedure of Travel Forecasting	70

			2.3.5.2 Sequential Decision Process of Travel Demand 74	
	2.4	Summa	ary 76	
3	of Transport Networks: Basics			
	3.1	Prelim	inary Examples	
		3.1.1	Max Flow–Min Cut Theorem	
		3.1.2	The Minimum Cost Problem for a Single Good 84	
			3.1.2.1 One Source and One Sink 84	ł
			3.1.2.2 Many Sources and Many Sinks 89	1
		3.1.3	Multicommodity Flows 93	•
			3.1.3.1 Cost Minimization 93	ŀ
			3.1.3.2 Production Technology 95	j
	3.2	Cost M	<i>M</i> inimal Trip Assignment 98	\$
3.2.1 Production Technology			Production Technology 98	5
			3.2.1.1 Feasible Network Activities	3
			3.2.1.2 Special Features of Data Networks 102	2
			3.2.1.3 Aspects of Trip Assignment 102	2
		3.2.2	Fixed Link Costs per Unit 104	ł
			3.2.2.1 System Optimality 104	ł
			3.2.2.2 User Optimality 107	7
		3.2.3	Capacity Constraints 110)
			3.2.3.1 Fixed Capacities 110)
			3.2.3.2 Other Resource Constraints 120)
			3.2.3.3 Existence of Feasible Solutions 123	3
			3.2.3.4 Revenue Maximization 123	3
		3.2.4	Alternative Mathematical Formulations	5
			3.2.4.1 Ordinary Convex Programs 126	б
			3.2.4.2 Variational Inequalities	7
			3.2.4.3 Algorithmic Remark	2
			3.2.4.4 Nonlinear Complementary Problems	5
		225	3.2.4.5 Fixed Point Problems	5
		3.2.5	Congested Networks	8
			3.2.5.1 System Optimality	8
			3.2.5.2 User Optimality	6
			3.2.5.3 Further Properties of User Optima	9
	2 2	6	3.2.5.4 Routing in Data Networks	3
	5.5	Sum	nary 16	6
4	Uti	lization	of Transport Networks: Extensions	9
	4.1	Stoch	astic Elements of Traffic Assignment	9
	4.1.1 Stochastic Route Choice			9
		4.1.2	Estimates from Trip Tables 17	3
		4.1.3	Estimates from Link Flows 17	7
		4.1.4	Doubly Constrained Models	, 19
4.2 Traffic Assignment with Price Sensitive Demand				5

		4.2.1	Price Dep	endent Demand for Traffic	185	
		4.2.2	Traffic Equilibria 1			
		4.2.3	User Optimality in Terms of a Variational Inequality Problem 1			
		4.2.4	Marginal Cost Pricing 2			
		4.2.5	Non-invertible Demand Functions			
	4.3	Specia	I Issues		215	
		4.3.1	Preliminary Remarks			
		4.3.2	Bilevel Programming 2			
		4.3.3	Multiclass-User Traffic Assignment			
		4.3.4	Dynamic Traffic Assignment			
		4.3.5	Spatial Price Equilibrium			
	4.4	Summ	ary	• • • • • • • • • • • • • • • • • • • •	225	
5	5 Design of Transport Networks				227	
	5.1	Introd	uctory Asp	ects of Network Optimization	227	
		5.1.1	Construct	tion of Networks	227	
		5.1.2	Network	Improvements	232	
		5.1.3	The Max	imum Flow Problem Revisited	235	
		5.1.4	Minimun	n Investment Cost	236	
	5.2	Multic	commodity	Flow Problem	239	
		5.2.1	Feasibility Conditions			
		5.2.2	Minimun	n Investment Cost	242	
			5.2.2.1	A Reference Case	242	
			5.2.2.2	An Application to Telecommunications Networks .	244	
			5.2.2.3	Traffic Diversion	246	
			5.2.2.4	Budget Design Problem	250	
			5.2.2.5	Price Sensitive Demand for Traffic	253	
		5.2.3	Special C	Cases	269	
			5.2.3.1	Hub-and-Spoke Networks	269	
			5.2.3.2	Hierarchic Networks	274	
			5.2.3.3	Data Networks with Queuing	275	
			5.2.3.4	Telephone Networks without Queuing	286	
	5.3	Surviv	vability Mo	odels	295	
		5.3.1	Normal	Operating State	295	
		5.3.2	Failure S	States of the Network	298	
5.3.3 Minimum F		Minimu	m Requirements on Failure States	299		
			5.3.3.1	Diversification	299	
			5.3.3.2	Reservation	300	
			5.3.3.3	Path Restoration	. 302	
	5.4	5.4 Summary				

6	Sync	hroniz	ation of N	letwork Processes	305	
•	6.1	Schedu	uling Disc	rete Event Dynamic Systems	305	
	0.1	6.1.1	Resource	e Utilization of Simultaneous Processes	305	
		6.1.2	Real Wo	rld Applications	307	
		6.1.3	Auxiliar	y Transportation Problems	310	
	6.2	Max-F	lus Algeb)ra	313	
	0	6.2.1	Basic Or	perations	313	
		6.2.2	Discrete	Event Dynamic Systems	316	
			6.2.2.1	Timetables without Delays	. 316	
			6.2.2.2	Average Interdeparture Time	. 318	
			6.2.2.3	Critical Cycles	. 320	
			6.2.2.4	Periodically Reiterated Timetables	. 324	
			6.2.2.5	Synchronization	. 326	
			6.2.2.6	Stability and Sensitivity	. 329	
	6.3	Solvir	ng the Rai	Iway Example by MATHEMATICA	. 331	
	6.4	Econo	omic Theo	bry of Synchronization	. 334	
		6.4.1	Product	ion Technology	. 334	
			6.4.1.1	Output Measurement	. 334	
			6.4.1.2	Time Limits	. 337	
		6.4.2	Assessn	nent of Synchronized Timetables	. 340	
			6.4.2.1	Passenger Waiting Times	. 340	
			6.4.2.2	Instruments of the Carrier	. 341	
		6.4.3	Cost Me	easurement	. 345	
			6.4.3.1	A Retrospect of Network Cost Evaluation	. 345	
			6.4.3.2	Prospective Approaches of Measuring Transport		
				Costs	. 349	
			6.4.3.3	The Railway Example Revisited	. 354	
	6.5	Sumr	nary		. 358	
7	Critical Review					
	7.1	7.1 Synopsis of Network Economics				
	7.2	Closi	ng Comm	ents	. 366	
Re	eferen	ices			. 369	
In	dov					
111	ucx .	• • • • • •	• • • • • • • • •		386	