

## Parameters

$\eta$	boiler efficiency [kJ/kg]
cc	calorific value of the fuel
a	consumption parameter for HP generation
b	fixed consumption constant for HP generation
$s_{SO_x}$	SO <sub>x</sub> emission parameter [Nm <sup>3</sup> /ton of fuel]
$s_{GHG}$	GHG emission parameter [kg/ton of fuel]
c	cost of unit amount of fuel [\$/ton]
e	coefficient of Electricity generation vs. HP steam input
g	coefficient of Electricity generation vs. MP-LP steam and condensate generation
cpt	storage capacity of a fuel tank [ton]
ssf	safety stock parameter (defined as a fraction of cpt)
$p^L, p^U$	lower and upper limits on fuel purchase [ton/order]
cpo	fixed cost of purchasing fuel [\$/order]
h	unit holding cost of fuel [\$/ton of fuel]
d	demand of a certain product [kWh/hr or ton/hr]
n	length of a period [hours]
$s_{SO_x}^U$	upper limit on SO <sub>x</sub> emission [Nm <sup>3</sup> /yr]
$s_{GHG}^U$	upper limit on GHG emission [kg/yr]
$\beta$	cost coefficient the exchange investment
$\alpha$	constant of the fixed cost of exchange investment [\$/]
ce	price of unit Electricity [\$/ kWh]
$cr_{SO_x}$	penalty cost of SO <sub>x</sub> release [\$/Nm <sup>3</sup> ]

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Table 1. Operating characteristics for the energy system in the 2-company problem.

	Company 1		Company 2	
	Fuel 1	Fuel 2	Fuel 1	Fuel 2
$cc_k$	10.50	9.65	6.65	10.20
$I_{ijkt0}$	100	40	120	100
$cpt$	120	50	130	110
$s_{SOxk}$	7.80	1.42	1.20	5.13
$s_{GHGk}$	17	5	3	10
$c_k$	200	76	83	145
	Boiler 1	Boiler 2	Boiler 1	Boiler 2
$\eta_{ijk_{fuel1}}$	0.590	0.575	0.560	0.565
$\eta_{ijk_{fuel2}}$	0.600	0.595	0.605	0.600
$a_{ijk_{MP}}$	0.11	0.12	0.11	0.12
$a_{ijk_{EL}}$	0.002	0.003	0.0025	0.0028
$X_{ijk_{HP}^u}^{gen}$	550	550	600	600
$b_{ijk_{HP}}$	0.001	0.001	0.001	0.001
$b_{ijk_{EL}}$	0.001	0.001	0.001	0.001
	Turbine 1	Turbine 2	Turbine 1	Turbine 2
$e_{ijk_{HP}}$	0.150	0.175	0.160	0.170
$e_{ijk_{MP}}$	0.070	0.080	0.070	0.075
$e_{ijk_{LP}}$	0.009	0.010	0.012	0.010
$X_{ijk_{EL}^u}^{gen}$	70	60	70	65
$X_{ijk_{HP}^u}^{in}$	900	900	900	900
$X_{ijk_{MP}^u}^{gen}$	300	300	400	400
$X_{ijk_{LP}^u}^{gen}$	70	60	70	65
	HP	MP	LP	
$\alpha_{ij}$	0.39	0.35	0.15	
$\beta_{ij}$	0.11	0.10	0.04	

Table 2. Energy demand in the 2-company problem.

Company 1	Period 1	Period 2	Period 3
Electricity	150	200	180
HP Steam	10	13	8
MP Steam	620	423	510
LP Steam	300	260	350
Company 2	Period 1	Period 2	Period 3
Electricity	140	180	160
HP Steam	10	15	12
MP Steam	300	345	385
LP Steam	680	500	570

Table 3. Model and solution statistics for the 2-company problem.

	Nonintegrated	Integrated
Number of constraints	627	627
Number of variables	665	665
Number of nodes in the branch and bound tree	0	0
Number of iterations	100	162
CPU time (*sec)	0.070	0.070

\* On a PC with Pentium 4 2.6 GHz Processor and 512 MB memory.

Table 4. Summary of the results for the non-integrated solution in the 2-company problem.

Company	Unit	Company	Unit	Period	Value
Company1	HP	Company1	MP	1	140.57
Company1	HP	Company1	MP	3	22.11
Company2	HP	Company2	MP	1	0.54
Company2	MP	Company2	LP	1	150.34
CompanyU	Electricity	Company1	Electricity	1	53.20
CompanyU	Electricity	Company1	Electricity	2	115.11
CompanyU	Electricity	Company1	Electricity	3	75.94
CompanyU	Electricity	Company2	Electricity	1	7.98
CompanyU	Electricity	Company2	Electricity	2	63.03
CompanyU	Electricity	Company2	Electricity	3	28.10

Table 5. Summary of the results for the integrated solution in the 2-company problem.

Company	Unit	Company	Unit	Period	Value
Company1	LP	Company2	LP	1	89.22
Company1	LP	Company2	LP	3	89.22
Company2	HP	Company2	MP	3	9.41
Company2	MP	Company1	MP	1	151.98
Company2	MP	Company1	MP	2	151.98
Company2	MP	Company1	MP	3	151.98
Company2	MP	Company2	LP	1	165.05
CompanyU	Electricity	Company1	Electricity	1	42.00
CompanyU	Electricity	Company1	Electricity	2	128.41
CompanyU	Electricity	Company1	Electricity	3	74.22
CompanyU	Electricity	Company2	Electricity	1	8.15
CompanyU	Electricity	Company2	Electricity	2	48.04
CompanyU	Electricity	Company2	Electricity	3	28.08

Table 6. Comparison of the results for the 2-company problem.

	Non-Integrated	Integrated	Improvement (%)
Total Cost	49,019.23	47,488.84	3.12
SO <sub>x</sub> Release	2,619,268.07	2,346,686.04	10.40
GHG Release	6,534,323.61	5,939,689.22	9.10

Table 7. Operating characteristics for the energy system in the 3-company problem.

	Company 1		Company 2		Company 2	
	Fuel 1	Fuel 2	Fuel 1	Fuel 2	Fuel 1	Fuel 2
$cc_k$	10.50	9.65	6.65	10.20	11.00	12.00
$I_{ijkt0}$	100	40	120	100	120	100
$cpt$	120	50	130	110	130	110
$s_{SOxk}$	7.80	1.42	1.20	5.13	4.83	2.62
$s_{GHGk}$	17	5	3	10	11	8
$c_k$	200	76	83	145	94	102
	Boiler 1	Boiler 2	Boiler 1	Boiler 2	Boiler 1	Boiler 2
$\eta_{ijk_{fuel1}}$	0.590	0.575	0.560	0.565	0.580	0.595
$\eta_{ijk_{fuel2}}$	0.600	0.595	0.605	0.600	0.570	0.605
$a_{ijk_{MP}}$	0.11	0.12	0.11	0.12	0.1150	0.1210
$a_{ijk_{EL}}$	0.002	0.003	0.0025	0.0028	0.0026	0.0029
$X_{ijk_{HP}^u}^{l_{gen}}$	550	550	600	600	600	600
$b_{ijk_{HP}}$	0.001	0.001	0.001	0.001	0.001	0.001
$b_{ijk_{EL}}$	0.001	0.001	0.001	0.001	0.001	0.001
	Turbine 1	Turbine 2	Turbine 1	Turbine 2	Turbine 1	Turbine 2
$e_{ijk_{HP}}$	0.150	0.175	0.160	0.170	0.160	0.170
$e_{ijk_{MP}}$	0.070	0.080	0.070	0.075	0.070	0.075
$e_{ijk_{LP}}$	0.009	0.010	0.012	0.010	0.012	0.010
$X_{ijk_{EL}^u}^{l_{gen}}$	70	60	70	65	70	65
$X_{ijk_{HP}^u}^{l_{in}}$	900	900	900	900	900	900
$X_{ijk_{MP}^u}^{l_{gen}}$	300	300	400	400	400	400
$X_{ijk_{LP}^u}^{l_{gen}}$	70	60	70	65	70	65
	HP	MP	LP			
$\alpha_{jj'}$	0.39	0.35	0.15			
$\beta_{jj'}$	0.11	0.10	0.04			

Table 8. Energy demand in the 3-company problem.

Company 1	Period 1	Period 2	Period 3
Electricity	150	200	180
HP Steam	10	13	8
MP Steam	620	423	510
LP Steam	300	260	350
Company 2	Period 1	Period 2	Period 3
Electricity	140	180	160
HP Steam	10	15	12
MP Steam	300	345	385
LP Steam	680	500	570
Company 3	Period 1	Period 2	Period 3
Electricity	150	170	170
HP Steam	11	14	13
MP Steam	320	350	440
LP Steam	300	340	450

Table 9. Model and solution statistics for the 3-company problem.

	Non-Integrated	Integrated
Number of constraints	993	993
Number of variables	1,042	1,042
Number of nodes in the branch and tree	0	0
Number of iterations	166	371
CPU time (*sec)	0.080	0.080

\* On a PC with Pentium 4 2.6 GHz Processor and 512 MB memory.

Table 10. Summary of the results for the non-integrated solution in the 3-company problem.

Company	Unit	Company	Unit	Period	Value
Company1	HP	Company1	MP	1	140.57
Company1	HP	Company1	MP	3	22.11
Company2	MP	Company2	LP	1	150.23
CompanyU	Electricity	Company1	Electricity	1	53.20
CompanyU	Electricity	Company1	Electricity	2	115.11
CompanyU	Electricity	Company1	Electricity	3	75.94
CompanyU	Electricity	Company2	Electricity	1	7.96
CompanyU	Electricity	Company2	Electricity	2	63.03
CompanyU	Electricity	Company2	Electricity	3	28.1
CompanyU	Electricity	Company3	Electricity	1	66.73
CompanyU	Electricity	Company3	Electricity	2	77.44
CompanyU	Electricity	Company3	Electricity	3	51.25

Table 11. Summary of the results for the integrated solution in the 3-company problem.

Company	Unit	Company	Unit	Period	Value
Company2	HP	Company1	HP	1	126.82
Company2	HP	Company1	HP	2	126.82
Company2	HP	Company1	HP	3	101.38
Company2	MP	Company2	LP	1	25.18
Company2	LP	Company1	LP	2	75.18
Company3	HP	Company3	MP	1	25.58
Company3	MP	Company1	MP	1	278.00
Company3	MP	Company1	MP	2	278.00
Company3	MP	Company1	MP	3	149.02
Company3	MP	Company3	LP	3	41.44
Company3	LP	Company1	LP	1	94.57
Company3	LP	Company1	LP	2	76.40
Company3	LP	Company2	LP	1	54.82
Company3	LP	Company2	LP	3	6.38
CompanyU	Electricity	Company1	Electricity	1	81.28
CompanyU	Electricity	Company1	Electricity	2	166.99
CompanyU	Electricity	Company1	Electricity	3	87.97
CompanyU	Electricity	Company2	Electricity	1	8.18
CompanyU	Electricity	Company2	Electricity	2	50.07
CompanyU	Electricity	Company2	Electricity	3	28.18
CompanyU	Electricity	Company3	Electricity	1	18.30
CompanyU	Electricity	Company3	Electricity	2	38.30
CompanyU	Electricity	Company3	Electricity	3	38.30

Table 12. Comparison of the results for the 3-company problem.

	Non-Integrated	Integrated	Improvement (%)
Total Cost	73,773.87	71,953.60	2.47
SO <sub>x</sub> Release	4,100,000.00	3,527,231.44	13.97
GHG Release	10,435,585.95	9,434,073.34	9.60