SUPPLEMENTARY MATERIAL FOR:

Subramanian, R., B. Talbot, and S. Gupta. 2010. An approach to integrating environmental considerations within managerial decision-making. *Journal of Industrial Ecology*.

Summary

This supplementary material contains the Appendices that include the data and figures of results for the numerical illustrations in the section of the paper titled “Model Solution: Illustration.” Specifically, Table D1 in Supplementary Appendix D summarizes the base data used for the illustrations. Supplementary Appendix E provides an overview of the characteristics of products 1 and 2 assumed in the base data. Results in the form of graphs are included in Supplementary Appendix F. The graphs are annotated with corresponding variations of the base data. Supplementary Appendix G includes brief descriptions of AMPL (mathematical programming language) and MINOS (non-linear solver), which we used to solve the model.

Appendix D: Data for Illustration

Table D1: Base Data

Parameter	**Symbol**	**Value**[†]
Number of Products	(Index i)	2, Labeled as {Product 1, Product 2}
Number of Periods	(Index t)	10
Demand Function Parameters for New Product 1	a_{1tn}, b_{1tn}, b_{1tnr}, b^C_{1tn}, b_{1tnq}, b^C_{1tnq}	750, 0.02, 0.005, 0.005, 175, 100
Demand Function Parameters for New Product 2	a_{2tn}, b_{2tn}, b_{2tnr}, b^C_{2tn}, b_{2tnq}, b^C_{2tnq}	500, 0.01, 0.0025, 0.0025, 175, 100
Demand Function Parameters for Remanufactured Product 1[‡]	a_{1tr}, b_{1tr}, b_{1trn}, b^C_{1tr}, b_{1trq}, b^C_{1trq}	500, 0.05, 0.01, 0.005, 100, 75
Demand Function Parameters for Remanufactured Product 2[‡]	a_{2tr}, b_{2tr}, b_{2trn}, b^C_{2tr}, b_{2trq}, b^C_{2trq}	400, 0.075, 0.025, 0.01, 125, 100
Discount Factor	α	0.95
Variable Cost of Collecting Cores of Product 1	$\tilde{c}_{1tc}$	100
Variable Cost of Collecting Cores of Product 2	$\tilde{c}_{2tc}$	100
Coefficients in Variable Cost of Manufacturing New Product 1	$\tilde{c}_{1tn0}, \tilde{c}_{1tn}$	100, 0.1
Coefficients in Variable Cost of Manufacturing New Product 2	$\tilde{c}_{2tn0}, \tilde{c}_{2tn}$	150, 0.2
Coefficients in Variable Cost of Remanufacturing Product 1	$\tilde{c}_{1tr0}, \tilde{c}_{1tr}$	50, 500
Coefficients in Variable Cost of Remanufacturing Product 2	$\tilde{c}_{2tr0}, \tilde{c}_{2tr}$	75, 600
Emissions attributable to a Unit of New Product 1	e_{1n}	20
Emissions attributable to a Unit of New Product 2	e_{2n}	24
Emissions attributable to a Unit of Remanufactured Product 1	e_{1r}	5
Emissions attributable to a Unit of Remanufactured Product 2	e_{2r}	6
Number of Allowances Available for Purchase	η_t	15000
Fixed Cost of Collecting Cores of Product 1	f_{1tc}	1000
Fixed Cost of Collecting Cores of Product 2	f_{2tc}	1000
Fixed Cost of Manufacturing New Product 1	f_{1tn}	2000

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Table D1: Base Data (continued from previous page)

Parameter	**Symbol**	**Value**†
Fixed Cost of Manufacturing New Product 2	f_{2tn}	2500
Fixed Cost of Remanufacturing Product 1	f_{1tr}	250
Fixed Cost of Remanufacturing Product 2	f_{2tr}	300
Unit Inventory Holding Cost of Cores of Product 1	h_{1tc}	50
Unit Inventory Holding Cost of Cores of Product 2	h_{2tc}	50
Unit Inventory Holding Cost of New Product 1	h_{1tn}	150
Unit Inventory Holding Cost of New Product 2	h_{2tn}	200
Unit Inventory Holding Cost of Remanufactured Product 1	h_{1tr}	75
Unit Inventory Holding Cost of Remanufactured Product 2	h_{2tr}	100
Assembly Capacity consumed per Unit of New Product 1	k_{a1n}	20
Assembly Capacity consumed per Unit of New Product 2	k_{a2n}	30
Assembly Capacity consumed per Unit of Remanufactured Product 1	k_{a1r}	4
Assembly Capacity consumed per Unit of Remanufactured Product 2	k_{a2r}	6
Machining Capacity consumed per Unit of New Product 1	k_{m1n}	30
Machining Capacity consumed per Unit of New Product 2	k_{m2n}	40
Machining Capacity consumed per Unit of Remanufactured Product 1	k_{m1r}	15
Machining Capacity consumed per Unit of Remanufactured Product 2	k_{m2r}	20
Available Assembly Capacity	K_{at}	15000
Machining Capacity available for Manufacturing	K_{mtn}	10000
Machining Capacity available for Remanufacturing	K_{mtr}	10000
Emissions Limit	l_t	5000
Sensitivity of Core Returns to Core Credit for Product 1	λ_{1t}	0.0025
Sensitivity of Core Returns to Core Credit for Product 2	λ_{2t}	0.005

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Table D1: Base Data (continued from previous page)

Parameter	**Symbol**	**Value**†
Price of Competitor's Product 1	P_{1t}^C	10000
Price of Competitor's Product 2	P_{2t}^C	15000
Unit Market Price of Allowances	ϕ_t	500
Performance Standard for Product 1	$Q_{1,\text{std}}$	2
Performance Standard for Product 2	$Q_{2,\text{std}}$	3
Performance of Competitor's Product 1	Q_{10}^C	2
Performance of Competitor's Product 2	Q_{20}^C	3
Unit Cost of Disposing of Cores of Product 1	ρ_{1t}	500
Unit Cost of Disposing of Cores of Product 2	ρ_{2t}	500
Economic Life of Product 1	τ_1	2
Economic Life of Product 2	τ_2	2
Inherent Level of Remanufacturability of Product 1	Θ_{1B}	0
Inherent Level of Remanufacturability of Product 2	Θ_{2B}	0
Unit Cost of Backordering New Product 1	u_{1tn}	2500
Unit Cost of Backordering New Product 2	u_{2tn}	3000
Unit Cost of Backordering Remanufactured Product 1	u_{1tr}	250
Unit Cost of Backordering Remanufactured Product 2	u_{2tr}	400
Design Cost Coefficient of Performance for Product 1	ξ_{11}	2000
Design Cost Coefficient of Performance for Product 2	ξ_{12}	2500
Design Cost Coefficient of Remanufacturability for Product 1	ξ_{21}	1500
Design Cost Coefficient of Remanufacturability for Product 2	ξ_{22}	2000

†Where applicable, tabulated values are to be interpreted as values in each time period; ‡Cores become first available for remanufacture in the τ_i^{th} period.

Appendix E: Product Features Assumed in Base Data

Following is a brief overview of the characteristics of products 1 and 2 assumed in the base data:

- Product 2 is more "complex" and requires more manufacturing and remanufacturing capacity per unit than product 1.
- Fixed and variable costs of manufacturing and remanufacturing are respectively higher for product 2 than for product 1. Also, holding and backordering costs are higher for product 2.
- Overall, customers of product 2 are less price sensitive and more quality conscious than customers of product 1. Customers of product 1 are less sensitive to the credit offered to induce core returns.
- The market sizes for both new and remanufactured product 1 are respectively larger than those for product 2.
- Emissions attributable to manufacturing and remanufacturing are respectively higher for product 2 than for product 1.
- The performance standard is higher for product 2.

Appendix F: Illustrative Results

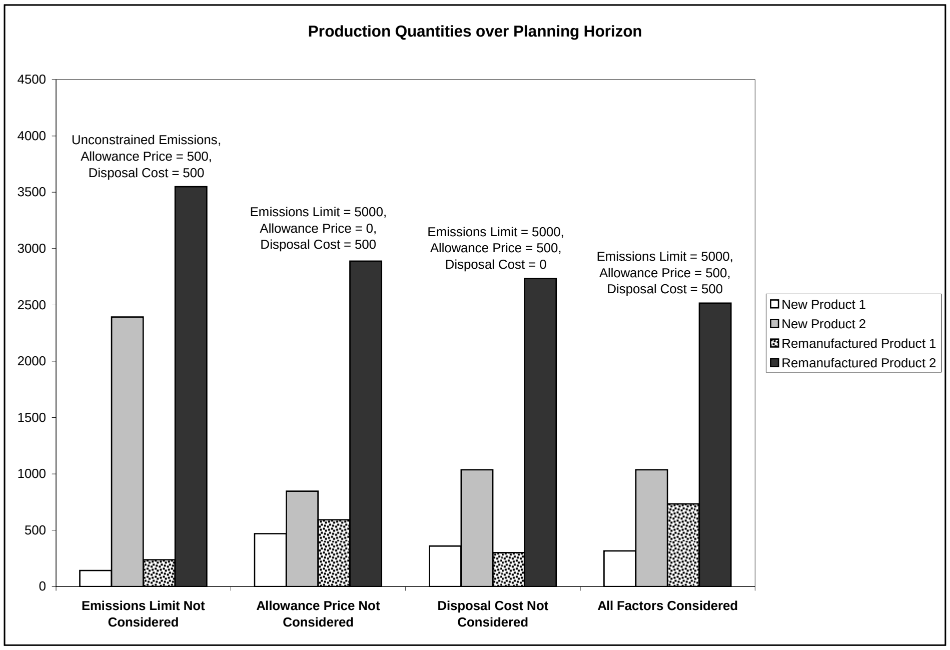

Figure F1: Impact of Environmental Factors on Product Mix Decision (1)
(Plotted Values = $\sum_{t=1}^{10} X_{1t}, \sum_{t=1}^{10} X_{2t}, \sum_{t=1}^{10} Y_{1t}, \sum_{t=1}^{10} Y_{2t}$)

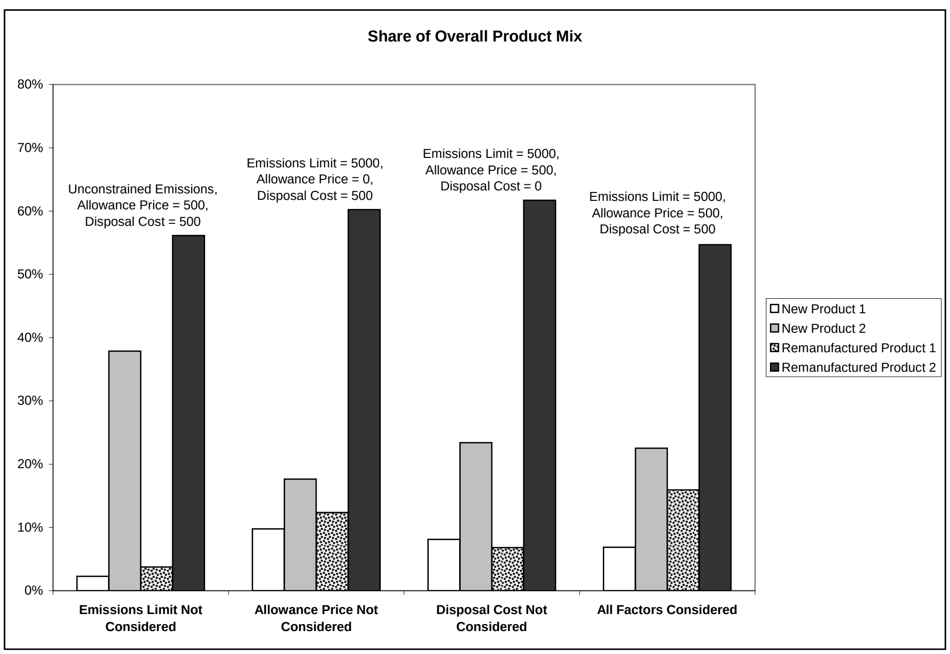

Figure F2: Impact of Environmental Factors on Product Mix Decision (2)
(Plotted Values = $\frac{\sum_{t=1}^{10} X_{1t}}{\sum_{i=1}^{2}\sum_{t=1}^{10}(X_{it}+Y_{it})}, \frac{\sum_{t=1}^{10} X_{2t}}{\sum_{i=1}^{2}\sum_{t=1}^{10}(X_{it}+Y_{it})}, \frac{\sum_{t=1}^{10} Y_{1t}}{\sum_{i=1}^{2}\sum_{t=1}^{10}(X_{it}+Y_{it})}, \frac{\sum_{t=1}^{10} Y_{2t}}{\sum_{i=1}^{2}\sum_{t=1}^{10}(X_{it}+Y_{it})}$)

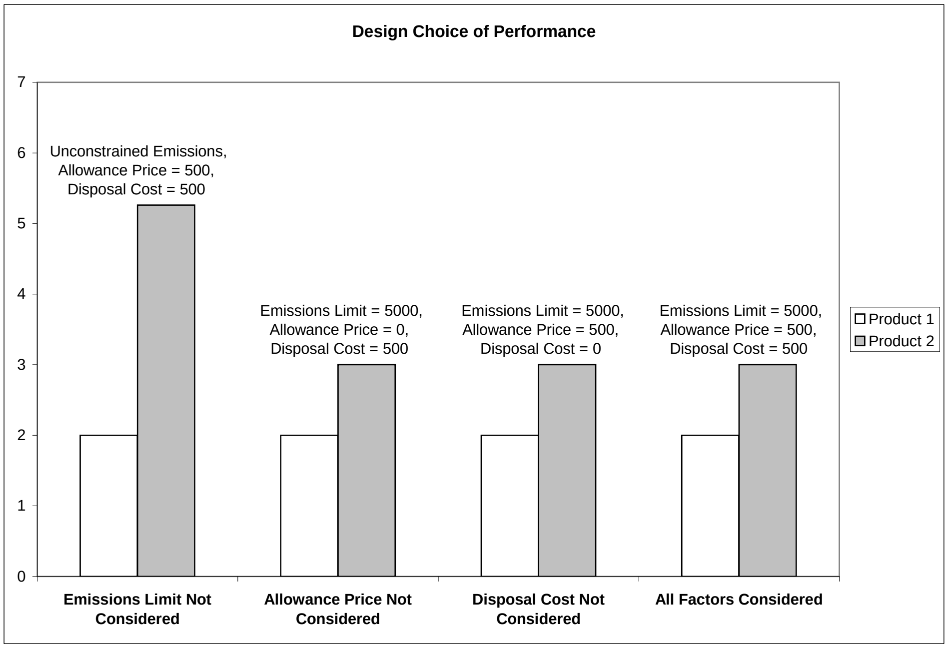

Figure F3: Impact of Environmental Factors on Design Choice of Performance (Plotted Values = Q_{10}, Q_{20})

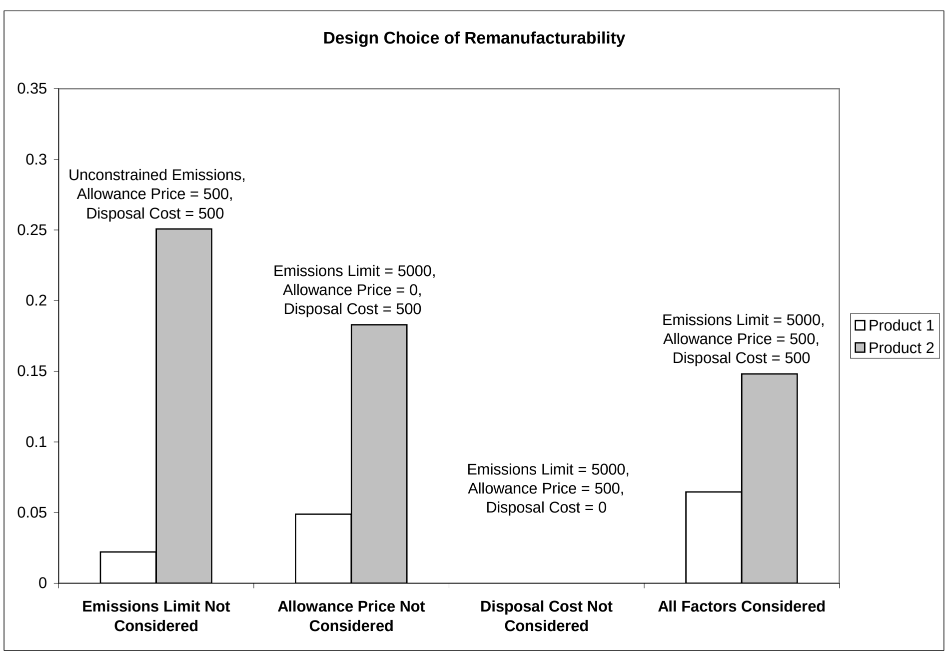

Figure F4: Impact of Environmental Factors on Design Choice of Remanufacturability (Plotted Values = Θ_{10}, Θ_{20})

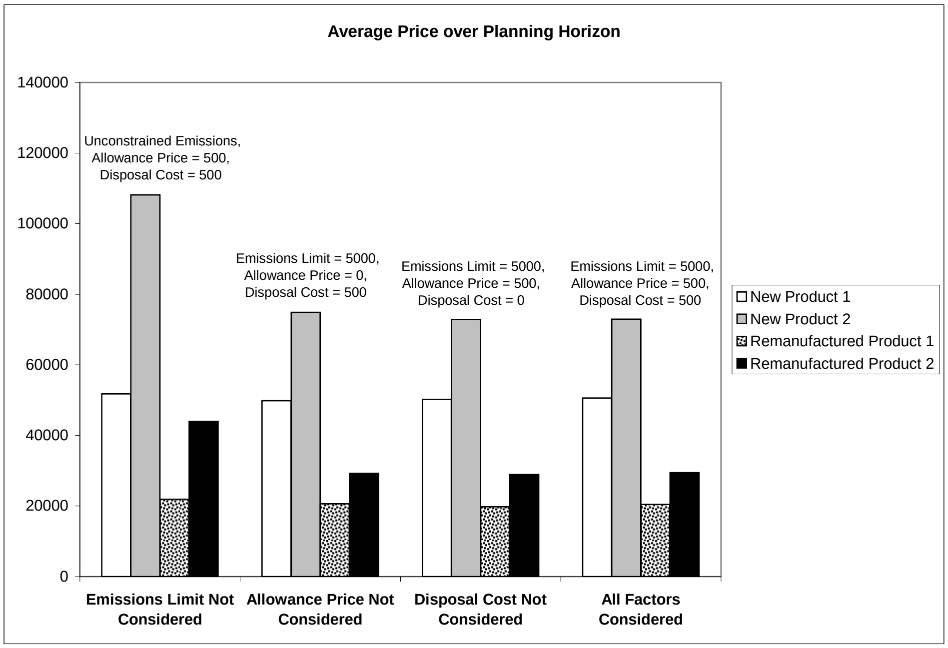

Figure F5: Impact of Environmental Factors on Pricing Decision (Plotted Values = $\frac{1}{10}\sum_{t=1}^{10} P_{1tn}$, $\frac{1}{10}\sum_{t=1}^{10} P_{2tn}$, $\frac{1}{10}\sum_{t=1}^{10} P_{1tr}$, $\frac{1}{10}\sum_{t=1}^{10} P_{2tr}$)

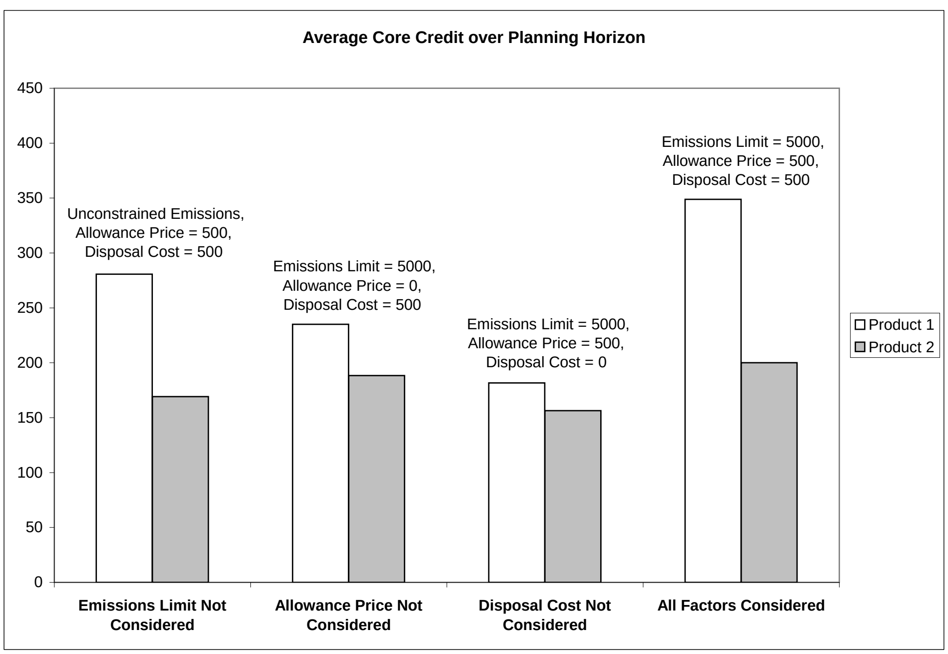

Figure F6: Impact of Environmental Factors on Core Credit Decision (Plotted Values = $\frac{1}{10}\sum_{t=1}^{10} \Psi_{1t}$, $\frac{1}{10}\sum_{t=1}^{10} \Psi_{2t}$)

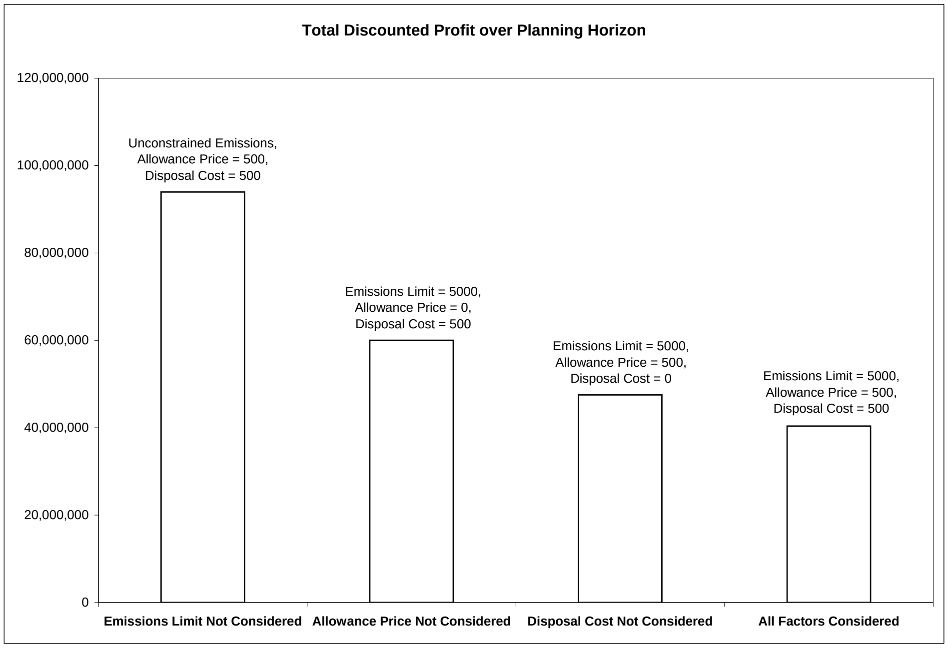

Figure F7: Impact of Environmental Factors on Profit

Appendix G: AMPL and MINOS

AMPL is an algebraic modeling language for mathematical programming initially developed at Bell Laboratories in 1985. Expressions and notations (including subscripting) in AMPL are similar to customary algebraic notation. AMPL's interface enables the user to switch among solvers and select options that might improve solver performance. The mathematical programming formulation is written as a *model* file and the data for the problem is provided through a separate *data* file. AMPL commands instruct the data to be read from the data file and the model to be solved using the selected solver (*paraphrased from Fourer et al. 2003*).

We use the MINOS solver to solve our non-linear programming problem. For mathematical programs that are non-linear in the objective but linear in the constraints, MINOS employs a reduced gradient approach. In addition to the basic variables, the algorithm maintains a subset of superbasic variables that may vary within their bounds. Iterations attempt to improve the objective within the subspace of basic and superbasic variables, through a quasi-Newton algorithm (adapted from unconstrained non-linear optimization) that selects a search direction and step length. When no further progress can be made with the current set of basic and superbasic variables, a new superbasic variable is chosen from among the non-basic ones. To deal with non-linear constraints, MINOS further generalizes its algorithm by means of a projected Lagrangian approach. At each major iteration, a linear approximation to the non-linear constraints is constructed around the current solution, and the objective is modified by adding two terms - the Lagrangian and a penalty term - which compensate for the inaccuracy of the linear approximation. The resulting subproblem is then solved by a series of minor iterations of the reduced gradient algorithm. The optimum of this subproblem becomes the current solution for the next major iteration (*paraphrased from Murtagh & Saunders 1998*).

References

Fourer, R., D. M. Gay, B. W. Kernighan. 2003. *AMPL: A Modeling Language for Mathematical Programming*. Brooks/Cole-Thomson Learning, California.

Murtagh, B. A., M. A. Saunders. Revised July 1998. *MINOS 5.5 User's Guide*. Department of Operations Research, Stanford University, California. Report SOL 83-20R.