

| | |
|--|----|
| CHAPTER XI: MULTI-OBJECTIVE PROGRAMMING..... | 2 |
| 11.1 Formulations | 3 |
| 11.1.1 Lexicographic Utility - Target Values | 4 |
| 11.1.2 Utility Tradeoff Model..... | 6 |
| 11.1.3 Unknown Utility Function..... | 7 |
| 11.2 Examples | 8 |
| 11.2.1 Lexicographic Formulation | 8 |
| 11.2.2 Weighted Tradeoff - No Targets | 9 |
| 11.2.3 Weighted Objective and Targets | 10 |
| 11.3 Choice Among Formulations | 10 |
| 11.4 Developing Utility Functions | 11 |
| 11.5 Shadow Prices | 13 |
| 11.5.1 Example..... | 14 |
| References..... | 16 |

CHAPTER XI: MULTI-OBJECTIVE PROGRAMMING

Optimization of a single objective oversimplifies the pertinent objective function in some potential mathematical programming application situations. Arguments can also be made following Simon that optimization is not as appropriate as satisficing. These two statements introduce the general topic of multiobjective programming. Multiobjective programming formally permits formulations where: a) solutions are generated which are as consistent as possible with target levels of goals; b) solutions are identified which represent maximum utility across multiple objectives; or c) solution sets are developed which contain all nondominated solutions. Multiple objectives can involve such considerations as leisure, decreasing marginal utility of income, risk avoidance, preferences for hired labor, and satisfaction of desirable, but not obligatory, constraints.

A discussion of this area requires some definitions. An objective is a measure that one is concerned about when making a choice among the decision variables (something to be maximized, minimized or satisfied like leisure, risk, profits, etc.). A goal implies that a particular goal target value has been chosen for an objective.

We will use "multiple objective programming" to refer to any mathematical program involving more than one objective regardless of whether there are goal target levels involved. Note, the literature contains conflicting definitions (see Blake and McCarl; Ignizio [1978,1983]; Romero [1989, 1991]). For example: a) goal programming has been used to refer to multiple objective problems with target levels; b) multiobjective programming has been used to refer to only the class of problems with weighted or unweighted multiple objectives; c) vector maximization has been used to refer to problems in which a vector of multiple objectives are to be optimized; and d) risk programming has been used to refer to multiobjective problems in which the objectives involve income and risk.

Multiobjective programming involves recognition that the decision maker is responding to multiple objectives. Generally, objectives are conflicting, so that not all objectives can simultaneously arrive at their optimal levels. An assumed utility function is used to choose appropriate solutions. Several fundamentally different utility function forms have been used in multiobjective models. These may be divided into three classes: lexicographic, multi-attribute utility and unknown utility.

The lexicographic utility function specification assumes the decision maker has a strictly ordered preemptive preference system among objectives with fixed target levels. For example, a lexicographic system could have its first priority goal as income of not less than \$10,000; the second priority as leisure of no less than 20 hours a week; the third as income of no less than \$12,000, etc. This formulation is typical of "goal programming models." (Charnes and Cooper (1961); Lee). The various goals are dealt with in strict sequential order - higher goals before lower order goals. Once a goal has been dealt with (meeting or failing to meet the target level), its satisfaction remains fixed and the next lower order goal is considered. Consideration of the lower level goals does not alter the satisfaction of higher level goals and cannot damage the higher level goals with respect to target level attainment.

Multi-attribute utility approaches allow tradeoffs between objectives in the attainment of maximum utility. The most common form involves maximization of the sum of linearly weighted objectives. This type of formulation has been used by Candler and Boeljhe; and Barnett, Blake and McCarl.

The third utility approach involves an unknown utility function assumption. Here the entire Pareto efficient (nondominated) solution set is generated so that every solution is reported wherein one of the multiple objectives is as satisfied as it possibly can be without making some other objective worse off (Steuer, Geoffrion (1968)).

11.1 Formulations

All of the above utility functions can be expressed in terms of the following problem. Assume there are multiple objectives which are given by

$$GX$$

where there are J decision variables (X) and R objectives. Thus, the matrix G is of dimension R by J while X is J by 1.

These objectives can also be expressed in summation notation as

$$\sum_j g_{rj} X_j \text{ for all } r$$

When target levels are added, the objectives become

$$GX \leq T$$

The general goal programming problem, then, is as follows:

Select X so that we

$$\begin{array}{ll} \text{optimize or achieve} & GX \\ \text{s.t.} & AX \leq b \\ \text{Possibly subject to} & GX \geq T \\ & X \geq 0 \end{array}$$

Here the normal LP objective function is replaced by a more general function which permits use of different utility function forms (it is difficult to write the Pareto utility function in this form). The problem involves selection of the X's. The selection is driven by either optimization of some weighted tradeoff of objectives or through lexicographic achievement of various goal target levels. The specific formulations used for each of the above utility function specifications are given below.

11.1.1 Lexicographic Utility - Target Values

Perhaps the first application of multiobjective programming was the Charnes and Cooper goal programming formulation. The formulation is: Select X so that

$$\begin{array}{ll} AX & \leq b \\ X & \geq 0 \end{array}$$

and so that the goals are handled in the following priority order:

$$\sum_j g_{1j} X_j \geq T_1$$

then

$$\sum_j g_{2j} X_j \geq T_2$$

on through to

$$\sum_j g_{Rj} X_j \geq T_R$$

for the R^{th} and last goal.

$$\begin{aligned} \text{Min } w_i \\ \text{s.t. } w_r + gl_r &\geq T_r \quad \text{for all } r \\ gl_r - \sum_j g_{rj} X_j &= 0 \quad \text{for all } r \\ \sum_j a_{mj} X_j &\leq b_m \quad \text{for all } m \\ w_r &\leq w_r \quad \text{for all } r < i \\ w_r &\leq \infty \quad \text{for all } r \geq i \\ w_r, X_j &\geq 0 \quad \text{for all } j \text{ and } r \\ gl_r &\text{ unrestricted for all } r \end{aligned}$$

The lexicographic multiple objective formulation is not precisely a LP problem. It has many structural characteristics in common with a LP problem; however, a conventional objective function is not defined, nor can a single LP formulation reflect imposition of the sequential ordering of the goals. Rather, an iterative procedure is needed (Lee). Essentially, the approach is to solve problems for each of the goals sequentially. When considering the i^{th} goal solve the problem

The new variable w_r gives the amount that the goal level ($\sum g_{rj} X_j$) is less than the target value (T_r), while gl_r is the current level of goal r . When $i = 1$ the problem minimizes the shortfall from the first goal target level, subject to the LP constraints. One of two solution situations will then occur. Either the optimum value of w_1 (denoted w_1^*) equals 0, indicating full satisfaction of the first goal, or $w_1^* > 0$, indicating the goal cannot be fully satisfied. Subsequently, a

second problem is solved. This problem is virtually identical to the first, except w_2 is minimized and a constraint is appended indicating that w_1 cannot be any worse than the optimum value obtained at the end of the solution of the first stage (w_1^*). This requires: 1) if goal 1 was met before, then goal 1 will continue to be met (i.e., w_1 must be less than or equal to zero); or 2) if goal 1 was not met, then the deviation from goal 1 will not get bigger than the minimum deviation obtained at the previous iteration. Thus, the prior objective is constrained to be no worse off than it was before. This problem, in effect, explores alternative optimums where we hold the prior objectives at their optimum values, then try to optimize the satisfaction of the subsequent objectives.

This procedure is executed for all R goals where different deviation variables are minimized at each stage and a constraint is added holding all previous deviations to maximum values prohibiting the earlier objectives from becoming worse off. Lee presents a more comprehensive discussion of the procedure while the example below gives an empirical application.

11.1.2 Utility Tradeoff Model

The second utility function type involves tradeoffs between various objectives. Such problems can be formulated as conventional linear programs. There have been two alternative formulations of this problem. They differ in their assumptions about target levels. The first formulation (appearing for example in Candler and Boelje) does not take into account target levels, maximizing the weighted sum of the quantities of each objective. This is

$$\begin{array}{ll}
 \text{Max} & \sum_r c_r q_r \\
 - \sum_j g_{rj} X_j + gl_r & = 0 \text{ for all } r \\
 - gl_r + N_r q_r & = 0 \text{ for all } r \\
 \sum_j a_{mj} X_j & \leq b_m \text{ for all } m \\
 X_j, & q_r \geq 0 \text{ for all } j \text{ and } r \\
 gl_r & \text{unrestricted for all } r
 \end{array}$$

where c_r is the weight which expresses the importance of the r^{th} objective in the context of the decision maker's total utility and N_r is a normalizing factor which converts the goal values so they are valued somewhere around one.. The c_r coefficients would be in utility units per percent deviation from full satisfaction at the normalizing factor for the r^{th}

objective achieved; gl_r is the amount of r^{th} objective in the optimal solution and q_r is the proportional satisfaction amount of r^{th} objective relative to the normalizing factor.

The objective function, maximizes multi-dimensional utility summed across all objectives. Each objective is weighted. The second equation sums the level of each objective into the variable gl_r . The third expresses satisfaction in terms of the normalizing factor. The fourth represents resource availability limitations, the fifth expresses nonnegativity constraints and the sixth allow the goal level to be positive or negative (note the normalizing factor must be of the appropriate sign).

The second weighted tradeoff formulation embodies goal target levels. The formulation is

$$\begin{aligned}
 & \text{Max} && \sum_r c_r^+ q_r^+ + \sum_r c_r^- q_r^- \\
 & \text{s.t.} && \sum_j g_{rj} X_j - gl_r = 0 \quad \text{for all } r \\
 & && gl_r - T_r q_r^+ + T_r q_r^- = 0 \quad \text{for all } r \\
 & && \sum_j a_{mj} X_j \leq b_m \quad \text{for all } m \\
 & && X_j, \quad q_r^+, \quad q_r^- \geq 0 \quad \text{for all } j \text{ and } r \\
 & && gl_r \quad \text{unrestricted for all } r
 \end{aligned}$$

where T_r is the goal target value for objective r , c_r^+ is the weight attached to overachieving objective r relative to its target, c_r^- is the weight attached to underachieving objective r relative to its target, gl_r is the level of the r th goal attained, q_r^+ is the proportion that the target for objective r is overachieved, and q_r^- is the proportion that the target for objective r is underachieved.

This is again a linear program. The formulation is adapted from Lee and is used in Barnett, et al. (1982).

11.1.3 Unknown Utility Function

The other approach to multiobjective programming involves an unknown utility function assumption. Instead, the entire nondominated set of alternatives is generated. The formulation for this approach is exactly like the first one under the weighted tradeoff section above except that all possible weights are utilized in the problem. This particular

approach has been studied extensively, (see, for example, the bibliographies in Steuer; and Ignizio, 1983) but does not appear to be very empirically useful.

11.2 Examples

A common example is used to demonstrate the above formulations. However, we will omit coverage of the unknown utility function model as its solutions would be rather extensive and its use has been limited.

The example builds upon the chair example used in the resource allocation section of the linear programming chapter. Suppose that the firm is interested in profit, idle labor, and idle lathe time in formulating its goals. Thus, the firm values leisure and slack lathe time as well as profits.

11.2.1 Lexicographic Formulation

The lexicographic formulation will be based on four different goals. The first goal is that the profit be greater than \$9,000, the second that idle labor be greater than or equal to 30 hours. The third is that idle lathe time be greater than or equal to 25 hours and the fourth, that profit be greater than or equal to \$9,500. The formulation of this problem with the deviation variables included is given in Table 11.1.

The approach in solving this problem is as above. First, the deviation from the \$9,000 profit target level will be minimized. This results in a deviation of zero. Subsequently, when minimizing the deviation from the idle labor goal, a constraint is entered allowing zero deviation from a profit level of \$9,000. Then we precede to consider idle lathe time holding the profits and idle labor goal achievement constant.

The GAMS implementation is given in Table 11.2 and file LEXICO. We have introduced profit accounting in line 67 through 69. Also, we have introduced slack variables accounting for idle resources (lines 71-73). The four goals are modeled in lines 75 through 79 where the idle large and small lathe time is added and set equal to the goal level in line 79. In turn, line 80 relates the goal levels to their associated targets. Namely, the goal achievement level plus a deviation variable to make up the shortfall is set greater than or equal to the target. The constraints defined in line 82 then restrict the goal shortfall to be less than or equal to an acceptable deviation level.

The lexicographic approach is implemented in lines 85 through 96. The initial allowable deviations are set to a

large number in line 30. The loop from lines 86 through 95 sets up the problem for each goal changing the objective function weights then solves. Subsequently, the maximum allowed deviation for future iterations is set equal to the shortfall. Report writing statements (lines 92-94) summarize the solution.

The solutions are presented in Table 11.3. Four solutions are involved, each arising when the goals are individually considered. In the first solution, the \$9,000 profit goal is easily attained while the labor and lathe time goals fall short with 4.024 units of idle labor and 17.073 units of idle lathe time. This plan has 12.195 units of functional normal chairs being produced and 108.337 units of fancy normal chairs.

In turn, when the idle labor problem is setup with the profit deviation restricted ($w_1 \neq 0$), the solution exhibits profits of \$9,482 full attainment of the idle labor goal but the lathe goal is now 20.641 units short and we are \$18.421 short of the \$9,500 profit goal. This is achieved with production of 115.296 fancy chairs and 3.289 fancy chairs with maximum large lathe use.

Now turning to the idle lathe time problem, we constrain $w_1 \neq 0$ and $w_2 \neq 0$ then solve. Here we fully attain the \$9,000 profit and idle labor goals but fall 4.337 units short of the idle lathe time goal. Profit is now \$9,000. This plan is achieved by producing 15.152 units of functional normal chairs and 99.811 units of fancy normal chairs.

Finally, turning our attention to the last goal we find that we can not make any progress on it and have a solution which is equivalent to the solution in the step before.

The above results show the action of a lexicographic solution. Namely, the \$9,000 profit goal was satisfied and held satisfied throughout the process while the \$9,500 profit was not considered until the last step and the \$9,500 profit goal was only pursued when the other goals had been held at their satisfaction levels and as a consequence no progress could be made.

11.2.2 Weighted Tradeoff - No Targets

One version of the weighted tradeoff formulation does not contain targets. We will follow the theoretical formulation but will also include weights and normalizing factors. The normalizing factors are used so the goal magnitudes are approximately equal. Namely, we divide the profit goal through by 10,500, the labor goal by the labor resource availability and the total lathe goal by the lathe resource availability. This then will convert all of these goal

numbers that range over 0 to 1 and allow relative weights to be used. In turn, the weight for profit equals one, while the weight for idle labor and lathe time both equal 0.4. The resultant formulation is in Table 11.4 and the GAMS instructions in Table 11.5 (file WEIGHT). Notice in the GAMS formulation the weight and normalization data are defined in lines 23-27, while the goal setup is essentially the same as in the previous example. The main variant is that the goal levels are normalized in lines 67-69 and the objective function is the sum of the goal weights times the goal levels (line 57).

The resultant solution to this problem is that 2.44 functional normal chairs are made while 112.2 fancy normal chairs are made and 6.829 fancy chairs with maximum use of the large lathe. The profit goal is achieved at a .92 level of the 10,500 normalization level (\$9,674) while the labor goal is achieved at a 0.217 level leaving 27.06 hours of labor idle. The idle lathe time variable equals 0.

11.2.3 Weighted Objective and Targets

Finally, let us consider the unified target levels and weighted tradeoff formulation. Here we will use the same target levels as in the lexicographic model, but introduce weights where we value profit at a weight of one if it is more than the first goal and at -10 units if it is less than that. Idle labor and lathe time are weighted at 0.1 if they are greater than their target level and -0.4 if less. Finally, the profit in excess of \$9,500 is valued at .9 and less than that at -1. The goals are normalized by multiplying the deviation variables by the target value. This formulation is portrayed in Table 11.6 with the GAMS instructions in Table 11.7 (see file WTTAR). Notice in this formulation both positive and negative deviations are defined and the objective function both reflects shortfalls and excesses. The solution shows profit equals \$9,000, idle labor 25.08 units, and idle lathe time 25 units. This makes for a labor shortfall of .164 units and a profit shortfall of .05.

11.3 Choice Among Formulations

An important question given the alternative formulations is: which one should be used for a problem? There are several general considerations involved in choosing among these formulations.

The first consideration is solver availability. Traditionally, the undominated approach requires a specially adapted solver. Such adaptations have been implemented (Steuer) although they are not routinely available for more

than small problems. In addition, the undominated set approach can be quite expensive computationally (Steuer). Thus, this criteria favors the weighted tradeoff or goal formulations where one could use standard algorithms.

Second, one needs to consider the required amount of decision maker contact, particularly if the model is being used for predictive purposes. The undominated solution alternative would not be satisfactory in a limited contact setting as it requires active choice of the "best" strategy by the decision maker. This would be particularly troubling in many predictive exercises as the methods would generate a large number of answers, any of which could be the solution depending on decision maker choice.

Third, the treatment of goal target levels is difficult in comparative static exercises. It is difficult to: 1) specify goal target levels and 2) conclude that the goal target levels do not depend upon the resource base. Certainly, an income goal is easier to satisfy if the resource base is augmented. Thus, the lexicographic utility function formulations are not scale neutral. Many LP models are built to do comparative static studies, such as what would happen if larger equipment were available, more land area, labor, etc. This causes difficulties in using comparative statics with the weighted tradeoff model using fixed goal target levels or the lexicographic model.

Fourth, weights are difficult to discover. A complex questioning or calculation procedure is required (we review procedures for establishing weights below). Further, the use of constant weights over the entire domain of goal levels may be questionable. Procedures for including diminishing marginal utility would involve quadratic or separable programs as covered in other chapters.

All things considered, we prefer the weighted tradeoff model due to its consistency with our perceptions that individuals are willing to establish tradeoffs between objectives on the margin and that most models will be used for comparative static analysis.

11.4 Developing Utility Functions

Conceptually, multiobjective programming problems look attractive. However, assuming one knows the objectives, it is difficult to specify the utility structure. Clearly, this is not a problem with the undominated solution procedure as there are no weights. On the other hand, one puts all the alternative solutions in the decision maker's lap, which could involve thousands of solutions. Here we address how to find the utility function for the other formulations.

The easiest system to use is the lexicographic system, where one has to establish goal targets and the preemptive order. Targets such as the minimum amount of debt service plus consumption or the desired length of a vacation can be used. However, one must be careful in using these targets in comparative static analysis, as the relative ability to satisfy the targets changes with alterations in the resource base. Also, one must ask whether tradeoffs are in order.

Weights are more difficult and are the subject of the bulk of the discussion herein. The first way of specifying weights is to take decision makers' past actions and then through a grid search over alternative weights, choose weights so as to minimize deviations of the model solution from observed actions. An example is given by Brink and McCarl for a risk analysis problem. We know of no formal attempt to do this in other than a risk analysis framework. The advantage here is that one obtains weights which are somehow consistent with revealed preferences. However, in a LP problem there is a range of weights which will generate the same solution. It is therefore possible that the proper set of weights is somewhere within the range, but that the wrong set of weights is chosen. In turn, this set of weights could lead to dramatically different behavior in a comparative static study.

A third procedure involves survey techniques. Here decision makers are asked questions about the relative importance of objectives and then through a scaling procedure a set of objective weights is obtained. This was done by Barnett, Blake and McCarl; Smith and Capstick; and Harman, et al. Two difficulties arise with this procedure. First, there is no assurance that the surveys generate results which mimic actions in actual situations. Second, it is difficult to translate the results into the proper specification of the programming model objective.

The fourth procedure we discuss was proposed by Candler and Boehlje and applies to the weighted tradeoff models. The procedure involves interaction with the decision maker and is based on revealed preference. To begin the process, modelers choose an initial set of weights and present the answers to the decision maker. In turn, the decision maker expresses preference for a change in the objective satisfaction levels (i.e., the decision maker could argue that there was insufficient income and excessive risk). The modeler would then alter the weights on those objectives and rerun the model. The process would continue until the decision maker was satisfied. This approach has the advantage of obtaining goal weights consistent with the decision maker's preferences and the potential disadvantage of obtaining the proper output with the wrong set of goal weights, leading to improper solutions when one is doing further analysis.

Finally, we must comment that there is no real way to abstractly set up a multiple objective model. The weights for the multiple objectives clearly require interaction with the decision maker.

11.5 Shadow Prices

Much discussion has been devoted in previous chapters to shadow prices but little here. In this section we explore the meaning of shadow prices in a weighted multiple objective problem and derive meaningful shadow prices.

The shadow prices for a weighted multiobjective problem nominally give the marginal change in the weighted utility of a marginal right hand side change. The weighted utility is a multi-dimensional utility measure constructed as the sum of the individual objectives times their weights. However, one must ask how useful it is to know the expected change in this multi-dimensional utility function. This ordinarily would probably not be terribly useful as decision makers will be more interested in knowing what happens to the specific objectives. Mathematically, the effect on the specific objectives may be derived as follows. The first weighted multiple objective function with the normalization factors set to one and the equality constraints substituted out becomes:

$$\begin{aligned} \text{Max} \quad & \sum_r w_r \left(\sum_j g_{rj} X_j \right) \\ \text{s.t.} \quad & \sum_j a_{kj} X_j \leq b_k \text{ for all } k \\ & X_j \geq 0 \text{ for all } j \end{aligned}$$

Rearranging, we obtain

$$\begin{aligned} \text{Max} \quad & \sum_j \left(\sum_r w_r g_{rj} \right) X_j \\ \text{s.t.} \quad & \sum_j a_{kj} X_j \leq b_k \text{ for all } k \\ & X_j \geq 0 \text{ for all } j \end{aligned}$$

Note that each variable X_j has an objective function coefficient which is the sum of the weights times its relative goal contributions. This can be collapsed using

$$C_j = \left(\sum_r w_r g_{rj} \right)$$

or, in matrix terms,

$$C = WG$$

We now turn our attention to shadow prices, given by

$$U = C_B B^{-1}$$

The C_B terms within the multiobjective programming model are given by the multiplication of goal weights times the goal levels involved with the basic variables

$$C_B = WG_B = \begin{bmatrix} w_1 & w_2 & w_r \end{bmatrix} \begin{bmatrix} g_{11}^b & g_{1M}^b \\ g_{21}^b & g_{2M}^b \\ g_{r1}^b & g_{rM}^b \end{bmatrix}$$

where the superscript b on the g terms refer to the coefficients associated with the basic variable in the various objectives.

The shadow price term can be rewritten as

$$U = C_B B^{-1} = W G_B B^{-1}$$

Here, the term $G_B B^{-1}$ gives an unweighted set of shadow prices, each column of $G_B B^{-1}$ shows how each objective function is affected by right hand side changes. Practically, these shadow prices could be obtained analytically from small problems and from larger problems by employing the solver starting from the optimal solution which can do a pricing pass but does not optimize (doing zero iterations).

11.5.1 Example

Suppose we were to maximize the following multiple goal objective problem

and we are willing to assume that the weights are each 1. The problem with the composite objective

$$\begin{aligned} & \text{Max} \begin{cases} 10X_1 + X_2 \\ -7X_1 + X_2 \end{cases} \\ & \text{s.t.} \quad \begin{aligned} X_1 - X_2 &\leq 5 \\ X_1 + X_2 &\leq 10 \\ X_1, X_2 &\geq 0 \end{aligned} \end{aligned}$$

function then becomes

$$\begin{array}{ll}
\text{Max} & 1(10X_1 + X_2) + 1(-7X_1 + X_2) = 3X_1 + 2X_2 \\
\text{s.t.} & X_1 - X_2 \leq 5 \\
& X_1 + X_2 \leq 10 \\
& X_1, X_2 \geq 0
\end{array}$$

Solving this problem (see file SHADOW) we find that our solution consists $X_1=7.5$ and $X_2=2.5$. equals 2.5. The basis matrix and its inverse are

$$B = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \quad B^{-1} = \begin{bmatrix} .5 & .5 \\ -.5 & .5 \end{bmatrix}$$

The composite shadow prices are

$$C_B B^{-1} = [3 \quad 2] \begin{bmatrix} .5 & .5 \\ -.5 & .5 \end{bmatrix} = [.5 \quad 2.5]$$

However, if we break this down we get

$$WG_B B^{-1} = [1 \quad 1] \begin{bmatrix} 10 & 1 \\ -7 & 1 \end{bmatrix} \begin{bmatrix} .5 & .5 \\ -.5 & .5 \end{bmatrix} = [1 \quad 1] \begin{bmatrix} 4.5 & 5.5 \\ -4 & -3 \end{bmatrix}$$

where the last matrix gives the shadow prices in terms of individual objectives. Thus, the change of one unit in the right hand side will increase the first objective by 4.5 while decreasing the second objective by 4. These shadow prices are more meaningful than the weighted shadow prices as they tell the implications of resource changes for each objective. Note that the weighted problem shadow prices are simply the individual weights times the shadow prices of this problem.

Preckel et al. proposed an alternative where they estimate relevant shadow prices by dividing through the by shadow prices on the individual objective accounting rows. However, this does not work as well as the theory above, as the shadow prices will be strictly proportional across the goals which need not happen in the general case (i.e. in the example above).

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Table 11.1. Tableau for Lexicographic Example

| | | Original Decision Variables | | | | | | Profit | Idle Resources | | | | Goal Levels | | | | Goal Deviations | | | | RHS |
|-------------------------------------|--------------------|-----------------------------|----------------|----------------|----------------|----------------|----------------|--------|----------------|-----------|--------|-------|-------------|------------|------------|-------------|-----------------|------------|------------|-------------|-----|
| | | X ₁ | X ₂ | X ₃ | X ₄ | X ₅ | X ₆ | | Sml Lathe | Lrg Lathe | Carver | Labor | Profit 9000 | Idle Labor | Idle Lathe | Profit 9500 | Prof 9000 | Idle Labor | Idle Lathe | Profit 9500 | |
| Objective | | | | | | | | | | | | | | | | 12 | | | | Min | |
| Original Lexicographic Satisfaction | Profit | 67 | 66 | 66.3 | 80 | 78.5 | 78.4 | -1 | | | | | | | | 1 | | | | = 0 | |
| | Profit 9000 | | | | | | | | | | | | | | | 1 | | | | # 0 | |
| | Small Lathe | 0.8 | 1.3 | 0.2 | 1.2 | 1.7 | 0.5 | 1 | | | | | | | | | | | | = 140 | |
| | Large Lathe | 0.5 | 0.2 | 1.3 | 0.7 | 0.3 | 1.5 | | | | | 1 | | | | | | | | = 90 | |
| | Carver | 0.4 | 0.4 | 0.4 | 1.0 | 1.0 | 1.0 | | | | | 1 | | | | | | | | = 120 | |
| | Labor | 1.0 | 1.05 | 1.1 | 0.8 | 0.82 | 0.84 | | | | | | | | | 1 | | | | = 125 | |
| | Idle Labor | | | | | | | | | | | | | | | 1 | | | | = 0 | |
| | Idle Lathe | | | | | | | 1 | | | | 1 | | | | | | | | = 0 | |
| | Profit 9500 | | | | | | | 1 | | | | | | | | -1 | | | | = 0 | |
| | Idle Labor | | | | | | | | | | | 1 | | | | 1 | | | | ∃ 30 | |
| | Idle Lathe | | | | | | | | | | | | | | | 1 | | | | ∃ 25 | |
| | Profit 9500 | | | | | | | | | | | | | | | 1 | | | | ∃ 9500 | |
| | Idle Labor | | | | | | | | | | | | | | | 1 | | | | # 99999999 | |
| | Idle Lathe | | | | | | | | | | | | | | | 1 | | | | # 99999999 | |
| | Profit 9500 | | | | | | | | | | | | | | | 1 | | | | # 99999999 | |
| Goal Satisfaction | Profit 9000 | | | | | | | | | | | 1 | | | | 1 | | | | ∃ 9000 | |
| Goal | Profit 9000 level1 | | | | | | | 1 | | | | -1 | | | | | | | | = 0 | |

Table 11.2. GAMS Formulation of Lexicographic Example

```

5  SET
6
7      PROCESS
8      /FUNCTNORM , FUNCTMXSML , FUNCTMXLRG
9      , FANCYNORM , FANCYMXSML , FANCYMXLRG/
10     RESOURCE
11     TYPES OF RESOURCES
12     /SMLLATHE, LRGLATHE, CARVER, LABOR/
13     ALIAS (GOALS, GOAL) ;
14     PARAMETER PRICE (PROCESS)
15     PRODUCT PRICES BY PROCESS
16     /FUNCTNORM 82, FUNCTMXSML 82, FUNCTMXLRG 82
17     , FANCYNORM 105, FANCYMXSML 105, FANCYMXLRG 105/
18     PRODCOST (PROCESS)
19     COST BY PROCESS
20     /FUNCTNORM 15, FUNCTMXSML 16 , FUNCTMXLRG 15.7
21     , FANCYNORM 25, FANCYMXSML 26.5, FANCYMXLRG 26.6/
22     RESORAVAIL (RESOURCE)
23     RESOURCE AVAILABILITY
24     /SMLLATHE 140, LRGLATHE 90,
25     CARVER 120, LABOR 125/
26     TARGET (GOALS)
27     GOAL TARGET LEVELS
28     /PROFIT1 9000, LABOR 30, LATHETIME 25
29     , PROFIT2 9500/
30     DEV (GOALS)
31     MAXIMUM DEVIATION BY GOAL
32     WEIGHTS (GOALS)
33     WEIGHTS BY GOAL ;
34     DEV (GOALS) = 999999;
35     WEIGHTS (GOALS) = 0.00001;
36     TABLE RESOURUSE (RESOURCE, PROCESS)
37     RESOURCE USAGE
38     FUNCTNORM  FUNCTMXSML  FUNCTMXLRG
39     SMLLATHE    0.80      1.30      0.20
40     LRGLATHE    0.50      0.20      1.30
41     CARVER      0.40      0.40      0.40
42     LABOR       1.00      1.05      1.10
43     +
44     FANCYNORM   1.20      1.70      0.50
45     LRGLATHE    0.70      0.30      1.50
46     CARVER      1.00      1.00      1.00
47     LABOR       0.80      0.82      0.84;
48     POSITIVE VARIABLES
49     PRODUCTION (PROCESS)
50     ITEMS PRODUCED BY PROCESS
51     IDLE (RESOURCE)
52     SLACK VARIABLES FOR RESOURCES
53     GOALLEVEL (GOALS)
54     GOAL LEVELS
55     PROFIT
56     TOTALPROFIT
57     SHORTFALL (GOALS)
58     GOAL SHORTFALLS;
59     VARIABLES
60     GOALOBJ
61     GOAL OBJECTIVE;
62     EQUATIONS
63     OBJT
64     OBJECTIVE FUNCTION
65     PROFITACCT
66     PROFIT ACCOUNTING
67     AVAILABLE (RESOURCE)
68     RESOURCES AVAILABLE
69     IDLLABGOAL
70     IDLE LABOR GOAL
71     PROFITGL1
72     PROFIT1 GOAL
73     PROFITGL2
74     PROFIT2 GOAL
75     LATHEGOAL
76     IDLE LATHE GOAL
77     TARGS (GOALS)
78     GOAL TARGETS
79     MAXSHORT (GOALS)
80     SHORTFALL LIMITS;
81     OBJT.. GOALOBJ =E= SUM (GOALS, WEIGHTS (GOALS) * SHORTFALL (GOALS)) ;
82
83     PROFITACCT.. PROFIT =E=
84     SUM (PROCESS, (PRICE (PROCESS) - PRODCOST (PROCESS))
85     * PRODUCTION (PROCESS)) ;
86
87     AVAILABLE (RESOURCE) ..
88     SUM (PROCESS, RESOURUSE (RESOURCE, PROCESS) * PRODUCTION (PROCESS))
89     + IDLE (RESOURCE) =E= RESORAVAIL (RESOURCE);
90     IDLLABGOAL.. IDLE ("LABOR") =E= GOALLEVEL ("LABOR") ;

```

Table 11.2. GAMS Formulation of Lexicographic Example (Continued)

```
76  PROFITGL1..  PROFIT      =E= GOALLEVEL("PROFIT1");
77  PROFITGL2..  PROFIT      =E= GOALLEVEL("PROFIT2");
78  LATHEGOAL..  IDLE("LRGLATHE")+IDLE("SMLLATHE")
79              =E= GOALLEVEL("LATHETIME");
80  TARGS(GOALS).. GOALLEVEL(GOALS) + SHORTFALL(GOALS) =G= TARGET(GOALS) ;
81
82  MAXSHORT(GOALS)..  SHORTFALL(GOALS) =L= DEV(GOALS);
83
84  MODEL RESALLOC /ALL/;
85  PARAMETER    GOALDATA(GOAL,*,*)
86  LOOP(GOAL,
87      WEIGHTS(GOAL)=1.
88
89      SOLVE RESALLOC USING LP MINIMIZING GOALOBJ;
90      DEV(GOAL)=SHORTFALL.L(GOAL);
91      WEIGHTS(GOAL)=0.00001;
92      GOALDATA(GOAL,GOALS,"ATTAIN")=GOALLEVEL.L(GOALS) ;
93      GOALDATA(GOAL,GOALS,"SHORT")=SHORTFALL.L(GOALS) ;
94      GOALDATA(GOAL,PROCESS,"XLEVEL")=PRODUCTION.L(PROCESS);
95  );
96  DISPLAY GOALDATA;
```

Table 11.3. Solution to Lexicographic Example

| Goal Being Pursued | Solution Item | Idle | Goal Attainment | Goal Level | Goal Shortfall | Production Level |
|--------------------|---------------|------|-----------------|------------|----------------|------------------|
| PROFIT1 | PROFIT1 | GOAL | 9500.000 | 9500 | 0 | |
| | .LABOR | GOAL | 25.976 | 30 | 4.024 | |
| | .LATHETIME | GOAL | 7.927 | 25 | 17.073 | |
| | .PROFIT2 | GOAL | 9500.000 | 9500 | 0 | |
| | .FUNCTNORM | PROD | | | | |
| 12.195 | | | | | | |
| 108.537 | .FANCYNORM | PROD | | | | |
| LABOR | .PROFIT1 | GOAL | 9481.579 | 9500 | 0 | |
| | .LABOR | GOAL | 30.000 | 30 | 0 | |
| | .LATHETIME | GOAL | 4.359 | 25 | 20.641 | |
| | .PROFIT2 | GOAL | 9481.579 | 9500 | 18.421 | |
| | .FANCYNORM | PROD | | | | |
| 115.296 | | | | | | |
| 3.289 | .FANCYMXLRG | PROD | | | | |
| LATHETIME | .PROFIT1 | GOAL | 9000.000 | 9500 | 0 | |
| | .LABOR | GOAL | 30.000 | 30 | 0 | |
| | .LATHETIME | GOAL | 20.663 | 25 | 4.337 | |
| | .PROFIT2 | GOAL | 9000.000 | 9500 | 500.000 | |
| | .FUNCTNORM | PROD | | | | |
| 15.152 | | | | | | |
| 99.811 | .FANCYNORM | PROD | | | | |
| PROFIT2 | .PROFIT1 | GOAL | 9000.000 | 9500 | 0 | |
| | .LABOR | GOAL | 30.000 | 30 | 0 | |
| | .LATHETIME | GOAL | 20.663 | 25 | 4.337 | |
| | .PROFIT2 | GOAL | 9000.000 | 9500 | 500.000 | |
| | .FUNCTNORM | PROD | | | | |
| 15.152 | | | | | | |
| 99.811 | .FANCYNORM | PROD | | | | |

Table 11.4. Tableau for Weighted Tradeoff Example

| | | Original Decision Variables | | | | | | Profit | Idle Resources | | | | Goal Levels | | | Goal Deviations | | | RHS |
|------------|-------------|-----------------------------|----------------|----------------|----------------|----------------|----------------|--------|----------------|-----------|--------|-------|-------------|------------|------------|-----------------|------------|------------|-----|
| | | X ₁ | X ₂ | X ₃ | X ₄ | X ₅ | X ₆ | | Lrg Lathe | Sml Lathe | Carver | Labor | Profit | Idle Labor | Idle Lathe | Profit | Idle Labor | Idle Lathe | |
| Objective | | | | | | | | | | | | | | | 1 | .4 | .4 | Min | |
| Original | Profit | 67 | 66 | 66.3 | 80 | 78.5 | 78.4 | -1 | | | | | | | | | | = 0 | |
| | Small Lathe | 0.8 | 1.3 | 0.2 | 1.2 | 1.7 | 0.5 | 1 | | | | | | | | | | = 140 | |
| | Large Lathe | 0.5 | 0.2 | 1.3 | 0.7 | 0.3 | 1.5 | 1 | | | | | | | | | | = 90 | |
| | Carver | 0.4 | 0.4 | 0.4 | 1.0 | 1.0 | 1.0 | 1 | | | | | | | | | | = 120 | |
| | Labor | 1.0 | 1.05 | 1.1 | 0.8 | 0.82 | 0.84 | 1 | | | | | | | | | | = 125 | |
| Goal | Profit | | | | | | | 1 | | | | -1 | | | | | | = 0 | |
| | Idle Labor | | | | | | | 1 | | | | -1 | | | | | | = 0 | |
| | Idle Lathe | | | | | | | 1 | 1 | | | | | -1 | | | = 0 | | |
| Goal Level | Profit 9000 | | | | | | | | | | | -1 | | | 10500 | | | = 0 | |
| | Idle Labor | | | | | | | | | | | -1 | | | 125 | | | = 0 | |
| | Idle Lathe | | | | | | | | | | | -1 | | | 230 | | | = 0 | |

Table 11.5. GAMS Setup for Weighted Objective Example

```

4
5  SET          GOALS          /PROFIT,LABOR,LATHETIME/
6              PROCESS        TYPES OF PRODUCTION PROCESSES
7                      /FUNCTNORM , FUNCTMXSML , FUNCTMXLRG
8                      ,FANCYNORM , FANCYMXSML , FANCYMXLRG/
9              RESOURCE        TYPES OF RESOURCES
10                      /SMLLATHE,LRGLATHE,CARVER,LABOR/
11
12  PARAMETER PRICE(PROCESS)      PRODUCT PRICES BY PROCESS
13                      /FUNCTNORM 82, FUNCTMXSML 82, FUNCTMXLRG 82
14                      ,FANCYNORM 105, FANCYMXSML 105, FANCYMXLRG 105/
15  PRODCOST(PROCESS)      COST BY PROCESS
16                      /FUNCTNORM 15, FUNCTMXSML 16 , FUNCTMXLRG 15.7
17                      ,FANCYNORM 25, FANCYMXSML 26.5, FANCYMXLRG 26.6/
18  RESORAVAIL(RESOURCE)  RESOURCE AVAILABILITY
19                      /SMLLATHE 140, LRGLATHE 90,
20                      CARVER 120, LABOR 125/
21  WEIGHTS(GOALS)        WEIGHT FOR GOALS
22                      /PROFIT 1,LABOR 0.4,LATHETIME 0.4/
23  MAGNITUDE(GOALS)      MAGNITUDE FOR GOALS
24                      /PROFIT 10500/;
25  MAGNITUDE("LATHETIME")=RESORAVAIL("SMLLATHE")+RESORAVAIL("LRGL ATHE");
26  MAGNITUDE("LABOR")=RESORAVAIL("LABOR");
27
28
29  TABLE RESOURUSE(RESOURCE,PROCESS) RESOURCE USAGE
30
31                      FUNCTNORM    FUNCTMXSML    FUNCTMXLRG
32  SMLLATHE            0.80         1.30         0.20
33  LRGLATHE            0.50         0.20         1.30
34  CARVER              0.40         0.40         0.40
35  LABOR              1.00         1.05         1.10
36  +
37  SMLLATHE            1.20         1.70         0.50
38  LRGLATHE            0.70         0.30         1.50
39  CARVER              1.00         1.00         1.00
40  LABOR              0.80         0.82         0.84;
41
42  POSITIVE VARIABLES
43      PRODUCTION(PROCESS) ITEMS PRODUCED BY PROCESS
44      IDLE(RESOURCE)      SLACK VARIABLES FOR RESOURCES
45      GOALLEVEL(GOALS)    GOAL LEVELS
46      PROFIT              TOTALPROFIT;
47  VARIABLES
48      GOALOBJ              GOAL OBJECTIVE;
49  EQUATIONS
50      OBJT                  OBJECTIVE FUNCTION
51      PROFITACCT            PROFIT ACCOUNTING
52      AVAILABLE(RESOURCE)  RESOURCES AVAILABLE
53      IDLLABGOAL            IDLE LABOR GOAL
54      PROFITGOAL            PROFIT GOAL
55      LATHEGOAL            IDLE LATHE GOAL;
56
57  OBJT.. GOALOBJ =E= SUM(GOALS,WEIGHTS(GOALS)*GOALLEVEL(GOALS)) ;
58
59  PROFITACCT.. PROFIT =E=
60      SUM(PROCESS,(PRICE(PROCESS)-PRODCOST(PROCESS))
61          * PRODUCTION(PROCESS)) ;
62
63  AVAILABLE(RESOURCE)..
64      SUM(PROCESS,RESOURUSE(RESOURCE,PROCESS)*PRODUCTION(PROCESS))
65          +IDLE(RESOURCE) =E= RESORAVAIL(RESOURCE);
66

```

```
67 IDLLABGOAL.. IDLE("LABOR") =E= GOALLEVEL("LABOR")*MAGNITUDE("LABOR");
68 PROFITGOAL.. PROFIT =E= GOALLEVEL("PROFIT")*MAGNITUDE("PROFIT");
69 LATHEGOAL.. IDLE("LRGLATHE")+IDLE("SMLLATHE")
70 =E= GOALLEVEL("LATHETIME")*MAGNITUDE("LATHETIM E");
71 MODEL RESALLOC /ALL/;
72 SOLVE RESALLOC USING LP MAXIMIZING GOALOBJ;
```

Table 11.6. Tableau for Weighted Tradeoff with Targets Example

| | | Original Decision Variables | | | | | | Profit | Idle Resources | | | | Goal Levels | | | | Goal Deviations | | | | | | | | RHS |
|-------------|--------------------|-----------------------------|----------------|----------------|----------------|----------------|----------------|--------|----------------|-------------|------------|-------|-------------|------------|------------|-------------|-----------------|---------------|--------------|--------------|--------------|--------------|---------------|---------------|--------|
| | | X ₁ | X ₂ | X ₃ | X ₄ | X ₅ | X ₆ | | Small Lathe | Large Lathe | Carv Lathe | Labor | Profit 9000 | Idle Labor | Idle Lathe | Profit 9500 | Profit 9000 + | Profit 9000 - | Idle Labor + | Idle Labor - | Idle Lathe + | Idle Lathe - | Profit 9500 + | Profit 9500 - | |
| Objective | | | | | | | | | | | | | | | | | 1 | -10 | .1 | -.4 | .1 | -.4 | 9 | -1 | Max |
| Origin | Profit | 67 | 66 | 66.3 | 80 | 78.5 | 78.4 | -1 | | | | | | | | | | | | | | | | | = 0 |
| | Small Lathe | 0.8 | 1.3 | 0.2 | 1.2 | 1.7 | 0.5 | 1 | | | | | | | | | | | | | | | | | = 140 |
| | Large Lathe | 0.5 | 0.2 | 1.3 | 0.7 | 0.3 | 1.5 | | 1 | | | | | | | | | | | | | | | | = 90 |
| | Carver | 0.4 | 0.4 | 0.4 | 1.0 | 1.0 | 1.0 | | | 1 | | | | | | | | | | | | | | | = 120 |
| | Labor | 1.0 | 1.05 | 1.1 | 0.8 | 0.82 | 0.84 | | | | | 1 | | | | | | | | | | | | | = 125 |
| Goal Level | Profit 9000 level1 | | | | | | | 1 | | | | | -1 | | | | | | | | | | | | = 0 |
| | Idle Labor | | | | | | | | | | | 1 | | -1 | | | | | | | | | | | = 0 |
| | Idle Lathe | | | | | | | | 1 | 1 | | | | | -1 | | | | | | | | | | = 0 |
| | Profit 9500 | | | | | | | 1 | | | | | | | | -1 | | | | | | | | | = 0 |
| Goal Satisf | Profit 9000 | | | | | | | | | | | | 1 | | | | -9000 | 9000 | | | | | | | = 9000 |
| | Idle Labor | | | | | | | | | | | | 1 | | | | | | -30 | 30 | | | | | = 30 |
| | Idle Lathe | | | | | | | | | | | | | 1 | | | | | | | -25 | 25 | | | = 25 |
| | Profit 9500 | | | | | | | | | | | | | | 1 | | | | | | | | -9500 | 9500 | = 9500 |

Table 11.7. GAMS Setup for Weighted Objective with Target Example

```

4
5  SET          GOALS          GOALS IN THE ORDER THEY ARE TO BE MET
6                                /PROFIT1,LABOR,LATHETIME,PROFIT2/
7                                PROCESS      TYPES OF PRODUCTION PROCESSES
8                                /FUNCTNORM , FUNCTMXSML , FUNCTMXLRG
9                                ,FANCYNORM , FANCYMXSML , FANCYMXLRG/
10                               RESOURCE     TYPES OF RESOURCES
11                               /SMLLATHE,LRGLATHE,CARVER,LABOR/
12                               DIR          GOAL DEVIATION DIRECTION /MORETHAN, LESSTHAN/
13
14  ALIAS (GOALS,GOAL) ;
15
16  PARAMETER PRICE (PROCESS)      PRODUCT PRICES BY PROCESS
17                                /FUNCTNORM 82, FUNCTMXSML 82, FUNCTMXLRG 82
18                                ,FANCYNORM 105, FANCYMXSML 105, FANCYMXLRG 105/
19  PRODCOST (PROCESS)      COST BY PROCESS
20  /FUNCTNORM 15, FUNCTMXSML 16 , FUNCTMXLRG 15.7
21  ,FANCYNORM 25, FANCYMXSML 26.5, FANCYMXLRG 26.6/
22  RESORAVAIL (RESOURCE) RESOURCE AVAILABILITY
23  /SMLLATHE 140, LRGLATHE 90,
24  CARVER 120, LABOR 125/
25  TARGET (GOALS)          GOAL TARGET LEVELS
26  /PROFIT1 9000,LABOR 30,LATHETIME 25
27  ,PROFIT2 9500/
28  MAGNITUDE (GOALS)      MAGNITUDE FOR GOALS;
29  MAGNITUDE (GOALS)=TARGET (GOALS) ;
30
31  TABLE              WEIGHTS (GOALS,dir)      WEIGHTS BY GOAL
32
33                                MORETHAN    LESSTHAN
34  PROFIT1              1                -10
35  LABOR                0.1              -0.4
36  LATHETIME            0.1              -0.4
37  PROFIT2              .9                -1.      ;
38
39  TABLE RESOURUSE (RESOURCE,PROCESS) RESOURCE USAGE
40
41  FUNCTNORM    FUNCTMXSML    FUNCTMXLRG
42  SMLLATHE     0.80          1.30          0.20
43  LRGLATHE     0.50          0.20          1.30
44  CARVER       0.40          0.40          0.40
45  LABOR        1.00          1.05          1.10
46  +            FANCYNORM    FANCYMXSML    FANCYMXLRG
47  SMLLATHE     1.20          1.70          0.50
48  LRGLATHE     0.70          0.30          1.50
49  CARVER       1.00          1.00          1.00
50  LABOR        0.80          0.82          0.84;
51
52  POSITIVE VARIABLES
53  PRODUCTION (PROCESS) ITEMS PRODUCED BY PROCESS
54  IDLE (RESOURCE)      SLACK VARIABLES FOR RESOURCES
55  GOALLEVEL (GOALS)    GOAL LEVELS
56  PROFIT              TOTALPROFIT
57  SHORTFALL (GOALS)    GOAL SHORTFALLS
58  EXCESS (GOALS)       GOAL EXCESSES;
59  VARIABLES
60  GOALOBJ              GOAL OBJECTIVE;
61  EQUATIONS
62  OBJT                  OBJECTIVE FUNCTION
63  PROFITACCT            PROFIT ACCOUNTING
64  AVAILABLE (RESOURCE)  RESOURCES AVAILABLE
65  IDLLABGOAL            IDLE LABOR GOAL
66  PROFITGL1             PROFIT1 GOAL
67  PROFITGL2             PROFIT2 GOAL

```

Table 11.7. GAMS Setup for Weighted Objective with Target Example (Continued)

```

68          LATHEGOAL          IDLE LATHE GOAL
69          TARGS (GOALS)      GOAL TARGETS  ;
70
71      OBJT.. GOALOBJ =E= SUM(GOALS,WEIGHTS(GOALS,"LESSTHAN")*SHORTFALL(GOALS)
72                          +WEIGHTS(GOALS,"MORETHAN")*EXCESS(GOALS)) ;
73
74      PROFITACCT.. PROFIT =E=
75          SUM(PROCESS,(PRICE(PROCESS)-PRODCOST(PROCESS))
76              * PRODUCTION(PROCESS)) ;
77
78      AVAILABLE(RESOURCE)..
79          SUM(PROCESS,RESOURUSE(RESOURCE,PROCESS)*PRODUCTION(PROCESS))
80              +IDLE(RESOURCE) =E= RESORAVAIL(RESOURCE);
81
82      PROFITGL1.. PROFIT =E= GOALLEVEL("PROFIT1");
83      IDLLABGOAL.. IDLE("LABOR") =E= GOALLEVEL("LABOR");
84      LATHEGOAL.. IDLE("LRGLATHE")+IDLE("SMLLATHE")
85                  =E= GOALLEVEL("LATHETIME");
86      PROFITGL2.. PROFIT =E= GOALLEVEL("PROFIT2");
87
88      TARGS(GOALS)..
89          GOALLEVEL(GOALS) + MAGNITUDE(GOALS)*( SHORTFALL(GOALS) -EXCESS(GOALS))
90              =E= TARGET(GOALS) ;
91
92
93      MODEL RESALLOC /ALL/;
94
95      SOLVE RESALLOC USING LP MAXIMIZING GOALOBJ;

```
