A Multicriteria Approach for the Choice of Remote Load Control Strategies

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Introduction

- The model presented in this communication is a slightly altered version of the model previously proposed by Jorge *et al*. (2000), taking into account the main concerns that have an important role in load management.

- Load management actions entail changing the regular working cycles of loads through the implementation of appropriate power curtailment actions.

- These actions consist of on/off patterns generally applied to groups of loads associated with energy services whose quality is not substantially affected by supply interruptions of short duration, such as electric water heaters and air conditioners in the residential sector. Since these are thermostatic loads, external changes to their working cycle have influence on their demand pattern in subsequent time periods.

Introduction

- Recently, further attention has been paid to this kind of programs mainly due to the volatility of wholesale electricity prices and reliability concerns (transmission congestion and generation shortfalls).
- However, load management programs can also give rise to undesirable effects, such as the payback effect (whenever power is restored simultaneously to loads thus eventually creating another peak) and possible reduction in revenues.

Models

- The selection of load control actions suggests the explicit consideration of multiple, incommensurate and conflicting evaluation criteria of the merit of alternative load shedding strategies, capable of reflecting economic, technical and quality of service aspects.

- Note that the quality of service dimension is crucial because consumers' acceptance is indispensable for the success of load management programs.

- The three criteria intend to minimize peak demand as perceived by the distribution network dispatch centre, to maximize utility profit corresponding to the energy services delivered by the controlled loads and to maximize quality of service in the context of load management.

FROM THE STEM METHOD TO A NEW REFERENCE POINT APPROACH

- The well known STEM method was used to analyse a case study using the tricriteria model referred to above. The quality of the solutions proposed in Jorge et al. (2000) is acceptable, but due to the limitations of STEM method it was not possible to make a comprehensive search of the nondominated solution set.

- So, the multicriteria interactive analysis should contribute to an indispensable learning process putting in evidence not only all the relevant profiles of well contrasted nondominated alternative options but also providing aids to achieve a satisfactory compromise solution for the various actors (namely, electricity supply companies and consumers)

FROM THE STEM METHOD TO A NEW REFERENCE POINT APPROACH

- The software used to reach these goals is based on an interactive reference point method for multicriteria integer linear programming (MCILP) combining Chebychev scalarizing programs with branch and bound techniques (Alves and Clímaco, 2000), and a visualization approach to the indifference sets of reference points dedicated to tricriteria integer linear programming (Alves and Clímaco, 2001).

- The flexibility of the search and the visual interface constitute the main characteristics of the software tool to analyse the tricriteria integer programming model for aiding the definition of remote load control strategies.

- In this talk we describe in detail the analysis of the tricriteria load management model using the MCILP software package and we compare the results with those obtained using the STEM method.

A Multiple objective model for the selection of control strategies

- The use of a multiple objective model allows the DM to select, from a set of predefined strategies, a satisfactory control strategy to apply to each group of controlled loads in order to guarantee a compromise (non-dominated) solution among the three objectives.
- The model can be used to select satisfactory remote load control strategies for an existing system.
- Control strategies define the on/off schedule of load groups, during the period of time where maximum demand control is to be achieved.
- At a preliminary design stage, it is also suited to make a previous economic analysis for evaluating the attractiveness of new LM programs, since it involves investments, namely in communication equipment and load switching interfaces.

A Multiple objective model for the selection of control strategies

- The multiobjective model does not depend on the type of controlled load, though it has been applied only to the control of groups of electric water heaters.

Notes:

- The total control period is divided into *n* equal intervals ($\Delta t = \Delta T/n$), in order to prevent a new peak demand caused by the payback phenomenon.

- Supply interruptions, as defined by the control strategies, always begin at the start of a Δt interval and last for an integer number of intervals.

Mathematical model

Under load control, demand at each elementary interval is given by:

$$X_i = \sum_j \sum_k (c_{ijk} x_{jk}) + L_i \qquad i = 1, \ldots, n \qquad (1)$$

Notation:

i Elementary time interval index (i = 1, …, n)

X_i Average network demand at interval *i* with load control

j Load group index (*j* = 1, …, *m*)

k Control strategy index (*k* = 1, …, q)

cijk Difference at interval *i* between load group *j* demand when control strategy *k* is applied to it and load group *j* demand without any control action.

xjk Binary decision variable that assumes the value 1 if control strategy *k* is selected to be applied to group *j*, and 0 otherwise.

Li Average forecasted network demand at interval *i* without load control

Objective Functions

1. Minimize peak demand

Consists in minimizing the maximum network controlled demand, that is:
Min Max $\{X_1, X_2, \ldots, X_n\}$

This objective can be formulated in an alternative way: maximizing the minimum value of the difference between the forecasted peak demand and the instantaneous controlled power demand, that is, maximizing the peak demand reduction.

Max Min $\{P\text{-}X_1, P\text{-}X_2, \ldots, P\text{-}X_n\}$

Objective Functions

1. Maximize peak demand reduction

$$Max\ Min\ \{P\text{-}X_1,\ P\text{-}X_2, \ldots,\ P\text{-}X_n\}$$

The optimization of this objective is not a linear problem, but it can be transformed into a linear problem considering a new decision variable *r* as the network peak demand reduction.

Thus, the *max min* problem can be re-written:

$$\begin{aligned} &Max\ r \\ &\text{subject to:} \\ &P - X_i - r \geq 0 \qquad (i = 1, \ldots, n) \qquad (2) \\ &r \geq 0 \end{aligned}$$

Notation:

i Elementary time interval index (*i* = 1, …, n)
P Forecasted network peak demand without control
X_i Average network demand at interval *i* with load control
r Decision variable that represents the network peak demand reduction

Objective Functions

2. Maximize Profit

The optimization of profit is equivalent to maximizing revenue variation caused by electricity consumption variation achieved with the application of control strategies.

Thus, maximizing profit may be stated as:

$$Max \sum_j \sum_k (R_{jk} x_{jk}) \qquad (3)$$

where R_{jk} is given by:

$$R_{jk} = \frac{\Delta t}{60} \sum_i c_{ijk} m_{ij} \qquad (4)$$

ΔT Total control period

Δt Elementary control time interval in minutes.

R_{jk} Profit variation corresponding to the consumption variation in group j when subject to control strategy k

m_{ij} Net revenue perceived by the utility per kWh at interval i by selling energy to group j.

Objective Functions

3. Minimize discomfort

- Measuring discomfort caused by control actions is based on the number of loads for which the minimum comfort threshold has been violated.
- In the case of electric water heating loads, it corresponds to the number of water heaters whose water temperature is below an admissible minimum.
- The lower the number of water heaters that violate the minimum comfort threshold, the higher the quality of service.

Objective Functions

3. Minimize discomfort

Minimizing discomfort caused to consumers corresponds to minimizing the following function:

$$Min \sum_{j} \sum_{k} D_{jk} x_{jk} \qquad (5)$$

where D_{jk} is given by:

$$D_{jk} = \alpha_A A_{jk} + \alpha_B B_{jk} \qquad (6)$$

D_{jk} Measure of discomfort defined as a function of A_{jk} and B_{jk}.

A_{jk} Total number of loads in group *j* whose minimum comfort threshold is violated when subject to control strategy *k*, during the control period.

B_{jk} Maximum number of loads in group *j* whose minimum comfort threshold is simultaneously violated when subject to control strategy *k*, during the control period.

Model constraints

a- One control strategy can be applied, at most, to each load group:

$$\sum_k x_{jk} \leq 1 \qquad (j = 1, ..., m) \qquad (7)$$

b- There is a maximum number of loads that are allowed to violate the minimum comfort threshold. Control strategies that lead to a higher number of loads in such situation are rejected.

$$\sum_k B_{jk} \, x_{jk} \leq b_j \qquad (j = 1, ..., m) \qquad (8)$$

Notation:

bj Maximum number of loads in group *j* that are allowed to simultaneously violate the minimum comfort threshold.

Bjk Maximum number of loads in group *j* whose minimum comfort threshold is simultaneously violated when subject to control strategy *k*, during the control period.

xjk Binary decision variable that assumes the value 1 if control strategy *k* is selected to be applied to group *j*, and 0 otherwise.

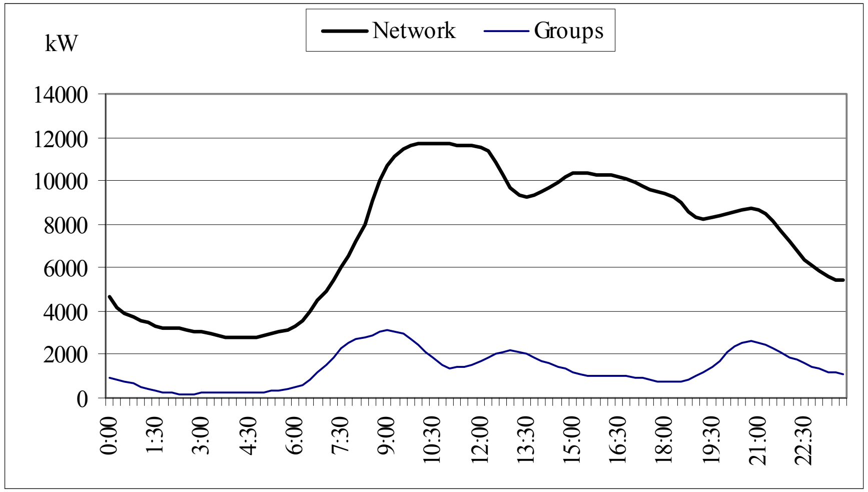
Case study

4000 water heaters aggregated into 8 groups are considered. Each group has 500 water heaters and is associated with several typical households each one characterized by a water consumption pattern.

A computer application using a physically-based load model has been used to generate the group load curves with and without remote control actions.

In next figure the network load curve is displayed. The network peak demand is 11750 kW at 10:30.

Without control actions, the load curve pertaining to all groups has a peak demand of 3110 kW at 9:00.



Network and total group load curves

Case study

- Discomfort is measured through the number of water heaters that violate the minimum comfort threshold. This condition is violated whenever the water temperature inside the tank is below 45 ºC (113 ºF).
- Eight control strategies have been generated for each load group by using a PBLM (physically-based load modeling). The computational load model has also been used to determine the impact of the different load control strategies on customers' discomfort and on load group curves

Notes:

- The information on the electricity consumption of the load groups and on hot water temperatures with or without the application of the control strategies to the load groups is obtained with a **physically-based load model** (Gomes and Martins, 1995).
- The network load diagram is assumed to be known by means of a load forecast procedure.

Analysis of the load management model using the MCILP software package

- The study of the model using the STEM method was reported in Jorge et al. (2000).
  - The problem corresponds to 4000 water heaters aggregated into 8 groups. It includes 65 variables (64 binary variables x_{jk} more variable *r*)
- In that study, the payoff table was firstly computed.
  - Note that the constraints of the model (of type "=") force that one strategy control is selected for each group. If it was considered constraints "≤", the optimal solution for F3 (which minimizes the discomfort caused to consumers) would not establish any control strategy, leading to (F1, F2, F3) =(0, 0, 0)

	Max. F1 (KW)	Max. F2 (PTE)	Min. F3	Control Strategies							
Optimal solution F1	**514**	8108	4420	1	2	8	3	2	2	2	2
Optimal solution F2	293	**15402**	7360	8	8	8	8	8	8	8	8
Optimal solution F3	17	2976	**980**	6	3	3	6	6	3	6	7

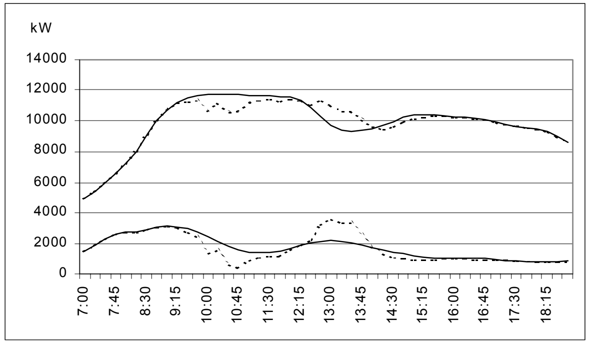
control strategies are identified by a number that represents the control strategy in each group (from 1 to 8).

Solutions computed by STEM method

- The first solution computed by STEM method was solution STEM-1
- Then, the decision maker decided to relax F2 by 3500 in order to improve the other objective functions
  - the STEM method computed solution STEM-2.
- The interactive process proceeded in the same way until the decision maker considered solution STEM-5 a satisfactory compromise solution.

	Max. F1 (KW)	Max. F2 (PTE)	Min. F3	Control Strategies							
Solution STEM-1	125	12607	4030	7	8	8	2	8	8	1	1
Solution STEM-2	364	9265	2450	7	4	6	4	2	8	1	2
Solution STEM-3	293	8072	1910	7	3	2	4	6	8	5	1
Solution STEM-4	310	8001	2100	2	4	4	2	2	8	1	1
Solution STEM-5	319	10255	2810	7	7	7	2	8	7	1	1

Due to the limitations of STEM method, it was not possible to make a comprehensive search of the nondominated solution set.



Solution STEM-5

The MCILP software

- Is based on an interactive reference point procedure for Multicriteria Integer (and mixed-integer) Linear Programming (MCILP)
  - It combines Chebychev scalarizing programs with branch-and-bound techniques (Alves and Clímaco, 2000).
  - It is mainly devoted to perform directional searches, for which the decision maker only has to specify the criterion he wants to improve with respect to the previous nondominated solution.
- This software also provides the visualization of indifference sets of reference points for tricriteria (or bicriteria) integer programs (Alves and Clímaco, 2001).
  - As nondominated solutions are a discrete set in multiobjective integer programming, there are multiple reference points that lead to the same solution, i.e. there are indifference regions on the reference point space.
    - A sensitivity analysis procedure provides the foundations to calculate approximation of those regions with a small computational effort.

The MCILP software - *indifference regions*

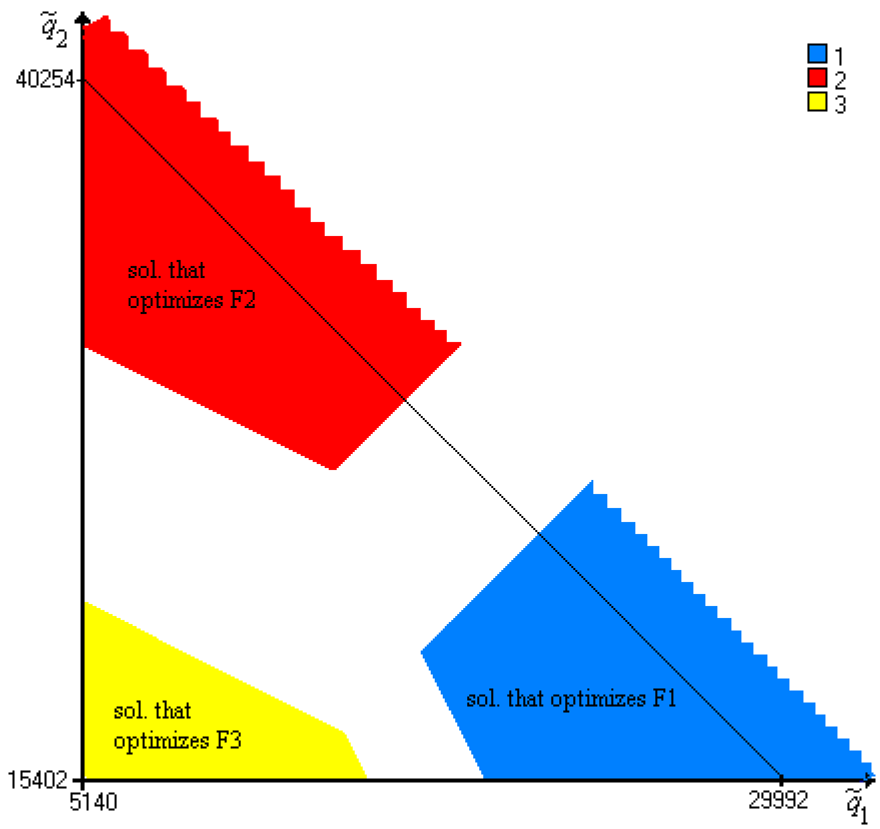
- Let (q_1, q_2, q_3) denote a reference point for a tricriteria problem
  - it belongs to the $\Re^3$ space
- We say that a reference point $q^a = (q_1^a, q_2^a, q_3^a)$ ***leads*** to the nondominated solution x^a if x^a optimizes the scalarizing program (being q^a the RHS vector of parameters):

$$\begin{array}{lll} \min & \alpha - \varepsilon_i \sum_{i=1}^{3} f_i(x) & \\ \text{s.t.} & f_i(x) + \alpha \geq q_i & i=1,\ldots,3 \\ & x \in X & \end{array}$$

- If both q^a and q^b *lead* to x^a, then q^a and q^b belong to the indifference region of x^a
- Moreover, and independently of the problem, (q_1, q_2, q_3) and (q_1+d, q_2+d, q_3+d) with d real, lead to the same nondominated solution.
  - So, if an appropriate constant S is chosen, such that $q_1+q_2+q_3=S$, the 3D graph of indifference regions can be visualized on a 2D graph, which improves the legibility.

The analysis of the load management problem

- We started by computing the 3 solutions that optimize individually each objective function, presented above
  - these are denoted by solutions 1, 2 and 3, respectively.
- The indifference regions computed for the first 3 solutions are presented in the figure.
- Note that:
  - since F3 is a minimizing function, the symmetric of F3 is considered for scalarizing purposes;
  - F1 has been rescaled to F1x10;
  - hence, an original reference point is transformed into (q_1x10, q_2, - q_3). The graph of indifference regions considers the transformed points .



The first directional search

- A directional search was performed starting from a reference point that leads to **solution that optimizes F2** and **choosing F3** to be improved, in order to diminish the consumers' discomfort.
- Several nondominated solutions were computed throughout this directional search, until we decided to **change the direction** because most of these solutions present very low values of reduction on the peak demand (F1).

	Max. F1 (KW)	Max. F2 (PTE)	Min. F3	Control Strategies							
Solution 4	183	14652	7240	8	8	8	8	8	7	8	8
Solution 5	94	14294	6930	8	8	8	8	7	8	8	8
Solution 10	11	13228	4870	8	8	8	2	2	6	2	8
Solution 11	51	13133	4430	4	8	8	1	8	6	8	8
Solution 20	44	11345	2770	7	7	7	6	8	6	1	8
Solution 21	44	11196	2610	7	7	1	6	8	6	1	8
Solution 27	44	10088	2180	7	7	1	6	7	6	1	8
Solution 28	126	10069	2170	7	3	1	4	2	6	3	8
Solution 29	16	10068	2140	7	3	1	6	8	6	5	8
Solution 30	16	9977	2110	7	4	6	4	3	6	1	8
Solution 31	126	9770	1990	7	3	1	4	3	6	1	8

The following directional searches (1)

- The search was redirected **to improve F1**.
  - The already known solution 28 was firstly presented;
  - new solutions were then computed (from solution 32 to 36).
    - Solution 36 is identical to solution STEM-2
- At this moment we considered that F1 had a reasonable value. Besides, values for F1 that satisfy F1 ≥300 would also be acceptable.

	Max. F1 (KW)	Max. F2 (PTE)	Min. F3	Control Strategies							
Solution 32	211	9644	2250	7	7	1	2	6	8	1	1
Solution 33	262	9776	2500	7	4	6	4	8	8	1	1
Solution 34	293	9497	2530	7	7	1	1	8	7	5	1
Solution 35	293	9679	2610	7	3	2	4	8	8	3	1
Solution 36 =Sol.STEM-2	364	9265	2450	7	4	6	4	2	8	1	2

The following directional searches (2)

- So, **F1 ≥ 300** was imposed and a **new search was performed in order to improve F2** (profits):
  - Solution 37 was computed and new solutions - from 38 to 41 - followed it.
    - As expected, all of them present a peak reduction of at least 300KW and growing values on profits.
    - Solution 39 is identical to solution STEM-5.

	Max. F1 (KW)	Max. F2 (PTE)	Min. F3	Control Strategies							
Solution 37	331	9646	2690	7	7	7	1	8	7	5	1
Solution 38	319	9744	2760	7	7	7	2	2	7	1	2
Solution 39=Sol.STEM-5	319	10255	2810	7	7	7	2	8	7	1	1
Solution 40	300	10288	2960	7	7	7	2	8	8	4	1
Solution 41	362	10415	3130	7	7	7	1	8	6	5	2

- As solution 39 = solution STEM-5 was considered a satisfactory compromise solution, we decided to make a **local analysis** around the last solutions obtained.

Local analysis

- The value of F3 was considered too high in solution 41. So, the following bound was imposed:
  - **F3 ≤ 3000** (which is not satisfied by solution 41)
  - Also, it was imposed **F2 ≥ 10200**,
  - maintaining **F1 ≥ 300**.
- The nondominated solution closest to the last reference point (which led to solution 41) that satisfies these additional constraints is **solution 40**.
- The **improvement of F1**, within the same constraints, leads to **solution 39**.
- Relaxing the bound on F2 to **F2 ≥ 10000**, and keeping the other bounds, the outcome for the same reference point **is also solution 39**.
- Moreover, if F1 is chosen to be improved from this point, and maintaining the previous bounds, the procedure announces:

  ⓘ No better value for F1 is possible!
- Identical message is shown if F3 is chosen to be improved.

➢**This region of nondominated solutions was completely explored.**

The main window of the system

The figure shows the main window of the system with bar graphs for the last three solutions presented to the decision maker:

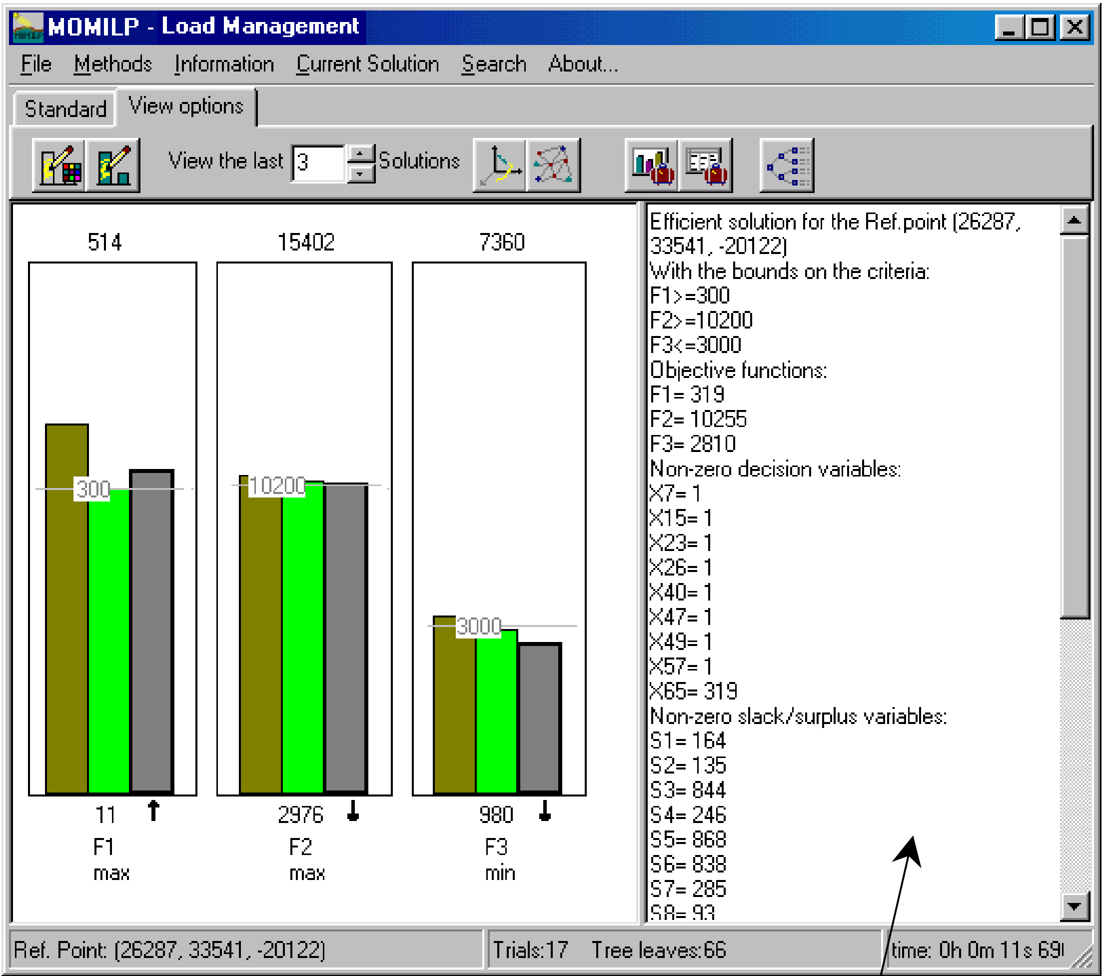
solution 41 (olive)

solution 40 (green)

solution 39, (grey)

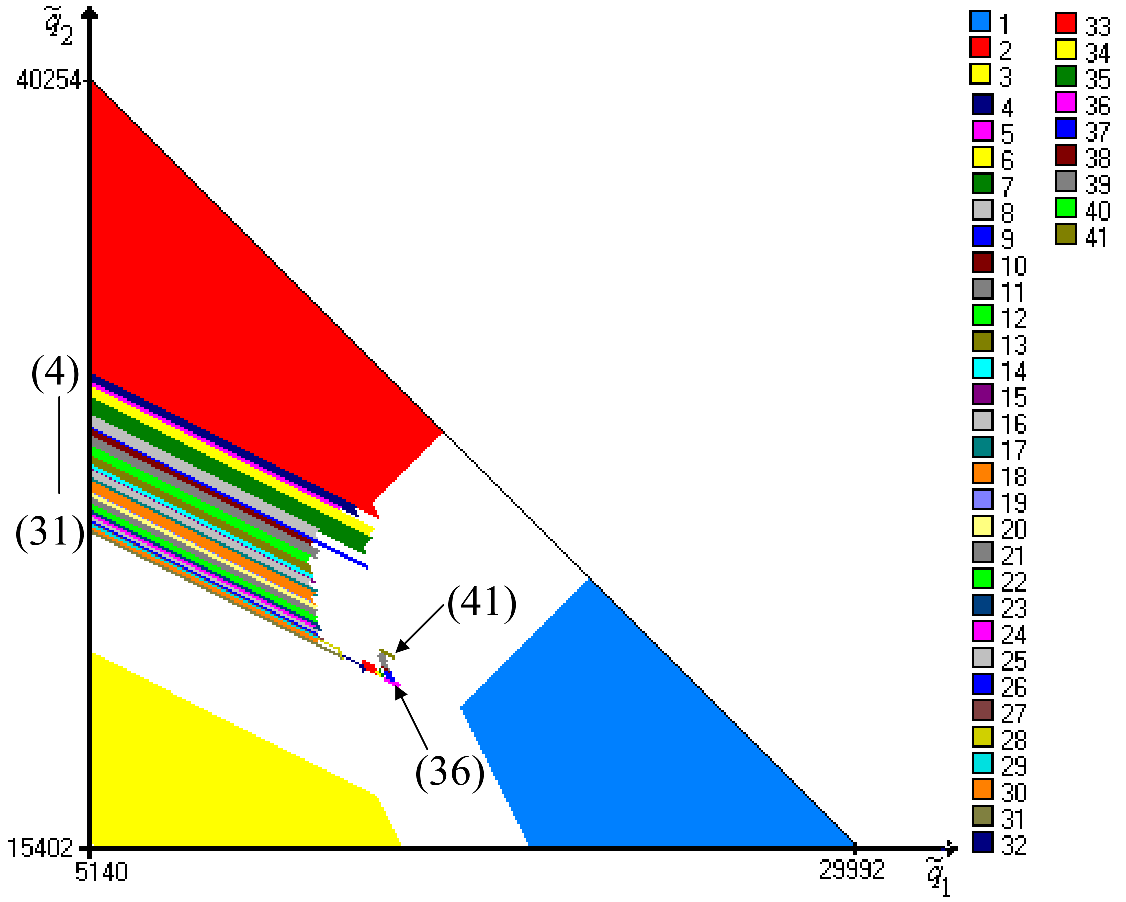
respectively,

and numerical information of solution 39.



Indifference regions for the known solutions

The indifference regions on the reference point space for all nondominated solutions computed are shown in the next figure.



Summary

- The above described analysis of the load management problem **is just an example** of a sequence of directional searches that could be followed.
- Since this software enables a **free exploration** of the problem, many other search strategies could be performed, providing more information about the problem.
- We may further expect that the nondominated set contains a large number of solutions, as suggested by the **unfilled areas** in the graph of indifference regions on the reference point space.
- In fact, from a deeper analysis of this problem, we realized that **more than 200 nondominated solutions exist for this problem**.
- Curiosities:
  - among those 200 solutions only 39 are nondominated supported solutions;
  - in what concerns the above search for 41 solutions, 12 of them are supported and 29 are unsupported solutions.

Conclusions (1)

- The use of this type of search, combined with the graphical display of indifference regions, can **provide important information** to the decision maker (DM).
- When compared with the STEM method, the following **advantages** can be pointed out:
  - Remember: In STEM method, the DM specifies a relaxation quantity for one criterion, in each interaction, in order to improve the others. However, the DM has not the possibility of choosing one criterion he would desire to be privileged in the following computation(s).
  - Instead, following directional searches the DM can **choose the criterion he wants to improve at each moment**, having also the possibility of **imposing constraints** on the criterion values.
  - These **constraints may be revised** whenever the decision maker wants, by relaxing or tightening the bounds.
  - If a **local analysis** is made - which may be useful in a final phase of the decision process - the DM can easy conclude whether a **region of interest is completely explored** or not.

Conclusions (2)

- Successive solutions obtained throughout directional searches can give a good **perception of the geometry of the problem**.

  There exist "consecutive" solutions that present similar values for all the objective functions, but there are others that present very different values in one (or more) objective(s), and the DM can perceive these asymmetries
  - An example of the first situation is the transition from solution 21 to 22:
    - F1 maintains its value;
    - F2 diminishes 1.5%;
    - F3 improves 3.8%.

    These solutions have close values for all the objective functions.
  - An example of the second situation is the transition from solution 27 to 28:
    - F1 improves 186%;
    - F2 diminishes 0.12%;
    - F3 improves 0.46%

    Solution 28 can be easily considered superior to solution 27.
- The **indifference regions** give an **idea of stability degrees** of the nondominated solutions with respect to the improvement of one criterion.