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DOR(CAM) RESEARCH NOTE 2000/11

SATISFYING REQUIREMENTS AT MINIMUM COST : LINGO IMPLEMENTATION OF A LINEAR PROGRAMMING SELECTION MODEL

BY

Y. GAUTHIER
and
DR P.F. O'NEILL

DECEMBER 2000

OTTAWA, CANADA

National Defence / Défense nationale

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Recommended by: Dr. Paul Desmier, DASOR

Approved by: J.G. Moscrip, DOR(CAM)

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ABSTRACT

The model described in JSORT Research Note RN 9605, "Satisfying Requirements At Minimum Cost: Methodology With Application To Unit Level STANO Requirements", was implemented using LINGO® optimisation software. The solution it provides is the lowest cost set of equipment that meets all the requirements of different mission elements. The LINGO® model was interfaced with two Microsoft Excel® spreadsheets in order to simplify its use. Although the model was implemented for equipment selection problems, it can be applied to a broad range of selection problems. In this research note, a description of the selection model is given. The procedure to use this model with LINGO® is then explained in detail.

RÉSUMÉ

La model décrite dans la note de recherche RN 9605 de l'EROI, « Satisfying requirements at minimum cost : methodology with application to unit level STANO requirements », a été implémentée à l'aide du logiciel d'optimisation LINGO®. Cette méthodologie permet de déterminer la configuration de plusieurs équipements étant la moins coûteuse et permettant de remplir toutes les conditions reliées différentes missions. Le modèle LINGO® a été interfacé avec deux feuilles de calcul MS-Excel® de manière à simplifier son utilisation. Malgré que le modèle ait été implémenté pour la sélection d'équipements, il pourrait aussi être utilisé pour résoudre une vaste gamme de problèmes de sélection. Dans cette note de recherche, un résumé du modèle est d'abord présenté. La procédure d'utilisation du modèle LINGO® est ensuite expliquée en détails.

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SATISFYING REQUIREMENTS AT MINIMUM COST: LINGO IMPLEMENTATION OF A LINEAR PROGRAMMING SELECTION MODEL

INTRODUCTION

1. This research note describes a numerical optimisation model for the analysis of military requirements. The formulation of the model was originally put forward by Dr. PF O'Neill in [1] as a generalisation of the *Minimum Cover Problem* [2] in order to optimise a particular equipment acquisition problem for Surveillance, Target Acquisition and Night Observation (STANO) at the unit level. However, the model can be applied to a broad class of selection problems of a hierarchical nature.

2. Essentially, the *selection problem*, as defined in [1], is the following:

> *given a set of tasks and implied tasks to be accomplished and a collection of equipment configurations such that each configuration is adequate to accomplish at least one of the tasks and implied tasks, what is the lowest cost set of equipment that can complete all of the tasks and implied tasks?*

3. In [1], the problem was solved by means of the SOLVER tool in Microsoft Excel®. However, this is unsatisfactory for problems with a large number of variables. Insofar as new equipment acquisition problems that involve a relatively large number of variables will have to be solved by the CF in the near future, a more capable implementation is required. For example, different types of equipment will be purchased for Intelligence, Surveillance, and Reconnaissance (ISR) and this equipment will have to fulfil numerous ISR requirements for the maritime, land, and air environments.

4. In order to be dealt with effectively, this class of problems will require fast and reliable numerical software. This has motivated the implementation of the selection problem using LINGO® optimisation software. This is special-purpose software for linear programming. Further, a user interface between LINGO® and Microsoft Excel® has also been created in order to facilitate the use of the software.

5. The purpose of this research note is to describe the selection model itself and then to present its implementation using LINGO®. A step-by-step procedure for the use of the model is then given. Finally, other uses of the model for different kinds of selection problems are presented.

THE SELECTION MODEL

6. The aim of the linear programming model described in [1] is to minimise the cost of equipment satisfying all the requirements for a defined set of tasks and implied tasks. An overview of the model is shown in Fig. 1. Its components are:

- *tasks and implied tasks;* describing the intended use of the equipment, the intended missions for the equipment or the conditions under which the equipment is used;
- *equipment types;* referring to the individual systems that can be utilised to assist with the different tasks, implied tasks and mission elements;
- *configurations;* (of equipment which) are collections of equipment types put together in order to satisfy one or more tasks, implied tasks or mission elements;
- *costs;* of equipment which include all costs that are relevant to the systems under consideration.

7. The costs of equipment can be separated in two categories: *variable* cost and *fixed* cost. The *variable cost* C_i of an equipment type i is the total of all the costs relevant to a particular system per unit of equipment. On the other hand, the *fixed cost* F_i of an equipment type i is the set-up cost, or the total cost related to the acquisition of at least one unit of a given system. The total cost of the equipment, i.e. the quantity that must be minimised in the selection problem, is given by:

$$\text{total cost of equipment} = \sum_{i=1}^{n} C_i y_i + \sum_{i=1}^{n} F_i z_i \qquad (1)$$

where

- n is the number of equipment types;
- y_i is the minimum number of units of an equipment i that is required to satisfy all the tasks and implied tasks, taken over all of the mission elements;
- z_i include/exclude fixed costs for equipment type i;

$$z_i = \begin{cases} 1 & \text{if } y_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

8. In the selection problem, the minimisation of the total cost is subject to a number of constraints. First, the selected configurations of equipment must fulfil *all of* the tasks and implied tasks. Mathematically, this can be expressed as:

$$\sum_{k=1}^{l} U_{jk} x_k \geq 1 \qquad (1 \leq j \leq m) \tag{2}$$

where:

U_{jk} is the *utility* of configuration k for mission j;

$$U_{jk} = \begin{cases} 1 & \text{if configuration } k \text{ fulfils the requirements of mission element } j \\ 0 & \text{otherwise} \end{cases}$$

l is the number of equipment configurations;
m is the number of mission elements;
x_k $1 \leq k \leq l$ include/exclude the configuration k;

$$x_k = \begin{cases} 1 & \text{if configuration } k \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

In other words, each mission element must be satisfied by at least one of the equipment configuration(s) that will be kept at the end of the selection process.

10. Furthermore, in order to be able to satisfy all the mission requirements, a minimum quantity of equipment is needed. This constraint can be expressed by the following equation:

$$y_i \geq Q_{ik} x_k \qquad (1 \leq i \leq n, 1 \leq k \leq l) \tag{3}$$

where Q_{ik} is the number of units of equipment i in configuration k. On the other hand, one can set an upper limit M on the number of units for any equipment type, such that :

$$y_i \leq M \qquad (1 \leq i \leq n). \tag{4}$$

11. Finally, for some applications, certain equipment configurations may be incompatible. For example, two systems in different configurations may be problematic in terms of functioning together, such that both configurations cannot be part of the solution. In other cases, even if two equipment types are under consideration to be purchased, maybe only one of them can ultimately be purchased so the pairing of their respective configurations is not feasible. This forbidden pairing of two configurations i and j can be written as :

$$x_i + x_j \leq 1 \qquad (x_k \in \{0,1\}, 1 \leq k \leq l). \tag{5}$$

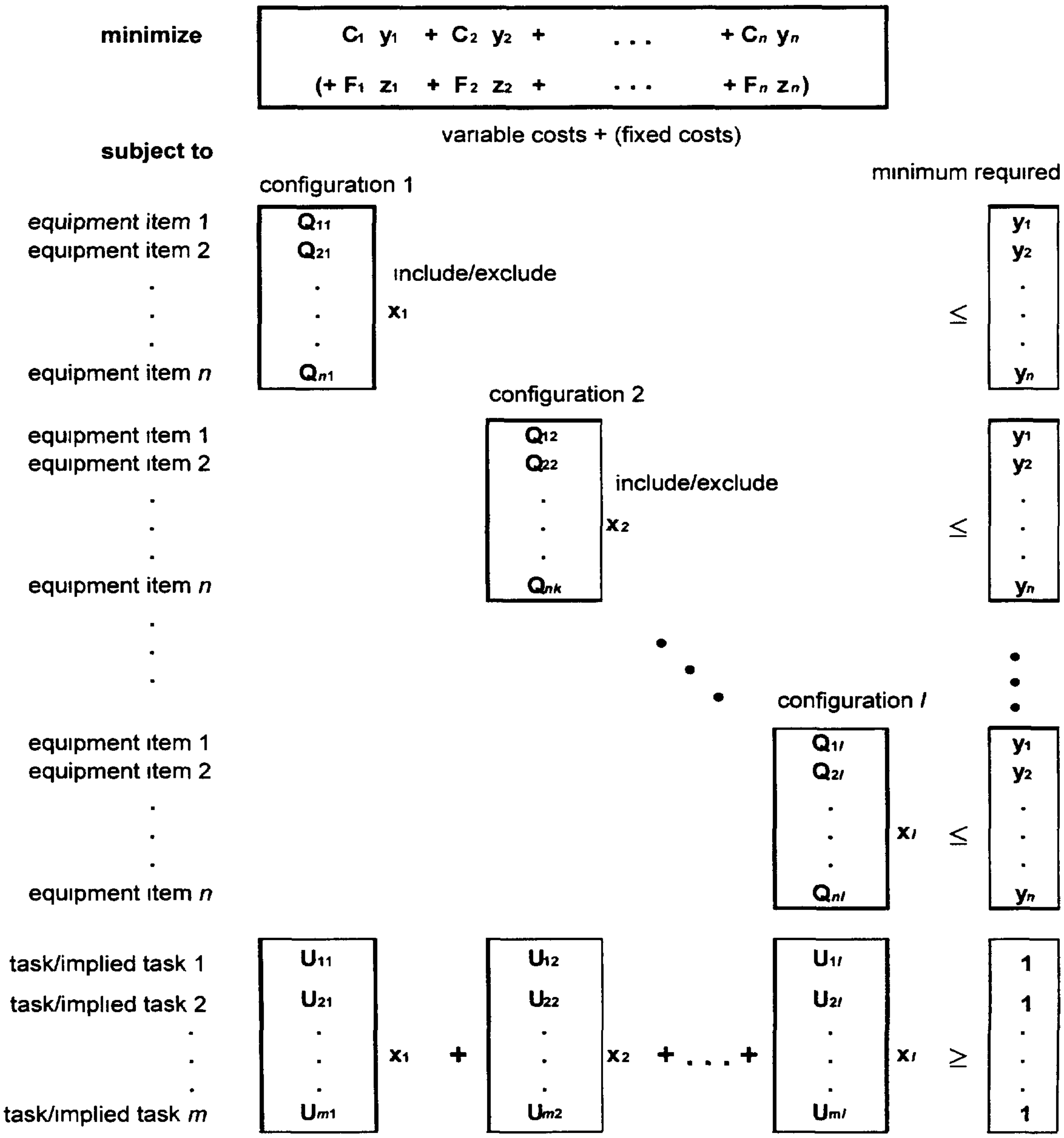
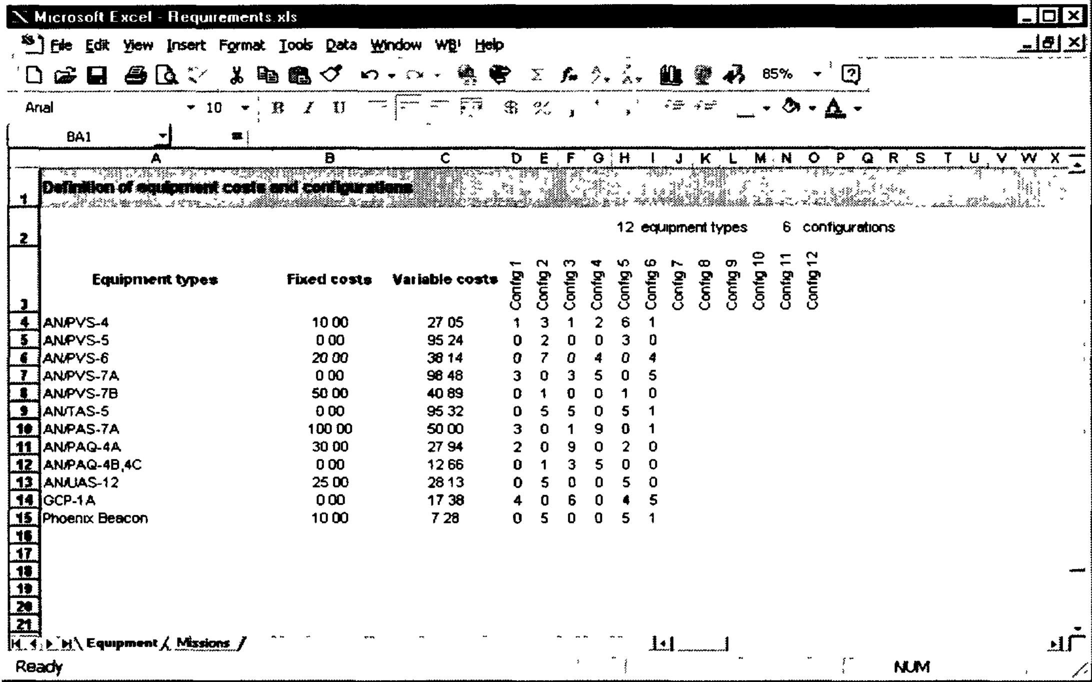


Figure 1. The Selection Problem showing the logic of the variables and constraints The n equipments are grouped into l configurations represented by the first $n \times l$ constraints where the Q values contain the number of each equipment which is needed in the corresponding configuration. The sufficiency of each configuration for each of the m tasks/implied tasks is represented by the last m constraints, where the appropriate U value is set at 1 if the corresponding configuration is sufficient to accomplish the respective task/implied task, or 0 otherwise. The x variables determine which configurations are chosen; the y variables record the number of each type of equipment that is required.

LINGO® IMPLEMENTATION

12. The model described in [1] for solving the selection problem was initially coded in Microsoft Excel® using the SOLVER tool in order to demonstrate the utility of the model and to estimate its running time. However, only a small number of constraints can be coded in SOLVER and this limits the size of the actual problem that can be solved. Moreover, the speed and the reliability of the SOLVER code are not suitable for selection problems with a large number of variables. For all these reasons, it has been decided to replace the SOLVER tool of Microsoft Excel® by LINGO 6.0® (LINDO Systems inc., Chicago, IL). This is special-purpose linear programming software which is more reliable and dramatically faster than SOLVER for the class of problems considered here.

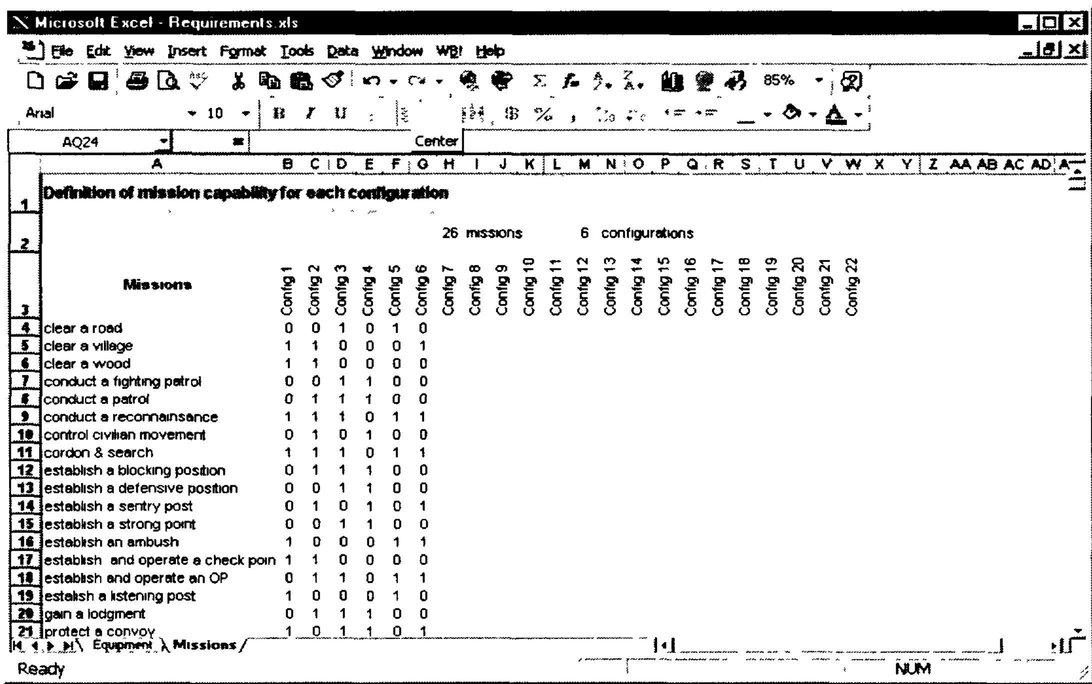
13. The LINGO implementation of the selection problem is described in Annex A. In order to facilitate the handling of data and the presentation of results, the model was interfaced with two



Definition of equipment costs and configurations

12 equipment types 6 configurations

Equipment types	Fixed costs	Variable costs	Config 1	Config 2	Config 3	Config 4	Config 5	Config 6	Config 7	Config 8	Config 9	Config 10	Config 11	Config 12
AN/PVS-4	10 00	27 05	1	3	1	2	6	1						
AN/PVS-5	0 00	95 24	0	2	0	0	3	0						
AN/PVS-6	20 00	38 14	0	7	0	4	0	4						
AN/PVS-7A	0 00	98 48	3	0	3	5	0	5						
AN/PVS-7B	50 00	40 89	0	1	0	0	1	0						
AN/TAS-5	0 00	95 32	0	5	5	0	5	1						
AN/PAS-7A	100 00	50 00	3	0	1	9	0	1						
AN/PAQ-4A	30 00	27 94	2	0	9	0	2	0						
AN/PAQ-4B,4C	0 00	12 66	0	1	3	5	0	0						
AN/UAS-12	25 00	28 13	0	5	0	0	5	0						
GCP-1A	0 00	17 38	4	0	6	0	4	5						
Phoenix Beacon	10 00	7 28	0	5	0	0	5	1						



Definition of mission capability for each configuration

26 missions 6 configurations

Missions	Config 1	Config 2	Config 3	Config 4	Config 5	Config 6	Config 7	Config 8	Config 9	Config 10	Config 11	Config 12	Config 13	Config 14	Config 15	Config 16	Config 17	Config 18	Config 19	Config 20	Config 21	Config 22
clear a road	0	0	1	0	1	0																
clear a village	1	1	0	0	0	1																
clear a wood	1	1	0	0	0	0																
conduct a fighting patrol	0	0	1	1	0	0																
conduct a patrol	0	1	1	1	0	0																
conduct a reconnainsance	1	1	1	0	1	1																
control civilian movement	0	1	0	1	0	0																
cordon & search	1	1	1	0	1	1																
establish a blocking position	0	1	1	1	0	0																
establish a defensive position	0	0	1	1	0	0																
establish a sentry post	0	1	0	1	0	1																
establish a strong point	0	0	1	1	0	0																
establish an ambush	1	0	0	0	1	1																
establish and operate a check poin	1	1	0	0	0	0																
establish and operate an OP	0	1	1	0	1	1																
estalish a listening post	1	0	0	0	1	0																
gain a lodgment	0	1	1	1	0	0																
protect a convoy	1	0	1	1	0	1																

Figure 2. REQUIREMENTS XLS spreadsheet with the definition of equipment costs and configurations (top) and the definition of mission capabilities (bottom).

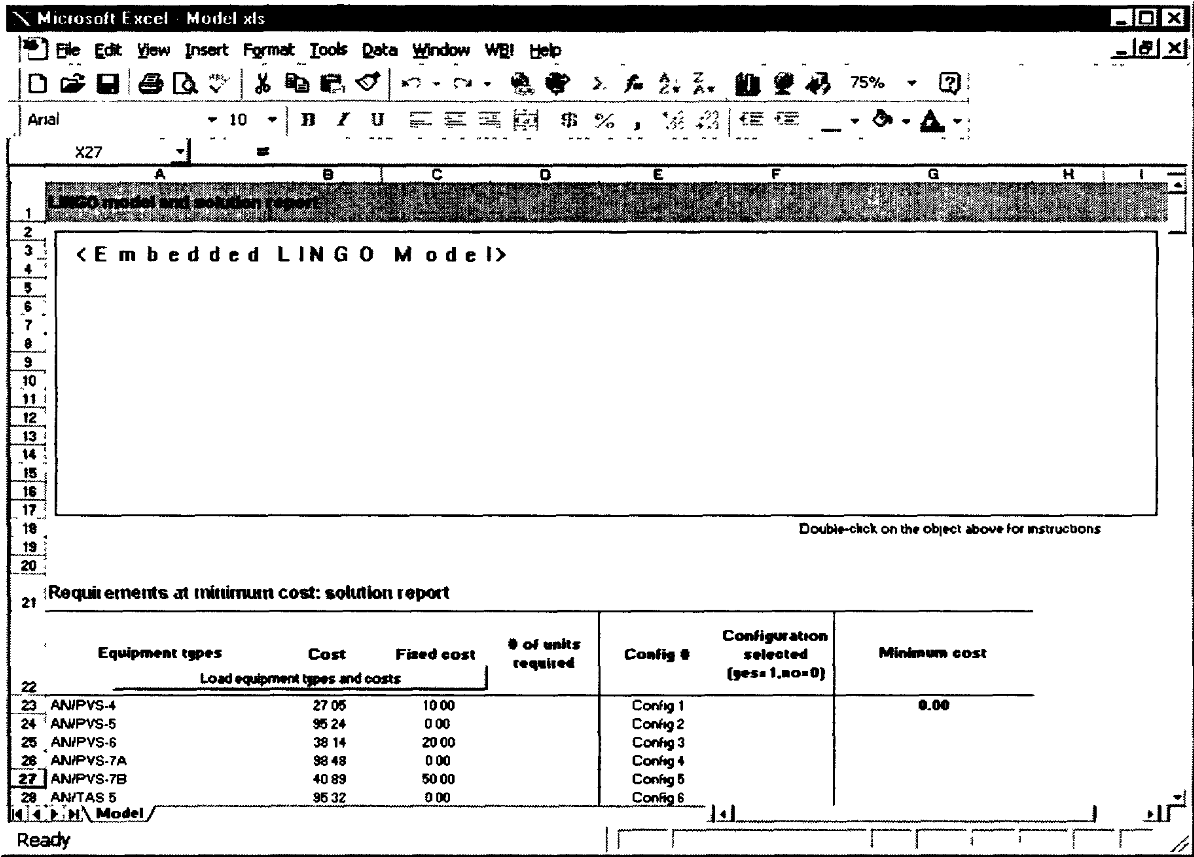


Figure 3. MODEL.XLS spreadsheet with the embedded LINGO® model.

MS-Excel spreadsheets. The first one, called REQUIREMENT.XLS, contains the input data of the model. As shown in Fig. 2, the equipment types, costs and configurations are defined in this sheet. The mission elements and the utility of each configuration for these mission elements are also defined in this file.

14. The second spreadsheet, shown in Fig. 3, is called MODEL.XLS and contains the selection model itself. The sheet is divided in 2 areas. At the top of the page is embedded the LINGO® control object which links into the linear programming code. Activating this object, by double-clicking on it, brings up the LINGO® task bar and generates the solution report area. This is where the optimal parameters appear once the LINGO® code has been executed and it can be used to produce solution reports once the code has been run.

INSTRUCTIONS FOR THE USE OF THE LINGO® MODEL

15. Open the REQUIREMENTS.XLS spreadsheet. Click on the "Equipment" thumbnail and enter the equipment types and the equipment costs (fixed and variable) in the appropriate columns. If no

fixed cost is associated with a particular equipment type, simply enter 0. Enter also the number of equipment units related to each configuration. Then click on the "Missions" thumbnail and enter all the configuration capabilities for each mission element. If a given configuration satisfies the requirements of a particular mission element, enter 1. Otherwise, enter 0.

16. Now, open the MODEL.XLS spreadsheet and click on the "Load equipment types and costs" button. This will prepare the spreadsheet to receive the results from the LINGO®. It will also to rename automatically some data ranges in both spreadsheets in order to link them with LINGO®.

17. By this point, everything is in place to solve the selection problem. However, for some applications, it may be necessary to exclude the simultaneous selection of certain pairs of configurations (e.g. if two configurations make use of equipment types that are mutually incompatible). Currently, the disjunctions between forbidden pairs of configurations, expressed by Eq. 5, are explicitly programmed in the LINGO® code. Accordingly, the user must verify the "Exclusive Disjunctions" section at the end of this code before using it. To do this, double-click on the LINGO® object in order to verify or change the code. For example, if the configurations 1 and 4 cannot be both selected in the solution, then enter the following line:

```
X(1) + X(4) <= 1;
```

If only one of configurations 1, 4 and 7 is allowed, then enter:

```
X(1) + X(4) + X(7) <= 1;
```

Note that more than one pair restriction can be entered if it is necessary.

18. Finally, to run the code, double-click on the LINGO® object and simply  press or select "Solve" from the LINGO® menu. The number of equipment unit required, the configuration selected and the minimum cost should appear in the solution report.

SOLUTION TIME

19. The computational complexity of the selection problem grows exponentially in the number of equipment configurations, quadratically in the number of equipment types and linearly in the number of mission elements [1]. Therefore, the number of configurations under study is the most significant factor in the solution time and the resolution of problems with a large set of equipment configurations might become very onerous in CPU time.

20. To illustrate this, about a dozen of trials were generated by filling the requirement spreadsheet with random data. On average, it took 4 seconds to solve a selection problem involving 8 configurations of 12 equipment types on a Pentium II running at 333 MHz. With 8 additional configurations, the solution time increased to 24 seconds. At this rate, a rough estimate of the time necessary to choose from 100 configurations would be approximately 2 hours.

21. A limit can be placed on the amount of time the LINGO® solver runs. Simply select *LINGO|Options|GeneralSolver* and set the runtime limit in seconds. If the solver hits this limit, it will stop and the best solution found so far will be returned in the solution report area. A window will also pop-up to warn the user that this solution may not be the optimal one.

REDUCING THE SOLUTION TIME

22. The model used here is an integer model, i.e. all the variables are contrained to take only integer values. To solve this kind of model, LINGO® uses a "branch and bound method", (*i.e.* tree search method), [3]. The LINGO® software systematically searches through the feasible solutions of the problem, keeping track of the best one yet found as it searches. Because the number of potential solutions it may need to explicitly check is exponentially large, the solution time of the problem might be quite long. Nevertheless, it is possible to narrow the search for the minimum cost by setting a *hurdle* value in LINGO®. By setting a hurdle, the software will skip branches of the search tree which cannot provide a solution which is at least as good as the hurdle value. In this way, the solution space will be reduced and so the solution time will be reduced.

23. If the selection problem is relatively large, it is a good strategy to place a runtime limit (e.g. 1-hour) before starting the solver. When LINGO® hits the time limit, the best solution found so far can be used as a hurdle and the code rerun. Because the software will then reduce the search space, the efficiency of the second run will be increased. To set the hurdle value, select *LINGO|Options|Integer Solver* and adjust the HURDLE tolerance to the maximum cost allowed, i.e. the lowest cost found at the end of the first run.

FUTURE USE OF THE MODEL

24. The selection model will be employed in the next few months for the resolution of different equipment acquisition problems. One of these problems will be to find the lowest cost set of equipment satisfying the ISR capabilities required by the sea, land, and air forces. Provided a list of the national ISR requirements, and also given several configurations of equipment (radar's, UAV's, etc.) such that each configuration provides at least one ISR capability, the selection model will identify, if it exists, the most affordable set of configurations that answers all the ISR needs. Note that if there is equipment configurations that are incompatible with each other, this will be taken into account during the selection process.

25. Even if the implementation of the selection model has been done in an effort to solve problems related to equipment acquisition, the model presented here can be applied to a broader class of selection problems. For instance, such problems could be:

- selection of personnel by ranks and MOC to be included in a military unit in order to minimise the total personnel costs or the total number of personnel;

- selection of alternative activities to achieve personnel training or equipment maintenance objectives with minimum cost;
- selection of equipment with the objective to minimise the total weight or the total volume of equipment.

26. Furthermore, the methodology used in the model could also be applied to situations where the selection process consists to *maximise* a certain quantity (e.g. profit, years of experience, equipment autonomy) since every minimisation problem can be viewed as a maximisation problem and conversely. That is, to maximise a certain quantity one can minimise its negative instead and then change the sign of the final answer.

CONCLUSIONS

27. This research note has described a linear programming model that finds the lowest cost set of equipment that meets the minimum requirements of a series of mission elements. The model was implemented with the LINGO® software and has been interfaced with MS-Excel to facilitate its use.

28. The computational complexity of the selection model is potentially time-consuming. Nevertheless, the model should be able to handle most equipment acquistion problems within the CF in a reasonable amount of time.

29. Although the linear programming model was implemented in terms of equipment selection, other sorts of selection problems could be addressed without any modification of the program besides minor changes to the spreadsheets.

LIST OF REFERENCES

1. O'Neill P.F., *Satisfying Requirements At Minimum Cost: Methodology With Application To Unit Level STANO Requirements*, JSORT Research Note RN 9605, October 1996

2. Garey, Michael R. and Johnson, Davis S., *Computers and Intractability: A Guide to the Theory of NP-Completeness*, W.H. Freeman and Company, San Francisco, 1979

3. *LINGO User's Guide*, LINDO Systems inc., Chicago IL, 1999

LINGO model

```
MODEL:
  !---------------------;
  ! Define the data sets;
  !---------------------;
  DATA:
       ! Verify that the number of configurations in the "Equipment" and "Missions"
       sheets are both the same;
       N_CONFIG1 = @OLE ('REQUIREMENTS.XLS','L');
       N_CONFIG2 = @OLE ('REQUIREMENTS.XLS','L_2');
  ENDDATA
  @WARN('The number of configurations is not the same in Equipment and Missions sheets
        are not the same.', N_CONFIG1 #NE# N_CONFIG2);

  SETS:
       CONFIGURATIONS / 1.. N_CONFIG1 /:
              X;              ! Include/Exclude (0 or 1) configuration k;
       EQUIPMENTS:
              C,              ! Total of any variable cost per unit of equipment i;
              F,              ! Total of all fixed cost per unit of equipment i;
              Z,              ! Include/exclude (0 or 1) fixed costs for equipment i;
              Y;              ! Minimum number of units required to satisfy each of the
                                individual mission elements, taken over all of the mission
                                elements;
       EQCNF_MATRIX(EQUIPMENTS,CONFIGURATIONS):
              Q;    ! Number of units of equipment i in config k;
       MISSIONS;
       UTILITY(MISSIONS,CONFIGURATIONS):
              U;    ! Utility of config k in mission element j;
  ENDSETS

  DATA:
       ! Import the equipment data from REQUIREMENTS.XLS spreadsheet;
       EQUIPMENTS,C,F,Q = @OLE('REQUIREMENTS.XLS','Equipment','Costs',
                               'Fixed_costs','Q_Matrix');

       ! Import the mission data from REQUIREMENTS.XLS spreadsheet;
       MISSIONS,U = @OLE ('REQUIREMENTS.XLS','Missions','U_Matrix');

       M = 1000;  ! Largest number of units in any configuration;
  ENDDATA


  !----------------------------------------------------------;
  ! Restrict some variables to binary values or integer values;
  !----------------------------------------------------------;
  ! Restrict X, Z and U elements to Yes/No decisions;
  @FOR(UTILITY: @BIN(U));
  @FOR(CONFIGURATIONS: @BIN(X));
  @FOR(EQUIPMENTS: @BIN(Z));

  ! Number of units of equipment can only take integer values;
  @FOR(EQCNF_MATRIX: @GIN(Q));
  !@FOR(EQUIPMENTS: @GIN(Y));      !Integrality constraint facultative
```

```
!----------------------------;
! Implementation of the model;
!----------------------------;
! Define the Z values depending if there is at least one unit required;
@FOR(EQUIPMENTS(I): Z(I) = 1*(@SIGN(Y(I)-1)+1)/2);

! Upper limit on the number of units for each equipment type;
@FOR(EQUIPMENTS(I). Y(I) <= M);

! A minimum quantity of equipment is necessary to accomplish all missions;
@FOR(CONFIGURATIONS(K):
   @FOR(EQUIPMENTS(I): Q(I,K)*X(K) <= Y(I)));

! Make sure of the adequate capability of equipment for each mission;
@FOR(MISSIONS(J):
   @SUM(CONFIGURATIONS(K): U(J,K)*X(K)) >= 1.0);


!-----------------------------------------------------------;
!                 Exclusive Disjunctions                    ;
! - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ;
! Define the set of exclusive disjunctions (forbidden pairs);
! For example, if the configurations 1 and 5 can't be used  ;
! together, the instruction  "X(1) + X(5) <= 1"  must be    ;
! included.                                                 ;
!-----------------------------------------------------------;
X(2) + X(3) <= 1;    ! Configurations 2 and 3 are exclusives;


!------------------------------------------;
! Minimise the total cost of the equipment ;
!------------------------------------------;
MIN = @SUM(EQUIPMENTS:C*Y) + @SUM(EQUIPMENTS:F*Z);

!------------------------------------------;
! Export the results to the spreadsheet    ;
!------------------------------------------;
DATA:
     @OLE('MODEL.XLS')=X,Y,Z;
ENDDATA

END
```

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The methodology described in the JSORT Research Note RN 9605, "Satisfying requirements at minimum cost : methodology with application to unit level STANO requirements", was implemented using the LINGO® optimization software. The solution it provides is the lowest cost set of equipment that meets all the requirements of different mission elements. The LINGO® model was interfaced with two MS-Excel spreadsheets in order to simplify its use. Although the model was implemented for equipment selection problems, it can be applied to a broad range of selection problems. In this research note, a summary of the selection model is given. The procedure to use this model with LINGO® is then explained in detail.

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