

## nag\_mv\_factor (g03cac)

### 1. Purpose

**nag\_mv\_factor (g03cac)** computes the maximum likelihood estimates of the parameters of a factor analysis model. Either the data matrix or a correlation/covariance matrix may be input. Factor loadings, communalities and residual correlations are returned.

### 2. Specification

```
#include <nag.h>
#include <nagg03.h>

void nag_mv_factor(Nag_FacMat matrix, Integer n, Integer m,
                  double x[], Integer tdx, Integer nvar, Integer isx[],
                  Integer nfac, double wt[], double e[], double stat[],
                  double com[], double psi[], double res[],
                  double fl[], Integer tdf1, Nag_E04_Opt *options,
                  double eps, NagError *fail)
```

### 3. Description

Let  $p$  variables,  $x_1, x_2, \dots, x_p$ , with variance-covariance matrix  $\Sigma$  be observed. The aim of factor analysis is to account for the covariances in these  $p$  variables in terms of a smaller number,  $k$ , of hypothetical variables, or factors,  $f_1, f_2, \dots, f_k$ . These are assumed to be independent and to have unit variance. The relationship between the observed variables and the factors is given by the model:

$$x_i = \sum_{j=1}^k \lambda_{ij} f_j + e_i \quad i = 1, 2, \dots, p$$

where  $\lambda_{ij}$ , for  $i = 1, 2, \dots, p$ ;  $j = 1, 2, \dots, k$ , are the factor loadings and  $e_i$ , for  $i = 1, 2, \dots, p$ , are independent random variables with variances  $\psi_i$ , for  $i = 1, 2, \dots, p$ . The  $\psi_i$  represent the unique component of the variation of each observed variable. The proportion of variation for each variable accounted for by the factors is known as the communality. For this routine it is assumed that both the  $k$  factors and the  $e_i$ 's follow independent Normal distributions.

The model for the variance-covariance matrix,  $\Sigma$ , can be written as:

$$\Sigma = \Lambda \Lambda^T + \Psi \tag{1}$$

where  $\Lambda$  is the matrix of the factor loadings,  $\lambda_{ij}$ , and  $\Psi$  is a diagonal matrix of unique variances,  $\psi_i$ , for  $i = 1, 2, \dots, p$ .

The estimation of the parameters of the model,  $\Lambda$  and  $\Psi$ , by maximum likelihood is described by Lawley and Maxwell (1971). The log likelihood is:

$$-\frac{1}{2}(n-1) \log(|\Sigma|) - \frac{1}{2}(n-1) \text{trace}(S \Sigma^{-1}) + \text{constant},$$

where  $n$  is the number of observations,  $S$  is the sample variance-covariance matrix or, if weights are used,  $S$  is the weighted sample variance-covariance matrix and  $n$  is the effective number of observations, that is, the sum of the weights. The constant is independent of the parameters of the model. A two stage maximization is employed. It makes use of the function  $F(\Psi)$ , which is, up to a constant,  $-2/(n-1)$  times the log likelihood maximized over  $\Lambda$ . This is then minimized with respect to  $\Psi$  to give the estimates,  $\hat{\Psi}$ , of  $\Psi$ . The function  $F(\Psi)$  can be written as:

$$F(\Psi) = \sum_{j=k+1}^p (\theta_j - \log \theta_j) - (p - k),$$

where values  $\theta_j$ , for  $j = 1, 2, \dots, p$  are the eigenvalues of the matrix:

$$S^* = \Psi^{-1/2} S \Psi^{-1/2}.$$

The estimates  $\hat{\Lambda}$ , of  $\Lambda$ , are then given by scaling the eigenvectors of  $S^*$ , which are denoted by  $V$ :

$$\hat{\Lambda} = \Psi^{1/2} V (\Theta - I)^{1/2}.$$

where  $\Theta$  is the diagonal matrix with elements  $\theta_i$ , and  $I$  is the identity matrix.

The minimization of  $F(\Psi)$  is performed using `nag_opt_bounds_2nd_deriv` (e04lbc) which uses a modified Newton algorithm. The computation of the Hessian matrix is described by Clarke (1970). However, instead of using the eigenvalue decomposition of the matrix  $S^*$  as described above, the singular value decomposition of the matrix  $R\Psi^{-1/2}$  is used, where  $R$  is obtained either from the  $QR$  decomposition of the (scaled) mean-centred data matrix or from the Cholesky decomposition of the correlation/covariance matrix. The routine `nag_opt_bounds_2nd_deriv` (e04lbc) ensures that the values of  $\psi_i$  are greater than a given small positive quantity,  $\delta$ , so that the communality is always less than one. This avoids the so called Heywood cases.

In addition to the values of  $\Lambda$ ,  $\Psi$  and the communalities, `nag_mv_factor` (g03cac) returns the residual correlations, i.e., the off-diagonal elements of  $C - (\Lambda\Lambda^T + \Psi)$  where  $C$  is the sample correlation matrix. `nag_mv_factor` (g03cac) also returns the test statistic:

$$\chi^2 = [n - 1 - (2p + 5)/6 - 2k/3]F(\hat{\Psi})$$

which can be used to test the goodness of fit of the model (1), see Lawley and Maxwell (1971) and Morrison (1967).

#### 4. Parameters

##### matrix

Input: selects the type of matrix on which factor analysis is to be performed.

If **matrix** = **Nag\_DataCorr** (Data input), then the data matrix will be input in **x** and factor analysis will be computed for the correlation matrix.

If **matrix** = **Nag\_DataCovar**, then the data matrix will be input in **x** and factor analysis will be computed for the covariance matrix, i.e., the results are scaled as described in Section 6.

If **matrix** = **Nag\_MatCorr\_Covar**, then the correlation/variance-covariance matrix will be input in **x** and factor analysis computed for this matrix.

Constraint: **matrix** = **Nag\_DataCorr**, **Nag\_DataCovar** or **Nag\_MatCorr\_Covar**.

##### n

Input: if **matrix** = **Nag\_DataCorr** or **Nag\_DataCovar** the number of observations in the data array **x**.

If **matrix** = **Nag\_MatCorr\_Covar** the (effective) number of observations used in computing the (possibly weighted) correlation/variance-covariance matrix input in **x**.

Constraint: **n** > **nvar**.

##### m

Input: the number of variables in the data/correlation/variance-covariance matrix.

Constraint: **m** ≥ **nvar**.

##### **x**[dim1][tdx]

Input: the input matrix. If **matrix** = **Nag\_DataCorr** or **Nag\_DataCovar**, then  $dim1 \geq n$  and **x** must contain the data matrix, i.e., **x**[ $i - 1$ ][ $j - 1$ ] must contain the  $i$ th observation for the  $j$ th variable, for  $i = 1, 2, \dots, n$ ;  $j = 1, 2, \dots, m$ .

If **matrix** = **Nag\_MatCorr\_Covar** then  $dim1 \geq m$  and **x** must contain the correlation or variance-covariance matrix. Only the upper triangular part is required.

**tdx**

Input: the last dimension of the array **x** as declared in the calling program.

Constraint: **tdx**  $\geq$  **m**.

**nvar**

Input: the number of variables in the factor analysis,  $p$ .

Constraint: **nvar**  $\geq$  2.

**isx[m]**

Input: **isx**[ $j - 1$ ] indicates whether or not the  $j$ th variable is to be included in the factor analysis.

If **isx**[ $j - 1$ ]  $\geq$  1, then the variable represented by the  $j$ th column of **x** is included in the analysis; otherwise it is excluded, for  $j = 1, 2, \dots, \mathbf{m}$ .

Constraint: **isx**[ $j - 1$ ]  $>$  0 for **nvar** values of  $j$ .

**nfac**

Input: the number of factors,  $k$ .

Constraint:  $1 \leq \mathbf{nfac} \leq \mathbf{nvar}$ .

**wt[n]**

Input: if **matrix** = **Nag\_DataCorr** or **Nag\_DataCovar** then the elements of **wt** must contain the weights to be used in the factor analysis. The effective number of observations is the sum of the weights. If **wt**[ $i - 1$ ] = 0.0 then the  $i$ th observation is not included in the analysis.

If **matrix** = **Nag\_MatCorr\_Covar** or **wt** is set to the null pointer **NULL**, i.e., (double \*)0, then **wt** is not referenced and the effective number of observations is  $n$ .

Constraint: if **wt** is referenced, then **wt**[ $i - 1$ ]  $\geq$  0 for  $i = 1, 2, \dots, n$ , and the sum of the weights  $>$  **nvar**.

**e[nvar]**

Output: the eigenvalues  $\theta_i$ , for  $i = 1, 2, \dots, p$ .

**stat[4]**

Output: the test statistics.

**stat**[0] contains the value  $F(\hat{\Psi})$ .

**stat**[1] contains the test statistic,  $\chi^2$ .

**stat**[2] contains the degrees of freedom associated with the test statistic.

**stat**[3] contains the significance level.

**com[nvar]**

Output: the communalities.

**psi[nvar]**

Output: the estimates of  $\psi_i$ , for  $i = 1, 2, \dots, p$ .

**res[nvar\*(nvar-1)/2]**

Output: the residual correlations. The residual correlation for the  $i$ th and  $j$ th variables is stored in **res**[( $j - 1$ )( $j - 2$ )/2 +  $i - 1$ ],  $i < j$ .

**fl[nvar][tdfl]**

Output: the factor loadings. **fl**[ $i - 1$ ][ $j - 1$ ] contains  $\lambda_{ij}$ , for  $i = 1, 2, \dots, p$ ;  $j = 1, 2, \dots, k$ .

**tdfl**

Input: the last dimension of the array **fl** as declared in the calling program.

Constraint: **tdfl**  $\geq$  **nfac**.

**options**

Input/Output: a pointer to a structure of type **Nag\_E04\_Opt** whose members are optional parameters for **nag\_opt\_bounds\_2nd\_deriv** (e04lbc). These structure members offer the means of adjusting some of the parameter values of the algorithm.

If the optional parameters are not required the NAG defined null pointer, **E04\_DEFAULT**, can be used in the function call. See the document for **nag\_opt\_bounds\_2nd\_deriv** (e04lbc) for further details.

**eps**

Input: A lower bound for the value of  $\Psi_i$ .  
 Constraint: *machine precision*  $\leq$  **eps**  $<$  1.0.

**fail**

The NAG error parameter, see the Essential Introduction to the NAG C Library.

**5. Error Indications and Warnings****NE\_BAD\_PARAM**

On entry, parameter **matrix** had an illegal value.

**NE\_INT\_ARG\_LT**

On entry, **nfac** must not be less than 1: **nfac** =  $\langle value \rangle$ .  
 On entry, **nvar** must not be less than 2: **nvar** =  $\langle value \rangle$ .

**NE\_2\_INT\_ARG\_LT**

On entry, **m** =  $\langle value \rangle$  while **nvar** =  $\langle value \rangle$ .  
 These parameters must satisfy **m**  $\geq$  **nvar**.  
 On entry, **tdx** =  $\langle value \rangle$  while **m** =  $\langle value \rangle$ .  
 These parameters must satisfy **tdx**  $\geq$  **m**.  
 On entry, **tdfl** =  $\langle value \rangle$  while **nfac** =  $\langle value \rangle$ .  
 These parameters must satisfy **tdfl**  $\geq$  **nfac**.

**NE\_2\_INT\_ARG\_LE**

On entry, **n** =  $\langle value \rangle$  while **nvar** =  $\langle value \rangle$ .  
 These parameters must satisfy **n**  $>$  **nvar**.

**NE\_2\_INT\_ARG\_GT**

On entry, **nfac** =  $\langle value \rangle$  while **nvar** =  $\langle value \rangle$ .  
 These parameters must satisfy **nfac**  $\leq$  **nvar**.

**NE\_INVALID\_REAL\_RANGE\_EF**

Value  $\langle value \rangle$  given to **eps** is not valid.  
 Correct range is *machine precision*  $\leq$  **eps**  $<$  1.0.

**NE\_NEG\_WEIGHT\_ELEMENT**

On entry, **wt**[ $\langle value \rangle$ ] =  $\langle value \rangle$ .  
 Constraint: When referenced, all elements of **wt** must be non-negative.

**NE\_VAR\_INCL\_INDICATED**

The number of variables, **nvar** in the analysis =  $\langle value \rangle$ , while number of variables included in the analysis via array **isx** =  $\langle value \rangle$ .  
 Constraint: these two numbers must be the same.

**NE\_OBSERV\_LT\_VAR**

With weighted data, the effective number of observations given by the sum of weights =  $\langle value \rangle$ , while the number of variables included in the analysis, **nvar** =  $\langle value \rangle$ .  
 Constraint: effective number of observations  $>$  **nvar** + 1.

**NE\_SVD\_NOT\_CONV**

A singular value decomposition has failed to converge.  
 This is a very unlikely error exit.

**NW\_COND\_MIN**

The conditions for a minimum have not all been satisfied but a lower point could not be found.  
 Note that in this case all the results are computed.  
 See nag\_opt\_bounds\_2nd\_deriv (e04lbc) for further details.

**NW\_TOO\_MANY\_ITER**

The maximum number of iterations,  $\langle value \rangle$ , have been performed.

**NE\_MAT\_RANK**

On entry, **matrix = Nag\_DataCorr** or **matrix = Nag\_DataCovar** and the data matrix is not of full column rank, or **matrix = Nag\_MatCorr\_Covar** and the input correlation/variance-covariance matrix is not positive-definite.

This exit may also be caused by two of the eigenvalues of  $S^*$  being equal; this is rare (see Lawley and Maxwell (1971)) and may be due to the data/correlation matrix being almost singular.

**NE\_ALLOC\_FAIL**

Memory allocation failed.

**NE\_INTERNAL\_ERROR**

An internal error has occurred in this function.

Check the function call and any array sizes. If the call is correct then please consult NAG for assistance.

Additional error messages are output if the optimisation fails to converge or if the options are set incorrectly. Details of these can be found in the `nag_opt_bounds_2nd_deriv` (e04lbc) document.

**6. Further Comments**

The factor loadings may be orthogonally rotated by using `nag_mv_orthomax` (g03bac) and factor score coefficients can be computed using `nag_mv_fac_score` (g03ccc). The maximum likelihood estimators are invariant to a change in scale. This means that the results obtained will be the same (up to a scaling factor) if either the correlation matrix or the variance-covariance matrix is used. As the correlation matrix ensures that all values of  $\psi_i$  are between 0 and 1 it will lead to a more efficient optimization. In the situation when the data matrix is input the results are always computed for the correlation matrix and then scaled if the results for the covariance matrix are required. When the user inputs the covariance/correlation matrix the input matrix itself is used and so the user is advised to input the correlation matrix rather than the covariance matrix.

**6.1. Accuracy**

The accuracy achieved is discussed in `nag_opt_bounds_2nd_deriv` (e04lbc).

**6.2. References**

Clark M R B (1970) A rapidly convergent method for maximum likelihood factor analysis *British J. Math. Statist. Psych.*.

Lawley D N and Maxwell A E (1971) *Factor Analysis as a Statistical Method* Butterworths (2nd Edition).

Hammarling S (1985) The singular value decomposition in multivariate statistics *SIGNUM* **20**(3) 2–25.

Morrison D F (1967) *Multivariate Statistical Methods* McGraw-Hill.

**7. See Also**

`nag_opt_bounds_2nd_deriv` (e04lbc)

**8. Example**

The example is taken from Lawley and Maxwell (1971). The correlation matrix for nine variables is input and the parameters of a factor analysis model with three factors are estimated and printed.

**8.1. Program Text**

```
/* nag_mv_factor (g03cac) Example Program.
 *
 * Copyright 1998 Numerical Algorithms Group.
 *
 * Mark 5, 1998.
 *
 */
#include <nag.h>
```

```

#include <stdio.h>
#include <nag_stdlib.h>
#include <nage04.h>
#include <nagg03.h>

#define NMAX 9
#define MMAX 9

main()
{
    double com[MMAX], e[MMAX], fl[MMAX][MMAX], psi[MMAX],
    res[MMAX*(MMAX-1)/2], stat[4], wt[NMAX], x[NMAX][MMAX];
    double *wtptr=0;
    double eps;

    Integer nfac, nvar;
    Integer i, j, l, m, n;
    Integer isx[MMAX];
    Integer tdf1 = MMAX, tdx = MMAX;

    char weight[2], char_matrix[2];

    Nag_FacMat matrix;
    Nag_E04_Opt options;

    Vprintf("g03cac Example Program Results\n\n");

    /* Skip headings in data file */
    Vscanf("%*[^\\n]");

    Vscanf("%s",char_matrix);
    Vscanf("%s",weight);
    Vscanf("%ld",&n);
    Vscanf("%ld",&m);
    Vscanf("%ld",&nvar);
    Vscanf("%ld",&nfac);

    if (m <= MMAX && (*char_matrix == 'C' || n <= NMAX ))
    {
        if (*char_matrix == 'C')
        {
            for (i = 0; i < m; ++i)
            {
                for (j = 0; j < m; ++j)
                    Vscanf("%lf",&x[i][j]);
            }
        }
        else
        {
            if (*weight == 'W' || *weight == 'w')
            {
                for (i = 0; i < n; ++i)
                {
                    for (j = 0; j < m; ++j)
                        Vscanf("%lf",&x[i][j]);
                    Vscanf("%lf",&wt[i]);
                }
                wtptr = wt;
            }
            else
            {
                for (i = 0; i < n; ++i)
                {
                    for (j = 0; j < m; ++j)
                        Vscanf("%lf",&x[i][j]);
                }
            }
        }
        for (j = 0; j < m; ++j)
            Vscanf("%ld",&isx[j]);
    }
}

```

```

    if (*char_matrix == 'D')
    {
        matrix = Nag_DataCorr;
    }
    else if (*char_matrix == 'S')
    {
        matrix = Nag_DataCovar;
    }
    else if (*char_matrix == 'C')
    {
        matrix = Nag_MatCorr_Covar;
    }

    e04xxc(&options);
    options.max_iter = 500;
    options.optim_tol = 1e-2;
    eps = 1e-5;
    g03cac(matrix, n, m, (double *)x, tdx, nvar, isx, nfac, wtptr, e,
           stat, com, psi, res, (double *)fl, tdf1, &options, eps, NAGERR_DEFAULT);

    Vprintf("\nEigenvalues\n\n");
    for (j = 0; j < m; ++j)
    {
        Vprintf(" %12.4e%s",e[j], (j+1)%6==0 ? "\n" : "");
    }
    Vprintf("\n\n%s%6.3f\n", "    Test Statistic = ",stat[1]);
    Vprintf("%s%6.3f\n", "          df = ",stat[2]);
    Vprintf("%s%6.3f\n", "Significance level = ",stat[3]);
    Vprintf("Residuals\n\n");
    l = 1;
    for (i = 1; i <= nvar-1; ++i)
    {
        for (j = 1; j <= l+i-1; ++j)
            Vprintf(" %8.3f",res[j-1]);
        Vprintf("\n");
        l += i;
    }
    Vprintf("\nLoadings, Communalities and PSI\n\n");
    for (i = 0; i < nvar; ++i)
    {
        for (j = 0; j < nfac; ++j)
            Vprintf(" %8.3f",fl[i][j]);
        Vprintf("%8.3f%8.3f\n", com[i], psi[i]);
    }
    exit(EXIT_SUCCESS);
}
else
{
    Vprintf("Incorrect input value of n or m.\n");
    exit(EXIT_FAILURE);
}
}

```

## 8.2. Program Data

g03cac Example Program Data

C U 211 9 9 3

1.000	0.523	0.395	0.471	0.346	0.426	0.576	0.434	0.639
0.523	1.000	0.479	0.506	0.418	0.462	0.547	0.283	0.645
0.395	0.479	1.000	0.355	0.270	0.254	0.452	0.219	0.504
0.471	0.506	0.355	1.000	0.691	0.791	0.443	0.285	0.505
0.346	0.418	0.270	0.691	1.000	0.679	0.383	0.149	0.409
0.426	0.462	0.254	0.791	0.679	1.000	0.372	0.314	0.472
0.576	0.547	0.452	0.443	0.383	0.372	1.000	0.385	0.680
0.434	0.283	0.219	0.285	0.149	0.314	0.385	1.000	0.470
0.639	0.645	0.504	0.505	0.409	0.472	0.680	0.470	1.000
1	1	1	1	1	1	1	1	1

8.3. Program Results

g03cac Example Program Results

Parameters to e04lbc  
-----

Number of variables..... 9

optim_tol.....	1.00e-02	linesearch_tol.....	9.00e-01
step_max.....	2.70e+01	max_iter.....	500
print_level.....	Nag_Soln_Iter	machine precision.....	1.11e-16
deriv_check.....	FALSE		
outfile.....	stdout		

Memory allocation:

state.....	User		
hesl.....	User	hesd.....	User

Iterations performed = 0, function evaluations = 1  
Criterion = 8.635756e-02

Variable	Standardized Communalities
1	0.5755
2	0.5863
3	0.4344
4	0.7496
5	0.6203
6	0.7329
7	0.6061
8	0.4053
9	0.7104

Iterations performed = 1, function evaluations = 3  
Criterion = 3.603203e-02

Variable	Standardized Communalities
1	0.5517
2	0.5800
3	0.3936
4	0.7926
5	0.6140
6	0.8254
7	0.6052
8	0.5076
9	0.7569

Iterations performed = 2, function evaluations = 4  
Criterion = 3.502097e-02

Variable	Standardized Communalities
1	0.5496
2	0.5731
3	0.3838
4	0.7875
5	0.6200
6	0.8238
7	0.6006
8	0.5349
9	0.7697

Iterations performed = 3, function evaluations = 5  
Criterion = 3.501729e-02

Variable	Standardized Communalities
----------	-------------------------------



1	0.5495
2	0.5729
3	0.3835
4	0.7877
5	0.6195
6	0.8231
7	0.6005
8	0.5384
9	0.7691

## Eigenvalues

1.5968e+01	4.3577e+00	1.8474e+00	1.1560e+00	1.1190e+00	1.0271e+00
9.2574e-01	8.9508e-01	8.7710e-01			

Test Statistic = 7.149  
df = 12.000  
Significance level = 0.848

## Residuals

0.000								
-0.013	0.022							
0.011	-0.005	0.023						
-0.010	-0.019	-0.016	0.003					
-0.005	0.011	-0.012	-0.001	-0.001				
0.015	-0.022	-0.011	0.002	0.029	-0.012			
-0.001	-0.011	0.013	0.005	-0.006	-0.001	0.003		
-0.006	0.010	-0.005	-0.011	0.002	0.007	0.003	-0.001	

## Loadings, Communalities and PSI

0.664	-0.321	0.074	0.550	0.450
0.689	-0.247	-0.193	0.573	0.427
0.493	-0.302	-0.222	0.383	0.617
0.837	0.292	-0.035	0.788	0.212
0.705	0.315	-0.153	0.619	0.381
0.819	0.377	0.105	0.823	0.177
0.661	-0.396	-0.078	0.600	0.400
0.458	-0.296	0.491	0.538	0.462
0.766	-0.427	-0.012	0.769	0.231

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