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# APPENDIX A

## APPENDIX A-1 : Case Study 1.1 GAMS Code

```
Set     i Source stream /i1*i4/
        j Sink stream /j1*j4/
;
Parameter
        CS      Source concentration
                /i1     50
                 i2     100
                 i3     150
                 i4     250 /
        FS      Source flowrate
                /i1     50
                 i2     100
                 i3     70
                 i4     60 /
        CKL     Sink concentration
                /j1     20
                 j2     50
                 j3     100
                 j4     200 /
        FK      Sink flowrate
                /j1     50
                 j2     100
                 j3     80
                 j4     70 /
;
Variable          OBJ    Objective function
;
Positive variable  x(i,j)  Source split fraction i to j
                FW(j)   Freshwater flowrate
                WW(i)   Waste of each source
                F(i,j)  Splitting Flowrate i to j
                CK(j)   Sink stream concentration
                OFW     Overall freshwater
                OWW     Overall waste
                OFWC    Overall freshwater cost
                OWWC    Overall waste cost
                OPC
;
Binary variable    y(i,j)
                z(j)
                w(i)
;
Scalar          OMEGA /10000/
                CF Cost Freshwater /1/
                CW Cost wastewater /1/
                CP Cost piping /1/
```

```
;
Equation
      MB1(j)        Mass balance (flowrate)
      MB2(j)        Mass balance (contaminant)
      Cons1(i)      Constraint for x
      Cons2(j)      Concentration constraint
      Flow(i,j)     Flowrate source i to sink j
      Waste(i)      Waste of each source
      OFresh        Overall freshwater
      OWaste        Overall waste
      Logical1(i,j) Logical constraint1
      Logical2(j)   Logical constraint2
      Logical3(i)   Logical constraint3
      FreshCost     Overall freshwater cost
      WasteCost     Overall waste cost
      PipingCost    Overall Piping cost
      Object        Objective
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FW(j) =e= FK(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =e= CKL(j) ;
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
OFresh .. OFW =e= sum(j,FW(j));
OWaste .. OWW =e= sum(i,WW(i));
Logical1(i,j) ..  F(i,j)-y(i,j)*OMEGA =l= 0;
Logical2(j) ..  FW(j)- z(j)*OMEGA =l= 0;
Logical3(i) ..  WW(i)- w(i)*OMEGA =l= 0;
FreshCost .. OFWC =e= OFW*CF;
WasteCost .. OWWC =e= OWW*CW;
PipingCost .. OPC =e= sum((i,j),y(i,j)*CP)+sum(j,z(j)*CP)+sum(i,w(i)*CP);
Object .. OBJ =e= OFWC+OWWC+OPC;

Model CASE11 /ALL/;
Solve CASE11 Using MIP Minimizing OBJ;
Display OBJ.l,OFW.l,OWW.l,OFWC.l,OWWC.l,OPC.l,FW.l,WW.l,x.l,F.l,y.l,z.l,CK.l;
```

## APPENDIX A-2 : Case Study 1.1a GAMS Code

```
Set    i Source stream /i1*i4/
       j Sink stream /j1*j4/
;
Parameter
      CS     Source concentration
           /i1    50
            i2    100
            i3    150
            i4    250 /
```

```
     FS     Source flowrate
          /i1    50
           i2    100
           i3    70
           i4    60 /
     CKL    Sink concentration
          /j1    20
           j2    50
           j3    100
           j4    200 /
     FK     Sink flowrate
          /j1    50
           j2    100
           j3    80
           j4    70 /
;
Variable          OBJ    Objective function
;
Positive variable   x(i,j)  Source split fraction i to j
               FW(j)   Freshwater flowrate
               WW(i)   Waste of each source
               F(i,j)  Splitting Flowrate i to j
               CK(j)   Sink stream concentration
               OFW     Overall freshwater
               OWW     Overall waste
               OFWC    Overall freshwater cost
               OWWC    Overall waste cost
               OPC
;
Binary variable     y(i,j)
                        z(j)
                    w(i)
;
Scalar            OMEGA /10000/
               CF Cost Freshwater /10/
               CW Cost wastewater /100/
               CP Cost piping /10/
;
Equation
     MB1(j)          Mass balance (flowrate)
     MB2(j)          Mass balance (contaminant)
     Cons1(i)        Constraint for x
     Cons2(j)        Concentration constraint
     Flow(i,j)       Flowrate source i to sink j
     Waste(i)        Waste of each source
     OFresh          Overall freshwater
     OWaste          Overall waste
     Logical1(i,j)   Logical constraint1
     Logical2(j)     Logical constraint2
     Logical3(i)     Logical constraint3
     FreshCost       Overall freshwater cost
```

```
     WasteCost     Overall waste cost
     PipingCost    Overall Piping cost
     Object        Objective
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FW(j) =e= FK(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =e= CKL(j) ;
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
OFresh .. OFW =e= sum(j,FW(j));
OWaste .. OWW =e= sum(i,WW(i));
Logical1(i,j) ..  F(i,j)-y(i,j)*OMEGA =l= 0;
Logical2(j) ..  FW(j)- z(j)*OMEGA =l= 0;
Logical3(i) ..  WW(i)- w(i)*OMEGA =l= 0;
FreshCost .. OFWC =e= OFW*CF;
WasteCost .. OWWC =e= OWW*CW;
PipingCost .. OPC =e= sum((i,j),y(i,j)*CP)+sum(j,z(j)*CP)+sum(i,w(i)*CP);
Object .. OBJ =e= OFWC+OWWC+OPC;

Model CASE11a /ALL/;
Solve CASE11a Using MIP Minimizing OBJ;
Display OBJ.l,OFW.l,OWW.l,OFWC.l,OWWC.l,OPC.l,FW.l,WW.l,x.l,F.l,y.l,z.l,CK.l;
```

## APPENDIX A-3 : Case Study 1.1b GAMS Code

```
Set    i Source stream /i1*i4/
       j Sink stream /j1*j4/
;
Parameter
     CS     Source concentration
          /i1    50
           i2    100
           i3    150
           i4    250 /
     FS     Source flowrate
          /i1    50
           i2    100
           i3    70
           i4    60 /
     CKL    Sink concentration
          /j1    20
           j2    50
           j3    100
           j4    200 /
     FK     Sink flowrate
          /j1    50
           j2    100
           j3    80
```

```
        j4    70  /
;
Variable          OBJ    Objective function
;
Positive variable  x(i,j)  Source split fraction i to j
                FW(j)   Freshwater flowrate
                WW(i)   Waste of each source
                F(i,j)  Splitting Flowrate i to j
                CK(j)   Sink stream concentration
                OFW     Overall freshwater
                OWW     Overall waste
                OFWC    Overall freshwater cost
                OWWC    Overall waste cost
                OPC
;
Binary variable    y(i,j)
                z(j)
                w(i)
;
Scalar            OMEGA /10000/
                CF Cost Freshwater /1/
                CW Cost wastewater /10/
                CP Cost piping /500/
;
Equation
       MB1(j)         Mass balance (flowrate)
       MB2(j)         Mass balance (contaminant)
       Cons1(i)       Constraint for x
       Cons2(j)       Concentration constraint
       Flow(i,j)      Flowrate source i to sink j
       Waste(i)       Waste of each source
       OFresh         Overall freshwater
       OWaste         Overall waste
       Logical1(i,j)  Logical constraint1
       Logical2(j)    Logical constraint2
       Logical3(i)    Logical constraint3
       FreshCost      Overall freshwater cost
       WasteCost      Overall waste cost
       PipingCost     Overall Piping cost
       Object         Objective
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FW(j) =e= FK(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =e= CKL(j) ;
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
OFresh .. OFW =e= sum(j,FW(j));
OWaste .. OWW =e= sum(i,WW(i));
Logical1(i,j) ..  F(i,j)-y(i,j)*OMEGA =l= 0;
```

```
Logical2(j) ..  FW(j)- z(j)*OMEGA =l= 0;
Logical3(i) ..  WW(i)- w(i)*OMEGA =l= 0;
FreshCost .. OFWC =e= OFW*CF;
WasteCost .. OWWC =e= OWW*CW;
PipingCost .. OPC =e= sum((i,j),y(i,j)*CP)+sum(j,z(j)*CP)+sum(i,w(i)*CP);
Object .. OBJ =e= OFWC+OWWC+OPC;

Model CASE11b /ALL/;
Solve CASE11b Using MIP Minimizing OBJ;
Display OBJ.l,OFW.l,OWW.l,OFWC.l,OWWC.l,OPC.l,FW.l,WW.l,x.l,F.l,y.l,z.l,CK.l;
```

## APPENDIX A-4 : Case Study 1.1c GAMS Code

```
Set     i Source stream /i1*i4/
        j Sink stream /j1*j4/
        r Freshwater /r1*r3/
;
Parameter
        CS     Source concentration
               /i1    50
                i2    100
                i3    150
                i4    250 /
        FS     Source flowrate
               /i1    50
                i2    100
                i3    70
                i4    60 /
        CKL    Sink concentration
               /j1    20
                j2    50
                j3    100
                j4    200 /
        FK     Sink flowrate
               /j1    50
                j2    100
                j3    80
                j4    70 /
        CF     Freshwater cost
               /r1    100
                r2    50
                r3    0 /
        ConF   Freshwater concentration
               /r1    0
                r2    20
                r3    50 /
;
Variable        OBJ    Objective function
;
```

```
Positive variable   x(i,j)  Source split fraction i to j
                    FW(r,j)   Freshwater flowrate
                    WW(i)   Waste of each source
                    F(i,j)  Splitting Flowrate i to j
                    CK(j)   Sink stream concentration
                    OFW(r)     Overall freshwater
                    OWW     Overall waste
                    OFWC    Overall freshwater cost
                    OWWC    Overall waste cost
                    OPC
;
Binary variable     y(i,j)
                    z(r,j)
                    w(i)
;
Scalar              OMEGA /10000/
                    CW Cost wastewater /100/
                    CP Cost piping /10/
;
Equation
       MB1(j)         Mass balance (flowrate)
       MB2(j)         Mass balance (contaminant)
       Cons1(i)       Constraint for x
       Cons2(j)       Concentration constraint
       Flow(i,j)      Flowrate source i to sink j
       Waste(i)       Waste of each source
       OFresh(r)         Overall freshwater
       OWaste         Overall waste
       Logical1(i,j)  Logical constraint1
       Logical2(r,j)    Logical constraint2
       Logical3(i)    Logical constraint3
       FreshCost      Overall freshwater cost
       WasteCost      Overall waste cost
       PipingCost     Overall Piping cost
       Object       Objective
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j))+ sum(r,FW(r,j)*ConF(r)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + sum(r,FW(r,j)) =e= FK(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =e= CKL(j) ;
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
OFresh(r) .. OFW(r) =e= sum(j,FW(r,j));
OWaste .. OWW =e= sum(i,WW(i));
Logical1(i,j) ..  F(i,j)-y(i,j)*OMEGA =l= 0;
Logical2(r,j) ..  FW(r,j)- z(r,j)*OMEGA =l= 0;
Logical3(i) ..  WW(i)- w(i)*OMEGA =l= 0;
FreshCost .. OFWC =e= sum(r,OFW(r)*CF(r));
WasteCost .. OWWC =e= OWW*CW;
PipingCost .. OPC =e= sum((i,j),y(i,j)*CP)+sum((r,j),z(r,j)*CP)+sum(i,w(i)*CP);
Object .. OBJ =e= OFWC+OWWC+OPC;
```

```
Model CASE11c /ALL/;
Solve CASE11c Using MIP Minimizing OBJ;
Display OBJ.l,OFW.l,OWW.l,OFWC.l,OWWC.l,OPC.l,FW.l,WW.l,x.l,F.l,y.l,z.l,CK.l;
```

## APPENDIX A-5 : Case Study 1.2 GAMS Code

```
Set     i Source stream /i1*i5/
        j Sink stream /j1*j5/
;
Parameter
    CS    Source concentration (ppm)
        /i1   130
         i2   108
         i3   70
         i4   44
         i5   22 /
    FS    Source flowrate (ton per h)
        /i1   9
         i2   9
         i3   9
         i4   9
         i5   4.5 /
    CKL   Sink concentration (ppm)
        /j1   127.8
         j2   108
         j3   63.0016667
         j4   62.975
         j5   45.72 /
    FK    Sink flowrate (ton per h)
        /j1   10
         j2   4
         j3   12
         j4   8
         j5   6.5 /
;
Variable        OBJ   Objective function
;
Positive variable  x(i,j)  Source split fraction i to j
                FW(j)  Freshwater flowrate
                WW(i)  Waste of each source
                F(i,j)  Splitting Flowrate i to j
                CK(j)  Sink stream concentration
                OFW    Overall freshwater
                OWW    Overall waste
                OFWC   Overall freshwater cost
                OWWC   Overall waste cost
                OPC
;
```

```
Binary variable    y(i,j)
             z(j)
             w(i)
;
Scalar         OMEGA /1000/
             CF Cost Freshwater /1/
             CW Cost wastewater /1/
             CP Cost piping /1/
;
Equation
      MB1(j)        Mass balance (flowrate)
      MB2(j)        Mass balance (contaminant)
      Cons1(i)      Constraint for x
      Cons2(j)      Concentration constraint
      Flow(i,j)     Flowrate source i to sink j
      Waste(i)      Waste of each source
      OFresh        Overall freshwater
      OWaste        Overall waste
      Logical1(i,j) Logical constraint1
      Logical2(j)   Logical constraint2
      Logical3(i)   Logical constraint3
      FreshCost     Overall freshwater cost
      WasteCost     Overall waste cost
      PipingCost    Overall Piping cost
      Object        Objective
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FW(j) =e= FK(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =e= CKL(j) ;
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
OFresh .. OFW =e= sum(j,FW(j));
OWaste .. OWW =e= sum(i,WW(i));
Logical1(i,j) ..  F(i,j)-y(i,j)*OMEGA =l= 0;
Logical2(j) ..  FW(j)- z(j)*OMEGA =l= 0;
Logical3(i) ..  WW(i)- w(i)*OMEGA =l= 0;
FreshCost .. OFWC =e= OFW*CF;
WasteCost .. OWWC =e= OWW*CW;
PipingCost .. OPC =e= sum((i,j),y(i,j)*CP)+sum(j,z(j)*CP)+sum(i,w(i)*CP);
Object .. OBJ =e= OFWC+OWWC+OPC;
Model CASE12 /ALL/;
Solve CASE12 Using MIP Minimizing OBJ;
Display OBJ.l,OFW.l,OWW.l,OFWC.l,OWWC.l,OPC.l,FW.l,WW.l,x.l,F.l,y.l,z.l,CK.l;
```

## APPENDIX A-6 : Case Study 1.3 GAMS Code

```
Set     i Source stream /i1*i5/
          j Sink stream /j1*j5/
;
Parameter
     CS     Source concentration (ppm)
          /i1    130
           i2    108
           i3    70
           i4    44
           i5    22 /
     FS     Source flowrate (ton per h)
          /i1    9
           i2    9
           i3    9
           i4    9
           i5    4.5 /
     CKL    Sink concentration (ppm)
          /j1    20
           j2    20
           j3    20
           j4    20
           j5    20 /
     FK     Sink flowrate (ton per h)
          /j1    10
           j2    4
           j3    12
           j4    8
           j5    6.5 /
;
Variable          OBJ    Objective function
;
Positive variable   x(i,j)  Source split fraction i to j
               FW(j)   Freshwater flowrate
               WW(i)   Waste of each source
               F(i,j)  Splitting Flowrate i to j
               CK(j)   Sink stream concentration
               OFW     Overall freshwater
               OWW     Overall waste
               OFWC    Overall freshwater cost
               OWWC    Overall waste cost
               OPC
;
Binary variable    y(i,j)
               z(j)
               w(i)
;
Scalar          OMEGA /10000/
               CF Cost Freshwater /1/
```

```
            CW Cost wastewater /1/
            CP Cost piping /1/
;
Equation
      MB1(j)        Mass balance (flowrate)
      MB2(j)        Mass balance (contaminant)
      Cons1(i)      Constraint for x
      Cons2(j)      Concentration constraint
      Flow(i,j)     Flowrate source i to sink j
      Waste(i)      Waste of each source
      OFresh        Overall freshwater
      OWaste        Overall waste
      Logical1(i,j) Logical constraint1
      Logical2(j)   Logical constraint2
      Logical3(i)   Logical constraint3
      FreshCost     Overall freshwater cost
      WasteCost     Overall waste cost
      PipingCost    Overall Piping cost
      Object        Objective
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FW(j) =e= FK(j) ;
Cons1(i) .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =e= CKL(j) ;
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
OFresh .. OFW =e= sum(j,FW(j));
OWaste .. OWW =e= sum(i,WW(i));
Logical1(i,j) .. F(i,j)-y(i,j)*OMEGA =l= 0;
Logical2(j) .. FW(j)- z(j)*OMEGA =l= 0;
Logical3(i) .. WW(i)- w(i)*OMEGA =l= 0;
FreshCost .. OFWC =e= OFW*CF;
WasteCost .. OWWC =e= OWW*CW;
PipingCost .. OPC =e= sum((i,j),y(i,j)*CP)+sum(j,z(j)*CP)+sum(i,w(i)*CP);
Object .. OBJ =e= OFWC+OWWC+OPC;


Model CASE13 /ALL/;
Solve CASE13 Using MIP Minimizing OBJ;
Display OBJ.l,OFW.l,OWW.l,OFWC.l,OWWC.l,OPC.l,FW.l,WW.l,x.l,F.l,y.l,z.l,CK.l;
```

## APPENDIX A-7 : Case Study 2 before regeneration GAMS Code

```
Set    i Source stream /i1*i4/
       j Sink stream /j1*j6/
;
Parameter
      CS    Source concentration (ppm)
         /i1    100
```

```
          i2    230
          i3    170
          i4    250 /
     FS     Source flowrate (ton per h)
          /i1    155.4
          i2    1305.78
          i3    201.84
          i4    469.8 /
     CKL    Sink concentration (ppm)
          /j1    20
          j2    80
          j3    100
          j4    200
          j5    20
          j6    200 /
     FK     Sink flowrate (ton per h)
          /j1    155.4
          j2    831.12
          j3    201.84
          j4    1149.84
          j5    34.68
          j6    68.7 /

;
Variable          OBJ    Objective function
;
Positive variable   x(i,j)  Source split fraction i to j
               FW(j)   Freshwater flowrate
               WW(i)   Waste of each source
               F(i,j)  Splitting Flowrate i to j
               CK(j)   Sink stream concentration
               OFW     Overall freshwater
               OWW     Overall waste
;
Binary variable     y(i,j)
               z(j)
;
Scalar            OMEGA /10000/
               GAMMA /100/
;
F.fx('i4','j6')=54;F.lo('i1','j4')=155.4;
F.lo('i2','j4')=41.28;F.lo('i3','j4')=201.84;
Equation
     MB1(j)        Mass balance (flowrate)
     MB2(j)        Mass balance (contaminant)
     Cons1(i)      Constraint for x
     Cons2(j)      Concentration constraint
     Flow(i,j)     Flowrate source i to sink j
     Waste(i)      Waste of each source
     OFresh        Overall freshwater
     OWaste        Overall waste
```

```
      Logical1(i,j)  Logical constraint
      Logical2(j)    Logical constraint
      Object         Objective
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FW(j) =e= FK(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =e= CKL(j) ;
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
OFresh .. OFW =e= sum(j,FW(j));
OWaste .. OWW =e= sum(i,WW(i));
Logical1(i,j) ..  F(i,j)-y(i,j)*OMEGA =l= 0;
Logical2(j) ..  FW(j)- z(j)*OMEGA =l= 0;
Object .. OBJ =e= OFW+OWW+sum((i,j),y(i,j)*GAMMA)+sum(j,z(j)*GAMMA);

Model CASE2 /ALL/;
Solve CASE2 Using MIP Minimizing OBJ;
Display OBJ.l,OFW.l,OWW.l,FW.l,WW.l,x.l,F.l,y.l,z.l,CK.l;
```

## APPENDIX A-8 : Case Study 2 with regeneration GAMS Code

```
Set    i Source stream /i1*i5/
       j Sink stream /j1*j6/
;
Parameter
      CS          Source concentration
           /i1    100
            i2    230
            i3    170
            i4    250 /
      FS          Source flowrate
           /i1    155.4
            i2    1305.78
            i3    201 84
            i4    469.8  /
      CKL    Sink concentration limit
           /j1    20
            j2    80
            j3    100
            j4    200
            j5    20
            j6    200    /
      FK          Sink flowrate
           /j1    155.4
            j2    831.12
            j3    201.84
            j4    1149.84
            j5    34.68
```

```
          j6    68.7     /
;
Scalar
          CR       Regeneration Concentration (ppm) /30/
          HL       Hydraulic loading rate (ton per m3hr) /1.807/
          FC       Freshwater Cost ($ per m3) /0.043/
          TC       River Treatment Cost ($ per m3) /0.297/
          RC       Operation Cost ($ per ton) /0.15/
          RFC      Regeneration fix cost ($) /780876/
          RVC      Regeneration variable cost ($ per m3) /2310.6/
          HY       Operation time (Hour) /7080/
;
Variables              OBJ           Objective
;
Positive variables     x(i,j)        Spliting fraction
                       y(j)          Spliting fraction after Regeneration
                       FW(j)         Freshwater flowrate (ton per h)
                       Fx(i,j)       Splitting Flowrate  (ton per h)
                       Fy(j)         Regeneration Splitting Flowrate (ton per h)
                       FR            Regeneration Flowrate (ton per h)
                       FK1(j)        Sink flowrate before Regeneration  (ton per h)
                       CK1(j)        Sink concentration before Regeneration (ppm)
                       CK2(j)        Sink stream concentration after Regeneration (ppm)
                       WW(i)         Waste flowrate of each source (ton per h)
                       OWW           Overall Wastewater  (ton per h)
                       OFW           Overall Freshwater (ton per h)
                       TW            Waste to treat flowrate (ton per h)
                       Rarea         Area of Regeneration unit (m3)
                       RINV          Regeneration investment Cost ($)
                       PINV          Piping investment cost ($)
                       INV           Total investment cost  ($)
                       INC           Initial operating Cost ($ per year)
                       OptCost       New operating Cost ($ per year)
                       Save          Saving Cost ($ per year)
                       Pay           Payback period (year)
;
*Existing flowrate*****************************************************
Fx.lo('i1','j4') = 155.4;Fx.lo('i3','j4') = 201.84;Fx.lo('i2','j4') = 41.28;
**********************************************************************
Equation
      MBR1(j)        Overall material balance before Regeneration (Contaminant)
      MBR2(j)        Overall material balance before Regeneration (Mass flowrate)
      Cons1(i)       Constraint for x value
      Cons2(j)       Constraint for CK1 and CK2
      MBR3(j)        Overall material balance after Regeneration (Contaminant)
      MBR4(j)        Overall material balance sfter Regeneration (Mass flowrate)
      Cons3(j)       Constraint for CK2 and CKL
      Fresh          Overall Freshwater usage of
      Flow(i,j)      Flowrate each sink
      Waste(i)       Waste of each source
      OWaste         Overall waste
```

```
     RegenF        Regeneration flowrate
     Treat         Treatment flowrate
     ConR          Constraint for y value
     Area          Regeneration area calculation
     INCost        Initial operation cost
     NewCost       New operation cost
     RCost         Regeneration investment cost
     PCost         Piping investment cost
     Invest        Total investment cost
     Saving        Saving calculation
     Objective     Objective function
;
MBR1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK1(j)*FK1(j) ;
MBR2(j) .. sum(i,FS(i)*x(i,j)) + FW(j) =e= FK1(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK1(j) =g= CK2(j);
MBR3(j) ..  CK1(j)*FK1(j) + Fy(j)*CR =e= CK2(j)*FK(j);
MBR4(j) .. FK1(j) + Fy(j) =e= FK(j);
Cons3(j) .. CK2(j) =l= CKL(j);
Fresh .. OFW =e= sum(j,FW(j));
Flow(i,j) .. Fx(i,j) =e= FS(i)*x(i,j) ;
Waste(i) .. WW(i) =e=  (1-sum(j,x(i,j)))*FS(i);
OWaste .. FR =l= sum(i,WW(i));
RegenF(j) .. Fy(j) =e= FR*y(j);
Treat .. TW =e= sum(i,WW(i))-FR;
ConR .. sum(j,y(j)) =l= 1;
Area .. Rarea =e= FR*sum(j,y(j))*HL;
INCost .. INC =e= FC*HY*1989.1 + TC*HY*1680.3;
NewCost .. OptCost =e= FC*HY*OFW + TC*TW*HY + RC*FR*HY;
RCost .. RINV =e= RFC+RVC*Rarea;
PCost .. PINV =e= RINV*0.16;
Invest .. INV =e= RINV + PINV;
Saving .. Save =e= INC - OptCost;
Objective ..OBJ =e= Save;
Model CASE2 /ALL/;
Solve CASE2 Using NLP Maximizing OBJ;
Display OBJ.l,INV.l,INC.l,Optcost.l,Save.l,FR.l,OFW.l,FW.l,WW.l,TW.l,Rarea.l,x.l,Fx.l,Fy.l,CK2.l;
```

## APPENDIX A-9 : Case Study 3.1 GAMS Code

```
SETS          i Source streams /i1*i2/
              j Sink streams /j1*j2/
              u Treatment unit /u1*u2/
              w Treat streams /w1*w2/
              r Freshwater source  /r1*r2/
              n Treatment stage /n1*n3/
;
PARAMETERS
     CS          Source composition
```

```
     /i1   0.035
      i2   0.024  /
FS          Source flowrate (kg per h)
     /i1   2500
      i2   2870   /
CKL         Sink composition limit
     /j1   0.014
      j2   0.012  /
FK          Sink flowrate (kg per h)
     /j1   2800
      j2   2300   /
CostFW  Freshwater cost ($ per kg)
     /r1   0.0019
      r2   0.0014   /
CFW         Freshwater composition
     /r1   0
      r2   0.005   /
TFCI        Treatment fix cost extra ($)
     /u1   800
      u2   900     /
TVCI        Treatment variable cost extra ($ per kg)
     /u1   1.1367
      u2   0.9548    /
OC          Treatment operation cost ($ per kg)
     /u1   0.79e-3
      u2   0.63e-3    /
Alpha       Treatment efficiency
     /u1   0.91
      u2   0.72      /
CPF6        Piping fix cost source to waste ($ per y)
     /i1   0.6
      i2   1.3       /
CP6         Piping variable cost source to waste ($ per kg)
     /i1   0.7e-4
      i2   1.4e-4    /
CPF7        Piping fix cost treat to waste ($ per y)
     /w1   1.1
      w2   0.9       /
CP7         Piping variable cost treat to waste ($ per kg)
     /w1   0.2e-4
      w2   0.2e-4    /

InYT(u,n)       YT parameter
InYTI(u)        YTI parameter
FTP(w)          FT parameter
FTIP(u)         FTI parameter
CTIP(u)         CTI parameter
CTP(w)          CT parameter
CKP(j)          CK parameter
CWP             CW parameter
xFP(i,j)        xF parameter
```

```
      yFP(i,u)        yF parameter
      zFP(w,j)        zF parameter
      tFP(w,u)        tF parameter
      FRP(r,j)        FW parameter
      WW1P(i)         WW1 parameter
      WW2P(w)         WW2 parameter
;
TABLE TFC(u,n)   Treatment fix cost ($ per y)
           n1          n2          n3
     u1    9875.43     13852.9     16125.94
     u2    7822.52     11133.56    13025.75     ;
TABLE TVC(u,n)   Treatment variable cost ($ per kg)
           n1          n2          n3
     u1    8.58269     6.36064     5.72571
     u2    7.14466     5.29491     4.76637      ;
TABLE CPF1(i,j)  Piping fix cost source to sink ($ per y)
           j1     j2
     i1    1.1    1.3
     i2    0.8    1.4                      ;
TABLE CP1(i,j)   Piping variable cost source to sink ($ per kg)
           j1       j2
     i1    1.1e-4   1.2e-4
     i2    0.8e-4   1.3e-4                 ;
TABLE CPF2(i,u)  Piping fix cost source to treat ($ per y)
           u1     u2
     i1    1.2    1.4
     i2    1.1    1.5                      ;
TABLE CP2(i,u)   Piping variable cost source to treat ($ per kg)
           u1       u2
     i1    1.2e-4   1.1e-4
     i2    0.9e-4   1.0e-4                 ;
TABLE CPF3(w,u)  Piping fix cost treat1 to treat2 ($ per y)
           u1     u2
     w1    0.6    0.4
     w2    0.6    0.4                      ;
TABLE CP3(w,u)   Piping variable cost treat1 to treat2 ($ per kg)
           u1       u2
     w1    0.4e-4   0.5e-4
     w2    0.4e-4   0.5e-4                 ;
TABLE CPF4(w,j)  Piping fix cost treat to sink ($ per y)
           j1     j2
     w1    1.4    1.3
     w2    1.2    1.0                      ;
TABLE CP4(w,j)   Piping variable cost treat to sink ($ per kg)
           j1       j2
     w1    1.3e-4   1.1e-4
     w2    1.1e-4   0.8e-4                 ;
TABLE CPF5(r,j)  Piping fix cost fresh to sink ($ per y)
           j1     j2
     r1    1.4    1.7
     r2    1.3    1.9                      ;
```

```
TABLE CP5(r,j)  Piping variable cost fresh to sink ($ per kg)
          j1      j2
    r1    1.6e-4  1.7e-4
    r2    1.4e-4  1.5e-4
;
SCALAR      CWL   Waste concentration limit (ppm) /0.015/
            HY    Operation time (h per y)  /8000/
            KY    Operation year (1 per y)  /0.333/
            OMEGA /1000000/
;
VARIABLE  OBJ1, OBJ2, OBJ3, OBJ4, TAC
;
POSITIVE VARIABLE
          x(i,j)        Split fraction source to sink
            y(i,u)      Split fraction source to treat
            y1(i)       Split fraction source to treat for model 1
            t(w,u)      Split fraction treat to treat
            z(w,j)      Split fraction treat to sink
            FR(r,j)     Freshwater flowrate (kg per h)
            WW1(i)      Waste i flowrate (kg per h)
            WW2(w)      Waste w flowrate (kg per h)
            FT(w)       Treatment flowrate out (kg per h)
            FTI(u)      Treatment flowrate in  (kg per h)
            CT(w)       Treatment composition out
            CTI(u)      Treatment composition in
            OWW         Overall waste flowrate (kg per h)
            OFW         Overall freshwater flowrate (kg per h)
            CW          Waste discharge composition
            CK(j)       Sink composition
            FACost      Freshwater annual cost ($ per y)
            TFCost      Treatment investment cost ($ per y)
            TFCostI     Increase capacity treatment investment cost ($ per y)
            TTCost      Total treatment investment annual cost ($ per y)
            TOCost      Treatment operation annual cost ($ per y)
            PA1         Piping cost source to sink ($ per y)
            PA2         Piping cost source to treat ($ per y)
            PA3         Piping cost treat to treat ($ per y)
            PA4         Piping cost treat to sink ($ per y)
            PA5         Piping cost fresh to sink ($ per y)
            PA6         Piping cost source to waste ($ per y)
            PA7         Piping cost treat to waste ($ per y)
            PACost      Piping annual cost ($ per y)
            xF(i,j)     Split Flowrate source to sink (kg per h)
            yF(i,u)     Split Flowrate source to treat (kg per h)
            zF(w,j)     Split Flowrate treat to sink (kg per h)
            tF(w,u)     Split Flowrate treat to treat (kg per h)
            Am(i)
            Bm(i)
            Ac(i)
            Bc(i)
            A1t(u)
```

```
            B1t(u)
            A2t(u)
            B2t(u)
            A1k(j)
            B1k(j)
            C1k(j)
            A2k(j)
            B2k(j)
            C2k(j)
;
********Bounding*********
x.lo(i,j)=0;x.up(i,j)=1;
y.lo(i,u)=0;y.up(i,u)=1;
z.lo(w,j)=0;z.up(w,j)=1;
BINARY VARIABLES
            YT(u,n)         Existing Treatment unit
            YTI(u)          Existing Increase capacity treatment unit
            zx(i,j)         Existing Split Flowrate source to sink
            zy(i,u)         Existing Split Flowrate source to treat
            zz(w,j)         Existing Split Flowrate treat to sink
            zfr(r,j)        Existing Flowrate fresh to sink
            zt(w,u)         Existing Split Flowrate treat to treat
            zw1(i)          Existing Split Flowrate source to waste
            zw2(w)          Existing Split Flowrate treat to waste
;
EQUATIONS
*Model 1 ******** Linear **********
        M1_mass(j)          LP mass balance
        M1_cont(j)          LP contaminant balance
        M1_cons(i)          x constraint
        M1_cons2(j)         Sink composition constraint
        M1_waste(i)         y value
***************************SourceMass Balance***********************
        SMB_1(i)            Source Mass Balance eq1
        SMB_2(i)            Source Mass Balance eq2
        SMB_3(i)            Source Mass Balance
        SCB_1(i)            Source Contaminant Balance eq1
        SCB_2(i)            Source Contaminant Balance eq2
        SCB_3(i)            Source Contaminant Balance
        Consx(i)            x variable constraint
**************************Treatment Mass Balance***********************
        TMB1_1(u)           Treatment Mass Balance 1 eq1
        TMB1_2(u)           Treatment Mass Balance 1 eq2
        TMB1_3(u)           Treatment Mass Balance 1 eq3
        TCB1_1(u)           Treatment Contaminant Balance 1 eq1
        TCB1_2(u)           Treatment Contaminant Balance 1 eq2
        TCB1_3(u)           Treatment Contaminant Balance 1 eq3
        TMB2(w)             Treatment Mass Balance 2
        TCB2(w)             Treatment Contaminant Balance 3
        TR(u,w)             Treat unit Contamiant balance
        ConsT1(u,w)         Treat Constraint1
```

```
        ConsT2(u,w)         Treat Constraint2
        ConsT3(w)           Treat Constraint3
*Fix parameters*********
        TMB1_1P(u)           Treatment Mass Balance 1 eq1
        TMB1_2P(u)           Treatment Mass Balance 1 eq2
        TMB1_3P(u)           Treatment Mass Balance 1 eq3
        TCB1_1P(u)           Treatment Contaminant Balance 1 eq1
        TCB1_2P(u)           Treatment Contaminant Balance 1 eq2
        TCB1_3P(u)           Treatment Contaminant Balance 1 eq3
        TMB2P(w)             Treatment Mass Balance 2
        TCB2P(w)             Treatment Contaminant Balance 3
        TRP(u,w)            Treat unit Contamiant balance
        ConsT1P(u,w)         Treat Constraint1
        ConsT2P(u,w)         Treat Constraint2
        ConsT3P(w)           Treat Constraint3
**************************Waste Mass Balance**************************
        WASTE               Overall Waste Flowrate
        CWASTE              Overall Waste Concentraion
        ConsW               Waste constraint
        FRESH               Overall freshwater
*Fix parameter***********
        WASTEP               Overall Waste Flowrate
        CWASTEP              Overall Waste Concentraion
        FRESHP               Overall freshwater
*************************
**************************Sink Mass Balance**************************
        SKMB_1(j)           Sink Mass Balance eq1
        SKMB_2(j)           Sink Mass Balance eq2
        SKMB_3(j)           Sink Mass Balance eq3
        SKMB_4(j)           Sink Mass Balance eq4
        SKCB_1(j)           Sink Contaminant Balance eq1
        SKCB_2(j)           Sink Contaminant Balance eq2
        SKCB_3(j)           Sink Contaminant Balance eq3
        SKCB_4(j)           Sink Contaminant Balance eq4
        ConsSK(j)           Sink Contaminant Constraint
*Fix parameter***********
        SKMB_1P(j)           Sink Mass Balance eq1
        SKMB_2P(j)           Sink Mass Balance eq2
        SKMB_3P(j)           Sink Mass Balance eq3
        SKMB_4P(j)           Sink Mass Balance eq4
        SKCB_1P(j)           Sink Contaminant Balance eq1
        SKCB_2P(j)           Sink Contaminant Balance eq2
        SKCB_3P(j)           Sink Contaminant Balance eq3
        SKCB_4P(j)           Sink Contaminant Balance eq4
        ConsSKP(j)           Sink Contaminant Constraint
*************************

**********************Flowrate existing and constraint*****************
        Dis1(i,j)           Split Flowrate source to sink
        Dis2(i,u)           Split Flowrate source to treat
        Dis3(w,j)           Split Flowrate treat to sink
```

```
        Dis4(w,u)          Split Flowrate treat to treat
        xexist(i,j)        Existing Split Flowrate source to sink
        yexist(i,u)        Existing Split Flowrate source to treat
        zexist(w,j)        Existing Split Flowrate treat to sink
        texist(w,u)        Existing Split Flowrate treat to treat
        frexist(r,j)       Existing Flowrate fresh to sink
        ww1exist(i)        Existing Flowrate source to waste
        ww2exist(w)        Existing Flowrate treat to waste
        xcons(i,j)         Split Flowrate source to sink constraint
        ycons(i,u)         Split Flowrate source to treat constraint
        zcons(w,j)         Split Flowrate treat to sink constraint
        frcons(r,j)        Flowrate fresh to sink constraint
        tcons(w,u)         Split Flowrate treat to treat constraint
        w1cons(i)          Flowrate source to waste constraint
        w2cons(w)          Flowrate treat to waste constraint
*Fix parameters*************
        Dis1P(i,j)         Split Flowrate source to sink
        Dis2P(i,u)         Split Flowrate source to treat
        Dis3P(w,j)         Split Flowrate treat to sink
        Dis4P(w,u)         Split Flowrate treat to treat

        xexistP(i,j)       Existing Split Flowrate source to sink
        yexistP(i,u)       Existing Split Flowrate source to treat
        zexistP(w,j)       Existing Split Flowrate treat to sink
        texistP(w,u)       Existing Split Flowrate treat to treat
        frexistP(r,j)      Existing Flowrate fresh to sink
        ww1existP(i)       Existing Flowrate source to waste
        ww2existP(w)       Existing Flowrate treat to waste
        xconsP(i,j)        Split Flowrate source to sink constraint
        yconsP(i,u)        Split Flowrate source to treat constraint
        zconsP(w,j)        Split Flowrate treat to sink constraint
        frconsP(r,j)       Flowrate fresh to sink constraint
        tconsP(w,u)        Split Flowrate treat to treat constraint
        w1consP(i)         Flowrate source to waste constraint
        w2consP(w)         Flowrate treat to waste constraint
******************************
***************************Cost Calculation****************************
        TUC1(u)            Treatment Unit Choosing 0-3187
        TUC2(u)            Treatment Unit Choosing 3188-6374
        TUC3(u)            Treatment Unit Choosing 6375-INF
        ConsB1             Binary constraint
        ConsB2             Flowrate constraint
        FreshCost          Freshwater cost1
        FreshCost2         Freshwater cost2
        TreatCost          Treatment unit cost
        TreatOCost         Treatment Operation Cost
        PIPCost1           Piping Cost source to sink
        PIPCost2           Piping Cost source to treat
        PIPCost3           Piping Cost treat to treat
        PIPCost4           Piping Cost treat to sink
        PIPCost5           Piping Cost fresh to sink
```

```
        PIPCost6        Piping Cost source to waste
        PIPCost7        Piping Cost treat to waste
        PIPCost         Total Piping Cost
        Total           Total annual cost
*Fix parameter*************
        TUC1P(u)        Treatment Unit Choosing 0-1700
        TUC2P(u)        Treatment Unit Choosing 1701-3580
        TUC3P(u)        Treatment Unit Choosing 1701-3580
        ConsBP1         Binary constraint
        ConsBP2         Flowrate constraint
        FreshCostP      Freshwater cost fix parameter
        TreatCostP      Treatment unit cost fix parameter
        TreatOCostP     Treatment Operation Cost fix parameter
        PIPCost1P       Piping Cost source to sink
        PIPCost2P       Piping Cost source to treat
        PIPCost3P       Piping Cost treat to treat
        PIPCost4P       Piping Cost treat to sink
        PIPCost5P       Piping Cost fresh to sink
        PIPCost6P       Piping Cost source to waste
        PIPCost7P       Piping Cost treat to waste
        PIPCostP        Total Piping Cost
***************************
****************************Objective function************************
        Object1         Objective Function1
        Object2         Objective Function2
        Object3         Objective Function3
        Object4         Objective Function4
**********************************************************************
*Model 1 ******** Linear *****************
M1_mass(j) .. FK(j) =e= SUM(i,FS(i)*x(i,j))+SUM(r,FR(r,j));
M1_cont(j) .. FK(j)*CK(j) =e= SUM(i,FS(i)*x(i,j)*CS(i))+SUM(r,FR(r,j)*CFW(r));
M1_cons(i) .. SUM(j,x(i,j)) =l= 1;
M1_cons2(j).. CK(j) =l= CKL(j);
M1_waste(i) .. y1(i) =e= (1-sum(j,x(i,j)));
**************************Source Mass Balance**************************
SMB_1(i) .. Am(i) =e= sum(j,FS(i)*x(i,j));
SMB_2(i) .. Bm(i) =e= sum(u,FS(i)*y(i,u));
SMB_3(i) .. FS(i) =e= Am(i)+Bm(i)+WW1(i);
SCB_1(i) .. Ac(i) =e= sum(j,FS(i)*x(i,j)*CS(i));
SCB_2(i) .. Bc(i) =e= sum(u,FS(i)*y(i,u)*CS(i));
SCB_3(i) .. FS(i)*CS(i) =e= Ac(i) + Bc(i) + WW1(i)*CS(i);
Consx(i) .. sum(j,x(i,j))+sum(u,y(i,u)) =l= 1;
*************************Treatment Mass Balance***********************
TMB1_1(u) .. A1t(u) =e= sum(i,FS(i)*y(i,u));
TMB1_2(u) .. B1t(u) =e= sum(w,FT(w)*t(w,u));
TMB1_3(u) .. A1t(u)+B1t(u) =e= FTI(u);
TCB1_1(u) .. A2t(u) =e= sum(i,FS(i)*y(i,u)*CS(i));
TCB1_2(u) .. B2t(u) =e= sum(w,FT(w)*t(w,u)*CT(w));
TCB1_3(u) .. A2t(u)+B2t(u) =e= FTI(u)*CTI(u);
TMB2(w) .. FT(w) =e= sum(u,FT(w)*t(w,u))+sum(j,FT(w)*z(w,j))+WW2(w);
TCB2(w) .. FT(w)*CT(w) =e= sum(u,FT(w)*t(w,u)*CT(w))+sum(j,FT(w)*z(w,j)*CT(w))+WW2(w)*CT(w);
```

```
TR(u,w)$(ord(w) eq ord(u)) .. CT(w) =e= (1-Alpha(u))*CTI(u);
ConsT1(u,w)$(ord(w) eq ord(u)) .. FTI(u) =e= FT(w);
ConsT2(u,w)$(ord(w) eq ord(u)) .. CTI(u) =g= CT(w);
ConsT3(w) .. sum(u,t(w,u))+sum(j,z(w,j)) =l= 1;
*Fixparameters**************
TMB1_1P(u) .. A1t(u) =e= sum(i,FS(i)*y(i,u));
TMB1_2P(u) .. B1t(u) =e= sum(w,FTP(w)*t(w,u));
TMB1_3P(u) .. A1t(u)+B1t(u) =e= FTIP(u);
TCB1_1P(u) .. A2t(u) =e= sum(i,FS(i)*y(i,u)*CS(i));
TCB1_2P(u) .. B2t(u) =e= sum(w,FTP(w)*t(w,u)*CTP(w));
TCB1_3P(u) .. A2t(u)+B2t(u) =e= FTIP(u)*CTIP(u);
TMB2P(w) .. FTP(w) =e= sum(u,FTP(w)*t(w,u))+sum(j,FTP(w)*z(w,j))+WW2(w);
TCB2P(w) .. FTP(w)*CTP(w) =e=
sum(u,FTP(w)*t(w,u)*CTP(w))+sum(j,FTP(w)*z(w,j)*CTP(w))+WW2(w)*CTP(w);
TRP(u,w)$(ord(w) eq ord(u)) .. CTP(w) =e= (1-Alpha(u))*CTIP(u);
ConsT1P(u,w)$(ord(w) eq ord(u)) .. FTIP(u) =e= FTP(w);
ConsT2P(u,w)$(ord(w) eq ord(u)) .. CTIP(u) =g= CTP(w);
ConsT3P(w) .. sum(u,t(w,u))+sum(j,z(w,j)) =l= 1;
***************************Waste Mass Balance***************************
WASTE .. OWW =e= sum(i,WW1(i))+sum(w,WW2(w));
CWASTE .. OWW*CW =e= sum(i,WW1(i)*CS(i))+sum(w,WW2(w)*CT(w));
ConsW .. CW =l= CWL;
FRESH .. OFW =e= sum((r,j),FR(r,j));
*Fix parameter************
WASTEP .. OWW =e= sum(i,WW1P(i))+sum(w,WW2P(w));
CWASTEP .. OWW*CWP =e= sum(i,WW1P(i)*CS(i))+sum(w,WW2P(w)*CTP(w));
FRESHP .. OFW =e= sum((r,j),FRP(r,j));
***************************Sink Mass Balance***************************
SKMB_1(j) .. A1k(j) =e= sum(i,FS(i)*x(i,j));
SKMB_2(j) .. B1k(j) =e= sum(w,FT(w)*z(w,j));
SKMB_3(j) .. C1k(j) =e= sum(r,FR(r,j));
SKMB_4(j) .. FK(j) =e= A1k(j) + B1k(j) + C1k(j);
SKCB_1(j) .. A2k(j) =e= sum(i,FS(i)*x(i,j)*CS(i));
SKCB_2(j) .. B2k(j) =e= sum(w,FT(w)*z(w,j)*CT(w));
SKCB_3(j) .. C2k(j) =e= sum(r,FR(r,j)*CFW(r));
SKCB_4(j) .. FK(j)*CK(j) =e= A2k(j) + B2k(j) + C2k(j);
ConsSK(j) .. CK(j) =l= CKL(j);
*Fix parameter*****************
SKMB_1P(j) .. A1k(j) =e= sum(i,FS(i)*x(i,j));
SKMB_2P(j) .. B1k(j) =e= sum(w,FTP(w)*z(w,j));
SKMB_3P(j) .. C1k(j) =e= sum(r,FR(r,j));
SKMB_4P(j) .. FK(j) =e= A1k(j) + B1k(j) + C1k(j);
SKCB_1P(j) .. A2k(j) =e= sum(i,FS(i)*x(i,j)*CS(i));
SKCB_2P(j) .. B2k(j) =e= sum(w,FTP(w)*z(w,j)*CTP(w));
SKCB_3P(j) .. C2k(j) =e= sum(r,FR(r,j)*CFW(r));
SKCB_4P(j) .. FK(j)*CKP(j) =e= A2k(j) + B2k(j) + C2k(j);
**********************Flowrate existing and constraint*****************
Dis1(i,j) .. xF(i,j) =e= x(i,j)*FS(i);
Dis2(i,u) .. yF(i,u) =e= y(i,u)*FS(i);
Dis3(w,j) .. zF(w,j) =e= z(w,j)*FT(w);
Dis4(w,u) .. tF(w,u) =e= t(w,u)*FT(w);
```

```
*Fix parameter*************
Dis1P(i,j) .. xFP(i,j) =e= x(i,j)*FS(i);
Dis2P(i,u) .. yFP(i,u) =e= y(i,u)*FS(i);
Dis3P(w,j) .. zFP(w,j) =e= z(w,j)*FTP(w);
Dis4P(w,u) .. tFP(w,u) =e= t(w,u)*FTP(w);
xexist(i,j) .. xF(i,j)-OMEGA*zx(i,j) =l= 0 ;
yexist(i,u) .. yF(i,u)-OMEGA*zy(i,u) =l= 0 ;
zexist(w,j) .. zF(w,j)-OMEGA*zz(w,j) =l= 0 ;
texist(w,u) .. tF(w,u)-OMEGA*zt(w,u) =l= 0 ;
frexist(r,j) .. FR(r,j)-OMEGA*zfr(r,j) =l= 0 ;
ww1exist(i) .. WW1(i)-OMEGA*zw1(i) =l= 0 ;
ww2exist(w) .. WW2(w)-OMEGA*zw2(w) =l= 0 ;
xcons(i,j) .. xF(i,j) =g= 300*zx(i,j) ;
ycons(i,u) .. yF(i,u) =g= 300*zy(i,u) ;
zcons(w,j) .. zF(w,j) =g= 300*zz(w,j)  ;
frcons(r,j) .. FR(r,j) =g= 300*zfr(r,j) ;
tcons(w,u) .. tF(w,u) =g= 300*zt(w,u)  ;
w1cons(i) .. WW1(i) =g= 300*zw1(i)  ;
w2cons(w) .. WW2(w) =g= 300*zw2(w) ;
**Fix parameters*********
xexistP(i,j) .. xFP(i,j)-OMEGA*zx(i,j) =l= 0 ;
yexistP(i,u) .. yFP(i,u)-OMEGA*zy(i,u) =l= 0 ;
zexistP(w,j) .. zFP(w,j)-OMEGA*zz(w,j) =l= 0 ;
texistP(w,u) .. tFP(w,u)-OMEGA*zt(w,u) =l= 0 ;
frexistP(r,j) .. FRP(r,j)-OMEGA*zfr(r,j) =l= 0 ;
ww1existP(i) .. WW1P(i)-OMEGA*zw1(i) =l= 0 ;
ww2existP(w) .. WW2P(w)-OMEGA*zw2(w) =l= 0 ;
xconsP(i,j) .. xFP(i,j) =g= 300*zx(i,j) ;
yconsP(i,u) .. yFP(i,u) =g= 300*zy(i,u) ;
zconsP(w,j) .. zFP(w,j) =g= 300*zz(w,j)  ;
frconsP(r,j) .. FRP(r,j) =g= 300*zfr(r,j) ;
tconsP(w,u) .. tFP(w,u) =g= 300*zt(w,u)  ;
w1consP(i) .. WW1P(i) =g= 300*zw1(i)  ;
w2consP(w) .. WW2P(w) =g= 300*zw2(w) ;
****************************Cost Calculation*****************************
TUC1(u).. FTI(u) =l= 1790*YT(u,'n1')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n3');
TUC2(u) .. FTI(u) =l= 3580*YT(u,'n2')+OMEGA*YT(u,'n1')+OMEGA*YT(u,'n3');
TUC3(u) .. FTI(u) =l= 5370*YT(u,'n3')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n1');
ConsB1(u)..sum(n,YT(u,n))=l=1;
ConsB2 .. sum(u,FTI(u)) =l= sum(i,FS(i));
*Fix parameter**************
TUC1P(u).. FTIP(u) =l= 1790*YT(u,'n1')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n3');
TUC2P(u) .. FTIP(u) =l= 3580*YT(u,'n2')+OMEGA*YT(u,'n1')+OMEGA*YT(u,'n3');
TUC3P(u) .. FTIP(u) =l= 5370*YT(u,'n3')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n1');
ConsBP1(u)..sum(n,YT(u,n))=l=1;
ConsBP2 .. sum(u,FTIP(u)) =l= sum(i,FS(i));
FreshCost .. FACost =e= sum((r,j),FR(r,j)*CostFW(r)*HY);
FreshCost2 .. FACost =e= sum((r,j),FR(r,j)*CostFW(r)*HY*zfr(r,j));
TreatCost .. TTCost =e= sum((u,n),(TFC(u,n)+FTI(u)*TVC(u,n))*KY*YT(u,n));
TreatOCost .. TOCost =e= sum(u,OC(u)*FTI(u)*HY);
PIPCost1 .. PA1 =e= sum((i,j),(CPF1(i,j)+CP1(i,j)*xF(i,j)*HY)*zx(i,j));
```

```
PIPCost2 .. PA2 =e= sum((i,u),(CPF2(i,u)+CP2(i,u)*yF(i,u)*HY)*zy(i,u));
PIPCost3 .. PA3 =e= sum((w,u),(CPF3(w,u)+CP3(w,u)*tF(w,u)*HY)*zt(w,u));
PIPCost4 .. PA4 =e= sum((w,j),(CPF4(w,j)+CP4(w,j)*zF(w,j)*HY)*zz(w,j));
PIPCost5 .. PA5 =e= sum((r,j),(CPF5(r,j)+CP5(r,j)*FR(r,j)*HY)*zfr(r,j));
PIPCost6 .. PA6 =e= sum(i,(CPF6(i)+CP6(i)*WW1(i)*HY)*zw1(i));
PIPCost7 .. PA7 =e= sum(w,(CPF7(w)+CP7(w)*WW2(w)*HY)*zw2(w));
PIPCost .. PACost =e= PA1+PA2+PA3+PA4+PA5+PA6+PA7;
Total .. TAC =e= FACost + TTCost + TOCost + PACost;
*Fix Parameter***********
TreatOCostP .. TOCost =e= sum(u,OC(u)*FTIP(u)*HY);
TreatCostP .. TTCost =e= sum((u,n),(TFC(u,n)+FTIP(u)*TVC(u,n))*KY*YT(u,n));
FreshCostP .. FACost =e= sum((r,j),FRP(r,j)*CostFW(r)*HY*zfr(r,j));
PIPCost1P .. PA1 =e= sum((i,j),(CPF1(i,j)+CP1(i,j)*xFP(i,j)*HY)*zx(i,j));
PIPCost2P .. PA2 =e= sum((i,u),(CPF2(i,u)+CP2(i,u)*yFP(i,u)*HY)*zy(i,u));
PIPCost3P .. PA3 =e= sum((w,u),(CPF3(w,u)+CP3(w,u)*tFP(w,u)*HY)*zt(w,u));
PIPCost4P .. PA4 =e= sum((w,j),(CPF4(w,j)+CP4(w,j)*zFP(w,j)*HY)*zz(w,j));
PIPCost5P .. PA5 =e= sum((r,j),(CPF5(r,j)+CP5(r,j)*FRP(r,j)*HY)*zfr(r,j));
PIPCost6P .. PA6 =e= sum(i,(CPF6(i)+CP6(i)*WW1P(i)*HY)*zw1(i));
PIPCost7P .. PA7 =e= sum(w,(CPF7(w)+CP7(w)*WW2P(w)*HY)*zw2(w));
PIPCostP .. PACost =e= PA1+PA2+PA3+PA4+PA5+PA6+PA7;
*****************************Objective function************************
Object1 .. OBJ1 =e= FACost;
Object2 .. OBJ2 =e= FACost+TTCost+TOCost;
Object3 .. OBJ3 =e= TAC;
Object4 .. OBJ4 =e= TAC;
******************************SOLVE 1******************************
MODEL CASE31CAL1
/ M1_mass,M1_cont,M1_cons,M1_cons2,M1_waste,FRESH,Object1,FreshCost,Dis1 /
SOLVE CASE31CAL1 USING LP MINIMIZING OBJ1;
DISPLAY OBJ1.l,x.l,FR.l,y1.l,xF.l;

******************************SOLVE 2******************************
Parameter
Inx(i,j) intermediate parameter x
InFR(r,j) intermediate parameter FR
Iny(i)
;
Inx(i,j) = x.l(i,j);
InFR(r,j) = FR.l(r,j);
Iny(i) = y1.l(i);
x.l(i,j) = Inx(i,j);
FR.l(r,j) = InFR(r,j);
y.l(i,u) = Iny(i);
*Initialization*****************
WW1.lo('i2')=300;
WW2.lo('w1')=300;
yF.fx('i2','u1')=0;
FR.fx('r2','j1')=0;
FR.fx('r2','j2')=0;
********************************
MODEL CASE31CAL2
```

```
/     SMB_1,SMB_2,SMB_3,SCB_1,SCB_2,SCB_3,Consx
,TMB1_1,TMB1_2,TMB1_3,TCB1_1,TCB1_2,TCB1_3,TMB2,TCB2,TR,ConsT1,
ConsT2,ConsT3,WASTE,CWASTE,ConsW,FRESH,SKMB_1,SKMB_2,SKMB_3,
SKMB_4,SKCB_1,SKCB_2,SKCB_3,SKCB_4,ConsSK,Dis1,Dis2,Dis3,Dis4,TUC1,
TUC2,TUC3,ConsB1,ConsB2,FreshCost,TreatCost,TreatOCost,Object2  / ;

SOLVE CASE31CAL2 USING MINLP MINIMIZING OBJ2;
DISPLAY OBJ1.l,OBJ2.l,xF.l,yF.l,zF.l,FR.l,WW1.l,WW2.l,CW.l,FTI.l,YT.l;

*****************************SOLVE 3*******************************
xFP(i,j) = xF.l(i,j);
yFP(i,u) = yF.l(i,u);
zFP(w,j) = zF.l(w,j);
tFP(w,u) = tF.l(w,u);
FRP(r,j) = FR.l(r,j);
WW1P(i) = WW1.l(i);
WW2P(w) = WW2.l(w);
FTIP(u) = FTI.l(u);
CTIP(u) = CTI.l(u);
CTP(w) = CT.l(w);
CWP = CW.l;
FTP(w) = FT.l(w);
CKP(j) = CK.l(j);
MODEL CASE31CAL3
/     SMB_1,SMB_2,SMB_3,SCB_1,SCB_2,SCB_3,Consx
,TMB1_1P,TMB1_2P,TMB1_3P,TCB1_1P,TCB1_2P,TCB1_3P,TMB2P,TCB2P,TRP,
ConsT1P,ConsT2P,ConsT3P,WASTEP,FRESHP,SKMB_1P,SKMB_2P,SKMB_3P,SKMB_4P,SKCB_1P,
SKCB_2P,SKCB_3P,SKCB_4P,Dis1P,Dis2P,Dis3P,Dis4P,TUC1P,TUC2P,TUC3P,ConsBP1,
xexistP,yexistP,zexistP,texistP,frexistP,ww1existP,ww2existP,xconsP,yconsP,
zconsP,tconsP,frconsP,w1consP,w2consP,PIPCost1P,PIPCost2P,PIPCost3P,PIPCost4P,
PIPCost5P,PIPCost6P,PIPCost7P,PIPCostP,FreshCostP,TreatCostP,TreatOCostP,
Total,Object3  /  ;

SOLVE CASE31CAL3 USING MIP MINIMIZING OBJ3;
DISPLAY OBJ2.l,OBJ3.l,FACost.l,TOCost.l,TTCost.l,PACost.l,CT.l,CTI.l,TAC.l,
xFP,yFP,zFP,FRP,WW1P,WW2P,YT.l,zx.l,zy.l,zz.l,zfr.l,zw1.l,zw2.l;

*****************************SOLVE 4*******************************
parameter
Inzx(i,j)
Inzy(i,u)
Inzt(w,u)
Inzz(w,j)
Inzfr(r,j)
Inzw1(i)
Inzw2(w)
InYT(u,n)
Inx1(i,j)  intermediate parameter x
Iny1(i,u)  intermediate parameter y
Inz1(w,j)  intermediate parameter z
InFR1(r,j) intermediate parameter FR
```

```
;
Inzx(i,j)=zx.l(i,j);
Inzy(i,u)=zy.l(i,u);
Inzt(w,u)=zt.l(w,u);
Inzz(w,j)=zz.l(w,j);
Inzfr(r,j)=zfr.l(r,j);
Inzw1(i)=zw1.l(i);
Inzw2(w)=zw2.l(w);
InYT(u,n)=YT.l(u,n);
Inx1(i,j) = x.l(i,j);
Iny1(i,u) = y.l(i,u);
Inz1(w,j) = z.l(w,j);
InFR1(r,j) = FRP(r,j);
*Innitial variable************
zx.l(i,j)=Inzx(i,j);
zy.l(i,u)=Inzy(i,u);
zt.l(w,u)=Inzt(w,u);
zz.l(w,j)=Inzz(w,j);
zfr.l(r,j)=Inzfr(r,j);
zw1.l(i)=Inzw1(i);
zw2.l(w)=Inzw2(w);
YT.l(u,n)=InYT(u,n);
x.l(i,j)=Inx1(i,j);
y.l(i,u)=Iny1(i,u);
z.l(w,j)=Inz1(w,j);
FR.l(r,j)=InFR1(r,j);

MODEL CASE31CAL4
/    SMB_1,SMB_2,SMB_3,SCB_1,SCB_2,SCB_3,Consx
,TMB1_1,TMB1_2,TMB1_3,TCB1_1,TCB1_2,TCB1_3,TMB2,TCB2,TR,ConsT1,ConsT2,ConsT3,
WASTE,CWASTE,ConsW,FRESH,SKMB_1,SKMB_2,SKMB_3,SKMB_4,SKCB_1,SKCB_2,SKCB_3,SKCB_4,
ConsSK,Dis1,Dis2,Dis3,Dis4,TUC1,TUC2,TUC3,ConsB1,ConsB2,xexist,yexist,zexist,
frexist,texist,ww1exist,ww2exist,xcons,ycons,zcons,frcons,tcons,w1cons,w2cons,
PIPCost1,PIPCost2,PIPCost3,PIPCost4,PIPCost5,PIPCost6,PIPCost7,PIPCost,FreshCost,
TreatCost,TreatOCost,Total,Object4  /
SOLVE CASE31CAL4 USING MINLP MINIMIZING OBJ4;
DISPLAY OBJ3.l,OBJ4.l,PACost.l,xF.l,yF.l,zF.l,FR.l,OFW.l,WW1.l,WW2.l,OWW.l,
YT.l,CT.l,CTI.l,CW.l,zx.l,zy.l,zfr.l;
```

## APPENDIX A-10 : Case Study 3.2 GAMS Code

```
SETS        i Source streams /i1*i4/
            j Sink streams /j1*j2/
            u Treatment unit /u1*u3/
            w Treat streams /w1*w3/
            r Freshwater source /r1*r2/
            n Treatment stage /n1*n3/

;
PARAMETERS
     CS        Source concentration (ppm)
```

```
     /i1    0
      i2    14
      i3    25
      i4    34    /
FS          Source flowrate (kg per h)
     /i1    2880
      i2    18000
      i3    21240
      i4    5040    /
CKL           Sink concentration limit (ppm)
     /j1    0
      j2    10  /
FK          Sink flowrate (kg per h)
     /j1    4320
      j2    20880   /
CostFW  Freshwater cost ($ per kg)
     /r1   0.00145
      r2   0.00094   /
CFW         Freshwater concentration (ppm)
     /r1   0
      r2   5        /
OC          Treatment operation cost ($ per kg)
     /u1   0.9e-3
      u2   0.6e-3
      u3   0.5e-3   /
Alpha         Treatment efficiency
     /u1   0.93
      u2   0.84
      u3   0.76   /
CPF6          Piping fix cost source to waste ($ per y)
     /i1    0.82
      i2    0.82
      i3    0.82
      i4    0.82    /
CP6         Piping variable cost source to waste ($ per kg)
     /i1    1.4e-3
      i2    1.4e-3
      i3    1.4e-3
      i4    1.4e-3    /
CPF7          Piping fix cost treat to waste ($ per y)
     /w1   0.89
      w2   0.89
      w3   0.89      /
CP7         Piping variable cost treat to waste ($ per kg)
     /w1   1.11e-3
      w2   1.11e-3
      w3   1.11e-3   /
lnYT(u,n)       YT parameter
lnYTI(u)        YTI parameter
FTP(w)          FT parameter
FTIP(u)         FTI parameter
```

```
      CTIP(u)       CTI parameter
      CTP(w)        CT parameter
      CKP(j)        CK parameter
      CWP           CW parameter
      xFP(i,j)      xF parameter
      yFP(i,u)      yF parameter
      zFP(w,j)      zF parameter
      tFP(w,u)      tF parameter
      FRP(r,j)      FW parameter
      WW1P(i)       WW1 parameter
      WW2P(w)       WW2 parameter
;
TABLE TFC(u,n)  Treatment fix cost ($ per y)
           n1          n2          n3
      u1   12470.71    19438.22    23420.05
      u2   9134.52     14506.78    17576.92
      u3   7873.48     12908.94    15786.6
;
TABLE TVC(u.n)  Treatment variable cost ($ per kg)
           n1          n2          n3
      u1   8.4443      6.2581      5.6334
      u2   6.5109      4.8252      4.3436
      u3   6.1027      5.5227      4.0713
;
TABLE CPF1(i,j)  Piping fix cost source to sink ($ per y)
           j1     j2
      i1   0.82   0.82
      i2   0.82   0.82
      i3   0.82   0.82
      i4   0.82   0.82
;
TABLE CP1(i,j)  Piping variable cost source to sink ($ per kg)
           j1       j2
      i1   1.4e-3   1.4e-3
      i2   1.4e-3   1.4e-3
      i3   1.4e-3   1.4e-3
      i4   1.4e-3   1.4e-3
;
TABLE CPF2(i,u)  Piping fix cost source to treat ($ per y)
           u1     u2     u3
      i1   0.96   0.96   0.96
      i2   0.96   0.96   0.96
      i3   0.96   0.96   0.96
      i4   0.96   0.96   0.96
;
TABLE CP2(i,u)  Piping variable cost source to treat ($ per kg)
           u1       u2       u3
      i1   1.2e-3   1.2e-3   1.2e-3
      i2   1.2e-3   1.2e-3   1.2e-3
      i3   1.2e-3   1.2e-3   1.2e-3
      i4   1.2e-3   1.2e-3   1.2e-3
```

```
TABLE CPF3(w,u)  Piping fix cost treat1 to treat2 ($ per y)
          u1      u2     u3
     w1    0.7     0.7   0.7
     w2    0.7     0.7   0.7
     w3    0.7     0.7   0.7
;
TABLE CP3(w,u)  Piping variable cost treat1 to treat2 ($ per kg)
          u1        u2        u3
     w1    0.63e-3  0.63e-3  0.63e-3
     w2    0.63e-3  0.63e-3  0.63e-3
     w3    0.63e-3  0.63e-3  0.63e-3
;
TABLE CPF4(w,j)  Piping fix cost treat to sink ($ per y)
          j1      j2
     w1    0.89    0.89
     w2    0.89    0.89
     w3    0.89    0.89
;
TABLE CP4(w,j)  Piping variable cost treat to sink ($ per kg)
          j1      j2
     w1    1.11e-3  1.11e-3
     w2    1.11e-3  1.11e-3
     w3    1.11e-3  1.11e-3
;
TABLE CPF5(r,j)  Piping fix cost fresh to sink ($ per y)
          j1      j2
     r1    1.635   1.635
     r2    1.635   1.635
;
TABLE CP5(r,j)  Piping variable cost fresh to sink ($ per kg)
          j1      j2
     r1    0.67e-3  0.67e-3
     r2    0.67e-3  0.67e-3
;
SCALAR       CWL    Waste concentration limit  (ppm)  /5/
             HY     Operation time (h per y)   /8000/
             KY     Operation year (1 per y)   /0.333/
             OMEGA  /1000000/
;
VARIABLE OBJ1, OBJ2, OBJ3, OBJ32, OBJ4, OBJ5, TAC
;
POSITIVE VARIABLE
             x(i,j)      Split fraction source to sink
             y(i,u)      Split fraction source to treat
             y1(i)       Split fraction source to treat for model 1
             t(w,u)      Split fraction treat to treat
             z(w,j)      Split fraction treat to sink
             FR(r,j)     Freshwater flowrate (kg per h)
             WW1(i)      Waste i flowrate (kg per h)
             WW2(w)      Waste w flowrate (kg per h)
             FT(w)       Treatment flowrate out (kg per h)
```

```
FTI(u)       Treatment flowrate in  (kg per h)
CT(w)        Treatment composition out
CTI(u)       Treatment composition in
OWW          Overall waste flowrate (kg per h)
OFW          Overall freshwater flowrate (kg per h)
CW           Waste discharge composition
CK(j)        Sink composition
FACost       Freshwater annual cost ($ per y)
TFCost       Treatment investment cost ($ per y)
TFCostI      Increase capacity treatment investment cost ($ per y)
TTCost       Total treatment investment annual cost ($ per y)
TOCost       Treatment operation annual cost ($ per y)
PA1          Piping cost source to sink ($ per y)
PA2          Piping cost source to treat ($ per y)
PA3          Piping cost treat to treat ($ per y)
PA4          Piping cost treat to sink ($ per y)
PA5          Piping cost fresh to sink ($ per y)
PA6          Piping cost source to waste ($ per y)
PA7          Piping cost treat to waste ($ per y)
PACost       Piping annual cost ($ per y)
xF(i,j)      Split Flowrate source to sink (kg per h)
yF(i,u)      Split Flowrate source to treat (kg per h)
zF(w,j)      Split Flowrate treat to sink (kg per h)
tF(w,u)      Split Flowrate treat to treat (kg per h)
Am(i)
Bm(i)
Ac(i)
Bc(i)
A1t(u)
B1t(u)
A2t(u)
B2t(u)
A1k(j)
B1k(j)
C1k(j)
A2k(j)
B2k(j)
C2k(j)
;

********Bounding**********
x.lo(i,j)=0;x.up(i,j)=1;
y.lo(i,u)=0;y.up(i,u)=1;
z.lo(w,j)=0;z.up(w,j)=1;

BINARY VARIABLES
        YT(u,n)        Existing Treatment unit
            YTI(u)        Existing Increase capacity treatment unit
            zx(i,j)       Existing Split Flowrate source to sink
            zy(i,u)       Existing Split Flowrate source to treat
            zz(w,j)       Existing Split Flowrate treat to sink
```

```
          zfr(r,j)          Existing Flowrate fresh to sink
          zt(w,u)           Existing Split Flowrate treat to treat
          zw1(i)            Existing Split Flowrate source to waste
          zw2(w)            Existing Split Flowrate treat to waste
;
EQUATIONS
*Model 1 ******* Linear **********
        M1_mass(j)          LP mass balance
        M1_cont(j)          LP contaminant balance
        M1_cons(i)          x constraint
        M1_cons2(j)         Sink composition constraint
        M1_waste(i)         y value
***************************SourceMass Balance***********************
        SMB_1(i)            Source Mass Balance eq1
        SMB_2(i)            Source Mass Balance eq2
        SMB_3(i)            Source Mass Balance
        SCB_1(i)            Source Contaminant Balance eq1
        SCB_2(i)            Source Contaminant Balance eq2
        SCB_3(i)            Source Contaminant Balance
        Consx(i)            x variable constraint
***************************Treatment Mass Balance************************
        TMB1_1(u)           Treatment Mass Balance 1 eq1
        TMB1_2(u)           Treatment Mass Balance 1 eq2
        TMB1_3(u)           Treatment Mass Balance 1 eq3
        TCB1_1(u)           Treatment Contaminant Balance 1 eq1
        TCB1_2(u)           Treatment Contaminant Balance 1 eq2
        TCB1_3(u)           Treatment Contaminant Balance 1 eq3
        TMB2(w)             Treatment Mass Balance 2
        TCB2(w)             Treatment Contaminant Balance 3
        TR(u,w)             Treat unit Contamiant balance
        ConsT1(u,w)         Treat Constraint1
        ConsT2(u,w)         Treat Constraint2
        ConsT3(w)           Treat Constraint3
*Fix parameters*********
        TMB1_1P(u)          Treatment Mass Balance 1 eq1
        TMB1_2P(u)          Treatment Mass Balance 1 eq2
        TMB1_3P(u)          Treatment Mass Balance 1 eq3
        TCB1_1P(u)          Treatment Contaminant Balance 1 eq1
        TCB1_2P(u)          Treatment Contaminant Balance 1 eq2
        TCB1_3P(u)          Treatment Contaminant Balance 1 eq3
        TMB2P(w)            Treatment Mass Balance 2
        TCB2P(w)            Treatment Contaminant Balance 3
        TRP(u,w)            Treat unit Contamiant balance
        ConsT1P(u,w)        Treat Constraint1
        ConsT2P(u,w)        Treat Constraint2
        ConsT3P(w)          Treat Constraint3
***************************Waste Mass Balance***************************
        WASTE               Overall Waste Flowrate
        CWASTE              Overall Waste Concentraion
        ConsW               Waste constraint
        FRESH               Overall freshwater
```

```
*Fix parameter************
        WASTEP          Overall Waste Flowrate
        CWASTEP         Overall Waste Concentraion
        FRESHP          Overall freshwater
**************************
***************************Sink Mass Balance****************************
        SKMB_1(j)       Sink Mass Balance eq1
        SKMB_2(j)       Sink Mass Balance eq2
        SKMB_3(j)       Sink Mass Balance eq3
        SKMB_4(j)       Sink Mass Balance eq4
        SKCB_1(j)       Sink Contaminant Balance eq1
        SKCB_2(j)       Sink Contaminant Balance eq2
        SKCB_3(j)       Sink Contaminant Balance eq3
        SKCB_4(j)       Sink Contaminant Balance eq4
        ConsSK(j)       Sink Contaminant Constraint
*Fix parameter************
        SKMB_1P(j)      Sink Mass Balance eq1
        SKMB_2P(j)      Sink Mass Balance eq2
        SKMB_3P(j)      Sink Mass Balance eq3
        SKMB_4P(j)      Sink Mass Balance eq4
        SKCB_1P(j)      Sink Contaminant Balance eq1
        SKCB_2P(j)      Sink Contaminant Balance eq2
        SKCB_3P(j)      Sink Contaminant Balance eq3
        SKCB_4P(j)      Sink Contaminant Balance eq4
        ConsSKP(j)      Sink Contaminant Constraint
**************************
***********************Flowrate existing and constraint******************
        Dis1(i,j)       Split Flowrate source to sink
        Dis2(i,u)       Split Flowrate source to treat
        Dis3(w,j)       Split Flowrate treat to sink
        Dis4(w,u)       Split Flowrate treat to treat
        xexist(i,j)     Existing Split Flowrate source to sink
        yexist(i,u)     Existing Split Flowrate source to treat
        zexist(w,j)     Existing Split Flowrate treat to sink
        texist(w,u)     Existing Split Flowrate treat to treat
        frexist(r,j)    Existing Flowrate fresh to sink
        ww1exist(i)     Existing Flowrate source to waste
        ww2exist(w)     Existing Flowrate treat to waste
        xcons(i,j)      Split Flowrate source to sink constraint
        ycons(i,u)      Split Flowrate source to treat constraint
        zcons(w,j)      Split Flowrate treat to sink constraint
        frcons(r,j)     Flowrate fresh to sink constraint
        tcons(w,u)      Split Flowrate treat to treat constraint
        w1cons(i)       Flowrate source to waste constraint
        w2cons(w)       Flowrate treat to waste constraint
*Fix parameters**************
        Dis1P(i,j)      Split Flowrate source to sink
        Dis2P(i,u)      Split Flowrate source to treat
        Dis3P(w,j)      Split Flowrate treat to sink
        Dis4P(w,u)      Split Flowrate treat to treat
        xexistP(i,j)    Existing Split Flowrate source to sink
```

```
        yexistP(i,u)        Existing Split Flowrate source to treat
        zexistP(w,j)        Existing Split Flowrate treat to sink
        texistP(w,u)        Existing Split Flowrate treat to treat
        frexistP(r,j)       Existing Flowrate fresh to sink
        ww1existP(i)        Existing Flowrate source to waste
        ww2existP(w)        Existing Flowrate treat to waste
        xconsP(i,j)         Split Flowrate source to sink constraint
        yconsP(i,u)         Split Flowrate source to treat constraint
        zconsP(w,j)         Split Flowrate treat to sink constraint
        frconsP(r,j)        Flowrate fresh to sink constraint
        tconsP(w,u)         Split Flowrate treat to treat constraint
        w1consP(i)          Flowrate source to waste constraint
        w2consP(w)          Flowrate treat to waste constraint
********************************
****************************Cost Calculation*****************************
        TUC1(u)             Treatment Unit Choosing 0-3187
        TUC2(u)             Treatment Unit Choosing 3188-6374
        TUC3(u)             Treatment Unit Choosing 6375-INF
        ConsB1              Binary constraint
        ConsB2              Flowrate constraint
        FreshCost           Freshwater cost1
        FreshCost2          Freshwater cost2
        TreatCost           Treatment unit cost
        TreatOCost          Treatment Operation Cost
        PIPCost1            Piping Cost source to sink
        PIPCost2            Piping Cost source to treat
        PIPCost3            Piping Cost treat to treat
        PIPCost4            Piping Cost treat to sink
        PIPCost5            Piping Cost fresh to sink
        PIPCost6            Piping Cost source to waste
        PIPCost7            Piping Cost treat to waste
        PIPCost             Total Piping Cost
        Total               Total annual cost
*Fix parameter**************
        TUC1P(u)            Treatment Unit Choosing 0-1700
        TUC2P(u)            Treatment Unit Choosing 1701-3580
        TUC3P(u)            Treatment Unit Choosing 1701-3580
        ConsBP1             Binary constraint
        ConsBP2             Flowrate constraint
        FreshCostP          Freshwater cost fix parameter
        TreatCostP          Treatment unit cost fix parameter
        TreatOCostP         Treatment Operation Cost fix parameter
        PIPCost1P           Piping Cost source to sink
        PIPCost2P           Piping Cost source to treat
        PIPCost3P           Piping Cost treat to treat
        PIPCost4P           Piping Cost treat to sink
        PIPCost5P           Piping Cost fresh to sink
        PIPCost6P           Piping Cost source to waste
        PIPCost7P           Piping Cost treat to waste
        PIPCostP            Total Piping Cost
****************************
```

```
******************************Objective function*************************
        Object1          Objective Function1
        Object2          Objective Function2
        Object3          Objective Function3
        Object4          Objective Function4                  ;
*********************************************************************
*Model 1 ******** Linear ****************
M1_mass(j) .. FK(j) =e= SUM(i,FS(i)*x(i,j))+SUM(r,FR(r,j));
M1_cont(j) .. FK(j)*CK(j) =e= SUM(i,FS(i)*x(i,j)*CS(i))+SUM(r,FR(r,j)*CFW(r));
M1_cons(i) .. SUM(j,x(i,j)) =l= 1;
M1_cons2(j).. CK(j) =l= CKL(j);
M1_waste(i) .. y1(i) =e= (1-sum(j,x(i,j)));
***************************Source Mass Balance***************************
SMB_1(i) .. Am(i) =e= sum(j,FS(i)*x(i,j));
SMB_2(i) .. Bm(i) =e= sum(u,FS(i)*y(i,u));
SMB_3(i) .. FS(i) =e= Am(i)+Bm(i)+WW1(i);
SCB_1(i) .. Ac(i) =e= sum(j,FS(i)*x(i,j)*CS(i));
SCB_2(i) .. Bc(i) =e= sum(u,FS(i)*y(i,u)*CS(i));
SCB_3(i) .. FS(i)*CS(i) =e= Ac(i) + Bc(i) + WW1(i)*CS(i);
Consx(i) .. sum(j,x(i,j))+sum(u,y(i,u)) =l= 1;
**************************Treatment Mass Balance***********************
TMB1_1(u) .. A1t(u) =e= sum(i,FS(i)*y(i,u));
TMB1_2(u) .. B1t(u) =e= sum(w,FT(w)*t(w,u));
TMB1_3(u) .. A1t(u)+B1t(u) =e= FTI(u);
TCB1_1(u) .. A2t(u) =e= sum(i,FS(i)*y(i,u)*CS(i));
TCB1_2(u) .. B2t(u) =e= sum(w,FT(w)*t(w,u)*CT(w));
TCB1_3(u) .. A2t(u)+B2t(u) =e= FTI(u)*CTI(u);
TMB2(w) .. FT(w) =e= sum(u,FT(w)*t(w,u))+sum(j,FT(w)*z(w,j))+WW2(w);
TCB2(w) .. FT(w)*CT(w) =e= sum(u,FT(w)*t(w,u)*CT(w))+sum(j,FT(w)*z(w,j)*CT(w))+WW2(w)*CT(w);
TR(u,w)$(ord(w) eq ord(u)) .. CT(w) =e= (1-Alpha(u))*CTI(u);
ConsT1(u,w)$(ord(w) eq ord(u)) .. FTI(u) =e= FT(w);
ConsT2(u,w)$(ord(w) eq ord(u)) .. CTI(u) =g= CT(w);
ConsT3(w) .. sum(u,t(w,u))+sum(j,z(w,j)) =l= 1;
*Fixparameters***************
TMB1_1P(u) .. A1t(u) =e= sum(i,FS(i)*y(i,u));
TMB1_2P(u) .. B1t(u) =e= sum(w,FTP(w)*t(w,u));
TMB1_3P(u) .. A1t(u)+B1t(u) =e= FTIP(u);
TCB1_1P(u) .. A2t(u) =e= sum(i,FS(i)*y(i,u)*CS(i));
TCB1_2P(u) .. B2t(u) =e= sum(w,FTP(w)*t(w,u)*CTP(w));
TCB1_3P(u) .. A2t(u)+B2t(u) =e= FTIP(u)*CTIP(u);
TMB2P(w) .. FTP(w) =e= sum(u,FTP(w)*t(w,u))+sum(j,FTP(w)*z(w,j))+WW2(w);
TCB2P(w) .. FTP(w)*CTP(w) =e=
sum(u,FTP(w)*t(w,u)*CTP(w))+sum(j,FTP(w)*z(w,j)*CTP(w))+WW2(w)*CTP(w);
TRP(u,w)$(ord(w) eq ord(u)) .. CTP(w) =e= (1-Alpha(u))*CTIP(u);
ConsT1P(u,w)$(ord(w) eq ord(u)) .. FTIP(u) =e= FTP(w);
ConsT2P(u,w)$(ord(w) eq ord(u)) .. CTIP(u) =g= CTP(w);
ConsT3P(w) .. sum(u,t(w,u))+sum(j,z(w,j)) =l= 1;
***************************Waste Mass Balance***************************
WASTE .. OWW =e= sum(i,WW1(i))+sum(w,WW2(w));
CWASTE .. OWW*CW =e= sum(i,WW1(i)*CS(i))+sum(w,WW2(w)*CT(w));
ConsW .. CW =l= CWL;
```

```
FRESH .. OFW =e= sum((r,j),FR(r,j));
*Fix parameter*************
WASTEP .. OWW =e= sum(i,WW1P(i))+sum(w,WW2P(w));
CWASTEP .. OWW*CWP =e= sum(i,WW1P(i)*CS(i))+sum(w,WW2P(w)*CTP(w));
FRESHP .. OFW =e= sum((r,j),FRP(r,j));
**************************Sink Mass Balance****************************
SKMB_1(j) .. A1k(j) =e= sum(i,FS(i)*x(i,j));
SKMB_2(j) .. B1k(j) =e= sum(w,FT(w)*z(w,j));
SKMB_3(j) .. C1k(j) =e= sum(r,FR(r,j));-
SKMB_4(j) .. FK(j) =e= A1k(j) + B1k(j) + C1k(j);
SKCB_1(j) .. A2k(j) =e= sum(i,FS(i)*x(i,j)*CS(i));
SKCB_2(j) .. B2k(j) =e= sum(w,FT(w)*z(w,j)*CT(w));
SKCB_3(j) .. C2k(j) =e= sum(r,FR(r,j)*CFW(r));
SKCB_4(j) .. FK(j)*CK(j) =e= A2k(j) + B2k(j) + C2k(j);
ConsSK(j) .. CK(j) =l= CKL(j);
*Fix parameter*****************
SKMB_1P(j) .. A1k(j) =e= sum(i,FS(i)*x(i,j));
SKMB_2P(j) .. B1k(j) =e= sum(w,FTP(w)*z(w,j));
SKMB_3P(j) .. C1k(j) =e= sum(r,FR(r,j));
SKMB_4P(j) .. FK(j) =e= A1k(j) + B1k(j) + C1k(j);
SKCB_1P(j) .. A2k(j) =e= sum(i,FS(i)*x(i,j)*CS(i));
SKCB_2P(j) .. B2k(j) =e= sum(w,FTP(w)*z(w,j)*CTP(w));
SKCB_3P(j) .. C2k(j) =e= sum(r,FR(r,j)*CFW(r));
SKCB_4P(j) .. FK(j)*CKP(j) =e= A2k(j) + B2k(j) + C2k(j);
**********************Flowrate existing and constraint*****************
Dis1(i,j) .. xF(i,j) =e= x(i,j)*FS(i);
Dis2(i,u) .. yF(i,u) =e= y(i,u)*FS(i);
Dis3(w,j) .. zF(w,j) =e= z(w,j)*FT(w);
Dis4(w,u) .. tF(w,u) =e= t(w,u)*FT(w);
*Fix parameter*************
Dis1P(i,j) .. xFP(i,j) =e= x(i,j)*FS(i);
Dis2P(i,u) .. yFP(i,u) =e= y(i,u)*FS(i);
Dis3P(w,j) .. zFP(w,j) =e= z(w,j)*FTP(w);
Dis4P(w,u) .. tFP(w,u) =e= t(w,u)*FTP(w);
xexist(i,j) .. xF(i,j)-OMEGA*zx(i,j) =l= 0 ;
yexist(i,u) .. yF(i,u)-OMEGA*zy(i,u) =l= 0 ;
zexist(w,j) .. zF(w,j)-OMEGA*zz(w,j) =l= 0 ;
texist(w,u) .. tF(w,u)-OMEGA*zt(w,u) =l= 0 ;
frexist(r,j) .. FR(r,j)-OMEGA*zfr(r,j) =l= 0 ;
ww1exist(i) .. WW1(i)-OMEGA*zw1(i) =l= 0 ;
ww2exist(w) .. WW2(w)-OMEGA*zw2(w) =l= 0 ;
xcons(i,j) .. xF(i,j) =g= 300*zx(i,j) ;
ycons(i,u) .. yF(i,u) =g= 300*zy(i,u) ;
zcons(w,j) .. zF(w,j) =g= 300*zz(w,j)  ;
frcons(r,j) .. FR(r,j) =g= 300*zfr(r,j) ;
tcons(w,u) .. tF(w,u) =g= 300*zt(w,u)  ;
w1cons(i) .. WW1(i) =g= 300*zw1(i)  ;
w2cons(w) .. WW2(w) =g= 300*zw2(w) ;
*Fix parameters************
xexistP(i,j) .. xFP(i,j)-OMEGA*zx(i,j) =l= 0 ;
yexistP(i,u) .. yFP(i,u)-OMEGA*zy(i,u) =l= 0 ;
```

```
zexistP(w,j) .. zFP(w,j)-OMEGA*zz(w,j) =l= 0 ;
texistP(w,u) .. tFP(w,u)-OMEGA*zt(w,u) =l= 0 ;
frexistP(r,j) .. FRP(r,j)-OMEGA*zfr(r,j) =l= 0 ;
ww1existP(i) .. WW1P(i)-OMEGA*zw1(i) =l= 0 ;
ww2existP(w) .. WW2P(w)-OMEGA*zw2(w) =l= 0 ;
xconsP(i,j) .. xFP(i,j) =g= 300*zx(i,j) ;
yconsP(i,u) .. yFP(i,u) =g= 300*zy(i,u) ;
zconsP(w,j) .. zFP(w,j) =g= 300*zz(w,j) ;
frconsP(r,j) .. FRP(r,j) =g= 300*zfr(r,j) ;
tconsP(w,u) .. tFP(w,u) =g= 300*zt(w,u) ;
w1consP(i) .. WW1P(i) =g= 300*zw1(i) ;
w2consP(w) .. WW2P(w) =g= 300*zw2(w) ;
***************************Cost Calculation*****************************
TUC1(u).. FTI(u) =l= 3187*YT(u,'n1')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n3');
TUC2(u) .. FTI(u) =l= 6374*YT(u,'n2')+OMEGA*YT(u,'n1')+OMEGA*YT(u,'n3');
TUC3(u) .. FTI(u) =l= OMEGA*YT(u,'n3')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n1');
ConsB1(u)..sum(n,YT(u,n))=l=1;
ConsB2 .. sum(u,FTI(u)) =l= sum(i,FS(i));
*Fix parameter**************
TUC1P(u).. FTIP(u) =l= 3187*YT(u,'n1')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n3');
TUC2P(u) .. FTIP(u) =l= 6374*YT(u,'n2')+OMEGA*YT(u,'n1')+OMEGA*YT(u,'n3');
TUC3P(u) .. FTIP(u) =l= OMEGA*YT(u,'n3')+OMEGA*YT(u,'n2')+OMEGA*YT(u,'n1');
ConsBP1(u)..sum(n,YT(u,n))=l=1;
ConsBP2 .. sum(u,FTIP(u)) =l= sum(i,FS(i));
FreshCost .. FACost =e= sum((r,j),FR(r,j)*CostFW(r)*HY);
FreshCost2 .. FACost =e= sum((r,j),FR(r,j)*CostFW(r)*HY*zfr(r,j));
TreatCost .. TTCost =e= sum((u,n),(TFC(u,n)+FTI(u)*TVC(u,n))*KY*YT(u,n));
TreatOCost .. TOCost =e= sum(u,OC(u)*FTI(u)*HY);
PIPCost1 .. PA1 =e= sum((i,j),(CPF1(i,j)+CP1(i,j)*xF(i,j)*HY)*zx(i,j));
PIPCost2 .. PA2 =e= sum((i,u),(CPF2(i,u)+CP2(i,u)*yF(i,u)*HY)*zy(i,u));
PIPCost3 .. PA3 =e= sum((w,u),(CPF3(w,u)+CP3(w,u)*tF(w,u)*HY)*zt(w,u));
PIPCost4 .. PA4 =e= sum((w,j),(CPF4(w,j)+CP4(w,j)*zF(w,j)*HY)*zz(w,j));
PIPCost5 .. PA5 =e= sum((r,j),(CPF5(r,j)+CP5(r,j)*FR(r,j)*HY)*zfr(r,j));
PIPCost6 .. PA6 =e= sum(i,(CPF6(i)+CP6(i)*WW1(i)*HY)*zw1(i));
PIPCost7 .. PA7 =e= sum(w,(CPF7(w)+CP7(w)*WW2(w)*HY)*zw2(w));
PIPCost .. PACost =e= PA1+PA2+PA3+PA4+PA5+PA6+PA7;
Total .. TAC =e= FACost + TTCost + TOCost + PACost;
*Fix Parameter***********
TreatOCostP .. TOCost =e= sum(u,OC(u)*FTIP(u)*HY);
TreatCostP .. TTCost =e= sum((u,n),(TFC(u,n)+FTIP(u)*TVC(u,n))*KY*YT(u,n));
FreshCostP .. FACost =e= sum((r,j),FRP(r,j)*CostFW(r)*HY*zfr(r,j));
PIPCost1P .. PA1 =e= sum((i,j),(CPF1(i,j)+CP1(i,j)*xFP(i,j)*HY)*zx(i,j));
PIPCost2P .. PA2 =e= sum((i,u),(CPF2(i,u)+CP2(i,u)*yFP(i,u)*HY)*zy(i,u));
PIPCost3P .. PA3 =e= sum((w,u),(CPF3(w,u)+CP3(w,u)*tFP(w,u)*HY)*zt(w,u));
PIPCost4P .. PA4 =e= sum((w,j),(CPF4(w,j)+CP4(w,j)*zFP(w,j)*HY)*zz(w,j));
PIPCost5P .. PA5 =e= sum((r,j),(CPF5(r,j)+CP5(r,j)*FRP(r,j)*HY)*zfr(r,j));
PIPCost6P .. PA6 =e= sum(i,(CPF6(i)+CP6(i)*WW1P(i)*HY)*zw1(i));
PIPCost7P .. PA7 =e= sum(w,(CPF7(w)+CP7(w)*WW2P(w)*HY)*zw2(w));
PIPCostP .. PACost =e= PA1+PA2+PA3+PA4+PA5+PA6+PA7;

*****************************Objective function************************
```

```
Object1 .. OBJ1 =e= FACost;
Object2 .. OBJ2 =e= FACost+TTCost+TOCost;
Object3 .. OBJ3 =e= TAC;
Object4 .. OBJ4 =e= TAC;
*************************************************************************
******************************SOLVE 1******************************
MODEL CASE32CAL1
/ M1_mass,M1_cont.M1_cons,M1_cons2,M1_waste,FRESH.Object1,FreshCost,Dis1 /
SOLVE CASE32CAL1 USING LP MINIMIZING OBJ1;
DISPLAY OBJ1.l,x.l,FR.l,y1.l,xF.l;
******************************SOLVE 2******************************
Parameter
Inx(i,j) intermediate parameter x
InFR(r,j) intermediate parameter FR
Iny(i)
;
Inx(i,j) = x.l(i,j);
InFR(r,j) = FR.l(r,j);
Iny(i) = y1.l(i);
x.l(i,j) = Inx(i,j);
FR.l(r,j) = InFR(r,j);
y.l(i,u) = Iny(i);
YT.fx('u1','n1')=0;YT.fx('u1','n3')=0;
MODEL CASE32CAL2
/     SMB_1,SMB_2,SMB_3,SCB_1.SCB_2,SCB_3.Consx
,TMB1_1,TMB1_2,TMB1_3,TCB1_1,TCB1_2,TCB1_3,TMB2,TCB2,TR,ConsT1,ConsT2,ConsT3,
WASTE,CWASTE,ConsW.FRESH,SKMB_1.SKMB_2,SKMB_3,SKMB_4.SKCB_1,SKCB_2,SKCB_3,SKCB_4,
ConsSK.Dis1,Dis2,Dis3,Dis4,TUC1,TUC2.TUC3.ConsB1.ConsB2,FreshCost,TreatCost,
TreatOCost,Object2 /;
SOLVE CASE32CAL2 USING MINLP MINIMIZING OBJ2;
DISPLAY OBJ1.l,OBJ2.l,xF.l,yF.l,zF.l,FR.l,WW1.l,WW2.l,CW.l,FTI.l,YT.l,
FACost.l,TTCost.l,TOCost.l;
******************************SOLVE 3******************************
xFP(i,j) = xF.l(i,j);
yFP(i,u) = yF.l(i,u);
zFP(w,j) = zF.l(w,j);
tFP(w,u) = tF.l(w,u);
FRP(r,j) = FR.l(r.j);
WW1P(i) = WW1.l(i);
WW2P(w) = WW2.l(w);
FTIP(u) = FTI.l(u);
CTIP(u) = CTI.l(u);
CTP(w) = CT.l(w);
CWP = CW.l;
FTP(w) = FT.l(w);
CKP(j) = CK.l(j);

MODEL CASE32CAL3
/     SMB_1,SMB_2,SMB_3.SCB_1,SCB_2,SCB_3.Consx,
TMB1_1P,TMB1_2P,TMB1_3P,TCB1_1P,TCB1_2P.TCB1_3P,TMB2P,TCB2P,TRP,
ConsT1P,ConsT2P.ConsT3P,WASTEP.CWASTEP,FRESHP,SKMB_1P.SKMB_2P,
```

```
SKMB_3P,SKMB_4P,SKCB_1P,SKCB_2P,SKCB_3P,SKCB_4P,Dis1P,Dis2P,Dis3P,
Dis4P,TUC1P,TUC2P,TUC3P,ConsBP1,xexistP,yexistP,zexistP,texistP,frexistP,
ww1existP,ww2existP,xconsP,yconsP,zconsP,tconsP,frconsP,w1consP,w2consP,
PIPCost1P,PIPCost2P,PIPCost3P,PIPCost4P,PIPCost5P,PIPCost6P,PIPCost7P,
PIPCostP,FreshCostP,TreatCostP,TreatOCostP,Total,Object3  /  ;

SOLVE CASE32CAL3 USING MIP MINIMIZING OBJ3;
DISPLAY OBJ2.l,OBJ3.l,FACost.l,TOCost.l,TTCost.l,PACost.l,CT.l,CTI.l,TAC.l,
xFP,yFP,zFP,FRP,WW1P,WW2P,YT.l,zx.l,zy.l,zz.l,zfr.l,zw1.l,zw2.l;
*****************************SOLVE 4*******************************
Parameter
Inzx(i,j)
Inzy(i,u)
Inzt(w,u)
Inzz(w,j)
Inzfr(r,j)
Inzw1(i)
Inzw2(w)
InYT(u,n)
Inx1(i,j)
Iny1(i,u)
Inz1(w,j)
InFR1(r,j)
;
Inzx(i,j)=zx.l(i,j);
Inzy(i,u)=zy.l(i,u);
Inzt(w,u)=zt.l(w,u);
Inzz(w,j)=zz.l(w,j);
Inzfr(r,j)=zfr.l(r,j);
Inzw1(i)=zw1.l(i);
Inzw2(w)=zw2.l(w);
InYT(u,n)=YT.l(u,n);
Inx1(i,j) = x.l(i,j);
Iny1(i,u) = y.l(i,u);
Inz1(w,j) = z.l(w,j);
InFR1(r,j) = FRP(r,j);
zx.l(i,j)=Inzx(i,j);
zy.l(i,u)=Inzy(i,u);
zt.l(w,u)=Inzt(w,u);
zz.l(w,j)=Inzz(w,j);
zfr.l(r,j)=Inzfr(r,j);
zw1.l(i)=Inzw1(i);
zw2.l(w)=Inzw2(w);
YT.l(u,n)=InYT(u,n);
x.l(i,j)=Inx1(i,j);
y.l(i,u)=Iny1(i,u);
z.l(w,j)=Inz1(w,j);
FR.l(r,j)=InFR1(r,j);
*Bounding**********
FTI.lo('u2')=29560.408;
WW1.lo('i2')=300;
```

```
WW1.up('i2')=3000;
WW2.lo('w2')=300;
WW2.up('w2')=25000;
FR.lo('r1','j1')=1440;
FR.up('r1','j1')=2000;
MODEL CASE32CAL4
/	SMB_1,SMB_2,SMB_3,SCB_1,SCB_2,SCB_3,Consx
,TMB1_1,TMB1_2,TMB1_3,TCB1_1,TCB1_2,TCB1_3,TMB2,TCB2,TR,ConsT1,
ConsT2,ConsT3,WASTE,CWASTE,ConsW,FRESH,SKMB_1,SKMB_2,SKMB_3,
SKMB_4,SKCB_1,SKCB_2,SKCB_3,SKCB_4,ConsSK,Dis1,Dis2,Dis3,Dis4,TUC1,
TUC2,TUC3,ConsB1,ConsB2,xexist,yexist,zexist,frexist,texist,ww1exist,ww2exist,
xcons,ycons,zcons,frcons,tcons,w1cons,w2cons,PIPCost1,PIPCost2,PIPCost3,PIPCost4,PIPCost5,PIPCost6,PIPCost7
,PIPCost,FreshCost,TreatCost,TreatOCost,Total,
Object4 /;
SOLVE CASE32CAL4 USING MINLP MINIMIZING OBJ4;
DISPLAY OBJ1.l,OBJ2.l,OBJ3.l,OBJ4.l,FACost.l,TOCost.l,TTCost.l,PACost.l,xF.l,
yF.l,zF.l,FR.l,OFW.l,WW1.l,WW2.l,OWW.l,YT.l,CT.l,CT1.l,CW.l,zx.l,zy.l,zfr.l,PA1.l,
PA2.l,PA3.l,PA4.l,PA5.l,PA6.l,PA7.l;
```

## APPENDIX A-11 : Case Study 4 WHEN without HEN design GAMS Code

```
set	i Source stream /i1*i5/
	j Sink stream /j1*j5/
	K location	/ firstlocation,location2*location4,lastlocation/
;
Parameter
	CS	/i1	130
		 i2	108
		 i3	70
		 i4	44
		 i5	22 /
	FS	/i1	9
		 i2	9
		 i3	9
		 i4	9
		 i5	4.5 /
	TS	/i1	120
		 i2	100
		 i3	130
		 i4	140
		 i5	80 /
	CKL	/j1	20
		 j2	20
		 j3	20
		 j4	20
		 j5	20 /
	FK	/j1	10
		 j2	4
		 j3	12
```

```
          j4    8
          j5    6.5 /
     TOUTH(I)  outlet temperature of hot stream
          /i1     30
           i2     30
           i3     30
           i4     30
           i5     30 /

     TOUTC(J)  outlet temperature of cold stream
          /j1      100
           j2      100
           j3      100
           j4      100
           j5      100 /
     CPF2   Piping fix cost fresh to sink ($ per year)
          /j1      200
           j2      300
           j3      150
           j4      120
           j5      250 /
     CP2    Piping variable fresh to sink ($ per ton)
          /j1      0.7e-3
           j2      1.4e-3
           j3      1.2e-3
           j4      1.1e-3
           j5      1.3e-3 /
     CPF3   Piping fix cost source to waste ($ per year)
          /i1     100
           i2     200
           i3     250
           i4     150
           i5     200 /
     CP3    Piping variable cost source to waste ($ per ton)
          /i1     0.7e-3
           i2     1.4e-3
           i3     1.1e-3
           i4     1.2e-3
           i5     1.3e-3 /

TINC(j)
TINH(i)
FH(i)
FC(j)

;
TABLE CPF1(i,j)  Piping fix cost source to sink ($ per year)
           j1   j2   j3   j4   j5
     i1   100  300  150  200  200
     i2   200  250  100  220  150
     i3   220  300  330  300  110
```

```
      i4    110   400   200   200   250
      i5    200   300   100   300   250
;
TABLE CP1(i,j)  Piping variable cost source to sink ($ per ton)
            j1      j2      j3      j4      j5
      i1    1.1e-3  1.2e-3  1.3e-3  1.4e-3  1.1e-3
      i2    0.8e-3  1.3e-3  1.1e-3  1.2e-3  0.9e-3
      i3    0.9e-3  1.3e-3  1.1e-3  1.4e-3  1.1e-3
      i4    1.3e-3  1.2e-3  1.3e-3  1.4e-3  1.1e-3
      i5    1.1e-3  0.8e-3  1.3e-3  1.4e-3  0.9e-3

;

Scalar      OMEGA1  /10000/
            TFW   /25/
            OMEGA  upper bound for heat exchange   /1000000/
            GAMMA  upper bound for temperature difference /1000000/
            EMAT   exchanger minimum approach temperature  /10/
            CP    heat capacity /4.2/
            FWC    Freshwater cost ($ per ton) /0.375/
            HF1    Heat Exchanger fixed cost ($) /8000/
            HF2    Heat Exchanger fixed cost ($) /19965.89/
            HV    Heat Exchanger variable cost ($ per m2) /55.74899/
            HUOC   Hot utility operation cost ($ per kW y) /377/
            CUOC   Cold utility operation cost ($ per kW y) /189/
            U    Overall heat transfer coefficient /0.5/
            WH    Working hour /8000/
            WY    Annaulize factor /0.333/
            TINHU  Hot utility inlet temperature  /120/
            TOUTHU Hot utility outlet temperature  /120/
            TINCU  Cold utility inlet temperature  /10/
            TOUTCU Cold utility outlet temperature  /20/
;
Variables
              OFW       Overall freshwater
              OWW        Overall wastewater
              FCost      Freshwater cost
              INV        Investment cost
              TAC        Total annual cost
              PIC1       Piping cost of source to sink
              PIC2       Piping cost of fresh to sink
              PIC3       Piping cost of source to waste
              PICost     Piping cost
              O11        Objective 1.1
              O12        Objective 1.2
              O2        Objective 2
              O3        Objective 3
;
Positive variables  x(i,j)
              FFW(j)  Freshwater flowrate
              F(i,j)  Splitting Flowrate
```

CK(j) Sink stream concentration
TK(j) Sink temperature
WW(i) Source Waste water

dt(I,J,K) Temperature approach for match ij at the left of stage k
dtcu(I) Temperature approach for match hot stream i and cold utility
dthu(J) Temperature approach for match cold stream j and hot utility

q(I,J,K) Heat exchanged between hot stream i and cold stream j at stage k
qcu(I) Heat exchanged between hot stream i and cold utility
qhu(J) Heat exchanged between cold stream j and hot utility
A(i,j,K)
Ahu(j)
Acu(i)
Atot
LMTD(i,j,K)
LMTDcu(i)
LMTDhu(j)
Costh
Costhu
Costcu
OCosthu
OCostcu
Oqcu Overall heat exchanged between hot stream i and cold utility
Oqhu Overall heat exchanged between cold stream j and hot utility
tH(I,K) Temperature of hot stream i at location k
tC(J.K) Temperature of cold stream j at location k
;
BINARY VARIABLE
y(i,j) Binary vriable to denote existence of match source to sink in WN
yFW(j) Binary vriable to denote existence of match FW to sink in WN
yWW(i) Binary vriable to denote existence of match WW from source in WN
z(I,J,K) Binary variable to denote existence of match ij in stage k
zcu(I) Binary variable to denote existence of cold utility with hot stream i
zhu(J) Binary variable to denote existence of hot utility with cold stream
;
Equation

*************************************WATER NETWORK****************************

MB1(j) Mass balance (flowrate)
MB2(j) Mass balance (contaminant)
Cons1(i) Constraint for x
Cons2(j) Concentration constraint
Fresh Freshwater usage
Waste(i) Waste of source
Allwaste Waste discharge
Flow(i,j) Flowrate each sink
Logical1(i,j) Logical constraint
Logical2(j) Logical constraint
Logical3(i) Logical constraint
TempK(j) Temperature of sink

```
     FRESHC    Freshwater cost
     PIP1      Piping cost of source to sink
     PIP2      Piping cost of fresh to sink
     PIP3      Piping cost of source to waste
     PIPC      Piping cost
OBJFN11
OBJFN12

Link1(j)
Link2(j)
Link3(i)
Link4(i)
*************************************HEATEX NETWORK***************************
      abc(I,J)       @#@$$#

      OHB_H(I)       overall heat balance for each hot stream
      OHB_C(J)       overall heat balance for each cold stream

      SHB_H(I,K)     heat balance at each stage for hot stream
      SHB_C(J,K)     heat balance at each stage for cold stream

      TINHASSGN(I)   assignment of inlet temperature of hot stream i
      TINCASSGN(J)   assignment of inlet temperature of cold stream j

      FH1(I,K)       feasibility of temperature at each stage for hot stream
      FH2(I)         feasibility of temperature at last stage for hot stream
      FC1(J,K)       feasibility of temperature at each stage for cold stream
      FC2(J)         feasibility of temperature at first stage for cold stream

      HULOAD(I)      hot utility load
      CULOAD(J)      cold utility load

      HECOUNT1(I,J,K) count heat exchanger
      HECOUNT2(I)     count hot utiility
      HECOUNT3(J)     count cold utility

      APPTEMPL(I,J,K) approach temperature at the left of stage k
      APPTEMPR(I,J,K) approach temperature at the right of stage k
      APPTEMPCU(I)    approach temperature at cold utility of hot stream i
      APPTEMPHU(J)    approach temperature at hot utility of cold stream j

      APPTEMPLIMIT(I,J,K)  limiting temperature approach
      APPTEMPLIMITCU(I)    limiting temperature approach
      APPTEMPLIMITHU(J)    limiting temperature approach


LOGMH(i,j,K)     Log mean temperature different of HE
LOGMHU(J)        Log mean temperature different of HU
LOGMCU(I)        Log mean temperature different of CU
HAREA(i,j,K)     Heat exchanger area
HUAREA(J)        Hot utility area
```

```
CUAREA(I)       Cold utility area
TOTAREA         Total area

HACOST        Heat exchanger area cost
HUACOST       Hot utility heat exchanger area cost
CUACOST       Cold utility heat exchanger area cost
HUOCOST       Hot utility operation cost
CUOCOST       Cold utility operation cost

      OAQCU         Overall Cold utility
      OAQHU         Overall hot utility
      OBJFN2        utility Q
      OBJFN3        utility AREA
      Invest        Investment cost
      Total         Total annual cost

;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FFW(j) =e= FK(j) ;
Cons1(i)  .. sum(j,x(i,j))-1 =l= 0 ;
Cons2(j) .. CK(j) =l= CKL(j) ;
Fresh .. OFW =e= sum(j,FFW(j));
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
Allwaste .. OWW =e= sum(i,WW(i));
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Logical1(i,j) .. F(i,j)-OMEGA1*y(i,j) =l= 0;
Logical2(j) .. FFW(j)-OMEGA1*yFW(j) =l= 0;
Logical3(i) .. WW(i)-OMEGA1*yWW(i) =l= 0;
TempK(j) .. sum(i,TS(i)*F(i,j))+TFW*FFW(j) =e= TK(j)*FK(j);
FRESHC .. FCost =e= OFW*FWC*WH;
PIP1 .. PIC1 =e= sum((i,j),y(i,j)*(CPF1(i,j)+F(i,j)*CP1(i,j)*WH));
PIP2 .. PIC2 =e= sum(j,yFW(j)*(CPF2(j)+FFW(j)*CP2(j)*WH));
PIP3 .. PIC3 =e= sum(i,yWW(i)*(CPF3(i)+WW(i)*CP3(i)*WH));
PIPC .. PICost =e= PIC1+PIC2+PIC3;
OBJFN11 .. O11 =e= FCost;
OBJFN12 .. O12 =e= FCost+PICost;

Link1(j) .. TK(j) =e= TINC(J);
Link2(j) .. FK(j) =e= FC(J);
Link3(i) .. TS(i) =e= TINH(I);
Link4(i) .. FH(I) =e= WW(i);

 abc(i,j) .. q(i,j,'lastlocation') =e= 0;

 OHB_H(i) ..  (TINH(i)-TOUTH(i))*FH(i)*CP*(1000/3600) =e= SUM((J,K),q(I,J,K))+qcu(I);
 OHB_C(j) ..  (TOUTC(J)-TINC(J))*FC(J)*CP*(1000/3600) =e= SUM((I,K),q(I,J,K))+qhu(J);

 SHB_H(I,K)$(ORD(K) NE CARD(K)) .. (tH(I,K)-tH(I,K+1))*FH(I)*CP*(1000/3600)
                        =e= SUM(J,q(I,J,K));
 SHB_C(J,K)$(ORD(K) NE CARD(K)) .. (tC(J,K)-tC(J,K+1))*FC(J)*CP*(1000/3600)
                        =e= SUM(I,q(I,J,K));
```

```
TINHASSGN(I) .. TINH(I) =e= tH(I,'firstlocation');
TINCASSGN(J) .. TINC(J) =e= tC(J,'lastlocation');

FH1(I,K)$(ORD(K) NE CARD(K)) .. tH(I,K) =g= tH(I,K+1);
FH2(I) .. TOUTH(I) =l= tH(I,'lastlocation');
FC1(J,K)$(ORD(K) NE CARD(K)) .. tC(J,K) =g= tC(J,K+1);
FC2(J) .. TOUTC(J) =g= tC(J,'firstlocation');

HULOAD(I) .. (tH(I,'lastlocation')-TOUTH(I))*FH(I)*CP*(1000/3600) =e= qcu(I);
CULOAD(J) .. (TOUTC(J)-tC(J,'firstlocation'))*FC(J)*CP*(1000/3600) =e= qhu(J);

HECOUNT1(I,J,K)$(ORD(K) NE CARD(K)) .. q(I,J,K)-OMEGA*z(I,J,K) =l= 0;
HECOUNT2(I) .. qcu(I)-OMEGA*zcu(I) =l= 0;
HECOUNT3(J) .. qhu(J)-OMEGA*zhu(J) =l= 0;

APPTEMPL(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =l= tH(I,K)-tC(J,K)+GAMMA*(1-z(I,J,K));
APPTEMPR(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K+1) =l= tH(I,K+1)-tC(J,K+1)+GAMMA*(1-z(I,J,K));
APPTEMPCU(I) .. dtcu(I) =l= tH(I,'lastlocation')-TOUTCU +GAMMA*(1-zcu(I));
APPTEMPHU(J) .. dthu(J) =l= TOUTHU - tC(J,'firstlocation')+GAMMA*(1-zhu(J));

APPTEMPLIMIT(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =g= EMAT;
APPTEMPLIMITCU(i) .. dtcu(I) =g= EMAT;
APPTEMPLIMITHU(j) .. dthu(J) =g= EMAT;

LOGMH(i,j,K) .. LMTD(i,j,K) =e= (((dt(i,j,K)*dt(i,j,K+1))*(dt(i,j,K)+dt(i,j,K+1))/2))**(1/3);
LOGMHU(j) .. LMTDhu(j) =e= ((((TOUTHU-tC(J,'firstlocation'))*(TINHU-TOUTC(J)))*((TOUTHU-
tC(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LOGMCU(i) .. LMTDcu(i) =e= ((((tH(i,'lastlocation')-TOUTCU)*(TOUTH(I)-TINCU))*((tH(i,'lastlocation')-
TOUTCU)+(TOUTH(I)-TINCU))/2))**(1/3);
HAREA(i,j,K)  .. A(i,j,K)*U*LMTD(i,j,K) =e= q(I,J,K);
HUAREA(j) .. Ahu(j)*U*LMTDhu(j) =e= qhu(j);
CUAREA(i) .. Acu(i)*U*LMTDcu(i) =e= qcu(i);
TOTAREA .. Atot =e= sum((i,j,k),A(i,j,K))+sum(j,Ahu(j))+sum(i,Acu(i));

HACOST .. Costh =e= sum((i,j,k),((HF1+HF2)*z(i,j,k)+HV*A(i,j,k))*WY);
HUACOST .. Costhu =e= sum(j,((HF1+HF2)*zhu(j)+HV*Ahu(j))*WY);
CUACOST .. Costcu =e= sum(i,((HF1+HF2)*zcu(i)+HV*Acu(i))*WY);
HUOCOST .. OCosthu =e= sum(j,HUOC*qhu(j));
CUOCOST .. OCostcu =e= sum(i,CUOC*qcu(i));

OAQCU .. OQCU =e= SUM(I,qcu(I));
OAQHU .. OQHU =e= SUM(J,qhu(J));
OBJFN2 .. O2 =e= OCosthu+OCostcu;
*+sum((i,j,k),z(i,j,k)*(HF1+HF2));
OBJFN3 .. O3 =e= Costh+Costhu+Costcu+OCosthu+OCostcu;
Invest .. INV =e= Costh+Costhu+Costcu;
Total .. TAC =e= Costh+Costhu+Costcu+OCosthu+OCostcu+FCost.l+PlCost.l;
```

```
Model MIXING1 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,OBJFN11/;
Solve MIXING1 using MIP minimizing O11;
Display FCost.l,OFW.l,OWW.l,FFW.l,yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;

Parameter
xin(i,j)
FFWin(j)
WWin(i)
yin(i,j)
yFWin(j)
yWWin(i)
;
xin(i,j) = x.l(i,j);
FFWin(j) = FFW.l(j);
WWin(i) = WW.l(i);
yin(i,j) = y.l(i,j);
yFWin(j) = yFW.l(j);
yWWin(i) = yWW.l(i);

x.l(i,j) = xin(i,j);
FFW.l(j) = FFWin(j);
WW.l(i) = WWin(i);
y.l(i,j) = yin(i,j);
yFW.l(j) = yFWin(j);
yWW.l(i) = yWWin(i);

Model MIXING2 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,PIP1,PIP2,PIP3,PIPC,OBJFN12/;
Solve MIXING2 using MINLP minimizing O12;
Display PIC1.l,PIC2.l,PIC3.l,PICost.l,FCost.l,OFW.l,OWW.l,FFW.l,
yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;

TINC(j) = TK.l(j);
TINH(i) = TS(i);
FH(i) = WW.l(i);
FC(j) = FK(j);

q.fx(i,j,k)=0;

MODEL STAGEMODEL1 /abc,OHB_H,OHB_C,SHB_H,SHB_C,TINHASSGN,TINCASSGN,FH1,FH2,
FC1,FC2,HULOAD,CULOAD,HECOUNT1,HECOUNT2,HECOUNT3,APPTEMPL,APPTEMPR,APPTEMPCU,
APPTEMPHU,APPTEMPLIMIT,APPTEMPLIMITCU,APPTEMPLIMITHU,OAQCU,OAQHU,
HUOCOST,CUOCOST,Invest,OBJFN2/
;
SOLVE STAGEMODEL1 USING MIP MINIMIZING O2;
DISPLAY z.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,OQHU.l,OQCU.l,INV.l,O2.l;

Parameter
qin(i,j,k)
qcuin(i)
```

```
qhuin(j)
THin(i,k)
TCin(j,k)
zin(i,j,k)
zcuin(i)
zhuin(j)
;
qin(i,j,k) = q.l(i,j,k);
qcuin(i) = qcu.l(i);
qhuin(j) = qhu.l(j);
THin(i,k) = TH.l(i,k);
TCin(j,k) = TC.l(j,k);
zin(i,j,k) = z.l(i,j,k);
zcuin(i) = zcu.l(i);
zhuin(j) = zhu.l(j);

q.l(i,j,k) = qin(i,j,k);
qcu.l(i) = qcuin(i) ;
qhu.l(j) = qhuin(j);
TH.l(i,k) = THin(i,k);
TC.l(j,k) = TCin(j,k);

z.fx(i,j,k) = zin(i,j,k);
zcu.fx(i) = zcuin(i);
zhu.fx(j) = zhuin(j);


LMTD.l(i,j,k) = (((dt.l(i,j,K)*dt.l(i,j,K+1))*(dt.l(i,j,K)+dt.l(i,j,K+1))/2))**(1/3);
LMTDhu.l(j) = ((((TOUTHU-tC.l(J,'firstlocation'))*(TINHU-TOUTC(J)))*((TOUTHU-
tC.l(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LMTDcu.l(i) = ((((tH.l(i,'lastlocation')-TOUTCU)*(TOUTH(I)-TINCU))*((tH.l(i,'lastlocation')-
TOUTCU)+(TOUTH(I)-TINCU))/2))**(1/3);
A.l(i,j,k) = qin(i,j,k)/(U*LMTD.l(i,j,k)+0.001);
Ahu.l(j) = qhuin(j)/(U*LMTDhu.l(j)+0.001);
Acu.l(i) = qcuin(i)/(U*LMTDcu.l(i)+0.001);


MODEL STAGEMODEL2 /abc,OHB_H,OHB_C,SHB_H,SHB_C,TINHASSGN,TINCASSGN,FH1,FH2,
FC1,FC2,HULOAD,CULOAD,HECOUNT1,HECOUNT2,HECOUNT3,APPTEMPL,APPTEMPR,APPTEMPCU,
APPTEMPHU,APPTEMPLIMIT,APPTEMPLIMITCU,APPTEMPLIMITHU,LOGMH,LOGMHU,LOGMCU,
HAREA,HUAREA,CUAREA,TOTAREA,HACOST,HUACOST,CUACOST,HUOCOST,CUOCOST,OAQCU,OAQ
HU,OBJFN3,
Invest,Total/
;
SOLVE STAGEMODEL2 USING MINLP MINIMIZING O3;
DISPLAY x.l,TK.l,z.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,OQHU.l,
OQCU.l,OCosthu.l,OCostcu.l,A.l,Ahu.l,Acu.l,Atot.l,O3.l,INV.l,Fcost.l,TAC.l;
```

## APPENDIX A-12 : Case Study 4 WHEN without WN design GAMS Code

```
set     i Source stream /i1*i5/
        j Sink stream /j1*j5/
        K  location    / firstlocation,location2*location4,lastlocation/
;
Parameter
      CS    /i1    130
             i2    108
             i3    70
             i4    44
             i5    22 /
      FS    /i1    9
             i2    9
             i3    9
             i4    9
             i5    4.5 /
      TS    /i1    120
             i2    100
             i3    130
             i4    140
             i5    80 /
      CKL   /j1    20
             j2    20
             j3    20
             j4    20
             j5    20 /
      FK    /j1    10
             j2    4
             j3    12
             j4    8
             j5    6.5 /
      TOUTH(I)  outlet temperature of hot stream
             /i1     30
              i2     30
              i3     30
              i4     30
              i5     30 /

      TOUTC(J)  outlet temperature of cold stream
             /j1     100
              j2     100
              j3     100
              j4     100
              j5     100 /
      CPF2   Piping fix cost fresh to sink ($ per year)
             /j1     200
              j2     300
              j3     150
              j4     120
```

```
            j5     250 /
      CP2    Piping variable fresh to sink ($ per ton)
            /j1     0.7e-3
             j2     1.4e-3
             j3     1.2e-3
             j4     1.1e-3
             j5     1.3e-3 /
      CPF3   Piping fix cost source to waste ($ per year)
            /i1     100
             i2     200
             i3     250
             i4     150
             i5     200 /
      CP3    Piping variable cost source to waste ($ per ton)
            /i1     0.7e-3
             i2     1.4e-3
             i3     1.1e-3
             i4     1.2e-3
             i5     1.3e-3 /

TINC(j)
TINH(i)
FH(i)
FC(j)

;
TABLE CPF1(i,j)  Piping fix cost source to sink ($ per year)
          j1   j2   j3   j4   j5
     i1   100  300  150  200  200
     i2   200  250  100  220  150
     i3   220  300  330  300  110
     i4   110  400  200  200  250
     i5   200  300  100  300  250
;
TABLE CP1(i,j)  Piping variable cost source to sink ($ per ton)
          j1      j2      j3      j4      j5
     i1   1.1e-3  1.2e-3  1.3e-3  1.4e-3  1.1e-3
     i2   0.8e-3  1.3e-3  1.1e-3  1.2e-3  0.9e-3
     i3   0.9e-3  1.3e-3  1.1e-3  1.4e-3  1.1e-3
     i4   1.3e-3  1.2e-3  1.3e-3  1.4e-3  1.1e-3
     i5   1.1e-3  0.8e-3  1.3e-3  1.4e-3  0.9e-3
;
Scalar      OMEGA1  /10000/
          TFW   /25/
          OMEGA  upper bound for heat exchange   /1000000/
          GAMMA  upper bound for temperature difference /1000000/
          EMAT   exchanger minimum approach temperature   /10/
          CP     heat capacity /4.2/
          FWC    Freshwater cost ($ per ton) /0.375/
          HF1    Heat Exchanger fixed cost ($) /8000/
          HF2    Heat Exchanger fixed cost ($) /19965.89/
```

```
        HV    Heat Exchanger variable cost ($ per m2) /55.74899/
        HUOC  Hot utility operation cost ($ per kW y) /377/
        CUOC  Cold utility operation cost ($ per kW y) /189/
        U     Overall heat transfer coefficient /0.5/
        WH    Working hour /8000/
        WY    Annaulize factor /0.333/
        TINHU Hot utility inlet temperature  /120/
        TOUTHU Hot utility outlet temperature  /120/
        TINCU Cold utility inlet temperature  /10/
        TOUTCU Cold utility outlet temperature  /20/
;
Variables
          OFW      Overall freshwater
          OWW      Overall wastewater
          FCost    Freshwater cost
          INV      Investment cost
          TAC      Total annual cost
          PIC1     Piping cost of source to sink
          PIC2     Piping cost of fresh to sink
          PIC3     Piping cost of source to waste
          PICost   Piping cost
          O11      Objective 1.1
          O12      Objective 1.2
          O2       Objective 2
          O3       Objective 3
;
Positive variables  x(i,j)
          FFW(j)  Freshwater flowrate
          F(i,j)  Splitting Flowrate
          CK(j)   Sink stream concentration
          TK(j)   Sink temperature
          WW(i)   Source Waste water

      dt(I,J,K) Temperature approach for mateh ij at the left of stage k
      dtcu(I)   Temperature approach for match hot stream i and cold utility
      dthu(J)   Temperature approach for match cold stream j and hot utility

      q(I,J,K)  Heat exchanged between hot stream i and cold stream j at stage k
      qcu(I)    Heat exchanged between hot stream i and cold utility
      qhu(J)    Heat exchanged between cold stream j and hot utility
      A(i,j,K)
      Ahu(j)
      Acu(i)
      Atot
      LMTD(i,j,K)
      LMTDcu(i)
      LMTDhu(j)
      Costh
      Costhu
      Costcu
      OCosthu
```

```
      OCostcu
      Oqcu     Overall heat exchanged between hot stream i and cold utility
      Oqhu     Overall heat exchanged between cold stream j and hot utility
      tH(I,K)  Temperature of hot stream i at location k
      tC(J,K)  Temperature of cold stream j at location k
;
BINARY VARIABLE
y(i,j)  Binary vriable to denote existence of match source to sink in WN
yFW(j)  Binary vriable to denote existence of match FW to sink in WN
yWW(i)  Binary vriable to denote existence of match WW from source in WN
z(I,J,K)  Binary variable to denote existence of match ij in stage k
zcu(I)  Binary variable to denote existence of cold utility with hot stream i
zhu(J)  Binary variable to denote existence of hot utility with cold stream
;
Equation

*************************************WATER NETWORK****************************
     MB1(j)    Mass balance (flowrate)
     MB2(j)    Mass balance (contaminant)
     Cons1(i)  Constraint for x
     Cons2(j)  Concentration constraint
     Fresh     Freshwater usage
     Waste(i)  Waste of source
     Allwaste  Waste discharge
     Flow(i,j)  Flowrate each sink
     Logical1(i,j) Logical constraint
     Logical2(j) Logical constraint
     Logical3(i) Logical constraint
     TempK(j)  Temperature of sink
     FRESHC    Freshwater cost
     PIP1      Piping cost of source to sink
     PIP2      Piping cost of fresh to sink
     PIP3      Piping cost of source to waste
     PIPC      Piping cost
OBJFN11
OBJFN12

Link1(j)
Link2(j)
Link3(i)
Link4(i)
*************************************HEATEX NETWORK***************************
      abc(I,J)       @#@$$#

      OHB_H(I)       overall heat balance for each hot stream
      OHB_C(J)       overall heat balance for each cold stream

      SHB_H(I,K)     heat balance at each stage for hot stream
      SHB_C(J,K)     heat balance at each stage for cold stream

      TINHASSGN(I)   assignment of inlet temperature of hot stream i
```

```
TINCASSGN(J)    assignment of inlet temperature of cold stream j

FH1(I,K)        feasibility of temperature at each stage for hot stream
FH2(I)          feasibility of temperature at last stage for hot stream
FC1(J,K)        feasibility of temperature at each stage for cold stream
FC2(J)          feasibility of temperature at first stage for cold stream

HULOAD(I)       hot utility load
CULOAD(J)       cold utility load

HECOUNT1(I,J,K) count heat exchanger
HECOUNT2(I)     count hot utiility
HECOUNT3(J)     count cold utility

APPTEMPL(I,J,K)  approach temperature at the left of stage k
APPTEMPR(I,J,K)  approach temperature at the right of stage k
APPTEMPCU(I)     approach temperature at cold utility of hot stream i
APPTEMPHU(J)     approach temperature at hot utility of cold stream j

APPTEMPLIMIT(I,J,K)  limiting temperature approach
APPTEMPLIMITCU(I)    limiting temperature approach
APPTEMPLIMITHU(J)    limiting temperature approach

LOGMH(i,j,K)    Log mean temperature different of HE
LOGMHU(J)       Log mean temperature different of HU
LOGMCU(I)       Log mean temperature different of CU
HAREA(i,j,K)    Heat exchanger area
HUAREA(J)       Hot utility area
CUAREA(I)       Cold utility area
TOTAREA         Total area

HACOST          Heat exchanger area cost
HUACOST         Hot utility heat exchanger area cost
CUACOST         Cold utility heat exchanger area cost
HUOCOST         Hot utility operation cost
CUOCOST         Cold utility operation cost

OAQCU           Overall Cold utility
OAQHU           Overall hot utility
OBJFN2          utility Q
OBJFN3          utility AREA
Invest          Investment cost
Total           Total annual cost
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FFW(j) =e= FK(j) ;
Cons1(i) .. sum(j,x(i,j))-1 =l= 0 ;
Cons2(j) .. CK(j) =l= CKL(j) ;
Fresh .. OFW =e= sum(j.FFW(j));
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
Allwaste .. OWW =e= sum(i,WW(i));
```

```
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Logical1(i,j) .. F(i,j)-OMEGA1*y(i,j) =l= 0;
Logical2(j) .. FFW(j)-OMEGA1*yFW(j) =l= 0;
Logical3(i) .. WW(i)-OMEGA1*yWW(i) =l= 0;
TempK(j) .. sum(i,TS(i)*F(i,j))+TFW*FFW(j) =e= TK(j)*FK(j);
FRESHC .. FCost =e= OFW*FWC*WH;
PIP1 .. PIC1 =e= sum((i,j),y(i,j)*(CPF1(i,j)+F(i,j)*CP1(i,j)*WH));
PIP2 .. PIC2 =e= sum(j,yFW(j)*(CPF2(j)+FFW(j)*CP2(j)*WH));
PIP3 .. PIC3 =e= sum(i,yWW(i)*(CPF3(i)+WW(i)*CP3(i)*WH));
PIPC .. PICost =e= PIC1+PIC2+PIC3;
OBJFN11 .. O11 =e= FCost;
OBJFN12 .. O12 =e= FCost+PICost;

Link1(j) .. TK(j) =e= TINC(J);
Link2(j) .. FK(j) =e= FC(J);
Link3(i) .. TS(i) =e= TINH(I);
Link4(i) .. FH(I) =e= WW(i);

 abc(i,j) .. q(i,j,'lastlocation') =e= 0;

 OHB_H(i) .. (TINH(i)-TOUTH(i))*FH(i)*CP*(1000/3600) =e= SUM((J,K),q(I,J,K))+qcu(I);
 OHB_C(j) .. (TOUTC(J)-TINC(J))*FC(J)*CP*(1000/3600) =e= SUM((I,K),q(I,J,K))+qhu(J);

 SHB_H(I,K)$(ORD(K) NE CARD(K)) .. (tH(I,K)-tH(I,K+1))*FH(I)*CP*(1000/3600)
                        =e= SUM(J,q(I,J,K));
 SHB_C(J,K)$(ORD(K) NE CARD(K)) .. (tC(J,K)-tC(J,K+1))*FC(J)*CP*(1000/3600)
                        =e= SUM(I,q(I,J,K));

 TINHASSGN(I) .. TINH(I) =e= tH(I,'firstlocation');
 TINCASSGN(J) .. TINC(J) =e= tC(J,'lastlocation');

 FH1(I,K)$(ORD(K) NE CARD(K)) .. tH(I,K) =g= tH(I,K+1);
 FH2(I) .. TOUTH(I) =l= tH(I,'lastlocation');
 FC1(J,K)$(ORD(K) NE CARD(K)) .. tC(J,K) =g= tC(J,K+1);
 FC2(J) .. TOUTC(J) =g= tC(J,'firstlocation');

 HULOAD(I) .. (tH(I,'lastlocation')-TOUTH(I))*FH(I)*CP*(1000/3600) =e= qcu(I);
 CULOAD(J) .. (TOUTC(J)-tC(J,'firstlocation'))*FC(J)*CP*(1000/3600) =e= qhu(J);

 HECOUNT1(I,J,K)$(ORD(K) NE CARD(K)) .. q(I,J,K)-OMEGA*z(I,J,K) =l= 0;
 HECOUNT2(I) .. qcu(I)-OMEGA*zcu(I) =l= 0;
 HECOUNT3(J) .. qhu(J)-OMEGA*zhu(J) =l= 0;

 APPTEMPL(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =l= tH(I,K)-tC(J,K)+GAMMA*(1-z(I,J,K));
 APPTEMPR(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K+1) =l= tH(I,K+1)-tC(J,K+1)+GAMMA*(1-z(I,J,K));
 APPTEMPCU(I) .. dtcu(I) =l= tH(I,'lastlocation')-TOUTCU +GAMMA*(1-zcu(I));
 APPTEMPHU(J) .. dthu(J) =l= TOUTHU - tC(J,'firstlocation')+GAMMA*(1-zhu(J));

 APPTEMPLIMIT(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =g= EMAT;
 APPTEMPLIMITCU(i) .. dtcu(I) =g= EMAT;
 APPTEMPLIMITHU(j) .. dthu(J) =g= EMAT;
```

```
LOGMH(i,j,K) .. LMTD(i,j,K) =e= (((dt(i,j,K)*dt(i,j,K+1))*(dt(i,j,K)+dt(i,j,K+1))/2))**(1/3);
LOGMHU(j) .. LMTDhu(j) =e= ((((TOUTHU-tC(J,'firstlocation'))*(TINHU-TOUTC(J)))*((TOUTHU-
tC(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LOGMCU(i) .. LMTDcu(i) =e= ((((tH(i,'lastlocation')-TOUTCU)*(TOUTH(I)-TINCU))*((tH(i,'lastlocation')-
TOUTCU)+(TOUTH(I)-TINCU))/2))**(1/3);
HAREA(i,j,K) .. A(i,j,K)*U*LMTD(i,j,K) =e= q(I,J,K);
HUAREA(j) .. Ahu(j)*U*LMTDhu(j) =e= qhu(j);
CUAREA(i) .. Acu(i)*U*LMTDcu(i) =e= qcu(i);
TOTAREA .. Atot =e= sum((i,j,k),A(i,j,K))+sum(j,Ahu(j))+sum(i,Acu(i));

HACOST .. Costh =e= sum((i,j,k),((HF1+HF2)*z(i,j,k)+HV*A(i,j,k))*WY);
HUACOST .. Costhu =e= sum(j,((HF1+HF2)*zhu(j)+HV*Ahu(j))*WY);
CUACOST .. Costcu =e= sum(i,((HF1+HF2)*zcu(i)+HV*Acu(i))*WY);
HUOCOST .. OCosthu =e= sum(j,HUOC*qhu(j));
CUOCOST .. OCostcu =e= sum(i,CUOC*qcu(i));

 OAQCU .. OQCU =e= SUM(I,qcu(I));
 OAQHU .. OQHU =e= SUM(J,qhu(J));
 OBJFN2 .. O2 =e= OCosthu+OCostcu
+sum((i,j,k),z(i,j,k)*(HF1+HF2));
 OBJFN3 .. O3 =e= Costh+Costhu+Costcu+OCosthu+OCostcu;
Invest .. INV =e= Costh+Costhu+Costcu;
Total .. TAC =e= Costh+Costhu+Costcu+OCosthu+OCostcu+FCost.l+PlCost.l;


x.fx(i,j)=0;

Model MIXING1 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,OBJFN11/;
Solve MIXING1 using MIP minimizing O11;
Display FCost.l,OFW.l,OWW.l,FFW.l,yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;

Parameter
xin(i,j)
FFWin(j)
WWin(i)
yin(i,j)
yFWin(j)
yWWin(i)
;
xin(i,j) = x.l(i,j);
FFWin(j) = FFW.l(j);
WWin(i) = WW.l(i);
yin(i,j) = y.l(i,j);
yFWin(j) = yFW.l(j);
yWWin(i) = yWW.l(i);

x.l(i,j) = xin(i,j);
FFW.l(j) = FFWin(j);
WW.l(i) = WWin(i);
```

```
y.l(i,j) = yin(i,j);
yFW.l(j) = yFWin(j);
yWW.l(i) = yWWin(i);

Model MIXING2 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,PIP1,PIP2,PIP3,PIPC,OBJFN12/;
Solve MIXING2 using MINLP minimizing O12;
Display PIC1.l,PIC2.l,PIC3.l,PICost.l,FCost.l,OFW.l,OWW.l,FFW.l,
yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;

TINC(j) = TK.l(j);
TINH(i) = TS(i);
FH(i) = WW.l(i);
FC(j) = FK(j);

MODEL STAGEMODEL1 /abc,OHB_H,OHB_C,SHB_H,SHB_C,TINHASSGN,TINCASSGN,FH1,FH2,
FC1,FC2,HULOAD,CULOAD,HECOUNT1,HECOUNT2,HECOUNT3,APPTEMPL,APPTEMPR,APPTEMPCU,
APPTEMPHU,APPTEMPLIMIT,APPTEMPLIMITCU,APPTEMPLIMITHU,OAQCU,OAQHU,
HUOCOST,CUOCOST,Invest,OBJFN2/
;
SOLVE STAGEMODEL1 USING MIP MINIMIZING O2;
DISPLAY z.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,OQHU.l,OQCU.l,INV.l,O2.l;

Parameter
qin(i,j,k)
qcuin(i)
qhuin(j)
THin(i,k)
TCin(j,k)
zin(i,j,k)
zcuin(i)
zhuin(j)
;
qin(i,j,k) = q.l(i,j,k);
qcuin(i) = qcu.l(i);
qhuin(j) = qhu.l(j);
THin(i,k) = TH.l(i,k);
TCin(j,k) = TC.l(j,k);
zin(i,j,k) = z.l(i,j,k);
zcuin(i) = zcu.l(i);
zhuin(j) = zhu.l(j);

q.l(i,j,k) = qin(i,j,k);
qcu.l(i) = qcuin(i) ;
qhu.l(j) = qhuin(j);
TH.l(i,k) = THin(i,k);
TC.l(j,k) = TCin(j,k);

z.fx(i,j,k) = zin(i,j,k);
zcu.fx(i) = zcuin(i);
```

```
zhu.fx(j) = zhuin(j);


LMTD.l(i,j,k) = (((dt.l(i,j,K)*dt.l(i,j,K+1))*(dt.l(i,j,K)+dt.l(i,j,K+1))/2))**(1/3);
LMTDhu.l(j) = ((((TOUTHU-tC.l(J,'firstlocation'))*(TINHU-TOUTC(J)))*((TOUTHU-
tC.l(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LMTDcu.l(i) = ((((tH.l(i,'lastlocation')-TOUTCU)*(TOUTH(I)-TINCU))*((tH.l(i,'lastlocation')-
TOUTCU)+(TOUTH(I)-TINCU))/2))**(1/3);
A.l(i,j,k) = qin(i,j,k)/(U*LMTD.l(i,j,k)+0.001);
Ahu.l(j) = qhuin(j)/(U*LMTDhu.l(j)+0.001);
Acu.l(i) = qcuin(i)/(U*LMTDcu.l(i)+0.001);

MODEL STAGEMODEL2 /abc,OHB_H,OHB_C,SHB_H,SHB_C,TINHASSGN,TINCASSGN,FH1,FH2,
FC1,FC2,HULOAD,CULOAD,HECOUNT1,HECOUNT2,HECOUNT3,APPTEMPL,APPTEMPR,APPTEMPCU,
APPTEMPHU,APPTEMPLIMIT,APPTEMPLIMITCU,APPTEMPLIMITHU,LOGMH,LOGMHU,LOGMCU,
HAREA,HUAREA,CUAREA,TOTAREA,HACOST,HUACOST,CUACOST,HUOCOST,CUOCOST,OAQCU,OAQ
HU,OBJFN3,
Invest,Total/
;
SOLVE STAGEMODEL2 USING MINLP MINIMIZING O3;
DISPLAY x.l,TK.l,z.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,OQHU.l,
OQCU.l,A.l,Ahu.l,Acu.l,Atot.l,O3.l,INV.l,Fcost.l,Costh.l,Costhu.l,Costcu.l,
OCosthu.l,OCostcu.l,TAC.l;
```

## APPENDIX A-13 : Case Study 4. WHEN by two-step design Code

```
set     i Source stream /i1*i5/
        j Sink stream /j1*j5/
        K  location     / firstlocation,location2*location4,lastlocation/
;
Parameter
        CS   Source concentration (ppm)
             /i1    130
              i2    108
              i3    70
              i4    44
              i5    22 /
        FS   Source flowrate (ton per h)
             /i1    9
              i2    9
              i3    9
              i4    9
              i5    4.5 /
        TS   Source temperature (degree celcius)
             /i1    120
              i2    100
              i3    130
              i4    140
              i5    80 /
```

```
CKL1  Sink concentration limit (ppm)
      /j1   70
       j2   70
       j3   70
       j4   70
       j5   70 /
CKL2  Sink concentration limit (ppm)
      /j1   20
       j2   20
       j3   20
       j4   20
       j5   20 /
FK    Sink flowrate (ton per h)
      /j1   10
       j2   4
       j3   12
       j4   8
       j5   6.5 /
TOUTH(I)  outlet temperature of hot stream (degree celcius)
      /i1   30
       i2   30
       i3   30
       i4   30
       i5   30 /

TOUTC(J)  outlet temperature of cold stream (degree celcius)
      /j1    100
       j2    100
       j3    100
       j4    100
       j5    100 /
CPF2  Piping fix cost fresh to sink ($ per year)
      /j1    200
       j2    300
       j3    150
       j4    120
       j5    250 /
CP2   Piping variable fresh to sink ($ per ton)
      /j1    0.7e-3
       j2    1.4e-3
       j3    1.2e-3
       j4    1.1e-3
       j5    1.3e-3 /
CPF3  Piping fix cost source to waste ($ per year)
      /i1    100
       i2    200
       i3    250
       i4    150
       i5    200 /
CP3   Piping variable cost source to waste ($ per ton)
      /i1    0.7e-3
```

```
            i2    1.4e-3
            i3    1.1e-3
            i4    1.2e-3
            i5    1.3e-3 /

TINC(j)
TINH(i)
FH(i)
FC(j)

;
TABLE CPF1(i,j)  Piping fix cost source to sink ($ per year)
          j1   j2   j3   j4   j5
     i1   100  300  150  200  200
     i2   200  250  100  220  150
     i3   220  300  330  300  110
     i4   110  400  200  200  250
     i5   200  300  100  300  250
;
TABLE CP1(i,j)  Piping variable cost source to sink ($ per ton)
          j1      j2      j3      j4      j5
     i1   1.1e-3  1.2e-3  1.3e-3  1.4e-3  1.1e-3
     i2   0.8e-3  1.3e-3  1.1e-3  1.2e-3  0.9e-3
     i3   0.9e-3  1.3e-3  1.1e-3  1.4e-3  1.1e-3
     i4   1.3e-3  1.2e-3  1.3e-3  1.4e-3  1.1e-3
     i5   1.1e-3  0.8e-3  1.3e-3  1.4e-3  0.9e-3
;

Scalar      OMEGA1  /10000/
          TFW   /25/
          OMEGA  upper bound for heat exchange   /1000000/
          GAMMA  upper bound for temperature difference /1000000/
          EMAT   exchanger minimum approach temperature  /10/
          CP     heat capacity /4.2/
          FWC    Freshwater cost ($ per ton) /0.375/
          HF1    Heat Exchanger fixed cost ($) /8000/
          HF2    Heat Exchanger fixed cost ($) /19965.89/
          HV     Heat Exchanger variable cost ($ per m2) /55.74899/
          HUOC   Hot utility operation cost ($ per kW y) /377/
          CUOC   Cold utility operation cost ($ per kW y) /189/
          U      Overall heat transfer coefficient /0.5/
          WH     Working hour /8000/
          WY     Annaulize factor /0.333/
          TINHU  Hot utility inlet temperature  /120/
          TOUTHU Hot utility outlet temperature  /120/
          TINCU  Cold utility inlet temperature  /10/
          TOUTCU Cold utility outlet temperature  /20/
;
Variables
            OFW      Overall freshwater
            OWW      Overall wastewater
```

FCost Freshwater cost
INV Investment cost
TAC Total annual cost
PIC1 Piping cost of source to sink
PIC2 Piping cost of fresh to sink
PIC3 Piping cost of source to waste
PICost Piping cost
O11 Objective 1.1
O12 Objective 1.2
O2 Objective 2
O3 Objective 3
;
Positive variables x(i,j)
FFW(j) Freshwater flowrate
F(i,j) Splitting Flowrate
CK(j) Sink stream concentration
TK(j) Sink temperature
WW(i) Source Waste water
dt(I,J,K) Temperature approach for match ij at the left of stage k
dtcu(I) Temperature approach for match hot stream i and cold utility
dthu(J) Temperature approach for match cold stream j and hot utility

q(I,J,K) Heat exchanged between hot stream i and cold stream j at stage k
qcu(I) Heat exchanged between hot stream i and cold utility
qhu(J) Heat exchanged between cold stream j and hot utility
A(i,j,K)
Ahu(j)
Acu(i)
Atot
LMTD(i,j,K)
LMTDcu(i)
LMTDhu(j)
Costh
Costhu
Costcu
OCosthu
OCostcu
Oqcu Overall heat exchanged between hot stream i and cold utility
Oqhu Overall heat exchanged between cold stream j and hot utility
tH(I,K) Temperature of hot stream i at location k
tC(J,K) Temperature of cold stream j at location k
;
BINARY VARIABLE
y(i,j) Binary vriable to denote existence of match source to sink in WN
yFW(j) Binary vriable to denote existence of match FW to sink in WN
yWW(i) Binary vriable to denote existence of match WW from source in WN
z(I,J,K) Binary variable to denote existence of match ij in stage k
zcu(I) Binary variable to denote existence of cold utility with hot stream i
zhu(J) Binary variable to denote existence of hot utility with cold stream
;
Equation

```
*************************************WATER NETWORK***************************
    MB1(j)    Mass balance (flowrate)
    MB2(j)    Mass balance (contaminant)
    Cons1(i)  Constraint for x
    Cons2(j)  Concentration constraint
    Fresh     Freshwater usage
    Waste(i)  Waste of source
    Allwaste  Waste discharge
    Flow(i,j) Flowrate each sink
    Logical1(i,j) Logical constraint
    Logical2(j) Logical constraint
    Logical3(i) Logical constraint
    TempK(j)  Temperature of sink
    FRESHC    Freshwater cost
    PIP1      Piping cost of source to sink
    PIP2      Piping cost of fresh to sink
    PIP3      Piping cost of source to waste
    PIPC      Piping cost
OBJFN11
OBJFN12

Link1(j)
Link2(j)
Link3(i)
Link4(i)
*************************************HEATEX NETWORK**************************
     abc(I,J)        @#@$$#

     OHB_H(I)       overall heat balance for each hot stream
     OHB_C(J)       overall heat balance for each cold stream

     SHB_H(I,K)      heat balance at each stage for hot stream
     SHB_C(J,K)      heat balance at each stage for cold stream

     TINHASSGN(I)    assignment of inlet temperature of hot stream i
     TINCASSGN(J)    assignment of inlet temperature of cold stream j

     FH1(I,K)      feasibility of temperature at each stage for hot stream
     FH2(I)        feasibility of temperature at last stage for hot stream
     FC1(J,K)      feasibility of temperature at each stage for cold stream
     FC2(J)        feasibility of temperature at first stage for cold stream

     HULOAD(I)      hot utility load
     CULOAD(J)      cold utility load

     HECOUNT1(I,J,K)  count heat exchanger
     HECOUNT2(I)     count hot utiility
     HECOUNT3(J)     count cold utility

     APPTEMPL(I,J,K)  approach temperature at the left of stage k
```

```
    APPTEMPR(I,J,K)  approach temperature at the right of stage k
    APPTEMPCU(I)     approach temperature at cold utility of hot stream i
    APPTEMPHU(J)     approach temperature at hot utility of cold stream j

    APPTEMPLIMIT(I,J,K)  limiting temperature approach
    APPTEMPLIMITCU(I)    limiting temperature approach
    APPTEMPLIMITHU(J)    limiting temperature approach


LOGMH(i,j,K)     Log mean temperature different of HE
LOGMHU(J)        Log mean temperature different of HU
LOGMCU(I)        Log mean temperature different of CU
HAREA(i,j,K)     Heat exchanger area
HUAREA(J)        Hot utility area
CUAREA(I)        Cold utility area
TOTAREA          Total area

HACOST         Heat exchanger area cost
HUACOST        Hot utility heat exchanger area cost
CUACOST        Cold utility heat exchanger area cost
HUOCOST        Hot utility operation cost
CUOCOST        Cold utility operation cost

    OAQCU       Overall Cold utility
    OAQHU       Overall hot utility
    OBJFN2      utility Q
    OBJFN3      utility AREA
    Invest      Investment cost
    Total       Total annual cost
;
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FK(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FFW(j) =e= FK(j) ;
Cons1(i) .. sum(j,x(i,j))-1 =l= 0 ;
Cons2(j) .. CK(j) =l= CKL2(j) ;
Fresh .. OFW =e= sum(j,FFW(j));
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
Allwaste .. OWW =e= sum(i,WW(i));
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Logical1(i,j) .. F(i,j)-OMEGA1*y(i,j) =l= 0;
Logical2(j) .. FFW(j)-OMEGA1*yFW(j) =l= 0;
Logical3(i) .. WW(i)-OMEGA1*yWW(i) =l= 0;
TempK(j) .. sum(i,TS(i)*F(i,j))+TFW*FFW(j) =e= TK(j)*FK(j);
FRESHC .. FCost =e= OFW*FWC*WH;
PIP1 .. PIC1 =e= sum((i,j),y(i,j)*(CPF1(i,j)+F(i,j)*CP1(i,j)*WH));
PIP2 .. PIC2 =e= sum(j,yFW(j)*(CPF2(j)+FFW(j)*CP2(j)*WH));
PIP3 .. PIC3 =e= sum(i,yWW(i)*(CPF3(i)+WW(i)*CP3(i)*WH));
PIPC .. PICost =e= PIC1+PIC2+PIC3;
OBJFN11 .. O11 =e= FCost;
OBJFN12 .. O12 =e= FCost+PICost;

Link1(j) .. TK(j) =e= TINC(J);
```

```
Link2(j) .. FK(j) =e= FC(J);
Link3(i) .. TS(i) =e= TINH(I);
Link4(i) .. FH(I) =e= WW(i);

 abc(i,j) .. q(i,j,'lastlocation') =e= 0;

 OHB_H(i) ..  (TINH(i)-TOUTH(i))*FH(i)*CP*(1000/3600) =e= SUM((J,K),q(I,J,K))+qcu(I);
 OHB_C(j) ..  (TOUTC(J)-TINC(J))*FC(J)*CP*(1000/3600) =e= SUM((I,K),q(I,J,K))+qhu(J);

 SHB_H(I,K)$(ORD(K) NE CARD(K)) .. (tH(I,K)-tH(I,K+1))*FH(I)*CP*(1000/3600)
                          =e= SUM(J,q(I,J,K));
 SHB_C(J,K)$(ORD(K) NE CARD(K)) .. (tC(J,K)-tC(J,K+1))*FC(J)*CP*(1000/3600)
                          =e= SUM(I,q(I,J,K));

 TINHASSGN(I) .. TINH(I) =e= tH(I,'firstlocation');
 TINCASSGN(J) .. TINC(J) =e= tC(J,'lastlocation');

 FH1(I,K)$(ORD(K) NE CARD(K)) .. tH(I,K) =g= tH(I,K+1);
 FH2(I) .. TOUTH(I) =l= tH(I,'lastlocation');
 FC1(J,K)$(ORD(K) NE CARD(K)) .. tC(J,K) =g= tC(J,K+1);
 FC2(J) .. TOUTC(J) =g= tC(J,'firstlocation');

 HULOAD(I) .. (tH(I,'lastlocation')-TOUTH(I))*FH(I)*CP*(1000/3600) =e= qcu(I);
 CULOAD(J) .. (TOUTC(J)-tC(J,'firstlocation'))*FC(J)*CP*(1000/3600) =e= qhu(J);

 HECOUNT1(I,J,K)$(ORD(K) NE CARD(K)) .. q(I,J,K)-OMEGA*z(I,J,K) =l= 0;
 HECOUNT2(I) .. qcu(I)-OMEGA*zcu(I) =l= 0;
 HECOUNT3(J) .. qhu(J)-OMEGA*zhu(J) =l= 0;

 APPTEMPL(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =l= tH(I,K)-tC(J,K)+GAMMA*(1-z(I,J,K));
 APPTEMPR(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K+1) =l= tH(I,K+1)-tC(J,K+1)+GAMMA*(1-
z(I,J,K));
 APPTEMPCU(I) .. dtcu(I) =l= tH(I,'lastlocation')-TOUTCU +GAMMA*(1-zcu(I));
 APPTEMPHU(J) .. dthu(J) =l= TOUTHU - tC(J,'firstlocation')+GAMMA*(1-zhu(J));

 APPTEMPLIMIT(I,J,K)$(ORD(K) NE CARD(K)) .. dt(I,J,K) =g= EMAT;
 APPTEMPLIMITCU(i) .. dtcu(I) =g= EMAT;
 APPTEMPLIMITHU(j) .. dthu(J) =g= EMAT;

LOGMH(i,j,K) .. LMTD(i,j,K) =e= (((dt(i,j,K)*dt(i,j,K+1))*(dt(i,j,K)+dt(i,j,K+1))/2))**(1/3);
LOGMHU(j) .. LMTDhu(j) =e= ((((TOUTHU-tC(J,'firstlocation'))*(TINHU-TOUTC(J)))*((TOUTHU-
tC(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LOGMCU(i) .. LMTDcu(i) =e= ((((tH(i,'lastlocation')-TOUTCU)*(TOUTH(I)-
TINCU))*((tH(i,'lastlocation')-TOUTCU)+(TOUTH(I)-TINCU))/2))**(1/3);
HAREA(i,j,K)  .. A(i,j,K)*U*LMTD(i,j,K) =e= q(I,J,K);
HUAREA(j) .. Ahu(j)*U*LMTDhu(j) =e= qhu(j);
CUAREA(i) .. Acu(i)*U*LMTDcu(i) =e= qcu(i);
TOTAREA .. Atot =e= sum((i,j,k),A(i,j,K))+sum(j,Ahu(j))+sum(i,Acu(i));

HACOST .. Costh =e= sum((i,j,k),((HF1+HF2)*z(i,j,k)+HV*A(i,j,k))*WY);
HUACOST .. Costhu =e= sum(j,((HF1+HF2)*zhu(j)+HV*Ahu(j))*WY);
```

```
CUACOST .. Costcu =e= sum(i,((HF1+HF2)*zcu(i)+HV*Acu(i))*WY);
HUOCOST .. OCosthu =e= sum(j,HUOC*qhu(j));
CUOCOST .. OCostcu =e= sum(i,CUOC*qcu(i));

 OAQCU .. OQCU =e= SUM(I,qcu(I));
 OAQHU .. OQHU =e= SUM(J,qhu(J));
 OBJFN2 .. O2 =e= OCosthu+OCostcu+sum((i,j,k),z(i,j,k)*(HF1+HF2));
 OBJFN3 . O3 =e= Costh+Costhu+Costcu+OCosthu+OCostcu;
Invest .. INV =e= Costh+Costhu+Costcu;
Total .. TAC =e= (Costh+Costhu+Costcu)+OCosthu+OCostcu+FCost.l+PICost.l;

Model MIXING1 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,OBJFN11/;
Solve MIXING1 using MIP minimizing O11;
Display FCost.l,OFW.l,OWW.l,FFW.l,yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;

Parameter
xin(i,j)
FFWin(j)
WWin(i)
yin(i,j)
yFWin(j)
yWWin(i)
;
xin(i,j) = x.l(i,j);
FFWin(j) = FFW.l(j);
WWin(i) = WW.l(i);
yin(i,j) = y.l(i,j);
yFWin(j) = yFW.l(j);
yWWin(i) = yWW.l(i);

x.l(i,j) = xin(i,j);
FFW.l(j) = FFWin(j);
WW.l(i) = WWin(i);
y.l(i,j) = yin(i,j);
yFW.l(j) = yFWin(j);
yWW.l(i) = yWWin(i);

Model MIXING2 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,PIP1,PIP2,PIP3,PIPC,OBJFN12/;
Solve MIXING2 using MINLP minimizing O12;
Display PIC1.l,PIC2.l,PIC3.l,PICost.l,FCost.l,OFW.l,OWW.l,FFW.l,
yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;

TINC(j) = TK.l(j);
TINH(i) = TS(i);
FH(i) = WW.l(i);
FC(j) = FK(j);


MODEL STAGEMODEL1 /abc,OHB_H,OHB_C,SHB_H,SHB_C,TINHASSGN,TINCASSGN,FH1,FH2,
```

```
FC1,FC2,HULOAD,CULOAD,HECOUNT1,HECOUNT2,HECOUNT3,APPTEMPL,APPTEMPR,APPTE
MPCU,
APPTEMPHU,APPTEMPLIMIT,APPTEMPLIMITCU,APPTEMPLIMITHU,OAQCU,OAQHU,
HUOCOST,CUOCOST,Invest,OBJFN2/
;
SOLVE STAGEMODEL1 USING MIP MINIMIZING O2;
DISPLAY z.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,OQHU.l,OQCU.l,INV.l,O2.l;

Parameter
qin(i,j,k)
qcuin(i)
qhuin(j)
THin(i,k)
TCin(j,k)
zin(i,j,k)
zcuin(i)
zhuin(j)
;
qin(i,j,k) = q.l(i,j,k);
qcuin(i) = qcu.l(i);
qhuin(j) = qhu.l(j);
THin(i,k) = TH.l(i,k);
TCin(j,k) = TC.l(j,k);
zin(i,j,k) = z.l(i,j,k);
zcuin(i) = zcu.l(i);
zhuin(j) = zhu.l(j);

q.l(i,j,k) = qin(i,j,k);
qcu.l(i) = qcuin(i) ;
qhu.l(j) = qhuin(j);
TH.l(i,k) = THin(i,k);
TC.l(j,k) = TCin(j,k);

z.fx(i,j,k) = zin(i,j,k);
zcu.fx(i) = zcuin(i);
zhu.fx(j) = zhuin(j);

LMTD.l(i,j,k) = (((dt.l(i,j,K)*dt.l(i,j,K+1))*(dt.l(i,j,K)+dt.l(i,j,K+1))/2))**(1/3);
LMTDhu.l(j) = ((((TOUTHU-tC.l(J,'firstlocation'))*(TINHU-TOUTC(J)))*((TOUTHU-
tC.l(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LMTDcu.l(i) = ((((tH.l(i,'lastlocation')-TOUTCU)*(TOUTH(I)-TINCU))*((tH.l(i,'lastlocation')-
TOUTCU)+(TOUTH(I)-TINCU))/2))**(1/3);
A.l(i,j,k) = qin(i,j,k)/(U*LMTD.l(i,j,k)+0.001);
Ahu.l(j) = qhuin(j)/(U*LMTDhu.l(j)+0.001);
Acu.l(i) = qcuin(i)/(U*LMTDcu.l(i)+0.001);

MODEL STAGEMODEL2 /abc,OHB_H,OHB_C,SHB_H,SHB_C,TINHASSGN,TINCASSGN,FH1,FH2,
FC1,FC2,HULOAD,CULOAD,HECOUNT1,HECOUNT2,HECOUNT3,APPTEMPL,APPTEMPR,APPTE
MPCU,
APPTEMPHU,APPTEMPLIMIT,APPTEMPLIMITCU,APPTEMPLIMITHU,LOGMH,LOGMHU,LOGM
CU,
```

```
HAREA,HUAREA,CUAREA,TOTAREA,HACOST,HUACOST,CUACOST,HUOCOST,CUOCOST,OA
QCU,OAQHU,OBJFN3,Invest,Total/
;
SOLVE STAGEMODEL2 USING MINLP MINIMIZING O3;
DISPLAY F.l,FFW.l,WW.l,TK.l,z.l,zcu.l,zhu.l,tH.l,tC.l,q.l,qcu.l,qhu.l,OQHU.l,
OQCU.l,A.l,Ahu.l,Acu.l,Atot.l,Fcost.l,O12.l,O2.l,OCosthu.l,OCostcu.l,INV.l,TAC.l
```

## APPENDIX A-14 : Case Study 4 WHEN by four-step design Code

```
set    i Source stream /i1*i5/
       j Sink stream /j1*j5/
       K  location    /firstlocation,location2*location4,lastlocation/
;
Parameter
       CS   Source concentration (ppm)
            /i1   130
             i2   108
             i3   70
             i4   44
             i5   22 /
       FS   Source flowrate (ton per h)
            /i1   9
             i2   9
             i3   9
             i4   9
             i5   4.5 /
       TS   Source temperature (degree celcius)
            /i1   120
             i2   100
             i3   130
             i4   140
             i5   80 /
       CKL1  Sink concentration limit (ppm)
            /j1   70
             j2   70
             j3   70
             j4   70
             j5   70 /
       CKL   Sink concentration limit (ppm)
            /j1   20
             j2   20
             j3   20
             j4   20
             j5   20 /
       FK   Sink flowrate (ton per h)
            /j1   10
             j2   4
             j3   12
             j4   0
```

```
      j5   0 /
FKL   Sink flowrate (ton per h)
      /j1    10
      j2    4
      j3    12
      j4    8
      j5    6.5 /
TOUTH(I)  outlet temperature of hot stream (degree celcius)
      /i1    30
      i2    30
      i3    30
      i4    30
      i5    30 /
TOUTH1P(I)  outlet temperature of hot stream (degree celcius)
      /i1    100
      i2    80
      i3    100
      i4    100
      i5    80 /

TOUTC(J)  outlet temperature of cold stream (degree celcius)
      /j1    100
      j2    100
      j3    100
      j4    100
      j5    100 /
CPF2   Piping fix cost fresh to sink ($ per year)
      /j1    200
      j2    300
      j3    150
      j4    120
      j5    250 /
CP2   Piping variable fresh to sink ($ per ton)
      /j1    0.7e-3
      j2    1.4e-3
      j3    1.2e-3
      j4    1.1e-3
      j5    1.3e-3 /
CPF3   Piping fix cost source to waste ($ per year)
      /i1    100
      i2    200
      i3    250
      i4    150
      i5    200 /
CP3   Piping variable cost source to waste ($ per ton)
      /i1    0.7e-3
      i2    1.4e-3
      i3    1.1e-3
      i4    1.2e-3
      i5    1.3e-3 /
```

```
;
TABLE CPF1(i,j)  Piping fix cost source to sink ($ per year)
          j1   j2   j3   j4   j5
     i1   100  300  150  200  200
     i2   200  250  100  220  150
     i3   220  300  330  300  110
     i4   110  400  200  200  250
     i5   200  300  100  300  250
;
TABLE CP1(i,j)  Piping variable cost source to sink ($ per ton)
          j1       j2       j3       j4       j5
     i1   1.1e-3   1.2e-3   1.3e-3   1.4e-3   1.1e-3
     i2   0.8e-3   1.3e-3   1.1e-3   1.2e-3   0.9e-3
     i3   0.9e-3   1.3e-3   1.1e-3   1.4e-3   1.1e-3
     i4   1.3e-3   1.2e-3   1.3e-3   1.4e-3   1.1e-3
     i5   1.1e-3   0.8e-3   1.3e-3   1.4e-3   0.9e-3
;

Scalar      OMEGA1  /100/
          TFW    /25/
          OMEGA  upper bound for heat exchange   /1000000/
          GAMMA  upper bound for temperature difference /1000000/
          EMAT   exchanger minimum approach temperature  /10/
          CP     heat capacity /4.2/
          FWC    Freshwater cost ($ per ton) /0.375/
          HF1    Heat Exchanger fixed cost ($) /8000/
          HF2    Heat Exchanger fixed cost ($) /19965.89/
          HV     Heat Exchanger variable cost ($ per m2) /55.74899/
          HUOC   Hot utility operation cost ($ per kW y) /377/
          CUOC   Cold utility operation cost ($ per kW y) /189/
          U      Overall heat transfer coefficient /0.5/
          WH     Working hour /8000/
          WY     Annaulize factor /0.333/
          TINHU  Hot utility inlet temperature  /120/
          TOUTHU Hot utility outlet temperature  /120/
          TINCU  Cold utility inlet temperature  /10/
          TOUTCU Cold utility outlet temperature  /20/
;
Variables       TAC1      Total annual cost 1
            TAC2      Total annual cost 2
            AREA      Total Area
            OFW       Overall freshwater
            OWW       Overall wastewater
            FCost
            PIC1      Piping cost of source to sink
            PIC2      Piping cost of fresh to sink
            PIC3      Piping cost of source to waste
            PICost    Piping cost
            O11       Objective 1.1
            O12       Objective 1.2
            O2        Objective 2
```

```
          O22       Objective 2.2
          O3        Objective 3
          O32       Objective 3.2
          O4        Objective 3
          OFW1      Overall freshwater
          OWW1      Overall wastewater
          FCost1
          PIC11     Piping cost of source to sink
          PIC21     Piping cost of fresh to sink
          PIC31     Piping cost of source to waste
          PICost1   Piping cost
          OBJWN1
          OFW2      Overall freshwater
          OWW2      Overall wastewater
          FCost2
          PIC12     Piping cost of source to sink
          PIC22     Piping cost of fresh to sink
          PIC32     Piping cost of source to waste
          PICost2   Piping cost
          OBJWN2
;

Positive variables  x(i,j)
          FFW(j) Freshwater flowrate
          F(i,j) Splitting Flowrate
          CK(j)  Sink stream concentration
          TK(j)  Sink temperature
          WW(i)  Source Waste water

*******************************************************************************
          x1(i,j)
          FFW1(j) Freshwater flowrate
          F1(i,j) Splitting Flowrate
          CK1(j)  Sink stream concentration
          TK1(j)  Sink temperature
          WW1(i)  Source Waste water
          FK1(j)
     TINH1(i)
     TOUTH1(i)
     TINC1(j)
     TOUTC1(j)
     FH1(i)
     FC1(j)
     dt1(I,J,K) Temperature approach for match ij at the left of stage k
     dtcu1(I)   Temperature approach for match hot stream i and cold utility
     dthu1(J)   Temperature approach for match cold stream j and hot utility

     q1(I,J,K)  Heat exchanged between hot stream i and cold stream j at stage k
     qcu1(I)    Heat exchanged between hot stream i and cold utility
     qhu1(J)    Heat exchanged between cold stream j and hot utility
     A1(i,j,K)
```

Ahu1(j)
Acu1(i)
Atot1
LMTD1(i,j,K)
LMTDcu1(i)
LMTDhu1(j)
Costh1
Costhu1
Costcu1
OCosthu1
OCostcu1
tH1(I,K) Temperature of hot stream i at location k
tC1(J,K) Temperature of cold stream j at location k
*********************************************************************************
x2(i,j)
FFW2(j) Freshwater flowrate
F2(i,j) Splitting Flowrate
CK2(j) Sink stream concentration
TK2(j) ddddd
WW2(i) Source Waste water
FK2(j)
TS2(i)
FS2(i)
TINH2(i)
TOUTH2(i)
TINC2(j)
TOUTC2(j)
FH2(i)
FC2(j)
dt2(I,J,K) Temperature approach for match ij at the left of stage k
dtcu2(I) Temperature approach for match hot stream i and cold utility
dthu2(J) Temperature approach for match cold stream j and hot utility
q2(I,J,K) Heat exchanged between hot stream i and cold stream j at stage k
qcu2(I) Heat exchanged between hot stream i and cold utility
qhu2(J) Heat exchanged between cold stream j and hot utility
A2(i,j,K)
Ahu2(j)
Acu2(i)
Atot2
LMTD2(i,j,K)
LMTDcu2(i)
LMTDhu2(j)
Costh2
Costhu2
Costcu2
OCosthu2
OCostcu2
tH2(I,K) Temperature of hot stream i at location k
tC2(J,K) Temperature of cold stream j at location k
*********************************************************************************

```
      Oqcu1    Overall heat exchanged between hot stream i and cold utility
      Oqhu1    Overall heat exchanged between cold stream j and hot utility
      Oqcu2    Overall heat exchanged between hot stream i and cold utility
      Oqhu2    Overall heat exchanged between cold stream j and hot utility

;
BINARY VARIABLE
y(i,j)   Binary vriable to denote existence of match source to sink in WN
yFW(j)   Binary vriable to denote existence of match FW to sink in WN
yWW(i)   Binary vriable to denote existence of match WW from source in WN

y1(i,j)   Binary vriable to denote existence of match source to sink in WN
yFW1(j)   Binary vriable to denote existence of match FW to sink in WN
yWW1(i)   Binary vriable to denote existence of match WW from source in WN
z1(I,J,K) Binary variable to denote existence of match ij in stage k
zcu1(I)   Binary variable to denote existence of cold utility with hot stream i
zhu1(J)   Binary variable to denote existence of hot utility with cold stream

y2(i,j)   Binary vriable to denote existence of match source to sink in WN
yFW2(j)   Binary vriable to denote existence of match FW to sink in WN
yWW2(i)   Binary vriable to denote existence of match WW from source in WN
z2(I,J,K) Binary variable to denote existence of match ij in stage k
zcu2(I)   Binary variable to denote existence of cold utility with hot stream i
zhu2(J)   Binary variable to denote existence of hot utility with cold stream
;
Equation

*************************************WATER initial***************************
      MB1(j)    Mass balance (flowrate)
      MB2(j)    Mass balance (contaminant)
      Cons1(i)  Constraint for x
      Cons2(j)  Concentration constraint
      Cons3(j)
      ConsF
      Fresh     Freshwater usage
      Waste(i)  Waste of source
      Allwaste  Waste discharge
      Flow(i,j) Flowrate each sink
      Logical1(i,j) Logical constraint
      Logical2(j) Logical constraint
      Logical3(i) Logical constraint
      TempK(j)  Temperature of sink
      FRESHC    Freshwater cost
      PIP1      Piping cost of source to sink
      PIP2      Piping cost of fresh to sink
      PIP3      Piping cost of source to waste
      PIPC      Piping cost
OBJFN11
OBJFN12
*****************************************************************************
******************************** WN1 ****************************************
```

```
MB1_1(j)    Mass balance (flowrate)
MB2_1(j)    Mass balance (contaminant)
Cons1_1(i)  Constraint for x
Cons2_1(j)  Concentration constraint
Cons3_1(j)
ConsF_1

Waste_1(i)  Waste of source
Allwaste_1  Waste discharge
Flow_1(i,j) Flowrate each sink
Logical1_1(i,j) Logical constraint
Logical2_1(j) Logical constraint
Logical3_1(i) Logical constraint
TempK_1(j)  Temperature of sink

PIP1_1      Piping cost of source to sink
OBJECTWN1

Link1_1(i)
Link2_1(i)
Link3_1(j)
Link4_1(j)
******************************** HEN1 ***************************************
abc_1(I,J)      @#@$$#

OHB_H_1(I)      overall heat balance for each hot stream
OHB_C_1(J)      overall heat balance for each cold stream

SHB_H_1(I,K)     heat balance at each stage for hot stream
SHB_C_1(J,K)     heat balance at each stage for cold stream

TINHASSGN_1(I)   assignment of inlet temperature of hot stream i
TINCASSGN_1(J)   assignment of inlet temperature of cold stream j

FH1_1(I,K)       feasibility of temperature at each stage for hot stream
FH2_1(I)        feasibility of temperature at last stage for hot stream
FC1_1(J,K)       feasibility of temperature at each stage for cold stream
FC2_1(J)        feasibility of temperature at first stage for cold stream

HULOAD_1(I)      hot utility load
CULOAD_1(J)      cold utility load

HECOUNT1_1(I,J,K) count heat exchanger
HECOUNT2_1(I)    count hot utility
HECOUNT3_1(J)    count cold utility

APPTEMPL_1(I,J,K) approach temperature at the left of stage k
APPTEMPR_1(I,J,K) approach temperature at the right of stage k
APPTEMPCU_1(I)   approach temperature at cold utility of hot stream i
APPTEMPHU_1(J)   approach temperature at hot utility of cold stream j
```

```
     APPTEMPLIMIT_1(I,J,K)  limiting temperature approach
     APPTEMPLIMITCU_1(I)   limiting temperature approach
     APPTEMPLIMITHU_1(J)   limiting temperature approach


LOGMH_1(i,j,K)      Log mean temperature different of HE
LOGMHU_1(J)         Log mean temperature different of HU
LOGMCU_1(I)         Log mean temperature different of CU
HAREA_1(i,j,K)      Heat exchanger area
HUAREA_1(J)         Hot utility area
CUAREA_1(I)         Cold utility area
TOTAREA_1           Total area

HACOST_1        Heat exchanger area cost
HUACOST_1        Hot utility heat exchanger area cost
CUACOST_1        Cold utility heat exchanger area cost
HUOCOST_1        Hot utility operation cost
CUOCOST_1        Cold utility operation cost

Link12_1(i)
Link12_2(i)
Link12_3(j)
********************************** WN2 ******************************************
     MB1_2(j)    Mass balance (flowrate)
     MB2_2(j)    Mass balance (contaminant)
     Cons1_2(i)  Constraint for x
     Cons2_2(j)  Concentration constraint
     Cons3_2(j)
     ConsF_2
     Fresh_2     Freshwater usage
     Waste_2(i)   Waste of source
     Allwaste_2   Waste discharge
     Flow_2(i,j)  Flowrate each sink
     Logical1_2(i,j) Logical constraint
     Logical2_2(j) Logical constraint
     Logical3_2(i) Logical constraint
     TempK_2(j)   Temperature of sink
     FRESHC_2     Freshwater cost
     PIP1_2      Piping cost of source to sink
     PIP2_2      Piping cost of fresh to sink
     PIP3_2      Piping cost of source to waste
     PIPC_2      Piping cost
     OBJECTWN2
Link1_2(i)
Link2_2(i)
Link3_2(j)
Link4_2(j)
********************************** HEN2 ****************************************
abc_2(I,J)       @#@$$#

      OHB_H_2(I)      overall heat balance for each hot stream
```

OHB_C_2(J) overall heat balance for each cold stream

SHB_H_2(I,K) heat balance at each stage for hot stream
SHB_C_2(J,K) heat balance at each stage for cold stream

TINHASSGN_2(I) assignment of inlet temperature of hot stream i
TINCASSGN_2(J) assignment of inlet temperature of cold stream j

FH1_2(I,K) feasibility of temperature at each stage for hot stream
FH2_2(I) feasibility of temperature at last stage for hot stream
FC1_2(J,K) feasibility of temperature at each stage for cold stream
FC2_2(J) feasibility of temperature at first stage for cold stream

HULOAD_2(I) hot utility load
CULOAD_2(J) cold utility load

HECOUNT1_2(I,J,K) count heat exchanger
HECOUNT2_2(I) count hot utility
HECOUNT3_2(J) count cold utility

APPTEMPL_2(I,J,K) approach temperature at the left of stage k
APPTEMPR_2(I,J,K) approach temperature at the right of stage k
APPTEMPCU_2(I) approach temperature at cold utility of hot stream i
APPTEMPHU_2(J) approach temperature at hot utility of cold stream j

APPTEMPLIMIT_2(I,J,K) limiting temperature approach
APPTEMPLIMITCU_2(I) limiting temperature approach
APPTEMPLIMITHU_2(J) limiting temperature approach

LOGMH_2(i,j,K) Log mean temperature different of HE
LOGMHU_2(J) Log mean temperature different of HU
LOGMCU_2(I) Log mean temperature different of CU
HAREA_2(i,j,K) Heat exchanger area
HUAREA_2(J) Hot utility area
CUAREA_2(I) Cold utility area
TOTAREA_2 Total area

HACOST_2 Heat exchanger area cost
HUACOST_2 Hot utility heat exchanger area cost
CUACOST_2 Cold utility heat exchanger area cost
HUOCOST_2 Hot utility operation cost
CUOCOST_2 Cold utility operation cost

************************************************************************************

Link_WN(i)

OAQCU1 Overall Cold utility
OAQHU1 Overall hot utility

```
    OAQCU2       Overall Cold utility
    OAQHU2       Overall hot utility
    OBJFN2       utility Q
    OBJFN22      utility Q
    OBJFN3       utility AREA
    OBJFN32
    Invest       Investment cost
    Total1       Total annual cost
    Total2       Total annual cost
    TotalA
    UTILITY
;
*************************************WN INITIAL***********************************
MB1(j) .. sum(i,CS(i)*FS(i)*x(i,j)) =e= CK(j)*FKL(j) ;
MB2(j) .. sum(i,FS(i)*x(i,j)) + FFW(j) =e= FKL(j) ;
Cons1(i)  .. sum(j,x(i,j)) =l= 1 ;
Cons2(j) .. CK(j) =l= CKL(j) ;
Fresh .. OFW =e= sum(j,FFW(j));
Waste(i) .. WW(i) =e= (1-sum(j,x(i,j)))*FS(i);
Allwaste .. OWW =e= sum(i,WW(i));
Flow(i,j) .. F(i,j) =e= FS(i)*x(i,j) ;
Logical1(i,j) .. F(i,j)-OMEGA1*y(i,j) =l= 0;
Logical2(j) .. FFW(j)-OMEGA1*yFW(j) =l= 0;
Logical3(i) .. WW(i)-OMEGA1*yWW(i) =l= 0;
TempK(j) .. sum(i,TS(i)*F(i,j))+TFW*FFW(j) =e= TK(j)*FKL(j);
FRESHC .. FCost =e= OFW*FWC*WH;
PIP1 .. PIC1 =e= sum((i,j),y(i,j)*(CPF1(i,j)+F(i,j)*CP1(i,j)*WH));
PIP2 .. PIC2 =e= sum(j,yFW(j)*(CPF2(j)+FFW(j)*CP2(j)*WH));
PIP3 .. PIC3 =e= sum(i,yWW(i)*(CPF3(i)+WW(i)*CP3(i)*WH));
PIPC .. PICost =e= PIC1+PIC2+PIC3;
OBJFN11 .. O11 =e= FCost;
OBJFN12 .. O12 =e= FCost+PICost;
*****************************************************************************
*********************************WN1*****************************************

MB1_1(j) .. sum(i,CS(i)*FS(i)*x1(i,j))+FK2(j)*CK2(j) =e= CK1(j)*FKL(j) ;
MB2_1(j) .. sum(i,FS(i)*x1(i,j)) + FK2(j) =e= FKL(j) ;
Cons1_1(i)  .. sum(j,x1(i,j)) =l= 1  ;
Cons2_1(j) .. CK1(j) =l= CKL(j) ;

Waste_1(i) .. WW1(i) =e= (1-sum(j,x1(i,j)))*FS(i);
Allwaste_1 .. OWW1 =e= sum(i,WW1(i));
Flow_1(i,j) .. F1(i,j) =e= FS(i)*x1(i,j) ;
Logical1_1(i,j) .. F1(i,j)-OMEGA1*y1(i,j) =l= 0;
*Logical2_1(j) .. FFW1(j)-OMEGA1*yFW1(j) =l= 0;
*Logical3_1(i) .. WW1(i)-OMEGA1*yWW1(i) =l= 0;
TempK_1(j) .. sum(i,TS(i)*F1(i,j))+FK2(j)*TOUTC2(j) =e= TK1(j)*FKL(j);
PIP1_1 .. PIC11 =e= sum((i,j),y1(i,j)*(CPF1(i,j)+F1(i,j)*CP1(i,j)*WH));
OBJECTWN1 .. OBJWN1 =e= sum((i,j),F1(i,j));

Link1_1(i) .. TINH1(i) =e= TS(i);
```

```
Link2_1(i) .. FH1(i) =e= WW1(i);
Link3_1(j) .. TINC1(j) =e= TK1(j);
Link4_1(j) .. FC1(j) =e= FKL(j);

********************************HEN1*******************************************
 abc_1(i,j) .. q1(i,j,'lastlocation') =e= 0;

 OHB_H_1(i) .. (TS(i)-TOUTH1(i))*WW1(i)*CP*(1000/3600) =e= SUM((J,K),q1(I,J,K))+qcu1(I);
 OHB_C_1(j) .. (TOUTC(J)-TK1(J))*FKL(J)*CP*(1000/3600) =e= SUM((I,K),q1(I,J,K))+qhu1(J);

 SHB_H_1(I,K)$(ORD(K) NE CARD(K)) .. (tH1(I,K)-tH1(I,K+1))*WW1(I)*CP*(1000/3600)
                         =e= SUM(J,q1(I,J,K));
 SHB_C_1(J,K)$(ORD(K) NE CARD(K)) .. (tC1(J,K)-tC1(J,K+1))*FC1(J)*CP*(1000/3600)
                         =e= SUM(I,q1(I,J,K));
 TINHASSGN_1(I) .. TS(I) =e= tH1(I,'firstlocation');
 TINCASSGN_1(J) .. TK1(J) =e= tC1(J,'lastlocation');

 FH1_1(I,K)$(ORD(K) NE CARD(K)) .. tH1(I,K) =g= tH1(I,K+1);
 FH2_1(I) .. TOUTH1(I) =l= tH1(I,'lastlocation');
 FC1_1(J,K)$(ORD(K) NE CARD(K)) .. tC1(J,K) =g= tC1(J,K+1);
 FC2_1(J) .. TOUTC(J) =g= tC1(J,'firstlocation');

 HULOAD_1(I) .. (tH1(I,'lastlocation')-TOUTH1(I))*WW1(I)*CP*(1000/3600) =e= qcu1(I);
 CULOAD_1(J) .. (TOUTC(J)-tC1(J,'firstlocation'))*FKL(J)*CP*(1000/3600) =e= qhu1(J);

 HECOUNT1_1(I,J,K)$(ORD(K) NE CARD(K)) .. q1(I,J,K)-OMEGA*z1(I,J,K) =l= 0;
 HECOUNT2_1(I) .. qcu1(I)-OMEGA*zcu1(I) =l= 0;
 HECOUNT3_1(J) . qhu1(J)-OMEGA*zhu1(J) =l= 0;

 APPTEMPL_1(I,J,K)$(ORD(K) NE CARD(K)) .. dt1(I,J,K) =l= tH1(I,K)-tC1(J,K)+GAMMA*(1-z1(I,J,K));
 APPTEMPR_1(I,J,K)$(ORD(K) NE CARD(K)) .. dt1(I,J,K+1) =l= tH1(I,K+1)-tC1(J,K+1)+GAMMA*(1-
z1(I,J,K));
 APPTEMPCU_1(I) .. dtcu1(I) =l= tH1(I,'lastlocation')-TOUTCU +GAMMA*(1-zcu1(I));
 APPTEMPHU_1(J) .. dthu1(J) =l= TOUTHU - tC1(J,'firstlocation')+GAMMA*(1-zhu1(J));

 APPTEMPLIMIT_1(I,J,K)$(ORD(K) NE CARD(K)) .. dt1(I,J,K) =g= EMAT;
 APPTEMPLIMITCU_1(i) .. dtcu1(I) =g= EMAT;
 APPTEMPLIMITHU_1(j) .. dthu1(J) =g= EMAT;

LOGMH_1(i,j,K) .. LMTD1(i,j,K) =e= (((dt1(i,j,K)*dt1(i,j,K+1))*(dt1(i,j,K)+dt1(i,j,K+1))/2))**(1/3);
LOGMHU_1(j) .. LMTDhu1(j) =e= ((((TOUTHU-tC1(J,'firstlocation'))*(TINHU-TOUTC1(J)))*((TOUTHU-
tC1(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LOGMCU_1(i) .. LMTDcu1(i) =e= ((((tH1(i,'lastlocation')-TOUTCU)*(TOUTH1(I)-TINCU))*((tH1(i,'lastlocation')-
TOUTCU)+(TOUTH1(I)-TINCU))/2))**(1/3);
HAREA_1(i,j,K) .. A1(i,j,K)*U*LMTD1(i,j,K) =e= q1(I,J,K);
HUAREA_1(j) .. Ahu1(j)*U*LMTDhu1(j) =e= qhu1(j);
CUAREA_1(i) .. Acu1(i)*U*LMTDcu1(i) =e= qcu1(i);
TOTAREA_1 .. Atot1 =e= sum((i,j,k),A1(i,j,K))+sum(j,Ahu1(j))+sum(i,Acu1(i));

HACOST_1 .. Costh1 =e= sum((i,j,k),((HF1+HF2)*z1(i,j,k)+HV*A1(i,j,k))*WY);
HUACOST_1 .. Costhu1 =e= sum(j,((HF1+HF2)*zhu1(j)+HV*Ahu1(j))*WY);
```

```
CUACOST_1 .. Costcu1 =e= sum(i,((HF1+HF2)*zcu1(i)+HV*Acu1(i))*WY);
HUOCOST_1 .. OCosthu1 =e= sum(j,HUOC*qhu1(j));
CUOCOST_1 .. OCostcu1 =e= sum(i,CUOC*qcu1(i));

Link12_1(i) .. TOUTH1(i) =e= TS2(i);
Link12_2(i) .. WW1(i) =e= FS2(i);

**********************************WN2******************************************
MB1_2(j) .. sum(i,CS(i)*FS2(i)*x2(i,j)) =e= CK2(j)*FK2(j) ;
MB2_2(j) .. sum(i,FS2(i)*x2(i,j)) + FFW2(j) =e= FK2(j) ;
Cons1_2(i) .. sum(j,x2(i,j)) =l= 1 ;
Cons2_2(j) .. CK2(j) =l= CKL(j) ;
Fresh_2 .. OFW2 =e= sum(j,FFW2(j));
Waste_2(i) .. WW2(i) =e= (1-sum(j,x2(i,j)))*FS2(i);
Allwaste_2 .. OWW2 =e= sum(i,WW2(i));
Flow_2(i,j) .. F2(i,j) =e= FS2(i)*x2(i,j) ;
Logical1_2(i,j) .. F2(i,j)-OMEGA1*y2(i,j) =l= 0;
Logical2_2(j) .. FFW2(j)-OMEGA1*yFW2(j) =l= 0;
Logical3_2(i) .. WW2(i)-OMEGA1*yWW2(i) =l= 0;
TempK_2(j) .. sum(i,TS2(i)*F2(i,j))+TFW*FFW2(j) =e= TK2(j)*FK2(j);
FRESHC_2 .. FCost2 =e= OFW2*FWC*WH;
PIP1_2 .. PIC12 =e= sum((i,j),y2(i,j)*(CPF1(i,j)+F2(i,j)*CP1(i,j)*WH));
PIP2_2 .. PIC22 =e= sum(j,yFW2(j)*(CPF2(j)+FFW2(j)*CP2(j)*WH));
PIP3_2 .. PIC32 =e= sum(i,yWW2(i)*(CPF3(i)+WW2(i)*CP3(i)*WH));
PIPC_2 .. PICost2 =e= PIC12+PIC22+PIC32;

OBJECTWN2 .. OBJWN2 =e= sum((i,j),F2(i,j));

Link1_2(i) .. TINH2(i) =e= TS2(i);
Link2_2(i) .. FH2(i) =e= WW2(i);
Link3_2(j) .. TINC2(j) =e= TK2(j);
Link4_2(j) .. FC2(j) =e= FK2(j);
*********************************HEN2*******************************************
 abc_2(i,j) .. q2(i,j,'lastlocation') =e= 0;

 OHB_H_2(i) .. (TINH2(i)-TOUTH(i))*FH2(i)*CP*(1000/3600) =e= SUM((J,K),q2(I,J,K))+qcu2(I);
 OHB_C_2(j) .. (TOUTC2(J)-TINC2(J))*FC2(J)*CP*(1000/3600) =e= SUM((I,K),q2(I,J,K))+qhu2(J);

 SHB_H_2(I,K)$(ORD(K) NE CARD(K)) .. (tH2(I,K)-tH2(I,K+1))*FH2(I)*CP*(1000/3600)
                     =e= SUM(J,q2(I,J,K));
 SHB_C_2(J,K)$(ORD(K) NE CARD(K)) .. (tC2(J,K)-tC2(J,K+1))*FC2(J)*CP*(1000/3600)
                     =e= SUM(I,q2(I,J,K));

 TINHASSGN_2(I) .. TINH2(I) =e= tH2(I,'firstlocation');
 TINCASSGN_2(J) .. TINC2(J) =e= tC2(J,'lastlocation');

 FH1_2(I,K)$(ORD(K) NE CARD(K)) .. tH2(I,K) =g= tH2(I,K+1);
 FH2_2(I) .. TOUTH(I) =l= tH1(I,'lastlocation');
 FC1_2(J,K)$(ORD(K) NE CARD(K)) .. tC2(J,K) =g= tC2(J,K+1);
 FC2_2(J) .. TOUTC2(J) =g= tC2(J,'firstlocation');
```

```
HULOAD_2(I) .. (tH2(I,'lastlocation')-TOUTH(I))*FH2(I)*CP*(1000/3600) =e= qcu2(I);
CULOAD_2(J) .. (TOUTC2(J)-tC2(J,'firstlocation'))*FC2(J)*CP*(1000/3600) =e= qhu2(J);

HECOUNT1_2(I,J,K)$(ORD(K) NE CARD(K)) .. q2(I,J,K)-OMEGA*z2(I,J,K) =l= 0;
HECOUNT2_2(I) .. qcu2(I)-OMEGA*zcu2(I) =l= 0;
HECOUNT3_2(J) .. qhu2(J)-OMEGA*zhu2(J) =l= 0;

APPTEMPL_2(I,J,K)$(ORD(K) NE CARD(K)) .. dt2(I,J,K) =l= tH2(I,K)-tC2(J,K)+GAMMA*(1-z2(I,J,K));
APPTEMPR_2(I,J,K)$(ORD(K) NE CARD(K)).. dt2(I,J,K+1) =l= tH2(I,K+1)-tC2(J,K+1)+GAMMA*(1-
z2(I,J,K));
APPTEMPCU_2(I) .. dtcu2(I) =l= tH2(I,'lastlocation')-TOUTCU +GAMMA*(1-zcu2(I));
APPTEMPHU_2(J) .. dthu2(J) =l= TOUTHU - tC2(J,'firstlocation')+GAMMA*(1-zhu2(J));

APPTEMPLIMIT_2(I,J,K)$(ORD(K) NE CARD(K)) .. dt2(I,J,K) =g= EMAT;
APPTEMPLIMITCU_2(i) .. dtcu2(I) =g= EMAT;
APPTEMPLIMITHU_2(j) .. dthu2(J) =g= EMAT;

LOGMH_2(i,j,K) .. LMTD2(i,j,K) =e= (((dt2(i,j,K)*dt2(i,j,K+1))*(dt2(i,j,K)+dt2(i,j,K+1))/2))**(1/3);
LOGMHU_2(j) .. LMTDhu2(j) =e= ((((TOUTHU-tC2(J,'firstlocation'))*(TINHU-TOUTC2(J)))*((TOUTHU-
tC2(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
LOGMCU_2(i) .. LMTDcu2(i) =e= ((((tH2(i,'lastlocation')-TOUTCU)*(TOUTH(I)-TINCU))*((tH2(i,'lastlocation')-
TOUTCU)+(TOUTH(I)-TINCU))/2))**(1/3);
HAREA_2(i,j,K) .. A2(i,j,K)*U*LMTD2(i,j,K) =e= q2(I,J,K);
HUAREA_2(j) .. Ahu2(j)*U*LMTDhu2(j) =e= qhu2(j);
CUAREA_2(i) .. Acu2(i)*U*LMTDcu2(i) =e= qcu2(i);
TOTAREA_2 .. Atot2 =e= sum((i,j,k),A2(i,j,K))+sum(j,Ahu2(j))+sum(i,Acu2(i));

HACOST_2 .. Costh2 =e= sum((i,j,k),((HF1+HF2)*z2(i,j,k)+HV*A2(i,j,k))*WY);
HUACOST_2 .. Costhu2 =e= sum(j,((HF1+HF2)*zhu2(j)+HV*Ahu2(j))*WY);
CUACOST_2 .. Costcu2 =e= sum(i,((HF1+HF2)*zcu2(i)+HV*Acu2(i))*WY);
HUOCOST_2 .. OCosthu2 =e= sum(j,HUOC*qhu2(j));
CUOCOST_2 .. OCostcu2 =e= sum(i,CUOC*qcu2(i));
*****************************************************************************


OAQCU1 .. OQCU1 =e= SUM(I,qcu1(I));
OAQHU1 .. OQHU1 =e= SUM(J,qhu1(J));
OAQCU2 .. OQCU2 =e= SUM(I,qcu2(I));
OAQHU2 .. OQHU2 =e= SUM(J,qhu2(J));


OBJFN2 .. O2 =e= OCosthu1+OCostcu1
+sum((i,j,k),z1(i,j,k)*(HF1+HF2)*WY);
*+sum(i,zcu1(i)*(HF1+HF2))+sum(j,zhu1(j)*(HF1+HF2));
OBJFN22 .. O22 =e= Costh1+Costhu1+OCosthu1+Costcu1+OCostcu1;
OBJFN3 .. O3 =e= OCosthu2+OCostcu2
+sum((i,j,k),z2(i,j,k)*(HF1+HF2)*WY);
*+sum(i,zcu2(i)*(HF1+HF2))+sum(j,zhu2(j)*(HF1+HF2));
OBJFN32 .. O32 =e= Costh2+Costhu2+OCosthu2+Costcu2+OCostcu2;
Total1 .. TAC1 =e= FCost2+PICost2+PIC11 ;
Total2 .. TAC2 =e= FCost2+PICost2+PIC11+O22+O32;
```

```
TotalA .. AREA =e= Atot1+Atot2;

UTILITY .. O4 =e= O2+O3;
********************************WN initial************************************
Model INITIAL1 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,OBJFN11/;
Solve INITIAL1 using MIP minimizing O11;
Display FCost.l,OFW.l,OWW.l,FFW.l,yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;

Parameter
xin(i,j)
FFWin(j)
WWin(i)
yin(i,j)
yFWin(j)
yWWin(i)
;
xin(i,j) = x.l(i,j);
FFWin(j) = FFW.l(j);
WWin(i) = WW.l(i);
yin(i,j) = y.l(i,j);
yFWin(j) = yFW.l(j);
yWWin(i) = yWW.l(i);

x.l(i,j) = xin(i,j);
FFW.l(j) = FFWin(j);
WW.l(i) = WWin(i);
y.l(i,j) = yin(i,j);
yFW.l(j) = yFWin(j);
yWW.l(i) = yWWin(i);

Model INITIAL2 /MB1,MB2,Cons1,Cons2,Fresh,Logical1,Logical2,Logical3,
Waste,Allwaste,Flow,TempK,FRESHC,PIP1,PIP2,PIP3,PIPC,OBJFN12/;
Solve INITIAL2 using MINLP minimizing O12;
Display PIC1.l,PIC2.l,PIC3.l,PICost.l,FCost.l,OFW.l,OWW.l,FFW.l,
yFW.l,WW.l,yWW.l,x.l,F.l,y.l,CK.l,TK.l;
*******************************************************************************


F1.fx(i,j)=0;F2.fx(i,j)=0;
F1.fx('i3','j1')=F.l('i3','j1');
F1.fx('i3','j5')=F.l('i3','j5');
F1.fx('i4','j1')=F.l('i4','j1');
F2.fx('i4','j3')=F.l('i4','j3');
F2.fx('i4','j4')=F.l('i4','j4');

F1.fx('i5','j3')=F.l('i5','j3');
F1.fx('i5','j2')=F.l('i5','j2');

WW2.fx(i) = WW.l(i);
FFW2.fx(j) = FFW.l(j);
```

```
*OBJWN1.lo = 4;
*OBJWN2.lo = 4;
*CK2.l(j) = CKL1(j);
*TS2.fx(i) = TS(i);
TOUTC2.fx('j1') = 70;TOUTC2.fx('j3') = 70;TOUTC2.fx('j5') = 70;
TOUTC2.fx('j2') = 70;TOUTC2.fx('j4') = 70;
*TOUTC2.lo(j) = 60;
*TK1.up(j) = 100;

Model MIXING1 /MB1_1,MB2_1,Cons1_1,Cons2_1,Waste_1,Allwaste_1,Flow_1,
TempK_1,PIP1_1,Logical1_1,
Link12_2,
MB1_2,MB2_2,Cons1_2,Cons2_2,
Fresh_2,Waste_2,Allwaste_2,Flow_2,
Logical1_2,Logical2_2,Logical3_2,
TempK_2,FRESHC_2,PIP1_2,PIP2_2,PIP3_2,PIPC_2,
Total1/;

Solve MIXING1 using MINLP minimizing TAC1;
Display x1.l,F1.l,WW1.l,OWW1.l,FS2.l,x2.l,F2.l,FFW2.l,WW2.l,OWW2.l,CK1.l,TK1.l,FK2.l,
TK2.l,CK2.l,Fcost2.l,TAC1.l;




parameter
x1in(i,j)
WW1in(i)
x2in(i,j)
TK1in(j);
;
x1in(i,j) =  x1.l(i,j);
WW1in(i) =  WW1.l(i);
x2in(i,j) = x2.l(i,j);
TK1in(j) = TK1.l(j);

*x1.fx(i,j) =  x1in(i,j);
WW1.fx(i) =  WW1in(i);
*x2.fx(i,j) = x2in(i,j);
TK1.fx(j) = TK1in(j);
*TOUTH1.l(i) = TOUTHIP(i);
*q1.fx('i4','j1','location4')=16.188;

Model WHEN1
/
abc_1,OHB_H_1,OHB_C_1,SHB_H_1,SHB_C_1,TINHASSGN_1,TINCASSGN_1,FH1_1,FH2_1,FC1_1,FC2_1,
HULOAD_1,CULOAD_1,HECOUNT1_1,HECOUNT2_1,HECOUNT3_1,
APPTEMPL_1,APPTEMPR_1,APPTEMPCU_1,APPTEMPHU_1,
APPTEMPLIMIT_1,APPTEMPLIMITCU_1,APPTEMPLIMITHU_1,
```

```
HUOCOST_1,CUOCOST_1,
OAQCU1,OAQHU1,OBJFN2 /

Solve WHEN1 using MINLP minimizing O2;
display F1.l,FFW2.l,q1.l,z1.l,qhu1.l,zhu1.l,qcu1.l,zcu1.l,OCosthu1.l,
OCostcu1.l,
TS2.l,TK1.l,TOUTC.tH1.l,tC1.l.TOUTH1.l,FK2.l,WW2.l,x2.l,FFW2.l;


Parameter
q1in(i,j,k)
qcu1in(i)
qhu1in(j)
TH1in(i,k)
TC1in(j,k)
z1in(i,j,k)
zcu1in(i)
zhu1in(j)
;
q1in(i,j,k) = q1.l(i,j.k);
qcu1in(i) = qcu1.l(i);
qhu1in(j) = qhu1.l(j);
TH1in(i,k) = TH1.l(i,k);
TC1in(j.k) = TC1.l(j,k);
z1in(i,j,k) = z1.l(i,j,k);
zcu1in(i) = zcu1.l(i);
zhu1in(j) = zhu1.l(j);

q1.fx(i,j,k) = q1in(i,j,k);
qcu1.fx(i) = qcu1in(i) ;
qhu1.fx(j) = qhu1in(j);
TH1.fx(i.k) = TH1in(i.k);
TC1.fx(j,k) = TC1in(j,k);
z1.fx(i,j,k) = z1in(i,j.k);
zcu1.fx(i) = zcu1in(i);
*z1.fx('i3','j1','location3')=0;
*z1.fx('i3','j5','location3')=0;
*z1.fx('i3','j5','location2')=0;
zhu1.fx(j) = zhu1in(j);
zhu1.fx('j1') = 0;zhu1.fx('j3') = 0;zhu1.fx('j4') = 0;zhu1.fx('j5') = 0;
zcu1.fx(i) = 0;

LMTD1.l(i,j,k) = (((dt1.l(i,j,K)*dt1.l(i,j,K+1))*(dt1.l(i,j,K)+dt1.l(i,j,K+1))/2))**(1/3);
LMTDhu1.l(j) = ((((TOUTHU-tC1.l(J,'firstlocation'))*(TINHU-TOUTC(J)))*((TOUTHU-
tC1.l(J,'firstlocation'))+(TINHU-TOUTC(J)))/2))**(1/3);
A1.l(i,j,k) = q1in(i,j,k)/(U*LMTD1.l(i,j,k)+0.001);
Ahu1.l(j) = qhu1in(j)/(U*LMTDhu1.l(j)+0.001);

Model WHEN1A
/Link1_1,Link2_1,Link3_1,Link4_1.
abc_1,OHB_H_1,OHB_C_1.SHB_H_1.SHB_C_1,TINHASSGN_1,TINCASSGN_1,FH1_1.FH2_1,FC1_1,FC2_1,
```

```
HULOAD_1,CULOAD_1,HECOUNT1_1,HECOUNT2_1,HECOUNT3_1,
APPTEMPL_1,APPTEMPR_1,APPTEMPCU_1,APPTEMPHU_1,
APPTEMPLIMIT_1,APPTEMPLIMITCU_1,APPTEMPLIMITHU_1,
HUOCOST_1,LOGMH_1.LOGMHU_1.HAREA_1,HUAREA_1,TOTAREA_1,
HACOST_1,HUACOST_1,
OAQCU1,OAQHU1,OBJFN2,OBJFN22 /

Solve WHEN1A using MINLP minimizing O22;
display q1.l,z1.l,qhu1.l,zhu1.l,qcu1.l,zcu1.l,OQHU1.l,OQCU1.l,A1.l,AHU1.l,
Costh1.l,Costhu1.l,OCosthu1.l,TOUTH1.l,
O22.l,O2.l,
tH1.l,tC1.l,TK1.l,TOUTC2.l,TS,F1.l,FK2.l,TK1.l,FKL;



Parameter
TS2in2(i)
x2in2(i,j)
FFW2in2(j)
WW1in2(i)
FK2in2(j)
CK2in2(j)
;
TS2in2(i) = TOUTH1.l(i);
x2in2(i,j) = x2.l(i,j);
FFW2in2(j) = FFW2.l(j);
WW1in2(i) = WW1.l(i);
FK2in2(j) = FK2.l(j);
CK2in2(j) = CK2.l(j);

TS2.fx(i) = TS2in2(i);
x2.fx(i,j) = x2in2(i,j);
FFW2.fx(j) = FFW2in2(j);
WW1.fx(i) = WW1in2(i);
FK2.fx(j) = FK2in2(j);
*CK2.l(j)= CK2in2(j);

Model MIX2
/
Link12_1,Link12_2,
MB1_2,MB2_2,Cons1_2,Fresh_2,Waste_2,Allwaste_2,Flow_2,
*Logical1_2,Logical2_2,Logical3_2,
TempK_2,FRESHC_2,OBJECTWN2 /
Solve MIX2 using NLP minimize Fcost2;
display TS2.l,F2.l,FFW2.l,TS2.l,TK1.l,TK2.l;


Parameter
TK2in(j)
WW2in(i)
TOUTC2in(j);
```

```
TK2in(j) = TK2.l(j);
WW2in(i) = WW2.l(i);
TOUTC2in(j) = TOUTC2.l(j);

TK2.fx(j) = TK2in(j);
WW2.fx(i) = WW2in(i);

TOUTC2.fx(j) =  TOUTC2in(j);

Model WHEN2
/
Link1_2,Link2_2,Link3_2,Link4_2,
abc_2,OHB_H_2,OHB_C_2,SHB_H_2,SHB_C_2,TINHASSGN_2,TINCASSGN_2,
FH1_2,FH2_2,FC1_2,FC2_2,
HULOAD_2,CULOAD_2,HECOUNT1_2,HECOUNT2_2,HECOUNT3_2,
APPTEMPL_2,APPTEMPR_2,APPTEMPCU_2,APPTEMPHU_2,
APPTEMPLIMIT_2,APPTEMPLIMITCU_2,APPTEMPLIMITHU_2,
HUOCOST_2,CUOCOST_2,OAQCU2,OAQHU2,OBJFN3,OBJFN2,UTILITY   /

Solve WHEN2 using MINLP minimize O3;
display q2.l,z2.l,qhu2.l,zhu2.l,qcu2.l,zcu2.l,
OQHU2.l,OQCU2.l,tH2.l,tC2.l,TS2.l,F2.l,FFW2.l,TK2.l,TS2.l,TOUTC2.l,
O3.l,OCosthu2.l,OCostcu2.l;
Parameter
q2in(i,j,k)
qcu2in(i)
qhu2in(j)
TH2in(i,k)
TC2in(j,k)
z2in(i,j,k)
zcu2in(i)
zhu2in(j)
;
q2in(i,j,k) = q2.l(i,j,k);
qcu2in(i) = qcu2.l(i);
qhu2in(j) = qhu2.l(j);
TH2in(i,k) = TH2.l(i,k);
TC2in(j,k) = TC2.l(j,k);
z2in(i,j,k) = z2.l(i,j,k);
zcu2in(i) = zcu2.l(i);
zhu2in(j) = zhu2.l(j);

q2.fx(i,j,k) = q2in(i,j,k);
qcu2.fx(i) = qcu2in(i) ;
qhu2.fx(j) = qhu2in(j);
TH2.fx(i,k) = TH2in(i,k);
TC2.fx(j,k) = TC2in(j,k);
z2.fx(i,j,k) = z2in(i,j,k);
zcu2.fx(i) = zcu2in(i);
;
zhu2.fx(j)=0;
```

```
LMTD2.l(i,j,k) = (((dt2.l(i,j,K)*dt2.l(i,j,K+1))*(dt2.l(i,j,K)+dt2.l(i,j,K+1))/2))**(1/3);
LMTDhu2.l(j) = ((((TOUTHU-tC2.l(J,'firstlocation'))*(TINHU-TOUTC2.l(J)))*((TOUTHU-
tC2.l(J,'firstlocation'))+(TINHU-TOUTC2.l(J)))/2))**(1/3);
A2.l(i,j,k) = q2in(i,j,k)/(U*LMTD2.l(i,j,k)+0.001);
Ahu2.l(j) = qhu2in(j)/(U*LMTDhu2.l(j)+0.001);


Model WHEN2A
/
abc_2,OHB_H_2,OHB_C_2,SHB_H_2,SHB_C_2,TINHASSGN_2,TINCASSGN_2,FH1_2,FH2_2,FC1_2,FC2_2,
HULOAD_2,CULOAD_2,HECOUNT1_2.HECOUNT2_2,HECOUNT3_2,HUOCOST_1
APPTEMPL_2,APPTEMPR_2,APPTEMPCU_2,APPTEMPHU_2,
APPTEMPLIMIT_2.APPTEMPLIMITCU_2,APPTEMPLIMITHU_2,
HUOCOST_2,CUOCOST_2.LOGMH_2,LOGMHU_2,LOGMCU_2,HAREA_2,HUAREA_2,CUAREA_2,
HACOST_2,HUACOST_2,CUACOST_2,
OAQCU2,OAQHU2,OBJFN32,Total2.TOTAREA_1,TOTAREA_2,TotalA /

Solve WHEN2A using MINLP minimizing O32;
display q1.l,z1.l,qhu1.l.zhu1.l.qcu1.l,zcu1.l.OQHU1.l,OQCU1.l,A1.l,AHU1.l,
tH1.l,tC1.l,WW1.l,TK1.l,TOUTC,
q2.l,z2.l,qhu2.l,zhu2.l.qcu2.l,zcu2.l,OQHU2.l.OQCU2.l.A2.l,ACU2.l.AHU2.l,
Costh1.l,Costhu1.l,OCosthu1.l,O32.l.Costh2.l,Costhu2.l,OCosthu2.l,Costcu2.l,OCostcu2.l,O22.l,O32.l,Fcost2.l,PIC11
.l,
PICost2.l,tH2.l,tC2.l,ww2.l.FFW2.l.F2.l.TK2.l,TOUTC2.l,O3.l,O32.l,Atot1.l,Atot2.l,AREA.l,TAC2.l,
TS,FS2.l,F1.l,TK2.l.FK2.l.TK1.l,FKL;
```

# APPENDIX B

## APPENDIX B-1 : Case Study 1.1 GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 11 SINGLE EQUATIONS 59

BLOCKS OF VARIABLES 10 SINGLE VARIABLES 67

NON ZERO ELEMENTS 185 DISCRETE VARIABLES 20

GENERATION TIME = 0.062 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.062 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 01/23/14 11:18:48 Page 5

General Algebraic Modeling System

Solution Report SOLVE CASE11 Using MIP From line 71

SOLVE SUMMARY

MODEL CASE11 OBJECTIVE OBJ

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 71

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 210.0000

RESOURCE USAGE, LIMIT 0.516 1000.000

ITERATION COUNT, LIMIT 13 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(102): integer optimal, tolerance

Cplex Time: 0.31sec (det. 0.46 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.05 ticks)

Solution satisfies tolerances.

MIP Solution: 210.000000 (13 iterations, 0 nodes)

Final Solve: 210.000000 (0 iterations)

Best possible: 193.000000

Absolute gap: 17.000000

Relative gap: 0.080952

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 01/23/14 11:18:48 Page 6

General Algebraic Modeling System

Execution

---- 72 VARIABLE OBJ.L = 210.000 Objective function

VARIABLE OFW.L = 70.000 Overall freshwater

VARIABLE OWW.L = 50.000 Overall wast

---- 72 VARIABLE FW.L Freshwater flowrate

j1 30.000, j2 40.000

---- 72 VARIABLE WW.L Waste of each source

i3 25.000, i4 25.000

---- 72 VARIABLE x.L Source split fraction i to j

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | 0.400 | 0.600 | | |
| i2 | | 0.200 | 0.800 | |
| i3 | | 0.143 | | 0.500 |
| i4 | | | | 0.583 |

---- 72 VARIABLE F.L Splitting Flowrate i to j

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | 20.000 | 30.000 | | |
| i2 | | 20.000 | 80.000 | |
| i3 | | 10.000 | | 35.000 |
| i4 | | | | 35.00 |

---- 72 VARIABLE y.L

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | 1.000 | 1.000 | | |
| i2 | | 1.000 | 1.000 | |
| i3 | | 1.000 | | 1.000 |
| i4 | | | | 1.000 |

---- 72 VARIABLE z.L

j1 1.000, j2 1.000

---- 72 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 50.000, j3 100.000, j4 200.000

EXECUTION TIME = 0.000 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

USER: The Petroleum and Petrochemical College G131219:2228AS-WIN

Chulalongkorn University DC4365

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**** FILE SUMMARY

Input C:\Users\Sarut\Desktop\Thesis water network\GAMS 24.2\case1withLogic.gms

Output C:\Users\Sarut\Documents\gamsdir\projdir\case1withLogic.lst

## APPENDIX B-2 : Case Study 1.1a GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 15 SINGLE EQUATIONS 66

BLOCKS OF VARIABLES 14 SINGLE VARIABLES 74

NON ZERO ELEMENTS 203 DISCRETE VARIABLES 24

GENERATION TIME = 0.032 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.032 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:15:23 Page 5

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

Solution Report SOLVE CASE11 Using MIP From line 83

S O L V E S U M M A R Y

MODEL CASE11 OBJECTIVE OBJ

TYPE MIP DIRECTION MINIMIZE

```
   SOLVER  CPLEX            FROM LINE  83
**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE            5810.0000
 RESOURCE USAGE, LIMIT          0.219      1000.000
 ITERATION COUNT, LIMIT         15    2000000000
IBM ILOG CPLEX   24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
Cplex 12.6.0.0
Space for names approximately 0.00 Mb
Use option 'names no' to turn use of names off
MIP status(102): integer optimal, tolerance
Cplex Time: 0.14sec (det. 0.53 ticks)
Fixing integer variables, and solving final LP...
Fixed MIP status(1): optimal
Cplex Time: 0.00sec (det. 0.06 ticks)
Solution satisfies tolerances.

MIP Solution:        5810.000000    (15 iterations, 0 nodes)
Final Solve:         5810.000000    (0 iterations)
Best possible:       5786.571389
Absolute gap:          23.428611
Relative gap:           0.004032
**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:15:23 Page 6
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n
----     84 VARIABLE OBJ.L              =     5810.000  Objective function
            VARIABLE OFW.L              =       70.000  Overall freshwater
            VARIABLE OWW.L              =       50.000  Overall waste
            VARIABLE OFWC.L             =      700.000  Overall freshwater cost
```

VARIABLE OWWC.L = 5000.000 Overall waste cost

VARIABLE OPC.L = 110.000

---- 84 VARIABLE FW.L Freshwater flowrate

j1 30.000, j2 40.000

---- 84 VARIABLE WW.L Waste of each source

i3 25.000, i4 25.000

---- 84 VARIABLE x.L Source split fraction i to j

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | 0.400 | 0.600 | | |
| i2 | | 0.200 | 0.800 | |
| i3 | | 0.143 | | 0.500 |
| i4 | | | | 0.583 |

---- 84 VARIABLE F.L Splitting Flowrate i to j

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | 20.000 | 30.000 | | |
| i2 | | 20.000 | 80.000 | |
| i3 | | 10.000 | | 35.000 |
| i4 | | | | 35.000 |

---- 84 VARIABLE y.L

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | 1.000 | 1.000 | | |
| i2 | | 1.000 | 1.000 | |
| i3 | | 1.000 | | 1.000 |
| i4 | | | | 1.000 |

---- 84 VARIABLE z.L

j1 1.000, j2 1.000

---- 84 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 50.000, j3 100.000, j4 200.000

## APPENDIX B-3 : Case Study 1.1b GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 15 SINGLE EQUATIONS 66

BLOCKS OF VARIABLES 14 SINGLE VARIABLES 74

NON ZERO ELEMENTS 203 DISCRETE VARIABLES 24

GENERATION TIME = 0.015 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.015 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:18:24 Page 5

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

Solution Report SOLVE CASE11b Using MIP From line 83

S O L V E S U M M A R Y

MODEL CASE11b OBJECTIVE OBJ

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 83

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 5753.3333

RESOURCE USAGE, LIMIT 0.141 1000.000

ITERATION COUNT, LIMIT 57 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(102): integer optimal, tolerance

Cplex Time: 0.08sec (det. 1.39 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.06sec (det. 0.06 ticks)

Solution satisfies tolerances.

MIP Solution: 5753.333333 (57 iterations, 0 nodes)

Final Solve: 5753.333333 (0 iterations)

Best possible: 5259.357630

Absolute gap: 493.975703

Relative gap: 0.085859

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:18:24 Page 6

General Algebraic Modeling System

Execution

---- 84 VARIABLE OBJ.L = 5753.333 Objective function

VARIABLE OFW.L = 86.667 Overall freshwater

VARIABLE OWW.L = 66.667 Overall waste

VARIABLE OFWC.L = 86.667 Overall freshwater cost

VARIABLE OWWC.L = 666.667 Overall waste cost

VARIABLE OPC.L = 5000.000

---- 84 VARIABLE FW.L Freshwater flowrate

j1 46.000, j2 26.667, j4 14.000

---- 84 VARIABLE WW.L Waste of each source

i3 66.667

---- 84 VARIABLE x.L Source split fraction i to j

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | | 1.000 | | |
| i2 | | 0.200 | 0.800 | |
| i3 | | 0.048 | | |
| i4 | 0.067 | | | 0.933 |

---- 84 VARIABLE F.L Splitting Flowrate i to j

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | | 50.000 | | |
| i2 | | 20.000 | 80.000 | |
| i3 | | 3.333 | | |
| i4 | 4.000 | | | 56.000 |

---- 84 VARIABLE y.L

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | | 1.000 | | |
| i2 | | 1.000 | 1.000 | |
| i3 | | 1.000 | | |
| i4 | 1.000 | | | 1.000 |

---- 84 VARIABLE z.L

j1 1.000, j2 1.000, j4 1.000

---- 84 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 50.000, j3 100.000, j4 200.000

## APPENDIX B-4 : Case Study 1.1c GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 15 SINGLE EQUATIONS 76

BLOCKS OF VARIABLES 14 SINGLE VARIABLES 92

NON ZERO ELEMENTS 254 DISCRETE VARIABLES 32

GENERATION TIME = 0.046 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.046 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:21:30 Page 5

General Algebraic Modeling System

Solution Report SOLVE CASE11c Using MIP From line 91

S O L V E S U M M A R Y

MODEL CASE11c OBJECTIVE OBJ

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 91

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 10287.5000

RESOURCE USAGE, LIMIT 0.063 1000.000

ITERATION COUNT, LIMIT 14 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(102): integer optimal, tolerance

Cplex Time: 0.05sec (det. 0.69 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.07 ticks)

Solution satisfies tolerances.

MIP Solution: 10287.500000 (14 iterations, 0 nodes)

Final Solve: 10287.500000 (0 iterations)

Best possible: 10248.616071

Absolute gap: 38.883929

Relative gap: 0.003780

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:21:30 Page 6

General Algebraic Modeling System

Execution

---- 92 VARIABLE OBJ.L = 10287.500 Objective function

---- 92 VARIABLE OFW.L Overall freshwater

r2 81.250

---- 92 VARIABLE OWW.L = 61.250 Overall waste

VARIABLE OFWC.L = 4062.500 Overall freshwater cost

VARIABLE OWWC.L = 6125.000 Overall waste cost

VARIABLE OPC.L = 100.000

---- 92 VARIABLE FW.L Freshwater flowrate

| | j1 | j2 |
|---|---|---|
| r2 | 50.000 | 31.250 |

---- 92 VARIABLE WW.L Waste of each source

i3 36.875, i4 24.375

---- 92 VARIABLE x.L Source split fraction i to j

| | j2 | j3 | j4 |
|---|---|---|---|
| i1 | 1.000 | | |
| i2 | 0.187 | 0.800 | 0.013 |
| i3 | | | 0.473 |
| i4 | | | 0.594 |

---- 92 VARIABLE F.L Splitting Flowrate i to j

| | j2 | j3 | j4 |
|---|---|---|---|
| i1 | 50.000 | | |
| i2 | 18.750 | 80.000 | 1.250 |
| i3 | | | 33.125 |
| i4 | | | 35.625 |

---- 92 VARIABLE y.L

| | j2 | j3 | j4 |
|---|---|---|---|
| i1 | 1.000 | | |
| i2 | 1.000 | 1.000 | 1.000 |
| i3 | | | 1.000 |
| i4 | | | 1.000 |

---- 92 VARIABLE z.L

| | j1 | j2 |
|---|---|---|
| r2 | 1.000 | 1.000 |

---- 92 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 50.000, j3 100.000, j4 200.000

## APPENDIX B-5 : Case Study 1.2 GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 15 SINGLE EQUATIONS 91

BLOCKS OF VARIABLES 14 SINGLE VARIABLES 106

NON ZERO ELEMENTS 296 DISCRETE VARIABLES 35

GENERATION TIME = 0.031 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.031 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:24:02 Page 5

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

Solution Report SOLVE CASE12 Using MIP From line 86

S O L V E S U M M A R Y

MODEL CASE12 OBJECTIVE OBJ

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 86

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 11.0000

RESOURCE USAGE, LIMIT 0.390 1000.000

ITERATION COUNT, LIMIT 82 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(102): integer optimal, tolerance

Cplex Time: 0.36sec (det. 2.57 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.09 ticks)

Solution satisfies tolerances.

MIP Solution: 11.000000 (81 iterations, 4 nodes)

Final Solve: 11.000000 (1 iterations)

Best possible: 10.000000

Absolute gap: 1.000000

Relative gap: 0.090909

```
**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
GAMS 24.2.1 r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:24:02 Page 6
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n

----     87 VARIABLE OBJ.L               =       11.000  Objective function
            VARIABLE OFW.L               =        0.000  Overall freshwater
            VARIABLE OWW.L               =        0.000  Overall waste
            VARIABLE OFWC.L              =        0.000  Overall freshwater cost
            VARIABLE OWWC.L              =        0.000  Overall waste cost
            VARIABLE OPC.L               =       11.000

----     87 VARIABLE FW.L  Freshwater flowrate

                  ( ALL       0.000 )

----     87 VARIABLE WW.L  Waste of each source

                  ( ALL       0.000 )

----     87 VARIABLE x.L  Source split fraction i to j

             j1          j2          j3          j4          j5

i1        1.000
i2        0.111       0.444                   0.409       0.035
i3                    0.974       0.026
i4                    0.359                   0.641
i5                                0.908       0.092
```

---- 87 VARIABLE F.L Splitting Flowrate i to j

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 9.000 | | | | |
| i2 | 1.000 | 4.000 | | 3.683 | 0.317 |
| i3 | | | 8.770 | 0.230 | |
| i4 | | | 3.230 | | 5.770 |
| i5 | | | | 4.087 | 0.413 |

---- 87 VARIABLE y.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 1.000 | | | | |
| i2 | 1.000 | 1.000 | | 1.000 | 1.000 |
| i3 | | | 1.000 | 1.000 | |
| i4 | | | 1.000 | | 1.000 |
| i5 | | | | 1.000 | 1.000 |

---- 87 VARIABLE z.L

( ALL 0.000 )

---- 87 VARIABLE CK.L Sink stream concentration

j1 127.800, j2 108.000, j3 63.002, j4 62.975, j5 45.720

## APPENDIX B-6 : Case Study 1.3 GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 15 SINGLE EQUATIONS 91

BLOCKS OF VARIABLES 14 SINGLE VARIABLES 106

NON ZERO ELEMENTS 296 DISCRETE VARIABLES 35

GENERATION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:26:29 Page 5

General Algebraic Modeling System

Solution Report SOLVE CASE11 Using MIP From line 86

SOLVE SUMMARY

MODEL CASE11 OBJECTIVE OBJ

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 86

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 60.0000

RESOURCE USAGE, LIMIT 0.078 1000.000

ITERATION COUNT, LIMIT 21 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(102): integer optimal, tolerance

Cplex Time: 0.06sec (det. 0.55 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.08 ticks)

Solution satisfies tolerances.

MIP Solution: 60.000000 (21 iterations, 0 nodes)

Final Solve: 60.000000 (0 iterations)

Best possible: 57.545765

Absolute gap: 2.454235

Relative gap: 0.040904

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:26:29 Page 6

General Algebraic Modeling System

Execution

---- 87 VARIABLE OBJ.L = 60.000 Objective function

VARIABLE OFW.L = 22.500 Overall freshwater

VARIABLE OWW.L = 22.500 Overall waste

VARIABLE OFWC.L = 22.500 Overall freshwater cost

VARIABLE OWWC.L = 22.500 Overall waste cost

VARIABLE OPC.L = 15.000

---- 87 VARIABLE FW.L Freshwater flowrate

j1 5.826, j2 0.364, j3 6.545, j4 5.714, j5 4.051

---- 87 VARIABLE WW.L Waste of each source

i1 9.000, i2 9.000, i3 4.500

---- 87 VARIABLE x.L Source split fraction i to j

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 0.070 | | | 0.254 | 0.176 |
| i4 | 0.394 | | 0.606 | | |
| i5 | | 0.808 | | | 0.192 |

---- 87 VARIABLE F.L Splitting Flowrate i to j

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 0.629 | | | 2.286 | 1.586 |
| i4 | 3.545 | | 5.455 | | |
| i5 | | 3.636 | | | 0.864 |

---- 87 VARIABLE y.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 1.000 | | | 1.000 | 1.000 |
| i4 | 1.000 | | 1.000 | | |
| i5 | | 1.000 | | | 1.000 |

---- 87 VARIABLE z.L

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 87 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

## APPENDIX B-7 : Case Study 2 before regenerationGAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 11 SINGLE EQUATIONS 83

BLOCKS OF VARIABLES 10 SINGLE VARIABLES 97 3 projected

NON ZERO ELEMENTS 271 DISCRETE VARIABLES 30

GENERATION TIME = 0.015 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.015 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/03/14 16:36:40 Page 5

General Algebraic Modeling System

Solution Report SOLVE CASE2 Using MIP From line 80

SOLVE SUMMARY

MODEL CASE2 OBJECTIVE OBJ

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 80

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 1 Optimal

**** OBJECTIVE VALUE 2896.8730

RESOURCE USAGE, LIMIT 0.031 1000.000

ITERATION COUNT, LIMIT 1 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(101): integer optimal solution

Cplex Time: 0.01sec (det 0.20 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.02sec (det. 0.07 ticks)

Proven optimal solution

MIP Solution: 2896.873043 (1 iterations, 0 nodes)

Final Solve: 2896.873043 (0 iterations)

Best possible: 2896.873043

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/03/14 16:36:40 Page 6

General Algebraic Modeling System

Execution

---- 81 VARIABLE OBJ.L = 2896.873 Objective function

VARIABLE OFW.L = 852.817 Overall freshwater

VARIABLE OWW.L = 544.057 Overall waste

---- 81 VARIABLE FW.L Freshwater flowrate

j1 141.887, j2 542.035, j3 114.083, j4 9.490, j5 31.664 j6 13.657

---- 81 VARIABLE WW.L Waste of each source

i2 128.257, i4 415.800

---- 81 VARIABLE x.L Source split fraction i to j

| | j1 | j2 | j3 | j4 | j5 | j6 |
|---|---|---|---|---|---|---|
| i1 | | | | 1.000 | | |
| i2 | 0.010 | 0.221 | 0.067 | 0.600 | 0.002 | 7.991226E-4 |
| i3 | | | | 1.000 | | |
| i4 | | | | | | 0.115 |

---- 81 VARIABLE F.L Splitting Flowrate i to j

| | j1 | j2 | j3 | j4 | j5 | j6 |
|---|---|---|---|---|---|---|
| i1 | | | | 155.400 | | |
| i2 | 13.513 | 289.085 | 87.757 | 783.110 | 3.016 | 1.043 |
| i3 | | | | 201.840 | | |
| i4 | | | | | | 54.000 |

---- 81 VARIABLE y.L

| | j1 | j2 | j3 | j4 | j5 | j6 |
|---|---|---|---|---|---|---|
| i1 | | | | 1.000 | | |
| i2 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i3 | | | | 1.000 | | |
| i4 | | | | | | 1.000 |

---- 81 VARIABLE z.L

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000, j6 1.000

---- 81 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 80.000, j3 100.000, j4 200.000, j5 20.000 j6 200.000

## APPENDIX B-8 : Case Study 2 with regeneration GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 22 SINGLE EQUATIONS 94

BLOCKS OF VARIABLES 20 SINGLE VARIABLES 112 3 projected

NON ZERO ELEMENTS 308 NON LINEAR N-Z 43

DERIVATIVE POOL 10 CONSTANT POOL 17

CODE LENGTH 96

GENERATION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/03/14 16:33:23 Page 5

General Algebraic Modeling System

```
Solution Report   SOLVE CASE2 Using NLP From line 116

      S O L V E    S U M M A R Y

  MODEL  CASE2          OBJECTIVE  OBJ

  TYPE   NLP           DIRECTION  MAXIMIZE

  SOLVER  CONOPT          FROM LINE  116

**** SOLVER STATUS     1 Normal Completion

**** MODEL STATUS     2 Locally Optimal

**** OBJECTIVE VALUE        3386108.9076

 RESOURCE USAGE, LIMIT         0.016     1000.000

 ITERATION COUNT, LIMIT       28    2000000000

 EVALUATION ERRORS            0          0

CONOPT 3       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows

  C O N O P T 3   version 3.15M

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            Bagsvaerdvej 246 A

            DK-2880 Bagsvaerd, Denmark


  The model has 112 variables and 94 constraints

  with 308 Jacobian elements, 43 of which are nonlinear.

  The Hessian of the Lagrangian has 0 elements on the diagonal,

  12 elements below the diagonal, and 19 nonlinear variables.

 ** Warning **  The variance of the derivatives in the initial

          point is large (= 4.8 ). A better initial

          point, a better scaling, or better bounds on the

          variables will probably help the optimization.

 ** Optimal solution. There are no superbasic variables.

**** REPORT SUMMARY :        0     NONOPT

                  0 INFEASIBLE

                  0  UNBOUNDED

                  0     ERRORS
```

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/03/14 16:33:23 Page 6

G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m

E x e c u t i o n

---- 117 VARIABLE OBJ.L = 3386108.908 Objective

VARIABLE INV.L = 3909942.454 Total investment cost ($)

VARIABLE INC.L = 4138829.232 Initial operating Cost ($ per year)

VARIABLE OptCost.L = 752720.324 New operating Cost ($ per year)

VARIABLE Save.L = 3386108.908 Saving Cost ($ per year)

VARIABLE FR.L = 620.265 Regeneration Flowrate (ton per h)

VARIABLE OFW.L = 308.760 Overall Freshwater (ton per h)

---- 117 VARIABLE FW.L Freshwater flowrate (ton per h)

j1 141.887, j2 126.248, j5 31.664, j6 8.961

---- 117 VARIABLE WW.L Waste flowrate of each source (ton per h)

i2 150.465, i4 469.800

---- 117 VARIABLE TW.L = 0.000 Waste to treat flowrate (ton per h)

VARIABLE Rarea.L = 1120.819 Area of Regeneration unit (m3)

---- 117 VARIABLE x.L Spliting fraction

| | j1 | j2 | j3 | j4 | j5 | j6 |
|---|---|---|---|---|---|---|
| i1 | | | | 1.000 | | |
| i2 | 0.010 | 0.174 | 0.054 | 0.599 | 0.002 | 0.046 |
| i3 | | | | 1.000 | | |

---- 117 VARIABLE Fx.L Splitting Flowrate (ton per h)

| | j1 | j2 | j3 | j4 | j5 | j6 |
|---|---|---|---|---|---|---|
| i1 | | | | 155.400 | | |
| i2 | 13.513 | 226.717 | 70.644 | 781.686 | 3.016 | 59.739 |
| i3 | | | | 201.840 | | |

---- 117 VARIABLE Fy.L Regeneration Splitting Flowrate (ton per h) j2 478.155, j3 131.196, j4 10.914

---- 117 VARIABLE CK2.L Sink stream concentration after Regeneration (ppm)

j1 20.000, j2 80.000, j3 100.000, j4 200.000, j5 20.000 j6 200.000

EXECUTION TIME = 0.000 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

USER: The Petroleum and Petrochemical College G131219:2228AS-WIN

Chulalongkorn University DC4365

License for teaching and research at degree granting institutions

## APPENDIX B-9 : Case Study 3.1 GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 9 SINGLE EQUATIONS 17

BLOCKS OF VARIABLES 8 SINGLE VARIABLES 19

NON ZERO ELEMENTS 48

GENERATION TIME = 0.000 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.000 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/03/14 20:10:13 Page 5

General Algebraic Modeling System

Solution Report SOLVE CASE31CAL1 Using LP From line 588

SOLVE SUMMARY

MODEL CASE31CAL1 OBJECTIVE OBJ1

TYPE LP DIRECTION MINIMIZE

SOLVER CONOPT FROM LINE 588

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 1 Optimal

**** OBJECTIVE VALUE 32774.7368

RESOURCE USAGE, LIMIT 0.000 1000.000

ITERATION COUNT, LIMIT 4 2000000000

CONOPT 3 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

C O N O P T 3 version 3.15M



** Optimal solution. There are no superbasic variables.

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/03/14 20:10:13 Page 6

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

E x e c u t i o n

---- 589 VARIABLE OBJ1.L = 32774 737

---- 589 VARIABLE x.L Split fraction source to sink

| | j1 | j2 |
|---|---|---|
| i2 | 0.462 | 0.295 |

---- 589 VARIABLE FR.L Freshwater flowrate (kg per h)

| | j1 | j2 |
|---|---|---|
| r2 | 1473.684 | 1452.632 |

---- 589 VARIABLE y1.L Split fraction source to treat for model 1

i1 1.000, i2 0.243

---- 589 VARIABLE xF.L Split Flowrate source to sink (kg per h)

| | j1 | j2 |
|---|---|---|
| i2 | 1326.316 | 847.368 |

MODEL STATISTICS

| | | | |
|---|---|---|---|
| BLOCKS OF EQUATIONS | 45 | SINGLE EQUATIONS | 89 |
| BLOCKS OF VARIABLES | 38 | SINGLE VARIABLES | 91 2 projected |
| NON ZERO ELEMENTS | 314 | NON LINEAR N-Z | 98 |
| DERIVATIVE POOL | 10 | CONSTANT POOL | 28 |
| CODE LENGTH | 240 | DISCRETE VARIABLES | 6 |

GENERATION TIME = 0.047 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

```
EXECUTION TIME      =     0.094 SECONDS     3 MB  24.2.1 r43572 WEX-WEI
GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:25:10 Page 10
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Solution Report     SOLVE CASE31CAL2 Using MINLP From line 588

          S O L V E      S U M M A R Y

     MODEL   CASE31CAL2          OBJECTIVE  OBJ2
     TYPE    MINLP               DIRECTION  MINIMIZE
     SOLVER  DICOPT              FROM LINE  588

**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE          31870.5818

 RESOURCE USAGE, LIMIT          0.062      1000.000
 ITERATION COUNT, LIMIT       100    2000000000
 EVALUATION ERRORS              0             0
**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
                             0     ERRORS
GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:25:10 Page 11
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m E x e c u t i o n
----    589 VARIABLE OBJ1.L              =    32774.737
            VARIABLE OBJ2.L              =    31870.582
----    589 VARIABLE xF.L  Split Flowrate source to sink (kg per h)

            j1          j2
i2    1457.074    1037.509

----    589 VARIABLE yF.L  Split Flowrate source to treat (kg per h)

            u1
i1    2500.000

----    589 VARIABLE zF.L  Split Flowrate treat to sink (kg per h)
```

```
        j1        j2
w1   1342.926   857.074

----  589 VARIABLE FR.L  Freshwater flowrate (kg per h)

        j2
r1   405.417

----  589 VARIABLE WW1.L  Waste i flowrate (kg per h)

i2 375.417


----  589 VARIABLE WW2.L  Waste w flowrate (kg per h)

w1 300.000

----  589 VARIABLE CW.L           =      0.015  Waste discharge composition

----  589 VARIABLE FTI.L  Treatment flowrate in  (kg per h)

u1 2500.000

----  589 VARIABLE YT.L  Existing Treatment unit

        n2
u1      1.000

MODEL STATISTICS

BLOCKS OF EQUATIONS        64    SINGLE EQUATIONS        130

BLOCKS OF VARIABLES        44    SINGLE VARIABLES         97

NON ZERO ELEMENTS         275    DISCRETE VARIABLES       30

GENERATION TIME    =      0.016 SECONDS      3 MB  24.2.1 r43572 WEX-WE

EXECUTION TIME     =      0.016 SECONDS      3 MB  24.2.1 r43572 WEX-WEI

GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:25:10 Page 15

General Algebraic Modeling System

Solution Report     SOLVE CASE31CAL3 Using MIP From line 616

        S O L V E      S U M M A R Y

   MODEL   CASE31CAL3        OBJECTIVE  OBJ3

   TYPE    MIP               DIRECTION  MINIMIZE

   SOLVER  CPLEX             FROM LINE  616

**** SOLVER STATUS     1 Normal Completion
```

```
**** MODEL STATUS      1 Optimal

**** OBJECTIVE VALUE          39463.0202

 RESOURCE USAGE, LIMIT         0.032      1000.000

 ITERATION COUNT, LIMIT        0    2000000000

IBM ILOG CPLEX   24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(101): integer optimal solution

Cplex Time: 0.03sec (det. 0.09 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.08 ticks)

Proven optimal solution.

MIP Solution:        39463.020203     (0 iterations, 0 nodes)

Final Solve:         39463.020203     (0 iterations)

Best possible:       39463.020203

Absolute gap:            0.000000

Relative gap:            0.000000

**** REPORT SUMMARY :        0     NONOPT

                    0 INFEASIBLE

                    0  UNBOUNDED

GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:25:10 Page 16

G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m

E x e c u t i o n

----    617 VARIABLE OBJ2.L              =   31870.582

        VARIABLE OBJ3.L              =   39463.020

        VARIABLE FACost.L            =    6162.333  Freshwater annual cost ($ per y)

        VARIABLE TOCost.L            =   15800.000  Treatment operation annual cost ($ per y)

        VARIABLE TTCost.L            =    9908.248  Total treatment investment annual cost ($per y)
```

VARIABLE PACost.L = 7592.438 Piping annual cost ($per y)

---- 617 VARIABLE CT.L Treatment composition out

w1 0.003

---- 617 VARIABLE CTI.L Treatment composition in

u1 0.035

---- 617 VARIABLE TAC.L = 39463.020

---- 617 PARAMETER xFP xF parameter

| | j1 | j2 |
|---|---|---|
| i2 | 1457.074 | 1037.509 |

---- 617 PARAMETER yFP yF parameter

| | u1 |
|---|---|
| i1 | 2500.000 |

---- 617 PARAMETER zFP zF parameter

| | j1 | j2 |
|---|---|---|
| w1 | 1342.926 | 857.074 |

---- 617 PARAMETER FRP FW parameter

| | j2 |
|---|---|
| r1 | 405.417 |

---- 617 PARAMETER WW1P WW1 parameter

i2 375.417

---- 617 PARAMETER WW2P WW2 parameter

w1 300.000

---- 617 VARIABLE YT.L Existing Treatment unit

| | n2 |
|---|---|
| u1 | 1.000 |

---- 617 VARIABLE zx.L Existing Split Flowrate source to sink

| | j1 | j2 |
|---|---|---|
| i2 | 1.000 | 1.000 |

---- 617 VARIABLE zy.L Existing Split Flowrate source to treat

| | u1 |
|---|---|
| i1 | 1.000 |

---- 617 VARIABLE zz.L Existing Split Flowrate treat to sink

| | j1 | j2 |
|---|---|---|
| w1 | 1.000 | 1.000 |

---- 617 VARIABLE zfr.L Existing Flowrate fresh to sink

| | j2 |
|---|---|
| r1 | 1.000 |

---- 617 VARIABLE zw1.L Existing Split Flowrate source to waste

i2 1.000

---- 617 VARIABLE zw2.L Existing Split Flowrate treat to waste

w1 1.000

MODEL STATISTICS

| | | | |
|---|---|---|---|
| BLOCKS OF EQUATIONS | 68 | SINGLE EQUATIONS | 146 |
| BLOCKS OF VARIABLES | 54 | SINGLE VARIABLES | 124 |
| NON ZERO ELEMENTS | 476 | NON LINEAR N-Z | 146 |
| DERIVATIVE POOL | 10 | CONSTANT POOL | 50 |
| CODE LENGTH | 374 | DISCRETE VARIABLES | 30 |

GENERATION TIME = 0.015 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.015 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:25:10 Page 20

General Algebraic Modeling System

Solution Report SOLVE CASE31CAL4 Using MINLP From line 674

S O L V E S U M M A R Y

MODEL CASE31CAL4 OBJECTIVE OBJ4

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 674

```
**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE         39331.1202

 RESOURCE USAGE, LIMIT        0.391      1000.000
 ITERATION COUNT, LIMIT     656    2000000000
 EVALUATION ERRORS            0           0

**** REPORT SUMMARY :       0     NONOPT
                            0 INFEASIBLE
                            0  UNBOUNDED
                            1     ERRORS ( ****)
GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:25:10 Page 21
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n

----    675 VARIABLE OBJ3.L              =    39463.020
            VARIABLE OBJ4.L              =    39331.120
            VARIABLE PACost.L            =     7460.538  Piping annual cost ($per y)

----    675 VARIABLE xF.L  Split Flowrate source to sink (kg per h)

            j1          j2

i2    1518.324     976.259

----    675 VARIABLE yF.L  Split Flowrate source to treat (kg per h)

            u1

i1    2500.000

----    675 VARIABLE zF.L  Split Flowrate treat to sink (kg per h)

            j1          j2

w1     876.259    1323.741

----    675 VARIABLE FR.L  Freshwater flowrate (kg per h)

            j1

r1     405.417

----    675 VARIABLE OFW.L               =      405.417  Overall freshwater flowrate (kg per h)

----    675 VARIABLE WW1.L  Waste i flowrate (kg per h)
```

i2 375.417

---- 675 VARIABLE WW2.L Waste w flowrate (kg per h)

w1 300.000

---- 675 VARIABLE OWW.L = 675.417 Overall waste flowrate (kg per h)

---- 675 VARIABLE YT.L Existing Treatment unit

n2

u1 1.000

---- 675 VARIABLE CT.L Treatment composition out

w1 0.003

---- 675 VARIABLE CTI.L Treatment composition in

u1 0.035

---- 675 VARIABLE CW.L = 0.015 Waste discharge composition

---- 675 VARIABLE zx.L Existing Split Flowrate source to sink

j1 j2

i2 1.000 1.000

---- 675 VARIABLE zy.L Existing Split Flowrate source to treat

u1

i1 1.000

---- 675 VARIABLE zfr.L Existing Flowrate fresh to sink

j1

r1 1.000

## APPENDIX B-10 : Case Study 3.2 GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 9 SINGLE EQUATIONS 25

BLOCKS OF VARIABLES 8 SINGLE VARIABLES 29

NON ZERO ELEMENTS 72

GENERATION TIME = 0.000 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.000 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 5

General Algebraic Modeling System

Solution Report SOLVE CASE32CAL1 Using LP From line 57

SOLVE SUMMARY

MODEL CASE32CAL1 OBJECTIVE OBJ1

TYPE LP DIRECTION MINIMIZE

SOLVER CONOPT FROM LINE 575

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 1 Optimal

**** OBJECTIVE VALUE 85906.2857

RESOURCE USAGE, LIMIT 0.000 1000.000

ITERATION COUNT, LIMIT 5 2000000000

CONOPT 3 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

CONOPT3 version 3.15M

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Bagsvaerdvej 246 A

DK-2880 Bagsvaerd, Denmark

** Optimal solution. There are no superbasic variables.

CONOPT time Total 0.001 seconds

of which: Function evaluations 0.000 = 0.0%

1st Derivative evaluations 0.000 = 0.0%

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 6

General Algebraic Modeling System

Execution

---- 576 VARIABLE OBJ1.L = 85906.286

---- 576 VARIABLE x.L Split fraction source to sink

| | j2 |
|---|---|
| i1 | 1.000 |

i2 0.829

---- 576 VARIABLE FR.L Freshwater flowrate (kg per h)

| | j1 | j2 |
|---|---|---|
| r1 | 4320.000 | 3085.714 |

---- 576 VARIABLE y1.L Split fraction source to treat for model 1

i2 0.171, i3 1.000, i4 1.000

---- 576 VARIABLE xF.L Split Flowrate source to sink (kg per h)

| | j2 |
|---|---|
| i1 | 2880.000 |
| i2 | 14914.286 |

MODEL STATISTICS

| | | | |
|---|---|---|---|
| BLOCKS OF EQUATIONS | 45 | SINGLE EQUATIONS | 138 |
| BLOCKS OF VARIABLES | 38 | SINGLE VARIABLES | 151 |
| NON ZERO ELEMENTS | 533 | NON LINEAR N-Z | 173 |
| DERIVATIVE POOL | 10 | CONSTANT POOL | 34 |
| CODE LENGTH | 410 | DISCRETE VARIABLES | 7 |

GENERATION TIME = 0.031 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.047 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 10

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

Solution Report SOLVE CASE32CAL2 Using MINLP From line 604

S O L V E S U M M A R Y

MODEL CASE32CAL2 OBJECTIVE OBJ2

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 604

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 207203.8036

RESOURCE USAGE, LIMIT 0.173 1000.000

ITERATION COUNT, LIMIT 121 2000000000

EVALUATION ERRORS 0 0

**** REPORT SUMMARY : 0 NONOPT

```
0 INFEASIBLE
0 UNBOUNDED
0 ERRORS

GAMS 24.2.1 r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 11
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m   E x e c u t i o n

----   605 VARIABLE OBJ1.L           =  85906.286
       VARIABLE OBJ2.L           =  207203.804

----   605 VARIABLE xF.L  Split Flowrate source to sink (kg per h)

      j1        j2
i1  2880.000
i2             12485.857

----   605 VARIABLE yF.L  Split Flowrate source to treat (kg per h)

       u2
i2   3280.408
i3  21240.000
i4   5040.000

----   605 VARIABLE zF.L  Split Flowrate treat to sink (kg per h)

       j2
w2   8394.143

----   605 VARIABLE FR.L  Freshwater flowrate (kg per h)

       j1
r1   1440.000

----   605 VARIABLE WW1.L  Waste i flowrate (kg per h)

i2 2233.735

----   605 VARIABLE WW2.L  Waste w flowrate (kg per h)

w2 21166.265

----   605 VARIABLE CW.L           =      5.000  Waste discharge composition

----   605 VARIABLE FTI.L  Treatment flowrate in  (kg per h)

u2 29560.408

----   605 VARIABLE YT.L  Existing Treatment unit

       n3
u2    1.000
```

---- 605 VARIABLE FACost.L = 16704.000 Freshwater annual cost ($ per y)

VARIABLE TTCost.L = 48609.844 Total treatment investment annual cost ($per y)

VARIABLE TOCost.L = 141889.959 Treatment operation annual cost ($ per y)

MODEL STATISTICS

BLOCKS OF EQUATIONS 65 SINGLE EQUATIONS 214

BLOCKS OF VARIABLES 44 SINGLE VARIABLES 156

NON ZERO ELEMENTS 459 DISCRETE VARIABLES 53

GENERATION TIME = 0.000 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 15

General Algebraic Modeling System

Solution Report SOLVE CASE32CAL3 Using MIP From line 637

SOLVE SUMMARY

MODEL CASE32CAL3 OBJECTIVE OBJ3

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 637

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 1 Optimal

**** OBJECTIVE VALUE 958322.7301

RESOURCE USAGE, LIMIT 0.063 1000.000

ITERATION COUNT, LIMIT 0 2000000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 16

General Algebraic Modeling System

Execution

---- 638 VARIABLE OBJ2.L = 207203.804

VARIABLE OBJ3.L = 958322.730

VARIABLE FACost.L = 16704.000 Freshwater annual cost ($ per y)

VARIABLE TOCost.L = 141889.959 Treatment operation annual cost ($ per y)

VARIABLE TTCost.L = 48609.844 Total treatment investment annual cost ($per y)

```
        VARIABLE PACost.L          =  751118.926  Piping annual cost ($per y)

----   638 VARIABLE CT.L  Treatment composition out

w2 4.050

----   638 VARIABLE CTI.L  Treatment composition in

u2 25.314

----   638 VARIABLE TAC.L            =  958322.730

----   638 PARAMETER xFP  xF parameter

        j1        j2

i1   2880.000

i2            12485.857

----   638 PARAMETER yFP  yF parameter

        u2

i2   3280.408

i3  21240.000

i4   5040.000

----   638 PARAMETER zFP  zF parameter

        j2

w2   8394.143

----   638 PARAMETER FRP  FW parameter

        j1

r1   1440.000

----   638 PARAMETER WW1P  WW1 parameter

i2 2233.735

----   638 PARAMETER WW2P  WW2 parameter

w2 21166.265

----   638 VARIABLE YT.L  Existing Treatment unit

        n3

u2      1.000

----   638 VARIABLE zx.L  Existing Split Flowrate source to sink

        j1        j2

i1      1.000
```

```
i2            1.000

----  638 VARIABLE zy.L  Existing Split Flowrate source to treat

        u2

i2     1.000

i3     1.000

i4     1.000

----  638 VARIABLE zz.L  Existing Split Flowrate treat to sink

        j2

w2     1.000

----  638 VARIABLE zfr.L  Existing Flowrate fresh to sink

        j1

r1     1.000

----  638 VARIABLE zw1.L  Existing Split Flowrate source to waste

i2 1.000

----  638 VARIABLE zw2.L  Existing Split Flowrate treat to waste

w2 1.000

MODEL STATISTICS

BLOCKS OF EQUATIONS        68    SINGLE EQUATIONS        239

BLOCKS OF VARIABLES        54    SINGLE VARIABLES        206

NON ZERO ELEMENTS         827    NON LINEAR N-Z          265

DERIVATIVE POOL            10    CONSTANT POOL            44

CODE LENGTH               654    DISCRETE VARIABLES       53

GENERATION TIME    =     0.016 SECONDS    3 MB  24.2.1 r43572 WEX-WEI

EXECUTION TIME     =     0.016 SECONDS    3 MB  24.2.1 r43572 WEX-WEI

GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 20

G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m

Solution Report    SOLVE CASE32CAL4 Using MINLP From line 699

          S O L V E     S U M M A R Y

   MODEL  CASE32CAL4        OBJECTIVE  OBJ4

   TYPE   MINLP             DIRECTION  MINIMIZE

   SOLVER  DICOPT           FROM LINE  699

**** SOLVER STATUS     1 Normal Completion
```

```
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE        958322.7301
 RESOURCE USAGE, LIMIT        0.671     1000.000
 ITERATION COUNT, LIMIT     869    2000000000
 EVALUATION ERRORS           0          0
**** REPORT SUMMARY :      0    NONOPT
                    0 INFEASIBLE
                    0  UNBOUNDED
                    0    ERRORS
GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/04/14 01:39:36 Page 21
General Algebraic Modeling System
Execution
----   700 VARIABLE OBJ1.L            =   85906.286
       VARIABLE OBJ2.L            =  207203.804
       VARIABLE OBJ3.L            =  958322.730
       VARIABLE OBJ4.L            =  958322.730
       VARIABLE FACost.L          =   16704.000  Freshwater annual cost ($ per y)
       VARIABLE TOCost.L          =  141889.959  Treatment operation annual cost ($ per y)
       VARIABLE TTCost.L          =   48609.844  Total treatment investment annual cost ($per y)
       VARIABLE PACost.L          =  751118.926  Piping annual cost ($per y)
----   700 VARIABLE xF.L  Split Flowrate source to sink (kg per h)
        j1         j2
i1   2880.000
i2             12485.857

----   700 VARIABLE yF.L  Split Flowrate source to treat (kg per h)
        u2
i2   3280.408
i3  21240.000
i4   5040.000
----   700 VARIABLE zF.L  Split Flowrate treat to sink (kg per h)
        j2
```

w2 8394.143

---- 700 VARIABLE FR.L Freshwater flowrate (kg per h)

j1

r1 1440.000

---- 700 VARIABLE OFW.L = 1440.000 Overall freshwater flowrate (kg per h)

---- 700 VARIABLE WW1.L Waste i flowrate (kg per h)

i2 2233.735

---- 700 VARIABLE WW2.L Waste w flowrate (kg per h)

w2 21166.265

---- 700 VARIABLE OWW.L = 23400.000 Overall waste flowrate (kg per h)

---- 700 VARIABLE YT.L Existing Treatment unit

n3

u2 1.000

---- 700 VARIABLE CT.L Treatment composition out

w2 4.050

---- 700 VARIABLE CTI.L Treatment composition in

u2 25.314

---- 700 VARIABLE CW.L = 5.000 Waste discharge composition

---- 700 VARIABLE zx.L Existing Split Flowrate source to sink

| | j1 | j2 |
|---|---|---|
| i1 | 1.000 | |
| i2 | | 1.000 |

---- 700 VARIABLE zy.L Existing Split Flowrate source to treat

| | u2 |
|---|---|
| i2 | 1.000 |
| i3 | 1.000 |
| i4 | 1.000 |

---- 700 VARIABLE zfr.L Existing Flowrate fresh to sink

| | j1 |
|---|---|
| r1 | 1.000 |

---- 700 VARIABLE PA1.L = 172099.240 Piping cost source to sink ($ per y)

VARIABLE PA2.L = 283782.798 Piping cost source to treat ($ per y)

VARIABLE PA3.L = 0.000 Piping cost treat to treat ($ per y)

VARIABLE PA4.L = 74540.878 Piping cost treat to ($ per y)

VARIABLE PA5.L = 7720.035 Piping cost fresh tosink ($ per y)

VARIABLE PA6.L = 25018.648 Piping cost source towaste ($ per y)

VARIABLE PA7.L = 187957.326 Piping cost treat to waste ($ per y)

## APPENDIX B-11 : Case Study 4 WN design GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 14 SINGLE EQUATIONS 94

BLOCKS OF VARIABLES 13 SINGLE VARIABLES 109

NON ZERO ELEMENTS 291 DISCRETE VARIABLES 35

GENERATION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 5

General Algebraic Modeling System

Solution Report SOLVE MIXING1 Using MIP From line 335

SOLVE SUMMARY

MODEL MIXING1 OBJECTIVE O11

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 335

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 1 Optimal

**** OBJECTIVE VALUE 67500.0000

RESOURCE USAGE, LIMIT 0.031 1000.000

ITERATION COUNT, LIMIT 41 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(101): integer optimal solution

Cplex Time: 0.00sec (det. 0.20 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.13 ticks)

Proven optimal solution.

MIP Solution: 67500.000000 (22 iterations, 0 nodes)

Final Solve: 67500.000000 (19 iterations)

Best possible: 67500.000000

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 6

General Algebraic Modeling System

Execution

---- 336 VARIABLE FCost.L = 67500.000 Freshwater cost

VARIABLE OFW.L = 22.500 Overall freshwater

VARIABLE OWW.L = 22.500 Overall wastewater

---- 336 VARIABLE FFW.L Freshwater flowrate

j1 3.205, j2 2.182, j3 8.107, j4 4.364, j5 4.643

---- 336 VARIABLE yFW.L Binary vriable to denote existence of match FW to sink in WN

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 336 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 336 VARIABLE yWW.L Binary vriable to denote existence of match WW from source in WN

i1 1.000, i2 1.000, i3 1.000, i4 1.000, i5 1.000

---- 336 VARIABLE x.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | | | 0.294 | | 0.206 |
| i4 | 0.255 | 0.202 | 0.139 | 0.404 | |

i5 1.000

---- 336 VARIABLE F.L Splitting Flowrate

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | | | 2.643 | | 1.857 |
| i4 | 2.295 | 1.818 | 1.250 | 3.636 | |
| i5 | 4.500 | | | | |

---- 336 VARIABLE y.L Binary vriable to denote existence of match source to sink in WN

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i2 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i3 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i4 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i5 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

---- 336 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

---- 336 VARIABLE TK.L Sink temperature

j1 76.148, j2 77.273, j3 60.104, j4 77.273, j5 55.000

MODEL STATISTICS

BLOCKS OF EQUATIONS 18 SINGLE EQUATIONS 98

BLOCKS OF VARIABLES 17 SINGLE VARIABLES 113

NON ZERO ELEMENTS 369 NON LINEAR N-Z 70

DERIVATIVE POOL 10 CONSTANT POOL 33

CODE LENGTH 216 DISCRETE VARIABLES 35

GENERATION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 10

General Algebraic Modeling System

Solution Report SOLVE MIXING2 Using MINLP From line 362

S O L V E S U M M A R Y

MODEL MIXING2 OBJECTIVE O12

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 362

```
**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE          70853.6753

 RESOURCE USAGE, LIMIT          0.234      1000.000
 ITERATION COUNT, LIMIT       564    2000000000
 EVALUATION ERRORS              0             0

-------------------------------------------------------------------
Dicopt       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
-------------------------------------------------------------------
   Aldo Vecchietti and Ignacio E. Grossmann
   Engineering Design Research Center
   Carnegie Mellon University
   Pittsburgh, Pennsylvania 15213
-------------------------------------------------------------------
CONOPT 3       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows

  C O N O P T 3   version 3.15M
  Copyright (C)   ARKI Consulting and Development A/S
                  Bagsvaerdvej 246 A
                  DK-2880 Bagsvaerd, Denmark

  The model has 113 variables and 98 constraints
  with 369 Jacobian elements, 70 of which are nonlinear.
  The Hessian of the Lagrangian has 0 elements on the diagonal,
  35 elements below the diagonal, and 70 nonlinear variables.

 ** Warning **  The variance of the derivatives in the initial
                point is large (= 4.1 ). A better initial
                point, a better scaling, or better bounds on the
                variables will probably help the optimization.

 ** Optimal solution. Reduced gradient less than tolerance.

 CONOPT time Total                          0.064 seconds
   of which: Function evaluations           0.001 =  1.6%
             1st Derivative evaluations     0.000 =  0.0%
```

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Unable to load names.

MIP status(101): integer optimal solution

Cplex Time: 0.11sec (det. 6.74 ticks)

Fixing integer variables, and solving final LP..

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.11 ticks)

Proven optimal solution.

MIP Solution: 70858.350859 (238 iterations, 40 nodes)

Final Solve: 70858.350859 (7 iterations)

Best possible: 70858.350859

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 11

General Algebraic Modeling System

Execution

---- 363 VARIABLE PIC1.L = 1404.135 Piping cost of source to sink

VARIABLE PIC2.L = 1208.740 Piping cost of fresh to sink

VARIABLE PIC3.L = 740.800 Piping cost of sourceto waste

VARIABLE PICost.L = 3353.675 Piping cost

VARIABLE FCost.L = 67500.000 Freshwater cost

VARIABLE OFW.L = 22.500 Overall freshwater

VARIABLE OWW.L = 22.500 Overall wastewater

---- 363 VARIABLE FFW.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 363 VARIABLE yFW.L Binary vriable to denote existence of match FW to sink in WN

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 363 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 363 VARIABLE yWW.L Binary vriable to denote existence of match WW from source in WN

i1 1.000, i2 1.000, i3 1.000

---- 363 VARIABLE x.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 0.294 | | | | 0.206 |
| i4 | 0.038 | | 0.558 | 0.404 | |
| i5 | | 0.808 | 0.192 | | |

---- 363 VARIABLE F.L Splitting Flowrate

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 2.643 | | | | 1.857 |
| i4 | 0.341 | | 5.023 | 3.636 | |
| i5 | | 3.636 | 0.864 | | |

---- 363 VARIABLE y.L Binary vriable to denote existence of match source to sink in WN

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 1.000 | | | | 1.000 |
| i4 | 1.000 | | 1.000 | 1.000 | |
| i5 | | 1.000 | 1.000 | | |

---- 363 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

---- 363 VARIABLE TK.L Sink temperature

j1 56.670, j2 75.000, j3 77.093, j4 77.273, j5 55.000

MODEL STATISTICS

BLOCKS OF EQUATIONS 29 SINGLE EQUATIONS 581

BLOCKS OF VARIABLES 20 SINGLE VARIABLES 439

NON ZERO ELEMENTS 1,858 DISCRETE VARIABLES 110

GENERATION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 15

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

Solution Report SOLVE STAGEMODEL1 Using MIP From line 378

S O L V E      S U M M A R Y

MODEL   STAGEMODEL1        OBJECTIVE  O2

TYPE    MIP              DIRECTION  MINIMIZE

SOLVER  CPLEX             FROM LINE  378

**** SOLVER STATUS     1 Normal Completion

**** MODEL STATUS      1 Optimal

**** OBJECTIVE VALUE          980831.2500

RESOURCE USAGE, LIMIT          0.032      1000.000

ITERATION COUNT, LIMIT         0    2000000000

IBM ILOG CPLEX   24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows

--- GAMS/Cplex licensed for continuous and discrete problems.

Cplex 12.6.0.0

Space for names approximately 0.03 Mb

Use option 'names no' to turn use of names off

MIP status(101): integer optimal solution

Cplex Time: 0.02sec (det. 0.37 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.44 ticks)

Proven optimal solution.

MIP Solution:      980831.250000    (0 iterations, 0 nodes)

Final Solve:       980831.250000    (0 iterations)

Best possible:     980831.250000

Absolute gap:          0.000000

Relative gap:          0.000000

**** REPORT SUMMARY :        0     NONOPT

0 INFEASIBLE

0  UNBOUNDED

GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 16

G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m

E x e c u t i o n

----    379 VARIABLE z.L  Binary variable to denote existence of match ij in sta k

( ALL 0.000 )

---- 379 VARIABLE zcu.L Binary variable to denote existence of cold utility with hot stream i

i1 1.000, i2 1.000, i3 1.000

---- 379 VARIABLE zhu.L Binary variable to denote existence of hot utility with cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 379 VARIABLE tH.L Temperature of hot stream i at location k

| | firstloca~ | location2- | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 120.000 | 120.000 | 120.000 | 120.000 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| i3 | 130.000 | 130.000 | 130.000 | 130.000 | 130.000 |
| i4 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 379 VARIABLE tC.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 56.670 | 56.670 | 56.670 | 56.670 | 56.670 |
| j2 | 75.000 | 75.000 | 75.000 | 75.000 | 75.000 |
| j3 | 77.093 | 77.093 | 77.093 | 77.093 | 77.093 |
| j4 | 77.273 | 77.273 | 77.273 | 77.273 | 77.273 |
| j5 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 |

---- 379 VARIABLE q.L Heat exchanged between hot stream i and cold stream j at stage k

( ALL 0.000 )

---- 379 VARIABLE qcu.L Heat exchanged between hot stream i and cold utility

i1 945.000, i2 735.000, i3 525.000

---- 379 VARIABLE qhu.L Heat exchanged between cold stream j and hot utility

j1 505.511, j2 116.667, j3 320.701, j4 212.121, j5 341.250

---- 379 VARIABLE Oqhu.L = 1496.250 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu.L = 2205.000 Overall heat exchanged between hot stream i and cold utility

VARIABLE INV.L = 0.000 Investment cost

VARIABLE O2.L = 980831.250 Objective 2

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 17

General Algebraic Modeling System

Equation Listing SOLVE STAGEMODEL2 Using MINLP From line 428

MODEL STATISTICS

BLOCKS OF EQUATIONS 40 SINGLE EQUATIONS 856

BLOCKS OF VARIABLES 28 SINGLE VARIABLES 736

NON ZERO ELEMENTS 3,026 NON LINEAR N-Z 480

DERIVATIVE POOL 10 CONSTANT POOL 22

CODE LENGTH 1,885

GENERATION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 20

General Algebraic Modeling System

Solution Report SOLVE STAGEMODEL2 Using MINLP From line 428

S O L V E S U M M A R Y

MODEL STAGEMODEL2 OBJECTIVE O3

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 428

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 2 Locally Optimal

**** OBJECTIVE VALUE 1058683.5867

RESOURCE USAGE, LIMIT 0.000 1000.000

ITERATION COUNT, LIMIT 4 2000000000

EVALUATION ERRORS 0 0

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 05:51:46 Page 21

General Algebraic Modeling System

Execution

---- 429 VARIABLE x.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 0.294 | | | | 0.206 |

| | | | | | |
|---|---|---|---|---|---|
| i4 | 0.038 | | 0.558 | 0.404 | |
| i5 | | 0.808 | 0.192 | | |

---- 429 VARIABLE TK.L Sink temperature

j1 56.670, j2 75.000, j3 77.093, j4 77.273, j5 55.000

---- 429 VARIABLE z.L Binary variable to denote existence of match ij in stage k

( ALL 0.000 )

---- 429 VARIABLE zcu.L Binary variable to denote existence of cold utility with hot stream i

i1 1.000, i2 1.000, i3 1.000

---- 429 VARIABLE zhu.L Binary variable to denote existence of hot utility with cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 429 VARIABLE tH.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 120.000 | 120.000 | 120.000 | 120.000 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| i3 | 130.000 | 130.000 | 130.000 | 130.000 | 130.000 |
| i4 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 429 VARIABLE tC.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 56.670 | 56.670 | 56.670 | 56.670 | 56.670 |
| j2 | 75.000 | 75.000 | 75.000 | 75.000 | 75.000 |
| j3 | 77.093 | 77.093 | 77.093 | 77.093 | 77.093 |
| j4 | 77.273 | 77.273 | 77.273 | 77.273 | 77.273 |
| j5 | 55.000 | 55.000 | 55.000 | 55.000 | 55.000 |

---- 429 VARIABLE q.L Heat exchanged between hot stream i and cold stream j stage k

( ALL 0.000 )

---- 429 VARIABLE qcu.L Heat exchanged between hot stream i and cold utility

i1 945.000, i2 735.000, i3 525.000

---- 429 VARIABLE qhu.L Heat exchanged between cold stream j and hot utility

j1 505.511, j2 116.667, j3 320.701, j4 212.121, j5 341.250

---- 429 VARIABLE Oqhu.L = 1496.250 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu L = 2205.000 Overall heat exchanged between hot stream i and cold utility

VARIABLE OCosthu L = 564086.250

VARIABLE OCostcu.L = 416745.000

---- 429 VARIABLE A.L

( ALL 0.000 )

---- 429 VARIABLE Ahu L

j1 26.954, j2 7.573, j3 21.382, j4 14.176, j5 17.919

---- 429 VARIABLE Acu L

i1 38.318, i2 34.116, i3 20.079

---- 429 VARIABLE Atot L = 180.518

VARIABLE O3 L = 1058683 587 Objective 3

VARIABLE INV L = 77852.337 Investment cost

VARIABLE FCost.L = 67500.000 Freshwater cost

VARIABLE TAC.L = 1129537.262 Total annual cost

EXECUTION TIME = 0.000 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

USER: The Petroleum and Petrochemical College G131219:2228AS-WIN

Chulalongkorn University DC4365

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**** FILE SUMMARY

Input C:\Users\Sarut\Desktop\WORK\Thesis water network\GAMS 24.2\WHEN_yWN_x

HEN.gms

Output C:\Users\Sarut\Documents\gamsdir\projdir\WHEN_yWN_xHEN.lst

## APPENDIX B-12 : Case Study 4 WHEN without WN design GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 14 SINGLE EQUATIONS 94

BLOCKS OF VARIABLES 13 SINGLE VARIABLES 109

NON ZERO ELEMENTS 291 DISCRETE VARIABLES 35

GENERATION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 5

General Algebraic Modeling System

Solution Report SOLVE MIXING1 Using MIP From line 335

```
        S O L V E      S U M M A R Y

   MODEL   MIXING1        OBJECTIVE  O11
   TYPE    MIP            DIRECTION  MINIMIZE
   SOLVER  CPLEX          FROM LINE  335

**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      1 Optimal
**** OBJECTIVE VALUE        121500.0000

 RESOURCE USAGE, LIMIT          0.063      1000.000
 ITERATION COUNT, LIMIT         0    2000000000

IBM ILOG CPLEX   24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
Cplex 12.6.0.0

Space for names approximately 0.00 Mb
Use option 'names no' to turn use of names off
MIP status(101): integer optimal solution
Cplex Time: 0.00sec (det. 0.06 ticks)
Fixing integer variables, and solving final LP...
Fixed MIP status(1): optimal
Cplex Time: 0.00sec (det. 0.07 ticks)
Proven optimal solution.

MIP Solution:       121500.000000    (0 iterations, 0 nodes)
Final Solve:        121500.000000    (0 iterations)

Best possible:      121500.000000
Absolute gap:            0.000000
Relative gap:            0.000000

**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
```

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 6

General Algebraic Modeling System

Execution

---- 336 VARIABLE FCost.L = 121500.000 Freshwater cost

VARIABLE OFW.L = 40.500 Overall freshwater

VARIABLE OWW.L = 40.500 Overall wastewater

---- 336 VARIABLE FFW.L Freshwater flowrate

j1 10.000, j2 4.000, j3 12.000, j4 8.000, j5 6.500

---- 336 VARIABLE yFW.L Binary vriable to denote existence of match FW to sink in WN

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 336 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 9.000, i4 9.000, i5 4.500

---- 336 VARIABLE yWW.L Binary vriable to denote existence of match WW from source in WN

i1 1.000, i2 1.000, i3 1.000, i4 1.000, i5 1.000

---- 336 VARIABLE x.L

( ALL 0.000 )

--- 336 VARIABLE F.L Splitting Flowrate

( ALL 0.000 )

---- 336 VARIABLE y.L Binary vriable to denote existence of match source to sink in WN

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i2 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i3 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i4 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i5 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

---- 336 VARIABLE CK.L Sink stream concentration

( ALL 0.000 )

---- 336 VARIABLE TK.L Sink temperature

j1 25.000, j2 25.000, j3 25.000, j4 25.000, j5 25.000

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 7

General Algebraic Modeling System

Equation Listing SOLVE MIXING2 Using MINLP From line 362

MODEL STATISTICS

BLOCKS OF EQUATIONS 18 SINGLE EQUATIONS 98

BLOCKS OF VARIABLES 17 SINGLE VARIABLES 113

NON ZERO ELEMENTS 369 NON LINEAR N-Z 70

DERIVATIVE POOL 10 CONSTANT POOL 33

CODE LENGTH 216 DISCRETE VARIABLES 35

GENERATION TIME = 0.094 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.094 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 10

General Algebraic Modeling System

Solution Report SOLVE MIXING2 Using MINLP From line 362

S O L V E S U M M A R Y

MODEL MIXING2 OBJECTIVE O12

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 362

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 124137.6000

RESOURCE USAGE, LIMIT 0.203 1000.000

ITERATION COUNT, LIMIT 14 2000000000

EVALUATION ERRORS 0 0

------------------------------------------------------------------

Dicopt 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

------------------------------------------------------------------

Aldo Vecchietti and Ignacio E. Grossmann

Engineering Design Research Center

Carnegie Mellon University

Pittsburgh, Pennsylvania 15213

------------------------------------------------------------------

CONOPT 3 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

C O N O P T 3 version 3.15M

Bagsvaerdvej 246 A

DK-2880 Bagsvaerd, Denmark

The model has 113 variables and 98 constraints

with 369 Jacobian elements, 70 of which are nonlinear.

The Hessian of the Lagrangian has 0 elements on the diagonal,

35 elements below the diagonal, and 70 nonlinear variables.

** Warning ** The variance of the derivatives in the initial

point is large (= 4.1 ). A better initial

point, a better scaling, or better bounds on the

variables will probably help the optimization.

** Optimal solution. There are no superbasic variables.

CONOPT time Total 0.082 seconds

of which: Function evaluations 0.000 = 0.0%

1st Derivative evaluations 0.000 = 0.0%

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Unable to load names.

MIP status(101): integer optimal solution

Cplex Time: 0.00sec (det. 0.08 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.08 ticks)

Proven optimal solution.

MIP Solution: 124137.600000 (0 iterations, 0 nodes)

Final Solve: 124137.600000 (0 iterations)

Best possible: 124137.600000

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 11

General Algebraic Modeling System

Execution

```
---- 363 VARIABLE PIC1.L       =     0.000  Piping cost of source to sink
         VARIABLE PIC2.L       =  1374.000  Piping cost of fresh to sink
         VARIABLE PIC3.L       =  1263.600  Piping cost of source to waste
         VARIABLE PICost.L     =  2637.600  Piping cost
         VARIABLE FCost.L      = 121500.000  Freshwater cost
         VARIABLE OFW.L        =    40.500  Overall freshwater
         VARIABLE OWW.L        =    40.500  Overall wastewater

---- 363 VARIABLE FFW.L  Freshwater flowrate

j1 10.000,   j2  4.000,   j3 12.000,   j4  8.000,   j5  6.500

---- 363 VARIABLE yFW.L  Binary vriable to denote existence of match FW to sink in WN

j1 1.000,   j2 1.000,   j3 1.000,   j4 1.000,   j5 1.000

---- 363 VARIABLE WW.L  Source Waste water

i1 9.000,   i2 9.000,   i3 9.000,   i4 9.000,   i5 4.500

---- 363 VARIABLE yWW.L  Binary vriable to denote existence of match WW from source in WN

i1 1.000,   i2 1.000,   i3 1.000,   i4 1.000,   i5 1.000

---- 363 VARIABLE x.L

            ( ALL       0.000 )

---- 363 VARIABLE F.L  Splitting Flowrate

            ( ALL       0.000 )


---- 363 VARIABLE y.L  Binary vriable to denote existence of match source to in WN

            ( ALL       0.000 )

---- 363 VARIABLE CK.L  Sink stream concentration

            ( ALL       0.000 )

---- 363 VARIABLE TK.L  Sink temperature

j1 25.000,   j2 25.000,   j3 25.000,   j4 25.000,   j5 25.000
```

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 12

General Algebraic Modeling System

Equation Listing SOLVE STAGEMODEL1 Using MIP From line 378

MODEL STATISTICS

BLOCKS OF EQUATIONS 29 SINGLE EQUATIONS 581

BLOCKS OF VARIABLES 20 SINGLE VARIABLES 464

NON ZERO ELEMENTS 2,001 DISCRETE VARIABLES 135

GENERATION TIME = 0.046 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.046 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 15

General Algebraic Modeling System

Solution Report SOLVE STAGEMODEL1 Using MIP From line 378

SOLVE SUMMARY

MODEL STAGEMODEL1 OBJECTIVE O2

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 378

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 281904.0900

RESOURCE USAGE, LIMIT 0.531 1000.000

ITERATION COUNT, LIMIT 8298 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

--- GAMS/Cplex licensed for continuous and discrete problems.

Cplex 12.6.0.0

Space for names approximately 0.03 Mb

Use option 'names no' to turn use of names off

MIP status(102): integer optimal, tolerance

Cplex Time: 0.47sec (det. 241.67 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.05sec (det. 0.50 ticks)

Solution satisfies tolerances

MIP Solution: 281904.090000 (8297 iterations, 490 nodes)

Final Solve: 281904.090000 (1 iterations)

Best possible: 263791.942913

Absolute gap: 18112.147087

Relative gap: 0.064249

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 16

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

E x e c u t i o n

---- 379 VARIABLE z.L Binary variable to denote existence of match ij in stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j1 | | | 1.000 |
| i2.j4 | | | 1.000 |
| i3.j2 | | 1.000 | |
| i3.j5 | | 1.000 | |
| i4.j3 | | | 1.000 |
| i4.j4 | 1.000 | | |

---- 379 VARIABLE zcu.L Binary variable to denote existence of cold utility with hot stream i

i1 1.000, i2 1.000, i3 1.000, i4 1.000, i5 1.000

---- 379 VARIABLE zhu.L Binary variable to denote existence of hot utility w ith cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 379 VARIABLE tH.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 120.000 | 120.000 | 120.000 | 36.667 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 42.222 |
| i3 | 130.000 | 130.000 | 130.000 | 42.500 | 42.500 |
| i4 | 140.000 | 131.111 | 131.111 | 131.111 | 31.111 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 379 VARIABLE tC.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 100.000 | 100.000 | 100.000 | 100.000 | 25.000 |
| j2 | 100.000 | 100.000 | 100.000 | 25.000 | 25.000 |

```
j3    100.000    100.000    100.000    100.000    25.000
j4    100.000     90.000     90.000     90.000    25.000
j5    100.000    100.000    100.000     25.000    25.000

----  379 VARIABLE q.L  Heat exchanged between hot stream i and cold stream j at stage k

      firstloca~  location3  location4

i1.j1                    875.000
i2.j4                    606.667
i3.j2         350.000
i3.j5         568.750
i4.j3                   1050.000
i4.j4    93.333

----  379 VARIABLE qcu.L  Heat exchanged between hot stream i and cold utility

i1 70.000,  i2 128.333,  i3 131.250,  i4 11.667,  i5 262.500

----  379 VARIABLE qhu.L  Heat exchanged between cold stream j and hot utility

            ( ALL      0.000 )

----  379 VARIABLE Oqhu.L           =      0.000  Overall heat exchange between cold streamj and hot utility
          VARIABLE Oqcu.L           =    603.750  Overall heat exchanged between hot stream and cold utility
          VARIABLE INV.L            =      0.000  Investment cost
          VARIABLE O2.L             = 281904.090  Objective 2

GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 17
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Equation Listing    SOLVE STAGEMODEL2 Using MINLP From line 429

MODEL STATISTICS


BLOCKS OF EQUATIONS         40     SINGLE EQUATIONS          856
BLOCKS OF VARIABLES         28     SINGLE VARIABLES          736
NON ZERO ELEMENTS        3,044     NON LINEAR N-Z            480
DERIVATIVE POOL             10     CONSTANT POOL              22
CODE LENGTH              1,885

GENERATION TIME      =        0.016 SECONDS      3 MB  24.2.1 r43572 WEX-WEI
EXECUTION TIME       =        0.016 SECONDS      3 MB  24.2.1 r43572 WEX-WEI

GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 20
```

General Algebraic Modeling System

Solution Report SOLVE STAGEMODEL2 Using MINLP From line 429

SOLVE SUMMARY

MODEL STAGEMODEL2 OBJECTIVE O3

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 429

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 2 Locally Optimal

**** OBJECTIVE VALUE 271917.5773

RESOURCE USAGE, LIMIT 0.219 1000.000

ITERATION COUNT, LIMIT 103 2000000000

EVALUATION ERRORS 0 0

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/28/14 21:29:51 Page 21

General Algebraic Modeling System

Execution

---- 430 VARIABLE x.L

( ALL 0.000 )

---- 430 VARIABLE TK.L Sink temperature

j1 25.000, j2 25.000, j3 25.000, j4 25.000, j5 25.000

---- 430 VARIABLE z.L Binary variable to denote existence of match ij in stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j1 | | | 1.000 |
| i2.j4 | | | 1.000 |
| i3.j2 | | 1.000 | |
| i3.j5 | | 1.000 | |
| i4.j3 | | | 1.000 |
| i4.j4 | 1.000 | | |

---- 430 VARIABLE zcu.L Binary variable to denote existence of cold utility with hot stream i

i1 1.000, i2 1.000, i3 1.000, i4 1.000, i5 1.000

---- 430 VARIABLE zhu.L Binary variable to denote existence of hot utility with cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 430 VARIABLE tH.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 120.000 | 120.000 | 120.000 | 36.667 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 42.222 |
| i3 | 130.000 | 130.000 | 130.000 | 42.500 | 42.500 |
| i4 | 140.000 | 131.111 | 131.111 | 131.111 | 31.111 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 430 VARIABLE tC.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 100.000 | 100.000 | 100.000 | 100.000 | 25.000 |
| j2 | 100.000 | 100.000 | 100.000 | 25.000 | 25.000 |
| j3 | 100.000 | 100.000 | 100.000 | 100.000 | 25.000 |
| j4 | 100.000 | 90.000 | 90.000 | 90.000 | 25.000 |
| j5 | 100.000 | 100.000 | 100.000 | 25.000 | 25.000 |

---- 430 VARIABLE q.L Heat exchanged between hot stream i and cold stream j at stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j1 | | | 875.000 |
| i2.j4 | | | 606.667 |
| i3.j2 | | 350.000 | |
| i3.j5 | | 568.750 | |
| i4.j3 | | | 1050.000 |
| i4.j4 | 93.333 | | |

---- 430 VARIABLE qcu.L Heat exchanged between hot stream i and cold utility

i1 70.000, i2 128.333, i3 131.250, i4 11.667, i5 262.500

---- 430 VARIABLE qhu.L Heat exchanged between cold stream j and hot utility

( ALL 0.000 )

---- 430 VARIABLE Oqhu.L = 0.000 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu.L = 603.750 Overall heat exchanged between hot stream i and cold utility

```
----  430 VARIABLE A.L

      firstloca~  location3  location4

i1.j1                  113.202
i2.j4                   91.338
i3.j2          30.187
i3.j5          49.054
i4.j3                  137.811
i4.j4   4.603

----  430 VARIABLE Ahu.L

              ( ALL      0.000 )

----  430 VARIABLE Acu.L

i1  7.658,   i2 12.169,   i3 12.367,   i4  1.543,   i5 14.446

----  430 VARIABLE Atot.L          =     474.379
        VARIABLE O3.L              =  271917.577  Objective 3
        VARIABLE INV.L             =  157808.827  Investment cost
        VARIABLE FCost.L           =  121500.000  Freshwater cost
        VARIABLE Costh.L           =   63787.924
        VARIABLE Costhu.L          =   46563.207
        VARIABLE Costcu.L          =   47457.696
        VARIABLE OCosthu.L         =       0.000
        VARIABLE OCostcu.L         =  114108.750
        VARIABLE TAC.L             =  396055.177  Total annual cost

EXECUTION TIME    =     0.016 SECONDS     3 MB  24.2.1 r43572 WEX-WEI


USER: The Petroleum and Petrochemical College       G131219:2228AS-WIN
      Chulalongkorn University                      DC4365
      License for teaching and research at degree granting institutions

**** FILE SUMMARY

Input     C:\Users\Sarut\Desktop\WORK\Thesis water network\GAMS 24.2\WHEN_xWN_y
          HEN.gms
Output    C:\Users\Sarut\Documents\gamsdir\projdir\WHEN_xWN_yHEN.lst
```

## APPENDIX B-13 : Case Study 4 WHEN by two-step design GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 14 SINGLE EQUATIONS 94

BLOCKS OF VARIABLES 13 SINGLE VARIABLES 109

NON ZERO ELEMENTS 291 DISCRETE VARIABLES 35

GENERATION TIME = 0.140 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.140 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 5

General Algebraic Modeling System

Solution Report SOLVE MIXING1 Using MIP From line 340

S O L V E S U M M A R Y

MODEL MIXING1 OBJECTIVE O11

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 340

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 1 Optimal

**** OBJECTIVE VALUE 67500.0000

RESOURCE USAGE, LIMIT 1.593 1000.000

ITERATION COUNT, LIMIT 41 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(101): integer optimal solution

Cplex Time: 0.75sec (det. 0.20 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.03sec (det. 0.13 ticks)

Proven optimal solution.

MIP Solution: 67500.000000 (22 iterations, 0 nodes)

Final Solve: 67500.000000 (19 iterations)

Best possible: 67500.000000

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 6

General Algebraic Modeling System

Execution

---- 341 VARIABLE FCost.L = 67500.000 Freshwater cost

VARIABLE OFW.L = 22.500 Overall freshwater

VARIABLE OWW.L = 22.500 Overall wastewater

---- 341 VARIABLE FFW.L Freshwater flowrate

j1 3.205, j2 2.182, j3 8.107, j4 4.364, j5 4.643

---- 341 VARIABLE yFW.L Binary vriable to denote existence of match FW to sink in WN

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 341 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 341 VARIABLE yWW.L Binary vriable to denote existence of match WW from source in WN

i1 1.000, i2 1.000, i3 1.000, i4 1.000, i5 1.000

---- 341 VARIABLE x.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | | | 0.294 | | 0.206 |
| i4 | 0.255 | 0.202 | 0.139 | 0.404 | |
| i5 | 1.000 | | | | |

---- 341 VARIABLE F.L Splitting Flowrate

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | | | 2.643 | | 1.857 |
| i4 | 2.295 | 1.818 | 1.250 | 3.636 | |
| i5 | 4.500 | | | | |

---- 341 VARIABLE y.L Binary vriable to denote existence of match source to sink in WN

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i2 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i3 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i4 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i5 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

---- 341 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

---- 341 VARIABLE TK.L Sink temperature

j1 76.148, j2 77.273, j3 60.104, j4 77.273, j5 55.000

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 7

General Algebraic Modeling System

Equation Listing SOLVE MIXING2 Using MINLP From line 367

MODEL STATISTICS

BLOCKS OF EQUATIONS 18 SINGLE EQUATIONS 98

BLOCKS OF VARIABLES 17 SINGLE VARIABLES 113

NON ZERO ELEMENTS 369 NON LINEAR N-Z 70

DERIVATIVE POOL 10 CONSTANT POOL 33

CODE LENGTH 216 DISCRETE VARIABLES 35

GENERATION TIME = 0.031 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.094 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 10

General Algebraic Modeling System

Solution Report SOLVE MIXING2 Using MINLP From line 367

S O L V E S U M M A R Y

MODEL MIXING2 OBJECTIVE O12

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 367

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 70853.6753

```
RESOURCE USAGE, LIMIT        1.937    1000.000
ITERATION COUNT, LIMIT     564    2000000000
EVALUATION ERRORS           0         0
-----------------------------------------------------------------
Dicopt      24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
-----------------------------------------------------------------
   Aldo Vecchietti and Ignacio E. Grossmann
   Engineering Design Research Center
   Carnegie Mellon University
   Pittsburgh, Pennsylvania 15213
-----------------------------------------------------------------
CONOPT 3      24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
   C O N O P T 3   version 3.15M
   Copyright (C)   ARKI Consulting and Development A/S
                   Bagsvaerdvej 246 A
                   DK-2880 Bagsvaerd, Denmark
   The model has 113 variables and 98 constraints
   with 369 Jacobian elements, 70 of which are nonlinear.
   The Hessian of the Lagrangian has 0 elements on the diagonal,
   35 elements below the diagonal, and 70 nonlinear variables.
 ** Warning **  The variance of the derivatives in the initial
                point is large (= 4.1 ). A better initial
                point, a better scaling, or better bounds on the
                variables will probably help the optimization.
 ** Optimal solution. Reduced gradient less than tolerance.
 CONOPT time Total                         1.087 seconds
   of which: Function evaluations          0.034 =  3.1%
             1st Derivative evaluations    0.000 =  0.0%
IBM ILOG CPLEX   24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
Cplex 12.6.0.0
Unable to load names.
MIP status(101): integer optimal solution
```

Cplex Time: 0.25sec (det. 6.74 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.11 ticks)

Proven optimal solution.

MIP Solution: 70858.350859 (238 iterations, 40 nodes)

Final Solve: 70858.350859 (7 iterations)

Best possible: 70858.350859

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 11

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

E x e c u t i o n

---- 368 VARIABLE PIC1.L = 1404.135 Piping cost of sourceto sink

VARIABLE PIC2.L = 1208.740 Piping cost of fresh to sink

VARIABLE PIC3.L = 740.800 Piping cost of sourceto waste

VARIABLE PICost.L = 3353.675 Piping cost

VARIABLE FCost.L = 67500.000 Freshwater cost

VARIABLE OFW.L = 22.500 Overall freshwater

VARIABLE OWW.L = 22.500 Overall wastewater

---- 368 VARIABLE FFW.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 368 VARIABLE yFW.L Binary vriable to denote existence of match FW to sink in WN

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 368 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 368 VARIABLE yWW.L Binary vriable to denote existence of match WW from source in WN

i1 1.000, i2 1.000, i3 1.000

---- 368 VARIABLE x.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 0.294 | | | | 0.206 |
| i4 | 0.038 | | 0.558 | 0.404 | |
| i5 | | 0.808 | 0.192 | | |

---- 368 VARIABLE F.L Splitting Flowrate

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 2.643 | | | | 1.857 |
| i4 | 0.341 | | 5.023 | 3.636 | |
| i5 | | 3.636 | 0.864 | | |

---- 368 VARIABLE y.L Binary vriable to denote existence of match source to sink in WN

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 1.000 | | | | 1.000 |
| i4 | 1.000 | | 1.000 | 1.000 | |
| i5 | | 1.000 | 1.000 | | |

---- 368 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

---- 368 VARIABLE TK.L Sink temperature

j1 56.670, j2 75.000, j3 77.093, j4 77.273, j5 55.000

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 12

General Algebraic Modeling System

Equation Listing SOLVE STAGEMODEL1 Using MIP From line 382

MODEL STATISTICS

BLOCKS OF EQUATIONS 29 SINGLE EQUATIONS 581

BLOCKS OF VARIABLES 20 SINGLE VARIABLES 464

NON ZERO ELEMENTS 1,983 DISCRETE VARIABLES 135

GENERATION TIME = 0.016 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.063 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 15

General Algebraic Modeling System

Solution Report SOLVE STAGEMODEL1 Using MIP From line 382

SOLVE SUMMARY

MODEL STAGEMODEL1 OBJECTIVE O2

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 382

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 423783.9197

RESOURCE USAGE, LIMIT 25.203 1000.000

ITERATION COUNT, LIMIT 812424 2000000000

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

--- GAMS/Cplex licensed for continuous and discrete problems.

Cplex 12.6.0.0

Space for names approximately 0.03 Mb

Use option 'names no' to turn use of names off

MIP status(102): integer optimal, tolerance

Cplex Time: 25.19sec (det. 17458.70 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.51 ticks)

Solution satisfies tolerances.

MIP Solution: 423783.919697 (812423 iterations, 69517 nodes)

Final Solve: 423783.919697 (1 iterations)

Best possible: 381406.362183

Absolute gap: 42377.557514

Relative gap: 0.099998

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 16

General Algebraic Modeling System

Execution

---- 383 VARIABLE z.L Binary variable to denote existence of match ij in stage k

| | firstloca~ | location4 |
|---|---|---|
| i1.j3 | | 1.000 |
| i1.j4 | | 1.000 |
| i2.j1 | | 1.000 |
| i3.j1 | 1.000 | |
| i3.j5 | | 1.000 |

---- 383 VARIABLE zcu.L Binary variable to denote existence of cold utility with hot stream i

i1 1.000, i2 1.000, i3 1.000

---- 383 VARIABLE zhu.L Binary variable to denote existence of hot utility with cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 383 VARIABLE tH.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 120.000 | 120.000 | 120.000 | 77.273 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 62.967 |
| i3 | 130.000 | 120.000 | 120.000 | 120.000 | 55.000 |
| i4 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 383 VARIABLE tC.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 94.500 | 90.000 | 90.000 | 90.000 | 56.670 |
| j2 | 75.000 | 75.000 | 75.000 | 75.000 | 75.000 |
| j3 | 100.000 | 100.000 | 100.000 | 100.000 | 77.093 |
| j4 | 90.980 | 90.980 | 90.980 | 90.980 | 77.273 |
| j5 | 100.000 | 100.000 | 100.000 | 100.000 | 55.000 |

---- 383 VARIABLE q.L Heat exchanged between hot stream i and cold stream j at stage k

| | firstloca~ | location4 |
|---|---|---|
| i1.j3 | | 320.701 |
| i1.j4 | | 127.936 |

i2.j1 388.845

i3.j1 52.500

i3.j5 341.250

---- 383 VARIABLE qcu.L Heat exchanged between hot stream i and cold utility

i1 496.364, i2 346.155, i3 131.250

---- 383 VARIABLE qhu.L Heat exchanged between cold stream j and hot utility

j1 64.167, j2 116.667, j4 84.186

---- 383 VARIABLE Oqhu.L = 265.019 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu.L = 973.769 Overall heat exchanged between hot stream i and cold utility

VARIABLE INV.L = 0.000 Investment cost

VARIABLE O2.L = 423783.920 Objective 2

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 17

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

Equation Listing SOLVE STAGEMODEL2 Using MINLP From line 426

MODEL STATISTICS

BLOCKS OF EQUATIONS 40 SINGLE EQUATIONS 856

BLOCKS OF VARIABLES 28 SINGLE VARIABLES 736

NON ZERO ELEMENTS 3,026 NON LINEAR N-Z 480

DERIVATIVE POOL 10 CONSTANT POOL 22

CODE LENGTH 1,885

GENERATION TIME = 0.094 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.110 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 20

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

Solution Report SOLVE STAGEMODEL2 Using MINLP From line 426

S O L V E S U M M A R Y

MODEL STAGEMODEL2 OBJECTIVE O3

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 426

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 2 Locally Optimal

**** OBJECTIVE VALUE 417306.9485

```
RESOURCE USAGE, LIMIT        0.437     1000.000
ITERATION COUNT, LIMIT       99   2000000000
EVALUATION ERRORS             0          0
-----------------------------------------------------------------
Dicopt       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
-----------------------------------------------------------------
   Aldo Vecchietti and Ignacio E. Grossmann
   Engineering Design Research Center
   Carnegie Mellon University
   Pittsburgh, Pennsylvania 15213
-----------------------------------------------------------------
CONOPT 3       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
  C O N O P T 3   version 3.15M
  Copyright (C)   ARKI Consulting and Development A/S
                  Bagsvaerdvej 246 A
                  DK-2880 Bagsvaerd, Denmark
  The model has 736 variables and 856 constraints
  with 3026 Jacobian elements, 480 of which are nonlinear.
  The Hessian of the Lagrangian has 135 elements on the diagonal,
  235 elements below the diagonal, and 405 nonlinear variables.
** Warning **  The variance of the derivatives in the initial
               point is large (= 5.7 ). A better initial
               point, a better scaling, or better bounds on the
               variables will probably help the optimization.
** Optimal solution. Reduced gradient less than tolerance.
CONOPT time Total                       0.445 seconds
  of which: Function evaluations          0.139 = 31.2%
            1st Derivative evaluations    0.008 =  1.8%
            2nd Derivative evaluations    0.008 =  1.8%
            Directional 2nd Derivative    0.013 =  2.9%
**** REPORT SUMMARY :        0    NONOPT
```

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:33:41 Page 21

G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m

E x e c u t i o n -

---- 427 VARIABLE F.L Splitting Flowrate

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 2.643 | | | | 1.857 |
| i4 | 0.341 | | 5.023 | 3.636 | |
| i5 | | 3.636 | 0.864 | | |

---- 427 VARIABLE FFW.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 427 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 427 VARIABLE TK.L Sink temperature

j1 56.670, j2 75.000, j3 77.093, j4 77.273, j5 55.000

---- 427 VARIABLE z.L Binary variable to denote existence of match ij in sta k

| | firstloca~ | location4 |
|---|---|---|
| i1.j3 | | 1.000 |
| i1.j4 | | 1.000 |
| i2.j1 | | 1.000 |
| i3.j1 | 1.000 | |
| i3.j5 | | 1.000 |

---- 427 VARIABLE zcu.L Binary variable to denote existence of cold utility with hot stream i

i1 1.000, i2 1.000, i3 1.000

---- 427 VARIABLE zhu.L Binary variable to denote existence of hot utility with cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 427 VARIABLE tH.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 120.000 | 120.000 | 120.000 | 77.426 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 62.967 |

| | | | | | |
|---|---|---|---|---|---|
| i3 | 130.000 | 107.778 | 107.778 | 107.778 | 55.338 |
| i4 | 140.000 | 140.000 | 140.000 | 140.000 | 140.000 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 427 VARIABLE tC.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 100.000 | 90.000 | 90.000 | 90.000 | 56.670 |
| j2 | 75.000 | 75.000 | 75.000 | 75.000 | 75.000 |
| j3 | 98.198 | 98.198 | 98.198 | 98.198 | 77.093 |
| j4 | 93.510 | 93.510 | 93.510 | 93.510 | 77.273 |
| j5 | 91.304 | 91.304 | 91.304 | 91.304 | 55.000 |

---- 427 VARIABLE q.L Heat exchanged between hot stream i and cold stream j at stage k

| | firstloca~ | location4 |
|---|---|---|
| i1.j3 | | 295.473 |
| i1.j4 | | 151.550 |
| i2.j1 | | 388.845 |
| i3.j1 | 116.667 | |
| i3.j5 | | 275.307 |

---- 427 VARIABLE qcu.L Heat exchanged between hot stream i and cold utility

i1 497.978, i2 346.155, i3 133.026

---- 427 VARIABLE qhu.L Heat exchanged between cold stream j and hot utility

j2 116.667, j3 25.228, j4 60.571, j5 65.943

---- 427 VARIABLE Oqhu.L = 268.409 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu.L = 977.159 Overall heat exchange between hot stream i and cold utility

---- 427 VARIABLE A.L

| | firstloca~ | location4 |
|---|---|---|
| i1.j3 | | 136.857 |
| i1.j4 | | 80.069 |
| i2.j1 | | 97.143 |
| i3.j1 | 9.990 | |
| i3.j5 | | 152.739 |

---- 427 VARIABLE Ahu.L

j2 7.573, j3 2.416, j4 5.246, j5 5.476

---- 427 VARIABLE Acu.L

i1 28.113, i2 23.061, i3 9.875

---- 427 VARIABLE Atot.L = 558.558

VARIABLE FCost.L = 67500.000 Freshwater cost

VARIABLE O12.L = 70853.675 Objective 1.2

VARIABLE O2.L = 423783.920 Objective 2

VARIABLE OCosthu.L = 101190.239

VARIABLE OCostcu.L = 184683.074

VARIABLE INV.L = 131433.636 Investment cost

VARIABLE TAC.L = 488160.624 Total annual cost

EXECUTION TIME = 0.000 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

USER: The Petroleum and Petrochemical College G131219:2228AS-WIN

Chulalongkorn University DC4365

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## APPENDIX B-14 : Case Study 4 WHEN by four-step design GAMS Solve summary

MODEL STATISTICS

BLOCKS OF EQUATIONS 14 SINGLE EQUATIONS 94

BLOCKS OF VARIABLES 13 SINGLE VARIABLES 109

NON ZERO ELEMENTS 291 DISCRETE VARIABLES 35

GENERATION TIME = 0.047 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.047 SECONDS 4 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 5

General Algebraic Modeling System

Solution Report SOLVE INITIAL1 Using MIP From line 653

SOLVE SUMMARY

MODEL INITIAL1 OBJECTIVE O11

TYPE MIP DIRECTION MINIMIZE

SOLVER CPLEX FROM LINE 653

**** SOLVER STATUS     1 Normal Completion

**** MODEL STATUS     1 Optimal

**** OBJECTIVE VALUE          67500.0000

RESOURCE USAGE, LIMIT          0.046     1000.000

ITERATION COUNT, LIMIT          41     2000000000

IBM ILOG CPLEX   24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Space for names approximately 0.00 Mb

Use option 'names no' to turn use of names off

MIP status(101): integer optimal solution

Cplex Time: 0.05sec (det. 0.20 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.13 ticks)

Proven optimal solution.

MIP Solution:          67500.000000     (22 iterations, 0 nodes)

Final Solve:          67500.000000     (19 iterations)

Best possible:          67500.000000

Absolute gap:          0.000000

Relative gap:          0.000000

**** REPORT SUMMARY :          0     NONOPT

0 INFEASIBLE

0 UNBOUNDED

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 6

G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m

E x e c u t i o n

---- 654 VARIABLE FCost.L          =     67500.000

VARIABLE OFW.L          =     22.500  Overall freshwater

VARIABLE OWW.L          =     22.500  Overall wastewater

---- 654 VARIABLE FFW.L  Freshwater flowrate

j1 3.205,    j2 2.182,    j3 8.107,    j4 4.364,    j5 4.643

---- 654 VARIABLE yFW.L  Binary vriable to denote existence of match FW to sink in WN

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 654 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 654 VARIABLE yWW.L Binary vriable to denote existence of match WW from source in WN

i1 1.000, i2 1.000, i3 1.000, i4 1.000, i5 1.000

---- 654 VARIABLE x.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | - | | 0.294 | | 0.206 |
| i4 | 0.255 | 0.202 | 0.139 | 0.404 | |
| i5 | 1.000 | | | | |

---- 654 VARIABLE F.L Splitting Flowrate

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | | | 2.643 | | 1.857 |
| i4 | 2.295 | 1.818 | 1.250 | 3.636 | |
| i5 | 4.500 | | | | |

---- 654 VARIABLE y.L Binary vriable to denote existence of match source to sink in WN

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i2 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i3 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i4 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| i5 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

---- 654 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

---- 654 VARIABLE TK.L Sink temperature

j1 76.148, j2 77.273, j3 60.104, j4 77.273, j5 55.000

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 7

General Algebraic Modeling System

Equation Listing SOLVE INITIAL2 Using MINLP From line 680

MODEL STATISTICS

BLOCKS OF EQUATIONS 18 SINGLE EQUATIONS 98

```
BLOCKS OF VARIABLES        17    SINGLE VARIABLES        113
NON ZERO ELEMENTS         369    NON LINEAR N-Z           70
DERIVATIVE POOL            10    CONSTANT POOL            33
CODE LENGTH               216    DISCRETE VARIABLES       35
GENERATION TIME    =    0.031 SECONDS    3 MB  24.2.1 r43572 WEX-WEI
EXECUTION TIME     =    0.031 SECONDS    3 MB  24.2.1 r43572 WEX-WEI
GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 10
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Solution Report    SOLVE INITIAL2 Using MINLP From line 680

          S O L V E     S U M M A R Y

   MODEL   INITIAL2          OBJECTIVE  O12
   TYPE    MINLP             DIRECTION  MINIMIZE
   SOLVER  DICOPT            FROM LINE  680

**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE         70853.6753

 RESOURCE USAGE, LIMIT          0.609      1000.000
 ITERATION COUNT, LIMIT       627    2000000000
 EVALUATION ERRORS              0             0
 -------------------------------------------------------------------
Dicopt          24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows
 -------------------------------------------------------------------
   Aldo Vecchietti and Ignacio E. Grossmann
   Engineering Design Research Center
   Carnegie Mellon University
   Pittsburgh, Pennsylvania 15213
 -------------------------------------------------------------------
CONOPT 3        24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows
   C O N O P T 3   version 3.15M
   Copyright (C)   ARKI Consulting and Development A/S
                   Bagsvaerdvej 246 A
```

DK-2880 Bagsvaerd, Denmark

The model has 113 variables and 98 constraints

with 369 Jacobian elements, 70 of which are nonlinear.

The Hessian of the Lagrangian has 0 elements on the diagonal,

35 elements below the diagonal, and 70 nonlinear variables.

** Optimal solution. Reduced gradient less than tolerance.

CONOPT time Total 0.099 seconds

of which: Function evaluations 0.000 = 0.0%

1st Derivative evaluations 0.000 = 0.0%

Directional 2nd Derivative 0.000 = 0.0%

IBM ILOG CPLEX 24 2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

Cplex 12.6.0.0

Unable to load names.

MIP status(101): integer optimal solution

Cplex Time: 0.06sec (det. 6.45 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0 03sec (det. 0.11 ticks)

Proven optimal solution.

MIP Solution: 70855.792819 (255 iterations, 43 nodes)

Final Solve: 70855.792819 (7 iterations)

Best possible: 70855.792819

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 11

General Algebraic Modeling System

Execution

---- 681 VARIABLE PIC1.L = 1404.135 Piping cost of sourceto sink

VARIABLE PIC2.L = 1208.740 Piping cost of fresh to sink

VARIABLE PIC3.L = 740.800 Piping cost of sourceto waste

VARIABLE PICost.L = 3353.675 Piping cost

VARIABLE FCost.L = 67500.000

VARIABLE OFW.L = 22.500 Overall freshwater

VARIABLE OWW.L = 22.500 Overall wastewater

---- 681 VARIABLE FFW.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 681 VARIABLE yFW.L Binary vriable to denote existence of match FW to sink in WN

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 681 VARIABLE WW.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 681 VARIABLE yWW.L Binary vriable to denote existence of match WW from source in WN

i1 1.000, i2 1.000, i3 1.000

---- 681 VARIABLE x.L

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 0.294 | | | | 0.206 |
| i4 | 0.038 | | 0.558 | 0.404 | |
| i5 | | 0.808 | 0.192 | | |

---- 681 VARIABLE F.L Splitting Flowrate

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 2.643 | | | | 1.857 |
| i4 | 0.341 | | 5.023 | 3.636 | |
| i5 | | 3.636 | 0.864 | | |

---- 681 VARIABLE y.L Binary vriable to denote existence of match source to sink in WN

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i3 | 1.000 | | | | 1.000 |
| i4 | 1.000 | | 1.000 | 1.000 | |
| i5 | | 1.000 | 1.000 | | |

---- 681 VARIABLE CK.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

---- 681 VARIABLE TK.L Sink temperature

j1 56.670, j2 75.000, j3 77.093, j4 77.273, j5 55.000

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 12

General Algebraic Modeling System

Equation Listing SOLVE MIXING1 Using MINLP From line 717

MODEL STATISTICS

BLOCKS OF EQUATIONS 29 SINGLE EQUATIONS 185

BLOCKS OF VARIABLES 29 SINGLE VARIABLES 225

NON ZERO ELEMENTS 827 NON LINEAR N-Z 390

DERIVATIVE POOL 10 CONSTANT POOL 38

CODE LENGTH 878 DISCRETE VARIABLES 60

GENERATION TIME = 0.110 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.110 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 15

General Algebraic Modeling System

Solution Report SOLVE MIXING1 Using MINLP From line 717

SOLVE SUMMARY

MODEL MIXING1 OBJECTIVE TAC1

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 717

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 8 Integer Solution

**** OBJECTIVE VALUE 70853.6753

RESOURCE USAGE, LIMIT 0.093 1000.000

ITERATION COUNT, LIMIT 11 2000000000

EVALUATION ERRORS 0 0

--------------------------------------------------------------------

Dicopt 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

--------------------------------------------------------------------

Aldo Vecchietti and Ignacio E. Grossmann

Engineering Design Research Center

Carnegie Mellon University

Pittsburgh, Pennsylvania 15213

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```
CONOPT 3       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows

   C O N O P T 3   version 3.15M
   Copyright (C)   ARKI Consulting and Development A/S
                   Bagsvaerdvej 246 A
                   DK-2880 Bagsvaerd, Denmark

   The model has 225 variables and 185 constraints
   with 827 Jacobian elements, 390 of which are nonlinear.
   The Hessian of the Lagrangian has 0 elements on the diagonal,
   125 elements below the diagonal, and 175 nonlinear variables.

 ** Warning **  The number of nonlinear derivatives equal to zero
         in the initial point is large (= 38 percent).
         A better initial point will probably help the
         optimization.

 ** Optimal solution. There are no superbasic variables.

 CONOPT time Total                    0.042 seconds
   of which: Function evaluations       0.000 =  0.0%
             1st Derivative evaluations 0.000 =  0.0%

IBM ILOG CPLEX   24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
--- GAMS/Cplex licensed for continuous and discrete problems
Cplex 12.6.0.0

Unable to load names.
MIP status(101): integer optimal solution
Cplex Time: 0.00sec (det. 0.19 ticks)
Fixing integer variables, and solving final LP...
Fixed MIP status(1): optimal
Cplex Time: 0.00sec (det. 0.18 ticks)
Proven optimal solution.

MIP Solution:       70853.675325    (0 iterations, 0 nodes)
Final Solve:        70853.675325    (0 iterations)

Best possible:      70853.675325
```

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 16

General Algebraic Modeling System

Execution

---- 718 VARIABLE x1.L

| | j1 | j2 | j3 | j5 |
|---|---|---|---|---|
| i3 | 0.294 | | | 0.206 |
| i4 | 0.038 | | | |
| i5 | | 0.808 | 0.192 | |

---- 718 VARIABLE F1.L Splitting Flowrate

| | j1 | j2 | j3 | j5 |
|---|---|---|---|---|
| i3 | 2.643 | | | 1.857 |
| i4 | 0.341 | | | |
| i5 | | 3.636 | 0.864 | |

---- 718 VARIABLE WW1.L Source Waste water

i1 9.000, i2 9.000, i3 4.500, i4 8.659

---- 718 VARIABLE OWW1.L = 31.159 Overall wastewater

---- 718 VARIABLE FS2.L

i1 9.000, i2 9.000, i3 4.500, i4 8.659

---- 718 VARIABLE x2.L

| | j3 | j4 |
|---|---|---|
| i4 | 0.580 | 0.420 |

---- 718 VARIABLE F2.L Splitting Flowrate

| | j3 | j4 |
|---|---|---|
| i4 | 5.023 | 3.636 |

---- 718 VARIABLE FFW2.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 718 VARIABLE WW2.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 718 VARIABLE OWW2.L = 22.500 Overall wastewater

---- 718 VARIABLE CK1.L Sink stream concentration

j1 20.000, j2 20.000, j3 20.000, j4 20.000, j5 20.000

---- 718 VARIABLE TK1.L Sink temperature

j1 88.244, j2 79.091, j3 70.720, j4 70.000, j5 87.143

---- 718 VARIABLE FK2.L

j1 7.016, j2 0.364, j3 11.136, j4 8.000, j5 4.643

---- 718 VARIABLE TK2.L ddddd

j1 25.000, j2 25.000, j3 13.724, j4 13.636, j5 25.000

---- 718 VARIABLE CK2.L Sink stream concentration

j3 19.845, j4 20.000

---- 718 VARIABLE FCost2.L = 67500.000

VARIABLE TAC1.L = 70853.675 Total annual cost 1

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 21

General Algebraic Modeling System

Execution

---- 753 VARIABLE F1.L Splitting Flowrate

| | j1 | j2 | j3 | j5 |
|---|---|---|---|---|
| i3 | 2.643 | | | 1.857 |
| i4 | 0.341 | | | |
| i5 | | 3.636 | 0.864 | |

---- 753 VARIABLE FFW2.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 753 VARIABLE q1.L Heat exchanged between hot stream i and cold stream j at stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 280.000 | |
| i1.j5 | 97.500 | | |
| i4.j1 | 137.159 | | |
| i4.j3 | | | 409.924 |

---- 753 VARIABLE z1.L Binary variable to denote existence of match ij in stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 1.000 | |
| i1.j5 | 1.000 | | |
| i4.j1 | 1.000 | | |
| i4.j3 | | | 1.000 |

---- 753 VARIABLE qhu1.L Heat exchanged between cold stream j and hot utility

j2 97.576

---- 753 VARIABLE zhu1.L Binary variable to denote existence of hot utility with cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 753 VARIABLE qcu1.L Heat exchanged between hot stream i and cold utility

( ALL 0.000 )

---- 753 VARIABLE zcu1.L Binary variable to denote existence of cold utility with hot stream i

i2 1.000, i4 1.000, i5 1.000

---- 753 VARIABLE OCosthu1.L = 36786.061

VARIABLE OCostcu1.L = 0.000

---- 753 VARIABLE TS2.L

( ALL 0.000 )

---- 753 VARIABLE TK1.L Sink temperature

j1 88.244, j2 79.091, j3 70.720, j4 70.000, j5 87.143

---- 753 PARAMETER TOUTC outlet temperature of cold stream (degree celcius)

j1 100.000, j2 100.000, j3 100.000, j4 100.000, j5 100.000

---- 753 VARIABLE tH1.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 110.714 | 110.714 | 84.048 | 84.048 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| i3 | 130.000 | 130.000 | 130.000 | 130.000 | 130.000 |
| i4 | 140.000 | 126.423 | 126.423 | 126.423 | 85.846 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 753 VARIABLE tC1.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 100.000 | 88.244 | 88.244 | 88.244 | 88.244 |
| j2 | 79.091 | 79.091 | 79.091 | 79.091 | 79.091 |
| j3 | 100.000 | 100.000 | 100.000 | 100.000 | 70.720 |
| j4 | 100.000 | 100.000 | 100.000 | 70.000 | 70.000 |
| j5 | 100.000 | 87.143 | 87.143 | 87.143 | 87.143 |

---- 753 VARIABLE TOUTH1.L

i1 84.048, i2 100.000, i3 130.000, i4 85.846

---- 753 VARIABLE FK2.L

j1 7.016, j2 0.364, j3 11.136, j4 8.000, j5 4.643

---- 753 VARIABLE WW2.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 753 VARIABLE x2.L

| | j3 | j4 |
|---|---|---|
| i4 | 0.580 | 0.420 |

---- 753 VARIABLE FFW2.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 22

General Algebraic Modeling System

Equation Listing SOLVE WHEN1A Using MINLP From line 807

MODEL STATISTICS

| | | | |
|---|---|---|---|
| BLOCKS OF EQUATIONS | 39 | SINGLE EQUATIONS | 863 |
| BLOCKS OF VARIABLES | 34 | SINGLE VARIABLES | 770 |
| NON ZERO ELEMENTS | 3,230 | NON LINEAR N-Z | 615 |

DERIVATIVE POOL 10 CONSTANT POOL 24

CODE LENGTH 2,170

GENERATION TIME = 0.031 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.031 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 25

General Algebraic Modeling System

Solution Report SOLVE WHEN1A Using MINLP From line 807

S O L V E S U M M A R Y

MODEL WHEN1A OBJECTIVE O22

TYPE MINLP DIRECTION MINIMIZE

SOLVER DICOPT FROM LINE 807

**** SOLVER STATUS 1 Normal Completion

**** MODEL STATUS 2 Locally Optimal

**** OBJECTIVE VALUE 85310.8197

RESOURCE USAGE, LIMIT 0.172 1000.000

ITERATION COUNT, LIMIT 34 2000000000

EVALUATION ERRORS 0 0

---------------------------------------------------------------

Dicopt 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

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Aldo Vecchietti and Ignacio E. Grossmann

Engineering Design Research Center

Carnegie Mellon University

Pittsburgh, Pennsylvania 15213

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CONOPT 3 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

C O N O P T 3 version 3.15M

Copyright (C) ARKI Consulting and Development A/S

Bagsvaerdvej 246 A

DK-2880 Bagsvaerd, Denmark

The model has 770 variables and 863 constraints

with 3230 Jacobian elements, 615 of which are nonlinear.

The Hessian of the Lagrangian has 135 elements on the diagonal,

290 elements below the diagonal, and 455 nonlinear variables.

** Warning ** The variance of the derivatives in the initial

point is large (= 5.9 ). A better initial

point, a better scaling, or better bounds on the

variables will probably help the optimization.

** Optimal solution. There are no superbasic variables.

CONOPT time Total 0.173 seconds

of which: Function evaluations 0.071 = 41.0%

1st Derivative evaluations 0.009 = 5.2%

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 17

General Algebraic Modeling System

Equation Listing SOLVE WHEN1 Using MINLP From line 752

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 26

General Algebraic Modeling System

Execution

---- 808 VARIABLE q1.L Heat exchanged between hot stream i and cold stream jat stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 280.000 | |
| i1.j5 | 97.500 | | |
| i4.j1 | 137.159 | | |
| i4.j3 | | | 409.924 |

---- 808 VARIABLE z1.L Binary variable to denote existence of match ij in st k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 1.000 | |
| i1.j5 | 1.000 | | |
| i4.j1 | 1.000 | | |
| i4.j3 | | | 1.000 |

---- 808 VARIABLE qhu1.L Heat exchanged between cold stream j and hot utility

j2 97.576

---- 808 VARIABLE zhu1.L Binary variable to denote existence of hot utility with cold stream

j2 1.000

---- 808 VARIABLE qcu1.L Heat exchanged between hot stream i and cold utility

( ALL 0.000 )

---- 808 VARIABLE zcu1.L Binary variable to denote existence of cold utilitywith hot stream i

( ALL - 0.000 )

---- 808 VARIABLE Oqhu1.L = 97.576 Overall heat exchanged between cold stream j and hot utility

VARIABLE Oqcu1.L = 0.000 Overall heat exchange between hot stream i and cold utility

---- 808 VARIABLE A1.L

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 45.507 | |
| i1.j5 | 8.971 | | |
| i4.j1 | 7.019 | | |
| i4.j3 | | | 40.488 |

---- 808 VARIABLE Ahu1.L

j2 3.677

---- 808 VARIABLE Costh1.L = 39143.857

VARIABLE Costhu1.L = 9380.902

VARIABLE OCosthu1.L = 36786.061

---- 808 VARIABLE TOUTH1.L

i1 84.048, i2 100.000, i3 130.000, i4 85.846

---- 808 VARIABLE O22.L = 85310.820 Objective 2.2

VARIABLE O2.L = 74036.626 Objective 2

---- 808 VARIABLE tH1.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 110.714 | 110.714 | 84.048 | 84.048 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| i3 | 130.000 | 130.000 | 130.000 | 130.000 | 130.000 |
| i4 | 140.000 | 126.423 | 126.423 | 126.423 | 85.846 |

| | | | | | |
|---|---|---|---|---|---|
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 808 VARIABLE tC1.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 100.000 | 88.244 | 88.244 | 88.244 | 88.244 |
| j2 | 79.091 | 79.091 | 79.091 | 79.091 | 79.091 |
| j3 | 100.000 | 100.000 | 100.000 | 100.000 | 70.720 |
| j4 | 100.000 | 100.000 | 100.000 | 70.000 | 70.000 |
| j5 | 100.000 | 87.143 | 87.143 | 87.143 | 87.143 |

---- 808 VARIABLE TK1.L Sink temperature

j1 88.244, j2 79.091, j3 70.720, j4 70.000, j5 87.143

---- 808 VARIABLE TOUTC2.L

j1 70.000, j2 70.000, j3 70.000, j4 70.000, j5 70.000

---- 808 PARAMETER TS Source temperature (degree celcius)

i1 120.000, i2 100.000, i3 130.000, i4 140.000, i5 80.000

---- 808 VARIABLE F1.L Splitting Flowrate

| | j1 | j2 | j3 | j5 |
|---|---|---|---|---|
| i3 | 2.643 | | | 1.857 |
| i4 | 0.341 | | | |
| i5 | | 3.636 | 0.864 | |

---- 808 VARIABLE FK2.L

j1 7.016, j2 0.364, j3 11.136, j4 8.000, j5 4.643

---- 808 VARIABLE TK1.L Sink temperature

j1 88.244, j2 79.091, j3 70.720, j4 70.000, j5 87.143

---- 808 PARAMETER FKL Sink flowrate (ton per h)

j1 10.000, j2 4.000, j3 12.000, j4 8.000, j5 6.500

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 27

General Algebraic Modeling System

Equation Listing SOLVE MIX2 Using NLP From line 843

MODEL STATISTICS

| | | | |
|---|---|---|---|
| BLOCKS OF EQUATIONS | 12 | SINGLE EQUATIONS | 64 |
| BLOCKS OF VARIABLES | 15 | SINGLE VARIABLES | 99 |
| NON ZERO ELEMENTS | 380 | NON LINEAR N-Z | 250 |

```
DERIVATIVE POOL          10    CONSTANT POOL          21
CODE LENGTH            470
GENERATION TIME    =     0.079 SECONDS     3 MB  24.2.1 r43572 WEX-WEI
EXECUTION TIME     =     0.079 SECONDS     3 MB  24.2.1 r43572 WEX-WEI
GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 30
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Solution Report     SOLVE MIX2 Using NLP From line 843
          S O L V E     S U M M A R Y
   MODEL   MIX2            OBJECTIVE  FCost2
   TYPE    NLP             DIRECTION  MINIMIZE
   SOLVER  CONOPT          FROM LINE  843
*** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS     2 Locally Optimal
**** OBJECTIVE VALUE          67500.0000

 RESOURCE USAGE, LIMIT          0.015      1000.000
 ITERATION COUNT, LIMIT         4    2000000000
 EVALUATION ERRORS              0             0
CONOPT 3         24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
   C O N O P T 3   version 3.15M
   Copyright (C)   ARKI Consulting and Development A/S
                   Bagsvaerdvej 246 A
    DK-2880 Bagsvaerd, Denmark
 ** Warning **  The number of nonlinear derivatives equal to zero
                in the initial point is large (= 31 percent).
                A better initial point will probably help the
                optimization.
 ** Optimal solution. There are no superbasic variables.
 CONOPT time Total                          0.001 seconds
   of which: Function evaluations           0.000 =  0.0%
             1st Derivative evaluations     0.000 =  0.0%
**** REPORT SUMMARY :        0     NONOPT
```

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 31

General Algebraic Modeling System

Execution

---- 844 VARIABLE TS2.L

i1 84.048, i2 100.000, i3 130.000, i4 85.846

---- 844 VARIABLE F2.L Splitting Flowrate

| | j3 | j4 |
|---|---|---|
| i4 | 5.023 | 3.636 |

---- 844 VARIABLE FFW2.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 844 VARIABLE TS2.L

i1 84.048, i2 100.000, i3 130.000, i4 85.846

---- 844 VARIABLE TK1.L Sink temperature

j1 88.244, j2 79.091, j3 70.720, j4 70.000, j5 87.143

---- 844 VARIABLE TK2.L ddddd

j1 25.000, j2 25.000, j3 52.443, j4 52.657, j5 25.000

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 32

General Algebraic Modeling System

Equation Listing SOLVE WHEN2 Using MINLP From line 872

MODEL STATISTICS

BLOCKS OF EQUATIONS 34 SINGLE EQUATIONS 602

BLOCKS OF VARIABLES 31 SINGLE VARIABLES 639

NON ZERO ELEMENTS 2,263 NON LINEAR N-Z 170

DERIVATIVE POOL 10 CONSTANT POOL 19

CODE LENGTH 420 DISCRETE VARIABLES 135

GENERATION TIME = 0.015 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

EXECUTION TIME = 0.015 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 35

```
General Algebraic Modeling System
Solution Report   SOLVE WHEN2 Using MINLP From line 872
  S O L V E     S U M M A R Y
   MODEL   WHEN2            OBJECTIVE  O3
   TYPE    MINLP            DIRECTION  MINIMIZE
   SOLVER  DICOPT           FROM LINE  872
**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      8 Integer Solution
**** OBJECTIVE VALUE         198958.7750
 RESOURCE USAGE, LIMIT          1.094      1000.000
 ITERATION COUNT, LIMIT      8929    2000000000
 EVALUATION ERRORS              0             0
 ----------------------------------------------------------------
Dicopt        24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
 ----------------------------------------------------------------
    Aldo Vecchietti and Ignacio E. Grossmann
    Engineering Design Research Center
    Carnegie Mellon University
    Pittsburgh, Pennsylvania 15213
 ----------------------------------------------------------------
CONOPT 3       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
   C O N O P T 3   version 3.15M
   Copyright (C)   ARKI Consulting and Development A/S
                   Bagsvaerdvej 246 A
    DK-2880 Bagsvaerd, Denmark
   The model has 639 variables and 602 constraints
   with 2263 Jacobian elements, 170 of which are nonlinear.
   The Hessian of the Lagrangian has 0 elements on the diagonal,
   65 elements below the diagonal, and 75 nonlinear variables.
 ** Warning **  The variance of the derivatives in the initial
                point is large (= 6.3 ). A better initial
                point, a better scaling, or better bounds on the
```

variables will probably help the optimization.

** Optimal solution. Reduced gradient less than tolerance.

CONOPT time Total 0.026 seconds

of which: Function evaluations 0.000 = 0.0%

1st Derivative evaluations 0.000 = 0.0%

--- GMO Resort Time 0ms

IBM ILOG CPLEX 24.2.1 r43572 Released Dec 9, 2013 WEI x86_64/MS Windows

--- GAMS/Cplex licensed for continuous and discrete problems.

Cplex 12.6.0.0

Unable to load names.

MIP status(101): integer optimal solution

Cplex Time: 0.45sec (det. 148.95 ticks)

Fixing integer variables, and solving final LP...

Fixed MIP status(1): optimal

Cplex Time: 0.00sec (det. 0.61 ticks)

Proven optimal solution.

MIP Solution: 193254.315229 (7722 iterations, 1364 nodes)

Final Solve: 193254.315229 (11 iterations)

Best possible: 193254.315229

Absolute gap: 0.000000

Relative gap: 0.000000

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

GAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 36

General Algebraic Modeling System

Execution

---- 873 VARIABLE q2.L Heat exchanged between hot stream i and cold stream j at stage k

| | firstloca~ | location2 | location4 |
|---|---|---|---|
| i1.j2 | 19.091 | | |
| i2.j1 | | 368.352 | |

i2.j5 243.750

i3.j3 228.114

i3.j4 161.867

---- 873 VARIABLE z2.L Binary variable to denote existence of match ij in st k

| | firstloca~ | location2 | location4 |
|---|---|---|---|
| i1.j2 | 1.000 | | |
| i2.j1 | | 1.000 | |
| i2.j5 | | 1.000 | |
| i3.j3 | 1.000 | | |
| i3.j4 | | | 1.000 |

---- 873 VARIABLE qhu2.L Heat exchanged between cold stream j and hot utility

( ALL 0.000 )

---- 873 VARIABLE zhu2.L Binary variable to denote existence of hot utility with cold stream

j1 1.000, j2 1.000, j3 1.000, j4 1.000, j5 1.000

---- 873 VARIABLE qcu2.L Heat exchanged between hot stream i and cold utility

i1 548.409, i2 122.898, i3 135.019

---- 873 VARIABLE zcu2.L Binary variable to denote existence of cold utility hot stream i

i1 1.000, i2 1.000, i3 1.000

---- 873 VARIABLE Oqhu2.L = 0.000 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu2.L = 806.326 Overall heat exchanged between hot stream i and cold utility

---- 873 VARIABLE tH2.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 84.048 | 82.229 | 82.229 | 82.229 | 82.229 |
| i2 | 100.000 | 100.000 | 41.705 | 41.705 | 41.705 |
| i3 | 130.000 | 86.550 | 86.550 | 86.550 | 55.718 |
| i4 | 85.846 | 85.846 | 85.846 | 85.846 | 85.846 |

---- 873 VARIABLE tC2.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 70.000 | 70.000 | 25.000 | 25.000 | 25.000 |
| j2 | 70.000 | 25.000 | 25.000 | 25.000 | 25.000 |
| j3 | 70.000 | 52.443 | 52.443 | 52.443 | 52.443 |

```
j4    70.000    70.000    70.000    70.000    52.657
j5    70.000    70.000    25.000    25.000    25.000

----  873 VARIABLE TS2.L

i1  84.048,   i2 100.000,   i3 130.000,   i4  85.846

----  873 VARIABLE F2.L  Splitting Flowrate

        j3        j4

i4     5.023     3.636

----  873 VARIABLE FFW2.L  Freshwater flowrate

j1 7.016,   j2 0.364,   j3 6.114,   j4 4.364,   j5 4.643

----  873 VARIABLE TK2.L  ddddd

j1 25.000,   j2 25.000,   j3 52.443,   j4 52.657,   j5 25.000

----  873 VARIABLE TS2.L

i1  84.048,   i2 100.000,   i3 130.000,   i4  85.846

----  873 VARIABLE TOUTC2.L

j1 70.000,   j2 70.000,   j3 70.000,   j4 70.000,   j5 70.000


----  873 VARIABLE O3.L             =  198958.775  Objective 3

         VARIABLE OCosthu2.L       =       0.000

         VARIABLE OCostcu2.L       =  152395.568

GAMS 24.2.1  r43572 Released Dec  9, 2013 WEX-WEI x86_64/MS Windows 03/31/14 14:54:02 Page 37

G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m

Equation Listing    SOLVE WHEN2A Using MINLP From line 927

MODEL STATISTICS

BLOCKS OF EQUATIONS        42    SINGLE EQUATIONS         858

BLOCKS OF VARIABLES        44    SINGLE VARIABLES         912

NON ZERO ELEMENTS       3,285    NON LINEAR N-Z           655

DERIVATIVE POOL            10    CONSTANT POOL             24

CODE LENGTH             2,315

GENERATION TIME    =     0.016 SECONDS      3 MB  24.2.1 r43572 WEX-WEI

EXECUTION TIME     =     0.032 SECONDS      3 MB  24.2.1 r43572 WEX-WEI

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G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
```

```
Solution Report     SOLVE WHEN2A Using MINLP From line 927

 S O L V E      S U M M A R Y

   MODEL   WHEN2A          OBJECTIVE  O32
   TYPE    MINLP           DIRECTION  MINIMIZE
   SOLVER  DICOPT          FROM LINE  927

**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      2 Locally Optimal
**** OBJECTIVE VALUE        229816.9353

 RESOURCE USAGE, LIMIT          0.141      1000.000
 ITERATION COUNT, LIMIT        33    2000000000
 EVALUATION ERRORS              0             0

-------------------------------------------------------------------
Dicopt        24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows
-------------------------------------------------------------------
   Aldo Vecchietti and Ignacio E. Grossmann
   Engineering Design Research Center
   Carnegie Mellon University
   Pittsburgh, Pennsylvania 15213
-------------------------------------------------------------------
CONOPT 3       24.2.1 r43572 Released Dec  9, 2013 WEI x86_64/MS Windows

  C O N O P T 3   version 3.15M
  Copyright (C)   ARKI Consulting and Development A/S
                  Bagsvaerdvej 246 A
   DK-2880 Bagsvaerd, Denmark

  The model has 912 variables and 858 constraints
  with 3285 Jacobian elements, 655 of which are nonlinear.
  The Hessian of the Lagrangian has 140 elements on the diagonal,
  305 elements below the diagonal, and 470 nonlinear variables.

 ** Warning **  The variance of the derivatives in the initial
                point is large (= 5.6 ). A better initial
                point, a better scaling, or better bounds on the
                variables will probably help the optimization.
```

** Optimal solution. Reduced gradient less than tolerance.

CONOPT time Total 0.141 seconds

of which: Function evaluations 0.080 = 56.7%

1st Derivative evaluations 0.015 = 10.6%

**** REPORT SUMMARY : 0 NONOPT

0 INFEASIBLE

0 UNBOUNDED

0 ERRORS

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General Algebraic Modeling System

Execution

---- 928 VARIABLE q1.L Heat exchanged between hot stream i and cold stream jat stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 280.000 | |
| i1.j5 | 97.500 | | |
| i4.j1 | 137.159 | | |
| i4.j3 | | | 409.924 |

---- 928 VARIABLE z1.L Binary variable to denote existence of match ij in stage k

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 1.000 | |
| i1.j5 | 1.000 | | |
| i4.j1 | 1.000 | | |
| i4.j3 | | | 1.000 |

---- 928 VARIABLE qhu1.L Heat exchanged between cold stream j and hot utility

j2 97.576

---- 928 VARIABLE zhu1.L Binary variable to denote existence of hot utility with cold stream

j2 1.000

---- 928 VARIABLE qcu1.L Heat exchanged between hot stream i and cold utility

( ALL 0.000 )

---- 928 VARIABLE zcu1.L Binary variable to denote existence of cold utility with hot stream i

( ALL 0.000 )

---- 928 VARIABLE Oqhu1.L = 97.576 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu1.L = 0.000 Overall heat exchanged between hot stream i and cold utility

---- 928 VARIABLE A1.L

| | firstloca~ | location3 | location4 |
|---|---|---|---|
| i1.j4 | | 45.507 | |
| i1.j5 | 8.971 | | |
| i4.j1 | 7.019 | | |
| i4.j3 | | | 40.488 |

---- 928 VARIABLE Ahu1.L

j2 3.677

---- 928 VARIABLE tH1.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 120.000 | 110.714 | 110.714 | 84.048 | 84.048 |
| i2 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| i3 | 130.000 | 130.000 | 130.000 | 130.000 | 130.000 |
| i4 | 140.000 | 126.423 | 126.423 | 126.423 | 85.846 |
| i5 | 80.000 | 80.000 | 80.000 | 80.000 | 80.000 |

---- 928 VARIABLE tC1.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 100.000 | 88.244 | 88.244 | 88.244 | 88.244 |
| j2 | 79.091 | 79.091 | 79.091 | 79.091 | 79.091 |
| j3 | 100.000 | 100.000 | 100.000 | 100.000 | 70.720 |
| j4 | 100.000 | 100.000 | 100.000 | 70.000 | 70.000 |
| j5 | 100.000 | 87.143 | 87.143 | 87.143 | 87.143 |

---- 928 VARIABLE WW1.L Source Waste water

i1 9.000, i2 9.000, i3 4.500, i4 8.659

---- 928 VARIABLE TK1.L Sink temperature

j1 88.244, j2 79.091, j3 70.720, j4 70.000, j5 87.143

---- 928 PARAMETER TOUTC outlet temperature of cold stream (degree celcius)

j1 100.000, j2 100.000, j3 100.000, j4 100.000, j5 100.000

---- 928 VARIABLE q2.L Heat exchanged between hot stream i and cold stream jat stage k

firstloca~ location2 location4

i1.j2 19.091

i2.j1 368.352

i2.j5 243.750

i3.j3 228.114

i3.j4 161.867

---- 928 VARIABLE z2.L Binary variable to denote existence of match ij in stage k

firstloca~ location2 location4

i1.j2 1.000

i2.j1 1.000

i2.j5 1.000

i3.j3 1.000

i3.j4 1.000

---- 928 VARIABLE qhu2.L Heat exchanged between cold stream j and hot utility

( ALL 0.000 )

---- 928 VARIABLE zhu2.L Binary variable to denote existence of hot utility with cold stream

( ALL 0.000 )

---- 928 VARIABLE qcu2.L Heat exchanged between hot stream i and cold utility

i1 548.409, i2 122.898, i3 135.019

---- 928 VARIABLE zcu2.L Binary variable to denote existence of cold utilitywith hot stream i

i1 1.000, i2 1.000, i3 1.000

---- 928 VARIABLE Oqhu2.L = 0.000 Overall heat exchanged between cold streamj and hot utility

VARIABLE Oqcu2.L = 806.326 Overall heat exchanged between hot stream i and cold utility

---- 928 VARIABLE A2.L

firstloca~ location2 location4

i1.j2 1.248

i2.j1 32.449

i2.j5 21.472

i3.j3 9.954

i3.j4 40.878

---- 928 VARIABLE Acu2.L

i1 29.543, i2 11.794, i3 9.965

---- 928 VARIABLE Ahu2.L

( ALL 0.000 )

---- 928 VARIABLE Costh1.L = 39143.857

VARIABLE Costhu1.L = 9380.902

VARIABLE OCosthu1.L = 36786.061

VARIABLE O32.L = 229816.935 Objective 3.2

VARIABLE Costh2.L = 48531.049

VARIABLE Costhu2.L = 0.000

VARIABLE OCosthu2.L = 0.000

VARIABLE Costcu2.L = 28890.318

VARIABLE OCostcu2.L = 152395.568

VARIABLE O22.L = 85310.820 Objective 2.2

VARIABLE O32.L = 229816.935 Objective 3.2

VARIABLE FCost2.L = 67500.000

VARIABLE PIC11 L = 911.171 Piping cost of sourceto sink

VARIABLE PICost2 L = 2442.504 Piping cost

---- 928 VARIABLE tH2.L Temperature of hot stream i at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| i1 | 84.048 | 82.229 | 82.229 | 82.229 | 82.229 |
| i2 | 100.000 | 100.000 | 41.705 | 41.705 | 41.705 |
| i3 | 130.000 | 86.550 | 86.550 | 86.550 | 55.718 |
| i4 | 85.846 | 85.846 | 85.846 | 85.846 | 85.846 |

---- 928 VARIABLE tC2.L Temperature of cold stream j at location k

| | firstloca~ | location2 | location3 | location4 | lastlocat~ |
|---|---|---|---|---|---|
| j1 | 70.000 | 70.000 | 25.000 | 25.000 | 25.000 |
| j2 | 70.000 | 25.000 | 25.000 | 25.000 | 25.000 |
| j3 | 70.000 | 52.443 | 52.443 | 52.443 | 52.443 |
| j4 | 70.000 | 70.000 | 70.000 | 70.000 | 52.657 |
| j5 | 70.000 | 70.000 | 25.000 | 25.000 | 25.000 |

---- 928 VARIABLE WW2.L Source Waste water

i1 9.000, i2 9.000, i3 4.500

---- 928 VARIABLE FFW2.L Freshwater flowrate

j1 7.016, j2 0.364, j3 6.114, j4 4.364, j5 4.643

---- 928 VARIABLE F2.L Splitting Flowrate

| | j3 | j4 |
|---|---|---|
| i4 | 5.023 | 3.636 |

---- 928 VARIABLE TK2.L ddddd

j1 25.000, j2 25.000, j3 52.443, j4 52.657, j5 25.000

---- 928 VARIABLE TOUTC2.L

j1 70.000, j2 70.000, j3 70.000, j4 70.000, j5 70.000

---- 928 VARIABLE O3.L = 198958.775 Objective 3

VARIABLE O32.L = 229816.935 Objective 3.2

VARIABLE Atot1.L = 105.662

VARIABLE Atot2.L = 157.303

VARIABLE AREA.L = 262.965 Total Area

VARIABLE TAC2.L = 385981.430 Total annual cost 2

---- 928 PARAMETER TS Source temperature (degree celcius)

i1 120.000, i2 100.000, i3 130.000, i4 140.000, i5 80.000

---- 928 VARIABLE FS2.L

i1 9.000, i2 9.000, i3 4.500, i4 8.659

---- 928 VARIABLE F1.L Splitting Flowrate

| | j1 | j2 | j3 | j5 |
|---|---|---|---|---|
| i3 | 2.643 | | | 1.857 |
| i4 | 0.341 | | | |
| i5 | | 3.636 | 0.864 | |

---- 928 VARIABLE TK2.L ddddd

j1 25.000, j2 25.000, j3 52.443, j4 52.657, j5 25.000

---- 928 VARIABLE FK2.L

j1 7.016, j2 0.364, j3 11.136, j4 8.000, j5 4.643

---- 928 VARIABLE TK1.L Sink temperature

j1 88.244, j2 79.091, j3 70.720, j4 70.000, j5 87.143

---- 928 PARAMETER FKL Sink flowrate (ton per h)

j1 10.000, j2 4.000, j3 12.000, j4 8.000, j5 6.500

EXECUTION TIME = 0.000 SECONDS 3 MB 24.2.1 r43572 WEX-WEI

USER: The Petroleum and Petrochemical College G131219:2228AS-WIN

Chulalongkorn University DC4365

License for teaching and research at degree granting institutions

*** FILE SUMMARY

Input C:\Users\Sarut\Desktop\WORK\Thesis water network\GAMS 24.2\WHEN case 4.2.gms

Output C:\Users\Sarut\Documents\gamsdir\projdir\WHEN case 4.2.lst

# CURRICULUM VITAE

**Name:** Mr. Sarut Thongpreecha

**Date of Birth:** October25, 1989

**Nationality:** Thai

**University Education:**

2008-2012 Bachelor Degree of Science, Major of Chemical Technology, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

**Work Experience:**

Mar – June 2011 Position: Student Internship

Company name:Siam Chemical Industry Co., Ltd.

**Papers presented at conferences**

**Proceedings:**

1. Thongpreecha, S., Siemanond, K. (2014, April) Sequential Approach for Water-and-Heat-Exchanger Network Design. Proceedings of the 5th Research Symposium on Petrochemical and Materials Technology and the 20th PPC Symposium on Petroleum, Petrochemicals, and Polymers, Ballroom, Queen Sirikit National Convention Center, Bangkok, Thailand.
2. Thongpreecha, S., Siemanond, K. (2014, June) Water Network Design with Treating Units by Four-Step Calculation Procedure. Proceedings of the 24th European Symposium on Computer Aided Process Engineering (ESCAPE 24), Hungarian Academy of Sciences,Budapest, Hungary.
3. Thongpreecha, S., Siemanond, K. (2014, August) Water and Heat Exchanger Network Design for Fixed-flowrate System. Proceedings of the 17th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRESS 2014),Clarion Congress Hotel,Prague, Czech Republic.

**Presentations:**

1. Thongpreecha, S., Siemanond, K. (2014, April 22) Sequential Approach for Water-and-Heat-Exchanger Network Design. Paper poster presented at the 5th Research Symposium on Petrochemical and Materials Technology and the 20th PPC Symposium on Petroleum, Petrochemicals, and Polymers. Ballroom, Queen Sirikit National Convention Center, Bangkok, Thailand.
2. Thongpreecha, S., Siemanond, K. (2014, June 15-18) Water Network Design with Treating Units by Four-Step Calculation Procedure. Oral presentation at the 24th European Symposium on Computer Aided Process Engineering (ESCAPE 24), Hungarian Academy of Sciences,Budapest, Hungary.