SIMULATION PROGRAM AS AN AID TO PROCESS DESIGN: THE CASE OF SMALL SCALE SUGAR EQUIPMENT.

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ABSTRACT

The program described here has been developed to serve as a design tool to assist in the evaluation of small scale sugar production plant which is made of batch and semi-continuous units. The governing theory for designing such a plant has been highlighted and the equations developed into a FORTRAN 77. Some examples of simulation results have been presented and compared with performance of the existing sugar plant.

INTRODUCTION

Execution of process design often involves synthesis, analysis, evaluation and optimization[1]. Synthesis is a step where structures and their inter connections that can meet stated design requirement are created. Analysis refers to the act of modelling and then solving the resultant equations to predict how a selected structure would behave if it was constructed. Evaluation is the activity of placing a worth on the structure where worth might be its cost, safety, or energy requirements. Optimization is the systematic searching over the allowed operating conditions to improve the evaluation as much as possible.

In carrying out process design through these steps, an engineer is likely to encounter a wide range of data which makes evaluation an enormous task if it has to be accomplished manually. Thus to improve process design the engineer should be complemented by an appropriate software.

Quite a number of computer programs do exists. However, most of them are not readily available, but also these programs may not be appropriate to solve a design problem the engineer might have due to specific nature of the problem.

The objective of this paper is to present description of a program that has been developed to solve a design problem involving small scale sugar production equipment developed by IPI. The paper will present the general features of the program, and some examples of simulation results so as to illustrate the capability of the program.

PROBLEM DEFINITION

Kaunde[2] proposed a design procedure to arrive at an optimum plant consisting of batch and semi-continuous units. The procedure requires that the process be decomposed into a number of sub-processes which can be optimized independently, and then merging the optimized sub-processes to describe an optimum plant. A case study involving design of small scale sugar production plant was used to demonstrate the procedure. The plant had four pieces of units; crusher, evaporator, crystallizer and centrifuge. Accordingly with the proposed design procedure the following sub-processes were identified:

i) Crusher and Evaporator sub-process,
ii) Crystallizer sub-process, and
iii) Centrifuge sub-process.

Synthesis and analysis

The synthesis problem may be stated that - given the required production capacity of a plant (product sugar in this case) what is the best structural layout of the equipment?

i) Crusher and evaporator sub-process

With regard to synthesis four alternative structural layouts (schedules) as proposed by Kaunde [2,3] can be possible. For quicker reference these schedules are reproduced as shown in Appendix A, Fig. A.1 to Fig. A.4. These figures also show the mathematical models for calculating the capacity of batch unit, V, cycle time of a semi-continuous unit, Ts, and capacity of intermediate material store Vint.

ii) Crystallizer sub-process

This is a single stage sub-process consisting of a batch unit. In this case the cycle time is fixed by the process, consequently the number of crystallizer sets is also fixed. That is, each day one set of crystalliser is filled up with syrup from the evaporator while the other set is emptied as massecuite with fully grown crystals is being processed by a centrifuge down stream.

However a crystallizer set can have several vessels arranged in parallel. The design problem with this equipment is therefore one of working out the optimum number of vessels in parallel for each of the crystalliser set.

iii) Centrifuge sub-process:

This is a single stage sub-process containing a batch unit. With this equipment several batches can be processed in a one day working shift. The design problem for this equipment involves specification of an optimum capacity of the centrifuge and the number of batches that can be processed so as to meet the production target.

Evaluation problem

For evaluation purposes the designer would like to know the relationship between the size of each equipment and its related costs. The six tenth rule for calculating various costs has been adapted in our case study, accordingly equations of the type shown below may be employed:

Capital cost

$$CostA = CostB\left(\frac{CapacityA}{CapacityB}\right)^{0.6} \qquad (1)$$

Energy cost of batch unit

$$Eb = P.B.Tb.Yd.p.\left(\frac{V}{V'}\right)^{w}.u \qquad (2)$$

Energy for the semi continuous unit

$$Esc = P.B.Ts.Yd.p.\left(\frac{R}{R'}\right)^{w}.u \qquad (3)$$

Annualized cost:

In its simplest form and as used in this paper annualized cost is the sum of capital cost (reduced to annual basis) and the operating cost per year. It is estimated using the formula:

$$ann = \frac{Capital.Cost}{Plant.life} + op.cost.per.year \qquad (4)$$

The above basic set of equations have been developed into computer statements and included in appropriate subroutines so that they can be used repeatedly when evaluating different pieces of units. The program has been written using the FORTRAN 77 language.

The optimization problem

Within the context of this paper the term optimization refers to identification of the best structure (plant layout, size of each processing unit, or number of batches to be processed over a given time interval) from among the possible alternatives.

Upon identifying the best structural layout, further optimization would refer to determining the best operating condition e.g. temperature, concentration etc. of the chosen structural layout. Optimization of this nature would involve a study in the kinetics of the process which is beyond the scope of this paper.

STRUCTURE OF THE PROGRAM

The program is basically divided into six sections which are inter-linked as shown in Fig 1. The general layout of the individual files and examples of extract of the program statements, data, and results are as shown in Appendix B (B1..B6).

The MAIN program plays a supervisory role for it allows calling other subroutines. This program first opens the file for reading data (**isept.dat**), and the file for writing the results (**isep.res**).

The subroutine SPECS(JFAIL) is then called so as to read the data from **isep.dat** and checking that the data has been entered correctly. In the event that the data is entered wrongly the ERRORS(JFAIL,K) subroutine is called and prints the corresponding error message and causes the program to stop continuing. Otherwise, if no data specification errors have been detected the program continues by calling calculation subroutines and handles calculation errors in the same way as just described above.

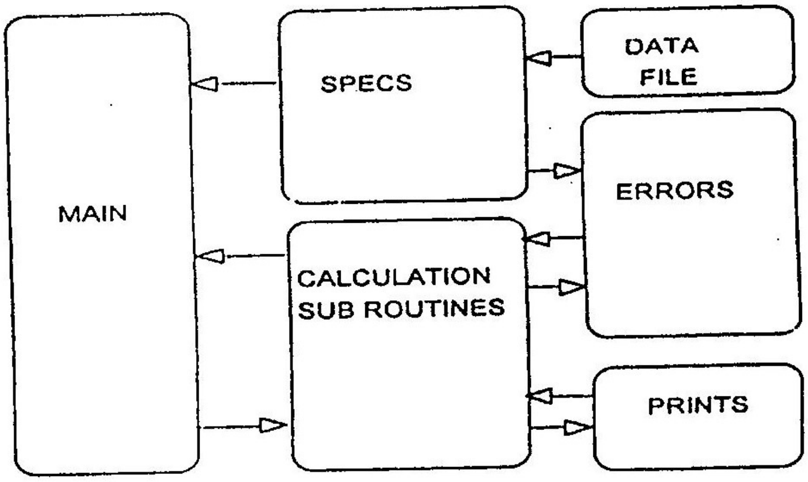


Fig. 1: Structure of the FORTRAN program

As seen from the MAIN program there are four calculation subroutines arranged in a sequence i.e. MASUGAR(JFAIL), CREVMN (JFAIL), CRYSTL(JFAIL), and CENTRIF(JFAIL). The user can make these subroutines active by calling them one at a time through the usual CALL statement.

A brief description of each of these calculation subroutines is as follows:

MASUGAR(JFAIL):

This subroutine carries mass balance calculations round the sugar plant. It calculates flow rates of materials going into the crusher, evaporator, crystallizer, centrifuge and the quantity of molasses produced as the by-product.

CREVMN(JFAIL)

This subroutine is for calculating the capacity of the crusher and evaporator for different alternative schedules shown in Appendix A.

CTCREV(JFAIL)

This subroutine calculates various costs related to economic criteria of the designers choice. Included in this subroutine are the models for calculating capital cost, energy cost and annualized cost.

CRYSTL(JFAIL)

This calculates the optimum capacity, the number of units (vessels) in parallel in one set of crystallizer and corresponding values of the economic objectives.

CENTRIF (JFAIL)

This subroutine calculates the optimum capacity, processing rate and the number of batches that would be required to meet the desired production. The sub-routine also calculates the values of economic objectives.

EXAMPLE OF SIMULATION RESULTS

Examples of simulation results for each of the sub-process of the sugar plant described in the foregoing sections are as follows:

Crusher and evaporator sub-process

With reference to Appendix A, the structural layout schedule 1, 3 and 4 have one crusher and one evaporator each, but their difference lies in the presence of intermediate material stores (schedule 1 vs. 3 and 4) or due to cycle limiting process (schedule 3 vs. 4)

From Fig. 2 we note that by designing the unit to process more batches the annualized cost associated with the schedule to achieve the same production capacity is reduced. This is consistent with the fact that by choosing to operate with more batches a smaller evaporator hence lower capital cost can be specified in each schedule. However the number of batches cannot be increased beyond a certain value. Instead this (the number of batches) will be limited by the available shift working hours. Also too many batches may result in increased operating cost and hence annualized cost. The program has been written in such a way that it stops iterating when the optimum number of batches for each schedule has been found. Further comparison of schedule 1,3 and 4 shows that schedule 3 gives the minimum annualised costs.

With regard to schedule 2, Fig 3 shows the effect on annualized cost due to variation in the number of parallel evaporator units and the number of batches each unit can process during working day shift. These results show that the annualized cost gets smaller with fewer parallel evaporators, and with more batches processed per day shift.

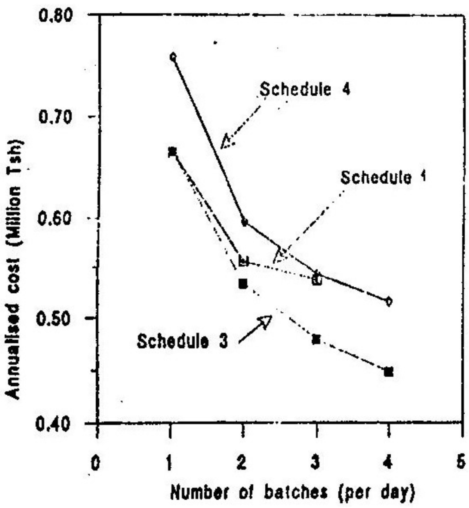
It can also be deduced by comparing the results from Fig 2 and Fig 3. that schedule 3 is the overall best structural layout / mode of operation.

Crystallizer sub-process

Examples of simulation results are as shown in Fig 4. These results shows that the effect of increasing the number of vessels per crystallizer set on the costs (capital, energy, and annualised cost). The results suggest that optimum design of crystalliser set should consist of only one vessel per set.

Centrifuge sub-process

Fig. 5 shows examples of simulation results for the centrifuge. The results show that by choosing to operate with large number of batches per day, a smaller centrifuge will be required, accordingly decrease the capital costs and annualised cost for the unit, but the energy (operating) cost tends to increase.



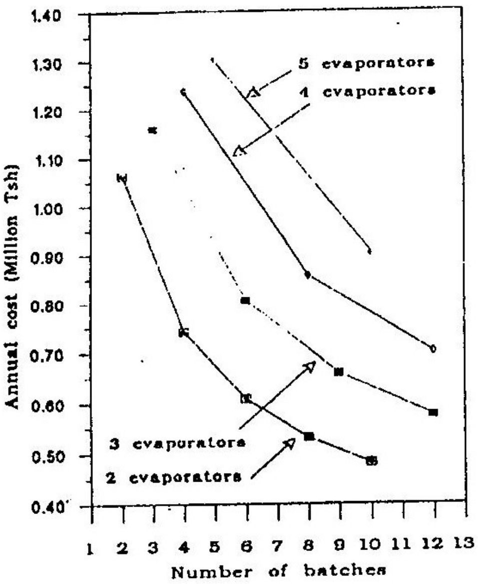


Fig.2 Annualised costs vs number of batches per day (schedule 1,3,4)

Fig. 3: Annula costs vs number of batches per day (schedule 2)

Table 1: Flowsheet epecifications and costs for the optimised sugar plant

	Crusher	Storage	Evaporator	Crystallizer	Centrifuge	
Units in parallel	1	1	1	3	1	
Capacity of unit	13 kg/min	400 kg	487 kg	600 kg	13 kg	
Cycle time	100 min	-	80 min	3 day	10 min	
Total batches/day	4	-	4	1	48	Total cost
Capital (Tsh)	836200	85300	869900	651000	461800	2904200
Energy (Tsh/yr)	32800	-	74000	635000	23600	765400
Annual (Tsh/yr)	200000	17100	248000	765200	116000	1346200

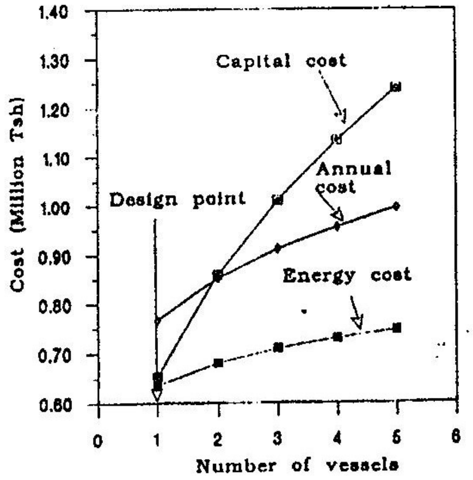


Fig 4: Cost Vs number of parallel of vessel crystallize

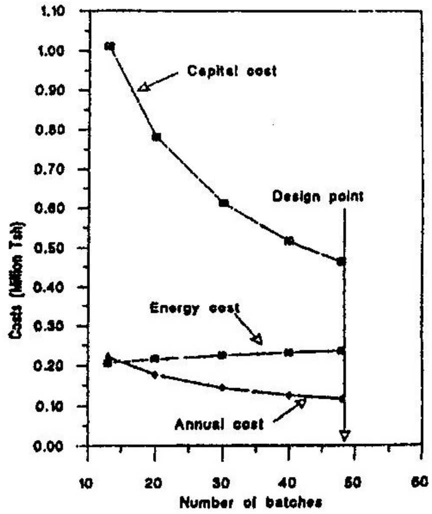


Fig. 5: Costs vs. number batches (centrifuge)

Table 2: Flowsheet specifications and costs for IPI sugar plant

	Crusher	Storage	Evaporator	Crystallizer	Centrifuge	
Units in parallel	1	1	2	3	1	
Capacity of unit	14 kg/min	200 kg	163 kg	600 kg	25 kg	
Cycle time	30 min	-	80 min	2 days	10 min	
Total batches/day	12	-	12	1	24	
						Total costs
Capital (Tsh)	900000	50000	960000	650000	700000	3260000
Energy (Tsh/yr)	33000	-	88800	635000	22000	779000
Annual (Tsh/yr)	213000	10000	280800	765000	162000	1431000

Table 3: Comparison between optimised and existing IPI sugar plant

	IPI Plant	Optimum plant	Savings (Tsh)	Savings in %
Capital (Tsh)	3260000	2904300	35500	11%
Energy (Tsh)	779000	765500	13400	2%
Annual (Tsh)	1431000	1346200	84600	6%

DISCUSSION

A FORTRAN program has been developed to serve as a useful tool for designing and evaluating layout of the small scale sugar equipment. The program has been written in such a way that the user is required to provide data in the data file and identify the subroutines which are necessary to simulate a particular equipment. The subroutines can also be easily structured, edited and modified to accommodate process units or situations which have not been modelled yet.

Using the developed computer program some simulation results have been worked out and presented. From the results it has been possible to draw some useful conclusions on how best the plant layout could be designed. Table 1 summarises the specification of the layout for the optimised simulated plant , whereas Table 2 shows some data from the existing plant.

For simulation purposes some of the coefficients and exponents used in the cost equations were derived from the existing sugar plant whereas for some, empirical values were used. Although these data should be treated with caution, comparison between the existing and the simulated plant as shown in Table 3 suggests there is room for optimising the existing plant. For specific set of data used for simulation, optimisation could result into savings of up to 11% in capital cost, 2% in energy cost, and 6% in annualized cost.

CONCLUSION

An approach for solving a typical optimisation problem of a batch and semi-continuous plant has been illustrated using a small scale sugar production plant as a case study. The use of a specially developed computer program and its benefits in solving such a problem has also been demonstrated. The structure of the program as presented in this paper could help the readers who might wish to develop other programs to assist in solving their specific design problem. With regard to the case study, the simulation results suggest that there is room for optimizing the existing sugar plant.

ACKNOWLEDGEMENT

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NOMENCLATURE

B	number of batches per day processed by a unit	-
Eb	energy cost of batch unit	Tsh/year
ESC	energy cost of semi-continuous unit	Tsh/year
P	number of batches per day treated by a unit	-
Q	production target of sugar	kg/day
R	Processing rate of semi-continuous unit	kg/min
r	pumping rate	kg/min
Si	capacity factor	wt/wt
Tb	cycle time of batch unit	min
Ts	cycle time of semi continuous unit	min
V	Capacity of batch unit	kg
Yd	number of working days per year	days

REFERENCES

1. A.W. Westerberg, H.P. Hutchison, R.L. Motard and P. Winter, Process Flowsheeting, Cambridge University Press (1979).
2. O.K. Kaunde, Flowsheeting approach for batch and semi-continuous plants, *Uhandisi Journal,* Vol 19(2), 1994.
3. O.K. Kaund, Design methods for small scale integrated plants, Ph.D thesis, Department of Chemical Engineering, University of Leeds, UK, 1993.

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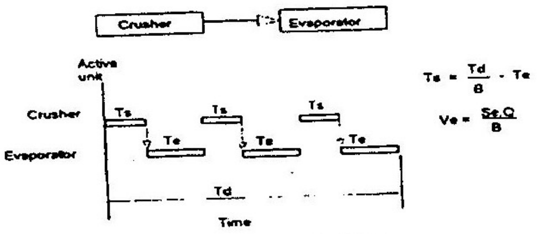
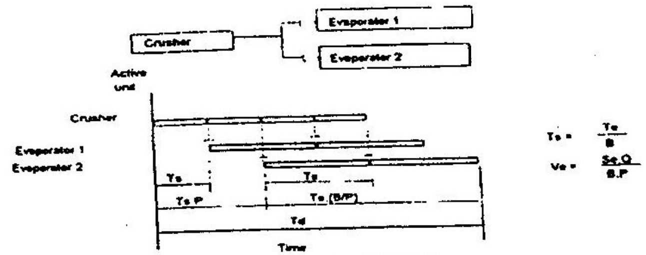
APPENDIX A. SCHEDULES FOR CRUSHER AND EVAPORATOR SUB-PROCESSES



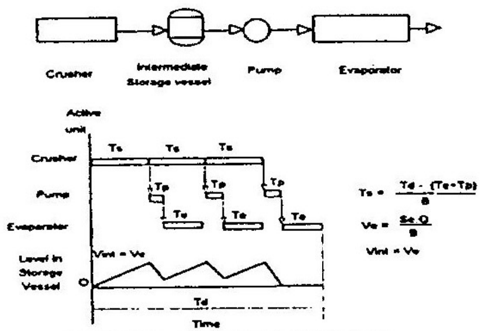
One crusher, one evaporator, non overlapping cycles

Fig. A.1. Crusher and evaporator sub-process (Schedule no. 1)



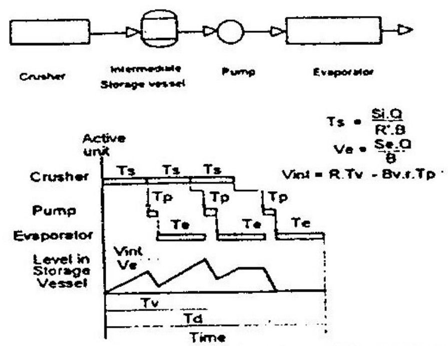
One crusher, two (or more) evaporators, without intermediate vessel.

Fig. A.2. Crusher and evaporator sub-process (Schedule no. 2)



One crusher, one evaporator, intermediate material store, crusher has limiting cycle time (Ts > Te+Tp)

Fig. A.3. Crusher and evaporator sub-process (Schedule no. 3)



One crusher, one evaporator, intermediate material store, evaporator has limiting cycle time (Ts < Te + Tp).

Fig. A.4. Crusher and evaporator sub-process (Schedule no. 4)

APPENDIX B. EXTRACTS OF PROGRAM STATEMENTS

B1. MAIN Program

```
      PROGRAM MAINS

      COMMON IP
      COMMON INP

      COMMON/GENER/Q,TFT,YRP,YD,CTOLD,ECON
      COMMON/CRUSH/SSH,CSH,EXSH,ASH,BPWSH,VSH,RSH,RSHKN,BVSH,TSH
      COMMON/CREVGT/CNB,XSH,XE,SCHD
      COMMON/STORE/RPU,BVMA,EVMAX,TP,VVES,CTVMAX,CVES
      COMMON/EVAP/SE,CE,EXE,AE,BPWE,TE,VE,BVE
      COMMON/CRYSZ/SZ,CZ,EXZ,AZ,BPWZ,TZ,BVZ
      COMMON/CENTR/SFG,CFG,EXFG,AFG,BPWFG,BVFG,TFG,VFGMX
      COMMON/FERMENT/SFM,CFM,EXFM,AFM,BPWFM,TFM,BVFM
      COMMON/SUSLMT/S(5),C(5),EX(5),A(5),BPW(5),YR(5),X(5),BV(5)
      CHARACTER*3 ECON

      IP=4
      INP=2
      open unit=2,file='isep.dat',status='old',form='formated')
      open (unit=4,file='isep.res',status='old')

      PROGRAM FOR OPTIMISATION OF SUGAR/DISTILLATION PLANTS.

      READIND AND TESTING DATA, PRINTING ERROR MESSAGES

      CALL SPECS(JFAIL)

      IF (JFAIL.EQ.1) CALL ERROR(JFAIL,1)

      WRITE(*,100)
  100 FORMAT(' CALCULATION IN PROGRESSS')

:     SUGAR PLANT. THREE EVALUATION CRITERIA.
: *** ALTER "DO STATEMENT" TO CHOOSE EVALUATION CRITERIA

      DO 2 N =1,2
         IF (N.EQ.1) ECON = 'CAP'
         IF (N.EQ.2) ECON = 'ENG'
         IF (N.EQ.3) ECON = 'ANN'

      CALL MASUGAR(JFAIL)
      CALL CREVMN(JFAIL)
      CALL CRYSTL(JFAIL)
      CALL CENTRIF(JFAIL)
      CALL FERMEN(JFAIL)

    2 CONTINUE
      WRITE(*,102)
  102 FORMAT(' CALCULATION COMPLETED')

      STOP
      END
```

B2. isep.dat file

```
300.      (Q      KG/DAY     PRODUCTION CAPACITY OF SUGAR)
480.       (TFT   MIN        SHIFT WORKING TIME)
105.       (YD    DAYS       NUMBER OF WORKING DAYS PER YEAR)
5.         (YRP   YEARS      EXPECTED PLANT LIFE)
80.        (TE    MIN        CYCLE TIME OF EVAPORATOR)
3.         (TZ    DAYS       CYCLE TIME OF CRYSTALLIZER)
10.        (TFG   MIN        CYCLE TIME OF CENTRIFUGE)
4.         (TFM   DAYS       CYCLE TIME OF FERMENTER)
14.2       (RSHKN KG/MIN     CRUSHING RATE IF KNOWN - CREV4)
400.       (RPU   KG/MIN     CAPACITY OF PUMP)
50000.     (BVMA  TSH        BASE COST OF MATERIAL STORE)
 .6        (EVMAX TSH        CAPITAL COST EXPONENT OF MATERIAL STORE)
200.       (CVES   KG        BASE CAPACITY OF INTERMEDIATE STORAGE VESSEL)
16.7      (SSH    WT/WT   CAPACITY FACTOR                        ****CRUSHER)
14.2       (BVSH  KG/MIN     BASE CAPACITY OF CRUSHER - CRUSHING RATE)
900000.    (CSH   TSH        CAPITAL COST OF BASE UNIT)
 .6        (EXSH   -         CAPITAL COST EXPONENT)
7.         (ASH   TSH/KWH    UNIT COST OF ENERGY)
7.5        (BPWSH  KW        POWER CONSUMPTION OF BASE UNIT)
6.5       (SE     WT/WT   CAPACITY FACTOR                        ****EVAPORATOR)
162.5      (BVE KG/BATCH     BASE CAPACITY)
450000.    (CE     TSH       CAPITAL COST OF BASE UNIT)
 .6        (EXE     -        CAPITAL COST EXPONENT)
 .24       (AE    TSH/KWH    UNIT COST OF ENERGY)
205.       (BPWE   KW        POWER CONSUMPTION OF BASE UNIT)
2.        (SZ      WT/WT CAPACITY FACTOR                         ****CRYSTALLIZER)
600.       (BVZ KG/BATCH     BASE CAPACITY )
217000.    (CZ     TSH       CAPITAL COST OF BASE UNIT)
 .6        (EXZ     -        CAPITAL COST EXPONENT)
7.         (AZ    TSH/KWH    UNIT COST OF ENERGY)
12.        (BPWZ   KW        POWER CONSUMPTION OF BASE UNIT)
2.        (SFG    WT/WT   CAPACITY FACTOR                        ****CENTRIFUGE)
25.        (BVFG KG/BATCH    BASE CAPACITY)
700000.    (CFG    TSH       CAPITAL COST OF BASE UNIT)
 .6        (EXFG    -        CAPITAL COST EXPONENT)
7.         (AFG  TSH/KWH     UNIT COST OF ENERGY)
7.5        (BPWFG   KW       POWER CONSUMPTION OF BASE UNIT)
 .8       (SFM    WT/WT   CAPACITY FACTOR                        ****FERMENTER)
960.       (BVFM KG/BATCH    BASE CAPACITY )
960000.    (CFM    TSH       CAPITAL COST OF BASE UNIT)
 .6        (EXFM    -        CAPITAL COST EXPONENT)
 .0001     (AFM  TSH/KWH     UNIT COST OF ENERGY)
 .0001     (BPWFM   KW       POWER CONSUMPTION OF BASE UNIT)
```

B3. SPECS file

```
C-------------------------------------------------------------
C      READING SPECIFICATIONS
C-------------------------------------------------------------
       SUBROUTINE SPECS(JFAIL)
       COMMON IP
       COMMON INP
       COMMON/GENER/Q,TFT,YRP,YD,CTOLD,ECO
       COMMON/CRUSH/SSH,CSH,EXSH,ASH,BPWSH,VSH,RSH,RSHKN,BVSH,TSH
       COMMON/CREVDT/CNB,XSH,XE,SCHD
       COMMON/EVAP/SE,CE,EXE,AE,BPWE,TE,VE,BVE
       COMMON/STORE/RPU,BVMA,EVMAX,TP,VVES,CTVMAX,CVES
       COMMON/CRYSZ/SZ,CZ,EXZ,AZ,BPWZ,TZ,BVZ
       COMMON/CENTR/SFG,CFG,EXFG,AFG,BPWFG,BVFG,TFG,VFGHX
       COMMON/FERMENT/SFM,CFM,EXFM,AFM,BPWFM,TFM,BVFM
       CHARACTER*3 ECON

       ...........
       READ(INP,*) YRP
       IF(YRP.LE.4..OR.YRP.GT.15.) CALL ERROR(JFAIL,2)
       READ(INP,*)TFT
       IF(TFT.LE.400..OR.TFT.GT.720.)CALL ERROR(JFAIL,3)

       ...........

    22 CONTINUE

       RETURN

       END
```

B4. ERRORS file

```
C-------------------------------------------------------------
C      CHECKING ERRORS
C-------------------------------------------------------------
C
       SUBROUTINE ERROR(JFAIL,K)
       COMMON IP

       IF(K.NE.1 ) GOTO 2
       WRITE(*,1001)
  1001 FORMAT('ERROR NO. 1; ERRORS STOP PROGRAM EXECUTION
       JFAIL=1
       STOP

     2 IF(K.NE.2 ) GOTO 3
       WRITE(*,1002)
  1002 FORMAT('ERROR NO. 2; EXPECTED PLANT LIFE
       JFAIL=1
       RETURN

     3 IF(K.NE.3 ) GOTO 4
       WRITE(*,1003)
  1003 FORMAT('ERROR NO. 3: SHIFT WORKING TIME
       JFAIL=1
       RETURN

       ..........

   100 CONTINUE
       WRITE (*,101)
   101 FORMAT('ERROR NUMBER NOT RECOGNISED')
       STOP
       END
```

B5. PRINTS file

```
C -------------------------------------------------------------
C    PRINTING RESULTS
C-------------------------------------------------------------
      SUBROUTINE PRINTS(L,J)
      COMMON IP
      COMMON/GENER/Q,TFT,YRP,YD,CTOLD,ECON
      COMMON/RESMAS/FSH,FE,FZ,FFG,FFM,FFWT,PCOL
      COMMON/CRUSH/SSH,CSH,EXSH,ASH,BPWSH,VSH,RSH,RSHKN,BVSH,TSH

      ...........

      WRITE(IP,1001)ECON,Q,FSH,FE
 1001 FORMAT('RESULTS OF SUGAR PLANT ',
     */,'EVALUATION CRITERIA USED   ____________',A3,
     *//,'PRODUCTION OF SUGAR REQUIRED  KG/Day = ',F13.2,
     */,'CANE CRUSHED                  Kg/Day      ',F13.2,
     */,'JUICE PROCESSED               Kg/Day      ',F13.2,
     */,'EXPECTED PLANT LIFE            years      ',F13.2)

    5 IF (L.NE.1) GOTO 10
      WRITE(IP,1000)SCHD,ECON,RSH,TSH,CNB,CTSH,EMSH
 1000 FORMAT(/, 'SCHEDULE NO.        = ',F4.1,' .....',A3,
     */,'-------------------------------',
     */,'CRUSHER SPECIFICATIONS:',
     */,'CRUSHING RATE            Kg/Min =',F13.2,
     */,'CYCLE TIME               Min    =',F13.2,
     */,'NO OF BATCHES PER DAY           =',F13.2,
     */,'CAPITAL COST             Tsh    =',F13.2,
     */,'ENERGY COST              Tsh/Yr =',F13.2)

      ............

  180 CONTINUE

      RETURN
      END
```

B6. isep.res file

```
RESULTS OF SUGAR PLANT

EVALUATION CRITERIA USED    ____________CAP

PRODUCTION OF SUGAR REQUIRED  KG/Day            300.00
CANE CRUSHED                Kg/Day             5010.00
JUICE PROCESSED             Kg/Day             1950.00
EXPECTED PLANT LIFE          years                5.00

SCHEDULE NO.       =  1.0 .....CAP
--------------------------------
CRUSHER SPECIFICATIONS:
CRUSHING RATE             Kg/Min -        20.88
CYCLE TIME                Min    -        80.00
NO OF BATCHES PER DAY            -         3.00
CAPITAL COST              Tsh    -   1134084.50
ENERGY COST               Tsh/Yr -     31189.83

.............
```