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FLEXIBILITY ANALYSIS OF A FOOD PROCESSING INDUSTRY

J. R. KHAN[1], *W. REHMAN[2] and M. S. TAHIR[3]

[1]NFC Institute of Engineering and Fertilizer Research, Faisalabad, Pakistan

[2]COMSATS Institute of Information Technology, Lahore, Pakistan

[3]Department of Chemical Engineering and Environmental Technology, Graz University of Technology, Austria

In this article, the flexibility analysis of a food processing industry (sugar) is carried out. The system is analysed under different operating conditions and its effect on output quality examined. If the overall system, design and operation, did not achieve the specific product quality (of sugar); the design was rendered as incompetent to achieve this objective. However, for certain regions of its operation, the design was able to meet the quality criteria as desired; in which case it was found to be in approach of the objective. Based upon this characterization, those values of feasible region were found where product specification could be achieved by the design. This region was then explored further to find optimum value of flexibility that can be achieved in case of variation in feed composition. The paper can be looked as a starting work in applying flexibility analysis approach to complex food processes where environmental uncertainties are common; such as in multi-purpose multi-product plants. When coupled with a suitable control, this technique can help to achieve optimum profit advantages to any batch industry. Monte Carlo Simulation is carried out to explore different regions of feasible operation and increase flexibility from 0.00865 to 0.08686 (an order of 10). This technique has helped to quantify flexibility and improve regions of feasible operation of a sugary industry and increase its profitability. This approach can be used to other food processing, pharmaceutical and batch type industries.

Keywords: Flexibility, Analysis, Food, Monte Carlo simulation, Design chemical Industry, Mathematical modelling

1. Introduction

The concept of flexibility has received more attention recently, especially in the last two decades when industries faced tough competition with other rivals in terms of costs and productivity. The globalization of chemical industries has virtually transformed the low performing chemical industries into highly competitive production units which are necessary for today's survival. Moreover, in addition to being "high tech", modern chemical plants should be able to produce products in very economical way.

Flexibility in plant operation is essential to meet the various objectives of management in presence of changing environmental conditions. These conditions can be attributed to the following changes:

- Price and demand changes of products
- Raw material physical property variation
- Raw material price fluctuation
- Fluctuations in operation within a chemical plant.
- Retrofit Design

The study of flexibility helps the management to decide on various objectives that could be achieved by adjusting the operation of the chemical plant. The process should be made robust to environmental conditions to ensure more productivity and lower losses. The process can be varied and layout could be altered to meet certain objectives, such as in case of retrofit design. In other words, flexibility analysis enhances the decision making criteria of the management.

The technology of chemical or manufacturing industry throughout the globe is more or less similar, within a respective sector. This is because every new technology which achieves greater benefits is readily adopted by many industries; consequently, no net big gain is achieved in terms of competitiveness. However, responsiveness of chemical industries to market conditions has attributed better advantages. This not only helps the industry to stay competitive among its rivals but also improves its consumer base. Many modern technologists have emphasized the importance of flexibility in modern chemical processes. According to them only those industries will survive in future which have better flexible processes and which

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* Corresponding author : wajid.rehman@gmail.com

can make the customers stay with their products by on-time delivery.

- Rapid technological change, global competitors and demanding customers are a few of the factors that influence firms' external environments. These external factors are often cited as influencing the need for increased operations flexibility[1].
- The ability to design and operate manufacturing facilities that can quickly and effectively adapt to changing technological and market requirements is becoming increasingly important to the success of any manufacturing organization [2].

The goal of the chemical industry nowadays is to improve its performance and cut costs. It should meet the desired objectives mirroring the market variations to keep it buoyant. When demands are changing; the preferences of the industry are changing. The aim of the management is towards more profit and productivity. It should alter its operation to meet the desired objectives and keep undesirable objectives at bay. The design offered by a plant can give some flexibility but in order to explore this flexibility and make useful implications from it, requires the review of its flexibility to explore at suitable measures to be adopted in case of future variations in market. In case of demand or price variations in future, the company should be able to adopt concise decisions to where its objectives should lie. Flexibility analysis helps the company to review the flexibility it has, improve it and utilize it when demand varies; so that it does not need to go abruptly for scale enhancing procedures, which can result in more capital and labour costs; thus yielding losses. This case is especially true for products with short lead times.

With the growth of the chemical industry across the globe and technology being the same for almost every industry, there is a growing competition between industrialists. The industry can achieve better performance by reducing time to market and cutting its costs in operation, labour and material. All this can be achieved if the system is well aligned to external conditions.

The aims of the article to meet the objectives of a Sugar Industry are as follows:

- To articulate and then quantify the management objectives of sugar manufacturing facility
- To analyze the flexibility of the given design and quantify it.
- To optimize the flexibility
- To study the effect of uncertain parameters on system flexibility
- To develop improved designs

1.1. Articulation and quantification of the management objectives

There were various objectives set for the flexibility study of the cane sugar industry. It was assumed that the product quality, which is sugar in this case, will be judged at various downstream units. The intermediate product quality of Sugar after Defecation is 8 % sucrose (sugar). It was set as a target for the manufacturing facility to achieve; as well as some other output qualities of sugar to ensure we get optimum quantity of sucrose needed to drive the plant effectively. This was the criteria, of say, the management, to achieve, as a demand objective or profit advantage to be fulfilled.

It is also worthmentioning that Sugar can be manufactured either by Sugar Cane or sugar beet and therefore, it is important to consider both the choices as a feedstock. Since Sugar beet does not vary widely with sugar cane in terms of its composition, however it is important to see if the plant can tolerate this external variation. It is convenient to use, Sugar beet as a raw material. It is only the subject of question which raw material is available and in what quantity. The flexibility of the plant to handle this alternate feedstock, sugar beet, should also be included. Typical feed composition of sugar cane and sugar beet are as follows:

Table 1. Composition of raw materials.

Contents in sugar cane	Sugar Cane composition as Mass Fraction	Sugar Beet composition as Mass Fraction
Sucrose	0.11	0.13
Water	0.75	0.73
Organics	0.05	0.05
Solids	0.09	0.09

Since the plant considered here has a crushing capacity of 3500 tons per day, which is equivalent to 40.509 kg/second. This unit of measurement was adopted for all the flow rates and specifications were assigned as a fraction of this feed inlet. The crushing efficiency of crusher was considered as 95%; based upon data received; as the milling efficiency. It was also considered that since the design pressure of steam is 16 kg/cm^2, it is not allowed to fluctuate $\pm 5\%$ of the base value. Based upon the market conditions of demand of various products or intermediate products, that could be manufactured by this process; feed stream was appropriately adjusted and where necessary, intermediate streams. Since many different grades of sugar can be manufactured; also many types of products, such as, molasses, clear juice, liquid sugar, caster sugar, icing sugar, alcohol and brown sugar; based upon demand.

2. Mathematical Modelling

Mathematical modelling of the sugar manufacturing process was done for crushing, milling, addition of water and addition of lime (Defecation).

2.1. Crushing and milling

If it is assumed that the crusher (shredder) has an efficiency by which some material is passed through "completely crushed" while some material is not crushed and passes as such; then a convenient way of relating crushing efficiency with product composition could be developed. It is also important to mention here that the material that passes through the crusher uncrushed, remains uncrushed in the milling because, crusher has a greater tendency of crushing than the mills. Thus we define an "index of preparation" of the crusher that relates to how much the material is crushed.

For this there are two assumptions:

- The crusher efficiency remains constant throughout the operation
- The feed material remains at a constant composition during the operation.

2.2. Index of Preparation Relationship

$$\text{I.P.} = \text{I.P.}^{\text{base}} + c_{o,j}\left(u_j - u_j^{\text{base}}\right) \qquad (1)$$

where I.P. is the index of preparation or in other words, the Efficiency.

I.P. is the base case index of preparation or efficiency value

$c_{o,j}$ is the coefficient between steam pressure and efficiency variation.

The mass balance of the shredder can be explained as follow:

$$F_{out,1} = \text{I.P.}\ F_{in} \qquad (2)$$

$$F_{out,1} + F_{out,2} = F_{in} \qquad (3)$$

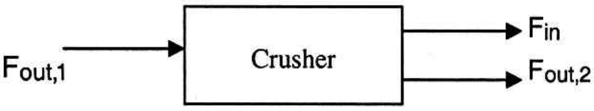

Figure 1. Mass balance at crusher.

Where $F_{out,1}$ represents the Efficient Stream and Fout2 represents the Waste stream that remains uncrushed even in the milling and is discharged into the solids as bagasse.

The composition of both the stream, Fout1 and Fout2, can be regarded to be the same. This method helps us in determining the recovery of sucrose from outlet streams.

In the milling operation, the following mass balance approach is applied:

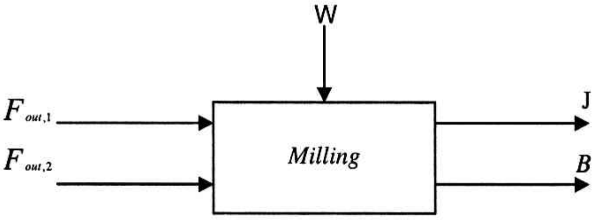

Figure 2. Mass Balance at Milling.

$$F_{out,1} + F_{out,2} + W = J + B$$

$$F_{out,1} x_{out,1,i-1} + F_{out,2}\, x_{out,2,i-1} + F_W\, x_{W,i-1} =$$
$$J\ x_{juice,i-1} + B\ x_{bagasse,}$$

The juice flow rate can be specified as:

$$J = 0.95 \left(\sum_{i=1}^{n-1} x_{out,1,i} \times F_{out,1} \right) + 0.95 \ W$$

$$\sum_{i=1}^{n-1} x_{juice} = 1$$

$$\sum_{i=1}^{n} x_{bagasse} = 1$$

The recovery equations is specified in equation 4

$$R_{2,i-1} = \frac{J \ x_{juice,i-1}}{F_{out,1} x_{out,1,i-1} + F_{out,2} x_{out,2,i-1}} \qquad (4)$$

Except bagasse; the fourth component

The recovery equations for bagasse is specified in equation 5

$$R_{2,i} = \frac{B \ x_{bagasse,i}}{F_{out,1} x_{out,1,i} + F_{out,2} x_{out,2,i}} \qquad (5)$$

where i= bagasse.

$\forall i = 1, n$

$\forall j = 1$

n is the number of components.

The above model was defined in Model Entity program1 alongwith some specifications in Process Entity program1.

There are four components in all; i.e. Sucrose, Water, Organic Impurities and Bagasse. The Bagasse or solids are separated after Milling and do not appear in the mass balance equations later on; so the value of the bagasse component for clarification process is neglected; as seen from the mass balances equations described above. Also the other component removed is Organic Impurities; which are separated after Defecation. So the components remaining after Defecation are only sucrose and water. These assignments were defined in the Process Entity of the gPROMs model.

It is important to note here, however that there is usually a third component called non-sugars is present in the liquid stream but its percentage is very low and at this preliminary stage it was neglected. However, provision can be made for a 5th component in the model very easily. This component, called non-sugars consists of compounds like, glucose, fructose, dextrose etc. which are separated during the crystallisation process. There are other minor impurities like fly ash (ash coming from boiler chimney) and other insoluble solid impurities can also add during the process which are separated in the Deep bed filter, pressure filters and ion exchange processes. Provision can be made in the model for these components.

Apart from four components, there is only one utility; live steam but provision is left for more utilities, such as, exhaust steam which comes through Refinery pans and is used for heating in the Evaporators. So, there was no need to add this utility at this stage till Defecation. Also the mass balances were defined earlier for heating equipments such as primary heaters and secondary heaters; but since their usefulness is in the efficient mixing and reaction with lime and polyelectrolyte, they are neglected from material balance equations. However, this assumption could not be carried out in Evaporation, when the liquid mixture of sucrose and water is heated to an appreciable degree and water removal takes place. The energy and mass balance at this stage become vital; and also is the inclusion of exhaust steam.*

The other specifications were the feed inlet flow rate at crusher. Since the sugar industry considered here has a crushing capacity of 3500 tons per day; it is equivalent to 40.509 kg/s. Based upon this, an inlet flow rate of water could be specified as about 20% of the feed flow rate ≈ 8.1; as the initial guess. The initial guess of steam pressure was taken as upper value of 16.8 (from base value of 16, allowing an $\pm 5\%$ allowance).

The efficiency of the crusher was fixed as 90% which remains constant throughout the operation. The initial guess of water was 8.4 and since water is a pure component; other components were absent. The feed compositions at the inlet of shredder we specified as follows:

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* Exhaust steam coming through Refinery Pans.

2.3.` Simulation result in gPROMs

Under the above mentioned conditions, simulation was carried out in gPROMs. It was found that under different operating characteristics i.e. steam pressure, lime addition and water flow rate; different qualities of end products were obtained. This behaviour showed the effect of operating conditions on product specifications. The target product quality was 8%, which means that the sucrose in the stream after defecation should be above 8% (remaining being water) to describe our product as satisfying the management objective. Some values were found to lie closer or slightly below the specification of 0.08 and were also included in the solution to better characterise our realization of feasible region*. There were also cases when gPROMs simulation failed to find a solution within the bounds of the variables specified, meaning an infeasible solution.

Table 1. Specification of inlet variablks

Sucrose	Water	Organics	Bagasse
0.11	0.75	0.05	0.09

3. Results and Discussions

Since there should be a way to characterise the product(s), it is suitable to state that our products lie within certain range, based upon management objectives. We characterised that the final product purity should be more than 8% of the total composition. Based upon this we can find different operating points where the product composition satisfies or fails to meet our requirements and we can characterise them in to different regions. The feasible regions are the ones which give some certain values of the product composition while infeasible regions are where the design does not allow the operation to take place.

These values were computed one by one in the gPROMs model and simulation results generated to observe the effect on quality of sucrose. After obtaining the simulation result, they were characterised by either feasible, required or infeasible and given specific colour.

3.1. Plotting regions in mat lab.

The next step is to plot these points in Mat Lab to exhibit how these regions look like. We want to see, regions where feasibility and desirability occurs (shown by green); feasibility occurs (though not desirability), shown by blue and regions which are infeasible (shown by red). These regions are plotted in Mat Lab to represent a view of the feasible/infeasible regions, as shown in Figure below:

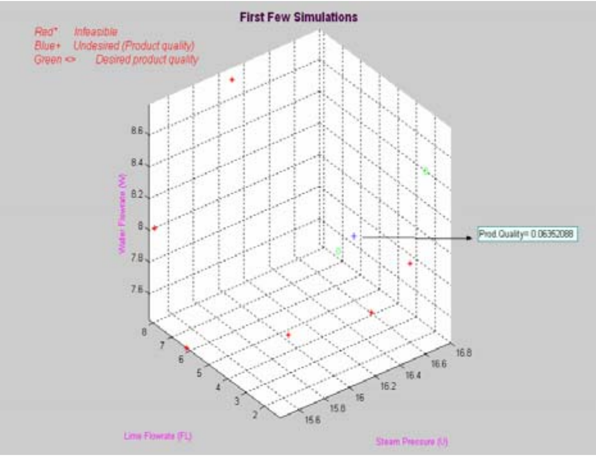

Figure 3. First few Monte Carlo Simulations to generate different regions.

The plotted graph shows a 3D view of different points representing to feasibility/infeasibility/ desirability. The steam pressure varies from 15.2-16.8; lime flow rate varies from 1-10; while water flow rate varies from 7.3 – 9.

There is however a point, very close to the feasible region (as we will explore later), where product quality is 0.0635. Though it is a feasible point but the desired quality is 0.08 or greater and it is slightly less than the desired value.

It is necessary to run few more simulations so that we can have a figure of our feasible region. So, some more Monte Carlo simulations were then carried out in Excel and different values of input variables calculated. These points were then put in gPROMs' Process Entity, one by one to see the effect on the product quality (sucrose) in the stream represented by XCJ (composition of clear juice, after defecation).

So the values were marked green, red or blue, based upon their analysis of feasibility/infeasibility and drawn in Mat Lab.

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[*] As can see in Mat Lab graphs in the next Section.

The graph above shows how the shape of the feasible region appears when more simulations were carried out and plotted in the Mat Lab graph obtained in first step. This graph has also the same characteristics as the previous graph for feasibility/infeasibility. The only difference is that we can see more feasible points.

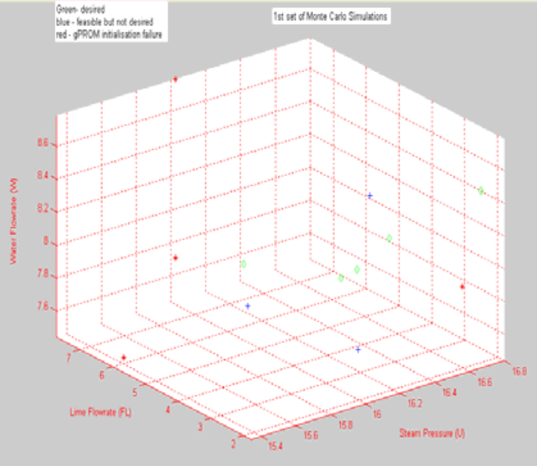

Figure 4. Better Picture of the Feasible region.

3.2. *Volume of the feasible region*

The graph shown above represents a volume occupied by the feasible region and we can calculate its volume in Mat Lab. Here, we assume that the feasible region can be represented by the convex hull of all the points and that the system is reasonably linear, so that there will be no undesired points within this space.

The volume of the region was found using Mat Lab which is able to compute both the convex hull and its volume.

Volume of the desired region = 0.036969

We can actually increase the volume of this region, if we find more feasibility in the volume of the operating variables. So few more MC simulations were carried out and based upon their feasibility/infeasibility/desirability they were plotted in Mat Lab as different region. However, there was one point of feasibility, which was found close to the infeasible/undesired region and slightly greater 0.08; where we achieved desirability. The value of sucrose in this final composition is 0.08416, which is shown in the following graph.

Magenta refers to the product quality in the final stream to be nearly or equal to zero.

After the inclusion of this point in the operating envelope, the feasibility of the overall system increased. The volume of the new region found came out to be 0.2492.

Volume of the New Feasible Region = 0.2492

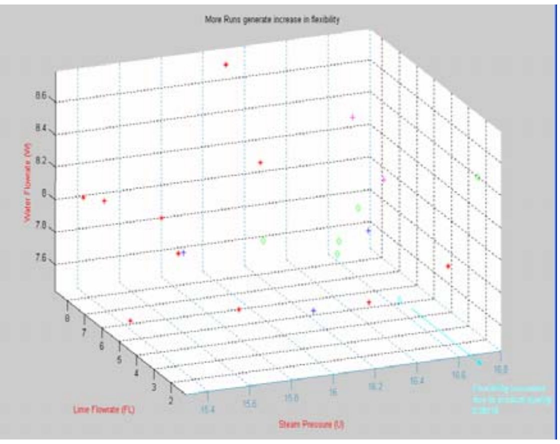

Figure 5. Increment in Feasibility.

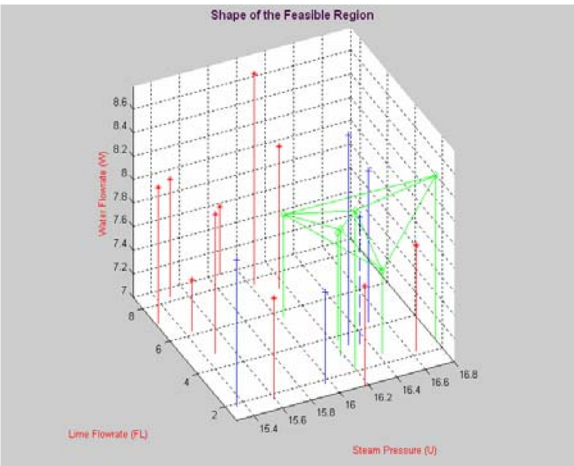

Figure 6. Shape of the Desired region.

3.3. *Shape of the feasible region*

We can see the shape of our desired feasible region by again using plotting in Mat Lab. Mat Lab gives an excellent pictorial view of drawings, especially 3D. The values of desired feasible points are joined together to represent the shape of the feasible region as shown in the graph below.

The points are projected on the x-axis to give a better location of these points.

It can be seen from above graph that a feasible point with slightly undesired value of 0.0635 lies inside the feasible region (also discussed earlier in Figure 3). This point is shown by a blue dotted line in the graph above.

3.4. Volume of various regions

The volume of the feasible (convex hull of all feasible simulations) and tested region (convex hull of all feasible simulations) can also be found out using Mat Lab. They are represented in the table below.

Table 3. Volume of different regions.

Volume of Required Region	Volume of feasible (not required) region	Volume of Infeasible Region	Volume of Tested Region
0.2492	1.5474	3.2878	28.8

Volume of the tested region represents the total volume of the operating envelope, occupied by U, FL and W, in the form of a cube.

3.5. Flexibility index of the given problem

From the volume of the test region and the desired volume, we can calculate the flexibility index as the volume of the feasible region over the volume of the space tested.

$$\text{Flexibility Index} = \frac{\text{Volume}_{\text{Desired}}}{\Delta U_1 \Delta U_2 \Delta U_3}$$

Where ΔU are the utility variables for steam, lime and water.

So, Flexibility Index

$$= {}^{0.2492}\!/_{28.8} = 0.00865278$$

3.6. Exploring more feasibility

From Figure 6, we can see that more feasibility and hence the flexibility can be explored if more run more simulations in the region when steam pressure takes an upper bound (between 16.4 and 16.8) and lime flow rate takes a lower bound (0–5). Water can be allowed to remain almost the same (7 – 10). Based upon these bounds on operating variables; more MC simulations were run in Excel and their values used for gPROMs simulation for feasible region. Since more data was collected and found to be useful in exploring the feasibility within this operating envelope. The feasibility/infeasibility/ desirability values were then plotted in Mat Lab as before, and the final graph obtained is represented below.

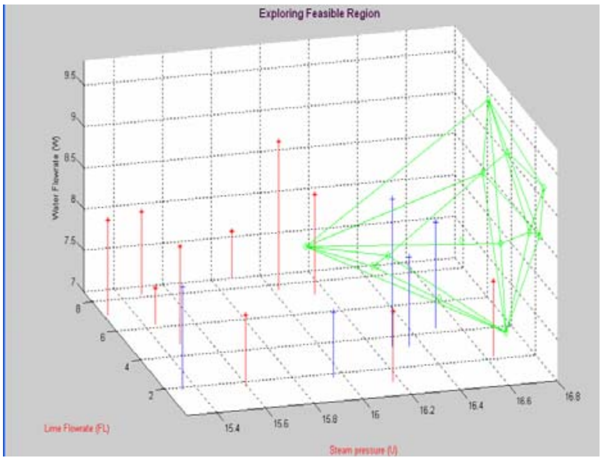

Figure 7. Exploring more feasibility of the desired region.

3.7. Optimizing flexibility

Optimization of flexibility was carried out in gProms. However it did not achieve the desired results. Optimization results subjected to problems of errors of computation. Different values of utility conditions, such as, steam pressure and lime flow rates variations were tried, however, after many attempts no satisfactory optimization result was obtained. However, few more Monte Carlo Simulations did increase the overall region of flexibility. Based upon Figure 7, we can find out the volume of this new region which was found to be 2.5015. Hence by dividing by the total tested volume we can find out the new flexibility index.

New Flexibility Index = 2.5015 / 28.8 = 0.08686

Which is ten times greater as previously calculated value of 0.00865.

3.8. Flexibility in terms of varying raw material properties

Varying raw material properties, such as feedstock properties, in case of using cane of different variety or sugar beet was also studied. The following table represents the relationship between composition variation in feedstock and its effect on product quality.

The table shows that when raw material composition were between 0.11 – 0.13 for sucrose and 0.75- 0.77 for water; the plant was able to produce a satisfactory output quality of 0.09663049. This shows that the plant is suitable to process sugar beet as a raw material for the sugar manufacturing plant.

Table 4. Product quality relationship with variation in compostition.

	Sugar Cane	Sugar Beet	Raw Material Composition	Raw Material Composition
Sucrose	0.11	0.13	0.11-0.13	0.09-0.11
Water	0.75	0.73	0.75-0.77	0.73-0.75
Organics	0.05	0.05	0.05	0.05
Product Quality after Defecation	0.09663049	0	0.09663049	Infeasible

3.9. Further exploring the tested region

1. Attempt was made to further explore the feasible region, if it exists, between

- Steam pressures of 15- 16
- Water flow rate of 8.4 – 8.6
- Lime Flow rate of 6-7.

This was done to ensure there is no feasibility and desirability within this region and it was found to be none.

2. Since there is a restriction on the design to go beyond ±5% of base value of 16; if however, this restriction could be relaxed, due to better design, we can achieve more feasible region and hence flexibility, as shown in graph below.

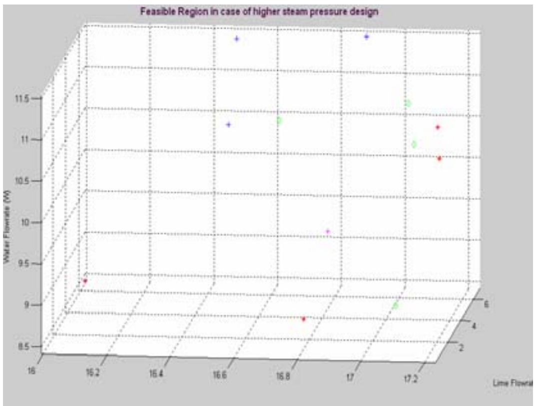

Figure 8. Exploring further feasible regions

The desired values of steam pressure greater than 16.6 indicate that there is a considerable potential of getting more feasibility and flexibility of the system if a good design can tolerate higher pressures.

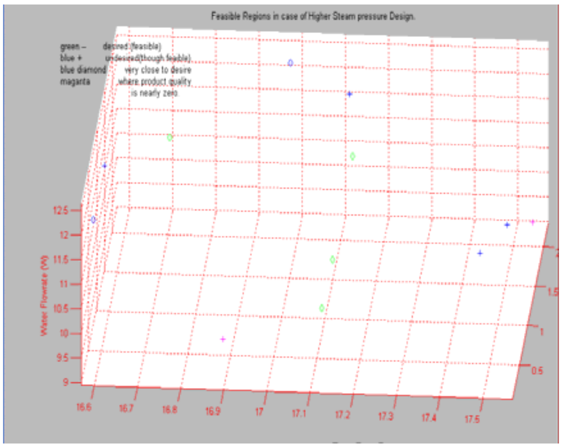

Figure 9. Another view of Regions of Feasibility and Desirability for higher steam pressure design*.

It was also found that increasing steam design pressure, if possible, till 21 kg/cm^2 would still yield the desired value of our end product.

4. Conclusions and Future Work

From the analysis of the Mat Lab graphs shown above, it is clear that the system has a tendency to go in the forward direction i.e. where there is an increment in operating variables. This case is true for all except lime flow rate, which should decrease to gain an increase in the feasibility of the process. We can see from the Mat Lab graphs that for steam pressures below 16 kg/cm^2, no desired feasibility is attained. Thus the trend of the operation should be to go towards the 'high side' except for the lime flow rate, the addition of which may cause the final product quality to decrease in composition.

The trend should be "up" from the management perspective and decreasing the use of raw material lime. Minimum use of lime would not also yield more feasibility but also lower the use of the purchased commodity and therefore operating costs. It is also observed that the quality of the end product is also dependent upon the composition of the raw material. If the cane is more in organic

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* red-infeasible; blue-unrequited; green, cyan-feasible. Magenta-product value=0.

impurities, more lime has to be added which not only increases the operating cost but also decreases the fraction of sucrose in the final stream.

The quality of sugar cane is also important to generate more feasibility of the desired region (as the upstream process affects the downstream process). Instead of just checking the final composition of sucrose (i.e. after Defecation); we could also observe the quality of sucrose in the bagasse (i.e. after milling) and also the quality after Defecation but since it would have unnecessarily extended the analysis of the results and not been very useful anyway, it was neglected and only the sucrose quality after Defecation was measured. So from the design prospective, it is important to note that the operation has an exponential growth in the forward direction which gives more feasibility and profit advantages. Also the flexibility here would be more than the flexibility analyzed earlier and it improved to 0.08686. Grossmann (1987) has also mentioned that without considering the adjustment of control variables, the feasibility or flexibility index of the plant is not fully explored. [*] So the next task for the future consideration would be to design a suitable controller for regions where the required feasible values lie close to undesired regions to give them more flexibility to ensure optimum quality at the output. It may be important to consider here that an undesired point which appeared in our required region as represented in Figure 3; can lie within the declared product specifications in presence of a suitable control.

In addition to efficient plant performance, more uncertainty variation can be tolerated with the addition of a good control strategy; while the introduction of new products would be easier; not withstanding the smooth and safe operation of the plant.

Abbreviations and Symbols

I.P. is the index of preparation or in other words, the Efficiency.

$I.P.^{base}$ is the base case index of preparation or efficiency value

$c_{o,j}$ is the coefficient between steam pressure and index of preparation variation.

F_{in} = Feed inlet to the crusher

$F_{out,1}$ = Flow rate of Efficient Stream from crusher (shredder) $F_{out,1}$

$F_{out,2}$ = Flow rate of waste stream from crusher (shredder)

W = Water Inlet in Milling operation (kg/s)

J= Flow rate of Juice after milling

B= Bagasse Flow rate

$x_{out1,i-1}$= Composition of Individual specie minus bagasse in the juice flow rate

$x_{out2,i-1}$= Composition of Individual specie minus bagasse in the waste stream

$x_{w,i-1}$= composition of water in Water Stream

$x_{juice,i-1}$= Composition of species in juice minus bagasse

$x_{bagasse,i}$=Composition of bagasse

$x_{out1,i}$ = Composition of juice (after crushing)

x_{juice} = Composition of Juice

$x_{bagasse}$ = Composition of Bagasse

U= Flow rate of Utility (Steam, Exhaust Steam)

FL= Flow rate of Lime

XCJ= Composition of Clear juice (after defecation)

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[*] For the flexibility analysis to be meaningful, one must anticipate that during plant operation control variables can be adjusted so as to try to maintain feasible operation for the prevailing condition. Neglecting this fact can lead to serious underestimation of the inherent flexibility of a process”.

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