The application of rigorous modelling with Monte Carlo simulation methods to assist decision-making in sugar factories

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Abstract

Technical and economic modelling of potential modifications to the X sugar factory in Country Y was carried out. The proposals included mill and process house improvements, an increase in crushing rate, and a new cogen boiler with export of electricity. The modelling incorporated mass and energy balances and financial analyses of the complete system, and uncertainty was taken into account using Monte Carlo simulation methods. This application of holistic and rigorous modelling provided valuable assistance in decision-making regarding the proposed improvement works. The predicted financial benefit for each stage of work was identified, together with confidence bands and probabilities of a negative return. Sensitivity analysis identified the major risks and opportunities, highlighting potential work to mitigate the risks or take advantage of the opportunities. Important issues were raised, such as the necessity for thermal efficiency improvements alongside mill extraction increases, and the potential benefits of improving cane quality. Overall, the work identified the optimum solution in terms of balancing benefits gained against investment cost, at an acceptable level of risk.

Keywords: factory, mill, modelling, simulation, risk, decision.

Introduction

The X Sugar Company (XSC) is considering investment at one of its four sugar factories. Tate & Lyle Process Technology (TLPT) were invited to assess the existing operations and equipment and propose solutions for (a) improving milling operations, (b) improving process house operations, and (c) increasing cane crushing capacity. There is also the possibility of replacing the existing low pressure boiler with a high pressure cogeneration boiler. This paper considers how technical and economic modelling using Monte Carlo simulation can be used to assist decision-making regarding identification and implementation of the proposed solutions. Any values given should be taken as indicative only: the primary objective is to describe the method of analysis. All monetary values are expressed in US$.

Materials and methods

<u>Modelling software</u>

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The work described in this paper was carried out using SugarCaneModel, a technical and economic modelling tool. SugarCaneModel carries out mass & energy balances and financial analysis of the system being modelled. It allows analysis of complete systems in a single model, capturing all significant dependencies, and accounts for uncertainty via the application of Monte Carlo simulation methods. SugarCaneModel operates in Microsoft Excel and uses Palisade's @RISK software[2] to perform the Monte Carlo simulation.

Monte Carlo simulation

Monte Carlo simulation is a computerised mathematical technique that furnishes the decision-maker with a range of possible outcomes and the probabilities that they will occur for any choice of action. The method can be described as comprising the following basic steps, which will be illustrated later:

1. Replace any input parameter which is subject to inherent uncertainty with a range of values, represented by a probability distribution (such as a normal distribution). See figure A1 in the appendix for an example.
2. Recalculate the model over and over again, each time using a different set of random inputs as sampled from the probability distributions.
3. Aggregate the results from each recalculation and generate probability distributions for each output value.

This approach contrasts with traditional static modelling, in which fixed input values result in fixed output values. Very few (if any) inputs to a model are actually known with 100% confidence, and therefore the results from a static model reflect no known reality.

Modelling stage 1: Baseline scenario

Stage 1 involved creating a model of the baseline scenario against which the proposed improvements will be assessed. The objective here was to establish a reasonably accurate reflection of the existing mill performance. XSC keep comprehensive technical records for each of their mills and this provided most of the data required to generate the model. Obviously the performance of the existing mill is not fixed: it has varied in the past and it will vary in the future. Therefore key inputs such as cane quality, mill extraction, thermal efficiency and boiling house yields were replaced by probability distributions. Average data from the 2009 and 2010 seasons was used to generate the distributions. This provided a more realistic reflection of performance, rather than taking fixed values from one particular month or season, which may reflect unusually good or bad performance.

Modelling stage 2: Milling improvements

Stage 2 involved adjusting the Baseline model to reflect the following areas of improvement as identified by TLPT:

[2] www.palisade.com/risk

- Removal of existing cane knives and installation of a new heavy duty shredder with electrical drive
- Installation of a new fourth mill and modification of the boiler feed bagasse conveyor
- Installation of pressure feeders on existing first mill and new fourth mill
- Replacement of existing steam mill drives with electric type
- Installation of new high speed gearbox on first and second mills
- Installation of new improved maceration system

Based on results from previous projects, these works were expected to increase milling sucrose extraction from 87-89% (in the Baseline) to 95-97% and reduce bagasse moisture from 55-57% to 45-47%. Imbibition water would increase from 120-130% to 180-220%, and absorbed power in the milling section would increase from 100 kWh/tonne fiber to 170-190 kWh/tonne fiber.

Modelling stage 3: Process house improvements

There were various process house improvements identified and many model parameters were adjusted between stages 2 and 3. Some of the major model changes were:

- Introduction of vapour bleeding to feed vacuum pans & juice heaters
- Reconfiguration of existing evaporator vessels to achieve a quintuplet effect evaporator station
- Increase of evaporated juice brix (via new evaporator brix control system)
- Improvements to boiling house yields (via new pan stirrers, centrifugals and C crystalliser)
- Reduction of heat and sucrose losses (via better operation and pH control)

Modelling stage 4: Increased crushing rate

Stage 4 involved increasing the maximum mill crushing capacity from 100 to 250 (-10%, +5%) t/h (metric tonnes). Various modifications and additions of equipment were identified to achieve this increase, but the mass and energy balances in the model remained unchanged (from stage 3).

Modelling stage 5: New boiler and export of electricity

Stage 5 involved replacing the existing boiler (~30 barg) with a new high pressure (~100 barg) boiler equipped with condensing turbine, and export of excess electricity to the national grid. In the Baseline model mill electricity is provided via a turboalternator where possible, but due to inefficiencies and steam drive requirements, there are shortfalls made up with imports from the grid.

Modelling stage 6: Improved cane quality

Stage 6 was added to explore the potential benefits of improving cane quality. Water content was reduced and the purity increased. The overall effect was to increase sucrose content from around 12.3% to around 14%, and increase fibre content from around 11.1% to around 13%. Wide ranges in the improved values were used to reflect the high degree of uncertainty as to what could realistically be achieved.

Financial analysis

For each modelling stage, a financial analysis was carried out. Revenues included the sales of raw sugar and molasses produced and, from stage 5 onwards, of electricity. Costs included the cost of cane, fuel, chemicals, maintenance, labour, etc. Actual price data was used from the 2010 season, with ranges defined to reflect potential variations up to 2020. The ranges were defined from a combination of historical data (such as annual average exchange rates or past variations in chemical and utility prices) and predicted forecasts (from institutions such as the World Bank and the US Government). The cost of the capital expenditure required for each stage was annualised using a Capital Recovery Factor (CRF)[3].

Modelling approach

Six model simulations were run on two models in parallel. In each simulation, the first model was as defined in the Baseline scenario, while the second model cycled through each of the stages identified above. The two models were compared with each other to assess the effects of each stage of improvements. In each simulation, 1000 model recalculations were carried out, each time varying the input parameters according to the ranges defined in the setting up of the models. The whole modelling and simulation process was automated using the modelling software.

Results and discussion

Table A1 in the appendix details the mean (from the 1000 recalculations) effect on costs and revenues throughout the changes. Figure 1 below shows the predicted range of the cumulative annual benefit resulting from each stage of improvements. This is the benefit taking into account the cost of capital, and is plotted in terms of mean, and 25-75% and 5-95% confidence intervals. This gives an indication of the uncertainty in the results. Figure 2 shows the mean values for high pressure (HP) and exhaust steam-on-cane, and sugar yield (sugar/cane).

[3] Capital Recovery Factor uses an interest rate (i) and project life (n) to determine the rate at which earnings could reasonably be expected if the same funds were invested over a length of time The formula is CRF = {i(1 + i)^n} / {[(1 + i)^n]-1}. The interest rate was estimated from the national Reserve Bank to be 6.5% (6-8%) and the economic life 15 (10-20) years.

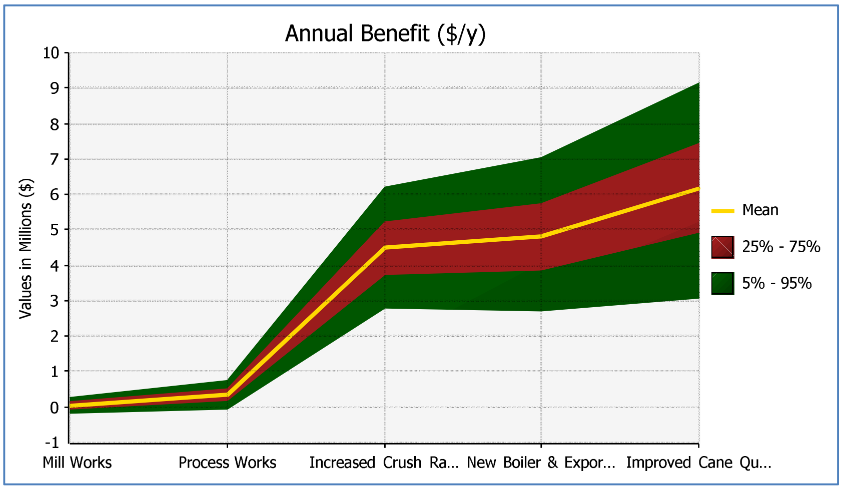

Figure 1: Predicted annual benefit throughout the stages

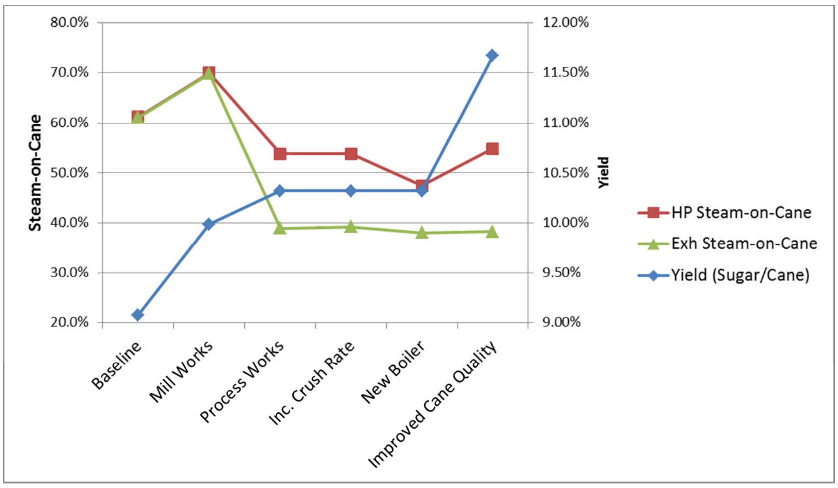

Figure 2: Steam-on-cane and sugar yield throughout the stages

<u>Milling improvements</u>

Figure 3 below shows the probability distribution of the predicted annual benefit from undertaking the milling improvement works. This gives a visual indication of the potential range of outcomes, and shows that the mean annual benefit is $32K/y, and that there is 41% probability that the works will not be beneficial (i.e. the benefits are outweighed by the cost of the capital expenditure required). It also shows a 5% probability of a benefit greater than $250K/y.

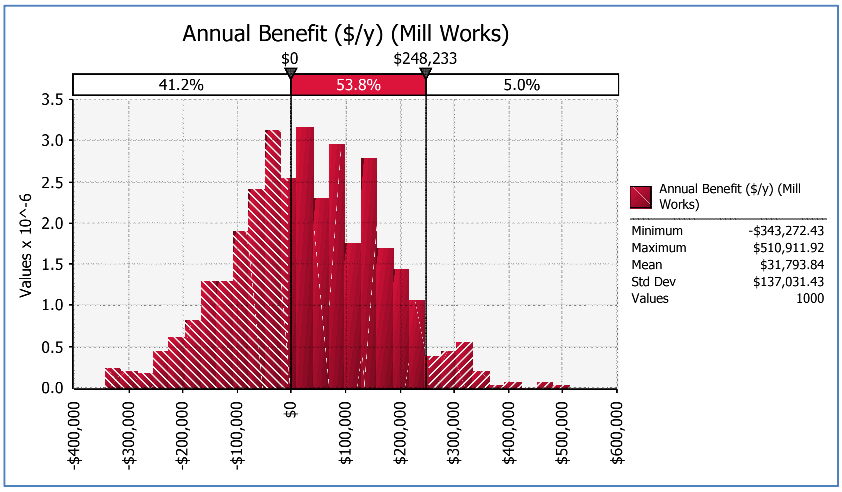

Figure 3: Probability distribution of annual benefit from carrying out mill works.

The significant increase in yield (caused by a reduction in sucrose loss to bagasse from 11-12% to 3-4%) as shown in figure 2 might be expected to result in a larger overall benefit; inspection of table A1 and the steam-on-cane curves in figure 2 indicate why this is not the case. The increased mill extraction and imbibition water result in increased energy requirements in the process house. The reduction in bagasse moisture might be expected to mitigate this, and indeed the increased boiler efficiency and bagasse heating value do increase the steam/bagasse ratio from 2.1 to around 3. However, the amount of bagasse is reduced, as is the sugar content (which provides energy), and the net effect is that the absolute steam generation from bagasse only increases by 2-3%. The mill is already importing small amounts of hog fuel to make up its energy requirements, and this now increases at a cost of $320K/y, partially offsetting the $1m/y increase in product revenues (although this is mitigated by the elimination of electricity imports due to the increased steam to the turbine).

Figure 4 below shows the sensitivity analysis i.e. the sensitivity of the annual benefit to the uncertainty in external (such as prices or cane quality) or internal (such as process performance) parameters. The biggest risks/opportunities in the mill works project are the CAPEX uncertainty (defined as ±30%), the actual mill extraction achieved and the imbibition rate required, the sugar price, the project economic life, and the hog fuel price. This highlights where efforts might be focussed prior to proceeding with the project, such as further CAPEX definition, mill performance trials, or fixing price agreements for hog fuel and sugar.

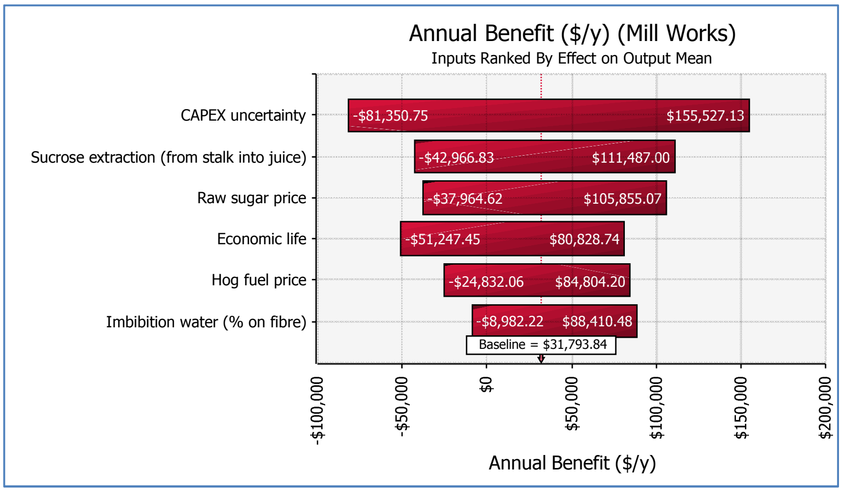

Figure 4: Sensitivity analysis of the annual benefit from carrying out the mill works.

In conclusion: carrying out the mill improvements alone is not an attractive option for investment. The mean predicted annual benefit is low ($30K) and there is a significant (>40%) probability of a negative financial return. This is mainly due to additional fuel imports required by the increased process house steam consumption.

Process House improvements

Figure 5 below shows the probability distribution of the predicted annual benefit from undertaking the milling and process house improvement works. The mean annual benefit has increased to $340K, and that probability that the works will not be beneficial is reduced to 9%.

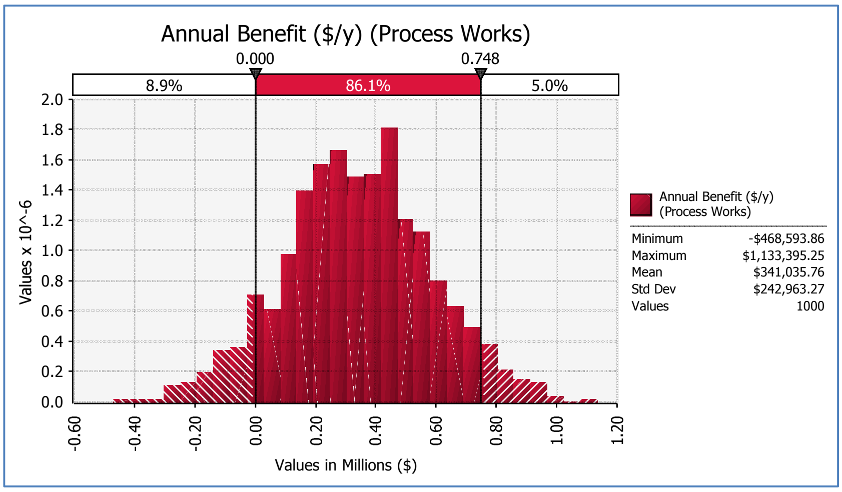

Figure 5: Probability distribution of annual benefit from carrying out mill and process house works.

Inspection of table A1 shows that the biggest contributor to the predicted increased benefit is the elimination of hog fuel imports. This is due to the sharp reduction in process steam-on-cane (see figure 2) achieved by the thermal efficiency improvements. There is actually now an excess of HP steam available from bagasse, and therefore either the thermal efficiency improvements can be relaxed, or bagasse can be sold for other uses. There is also an increase in yield (caused by a reduction in sucrose loss to molasses, and to a lesser extent, in miscellaneous sucrose losses).

In conclusion: carrying out the process house improvements in tandem with the mill improvements is a reasonable option for investment, with moderate gains, although there is still a 9% probability of a negative return. If this option is selected (e.g. if CAPEX is limited) then prior to committing funds efforts should be focussed on further definition of the CAPEX, of the mill extraction achievable, and on reducing exposure to raw sugar price.

Increased crushing rate

Figure 1 shows a sharp increase in the predicted annual benefit after carrying out the work to increase the crushing rate from 100 to 250 metric tonnes per hour. The mean benefit is $4.5m, with 90% confidence that it will be between $2.6m and $6.4m. Figure 6 below shows the sensitivity analysis for the project up to this stage. The biggest risk/opportunity is now the raw sugar price. Risks that were not significant previously (at the mill works stage) include the actual crushing rate achieved, the number of operating days per year (i.e. after taking away lost time), molasses price, and cane quality. Again, this highlights where efforts should be focussed prior to proceeding with the project, such as minimising stoppages, guaranteeing cane supply, or improving cane quality (see stage 6).

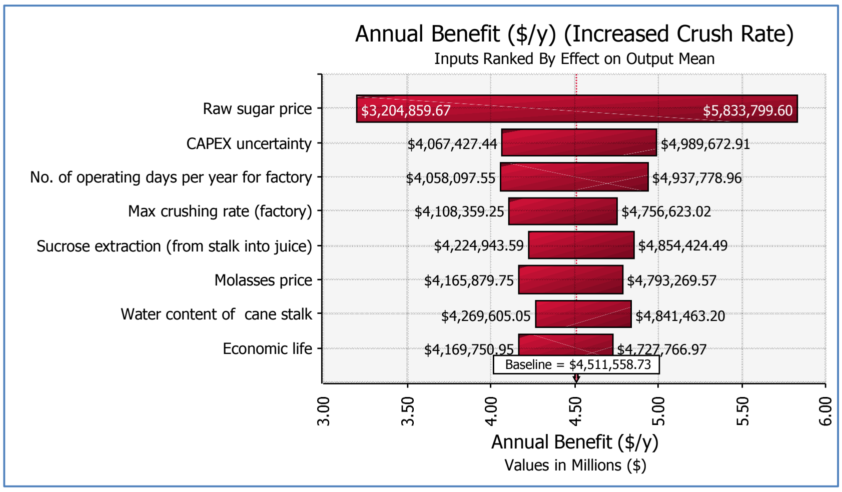

Figure 6: Sensitivity analysis of the annual benefit from carrying out the mill works, process house works and increasing the crushing rate.

In conclusion: carrying out the mill and process house improvements and expansion to 250 tpd is a good option for investment, with an expected benefit of $4.5m/y (90% confidence between $2.7m and $6.4m/y). In parallel with the project, efforts should be focussed on reducing lost time and maximising cane availability, in addition to further definition of the CAPEX, mill extraction and raw sugar price.

New boiler & export of electricity

Figure 1 shows a small increase in predicted annual benefit after installation of a new cogeneration boiler and commencing export of electricity. Table A1 shows that the benefit is due to electricity sales versus cost of investment. The mean benefit is now $4.9m, with 90% confidence that it will be between $2.6m and $7.2m. The 90% confidence band is wider, i.e. there is more uncertainty, and in fact the 5% percentile value is lower ($2.6m/y c/w $2.7m/y). Around 10.1 MW of power is expected to be exported, with 90% confidence between 9.3 and 11.0 MW. The condensing turbine processes around 20% of the HP steam available, eliminating the excess steam available in stages 3 and 4.

Figure 7 below shows the sensitivity analysis for the project up to this stage. Electricity price is now a big risk/opportunity, and efforts might be focussed on reducing the potential future price variability before committing to the project. Also of note is that the exchange rate appears as a risk; this is because electricity is priced in local currency, whereas the majority of the other costs/revenues are imported/exported and therefore priced in foreign currency.

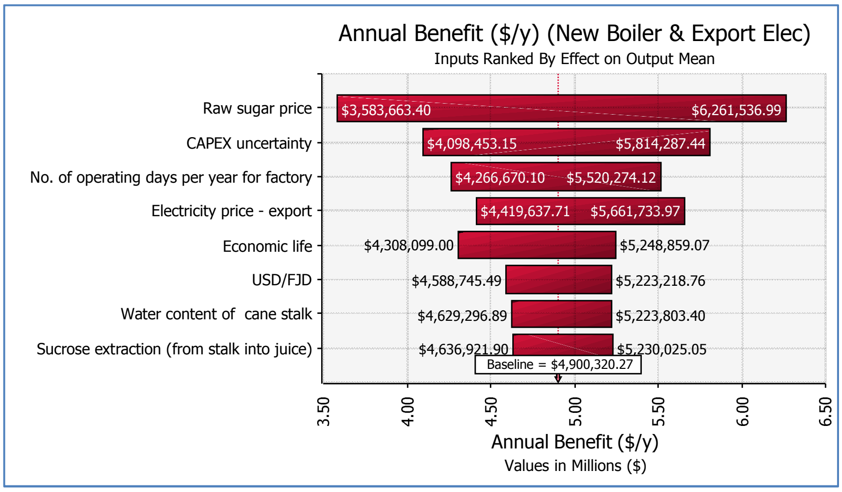

Figure 7: Sensitivity analysis of the annual benefit from carrying out the mill works, process house works, increasing the crushing rate, and installing a new cogeneration boiler.

<u>In conclusion</u>: installing a new high pressure boiler and exporting electricity shows a moderate predicted annual benefit ($390K/y). However, the uncertainty involved in these works is greater than previously, and there is a possibility that they will not be beneficial. Before committing to these works, more detailed analysis should be carried out (see below).

<u>Improved cane quality</u>

Improvements in cane quality were only identified following inspection of the sensitivity analysis charts above. Cane quality (expressed as cane water content) often emerged as a risk/opportunity. As this is a factor over which XSC has some potential control, it was considered worthwhile to investigate the potential benefits in investing in improvements. Figure 1 shows a significant increase in predicted annual benefit. The mean benefit is now $6.2m, with 90% confidence that it will be between $3.0m and $9.2m. The range of uncertainty has widened significantly; this is due to the uncertainty in exactly what improvements in cane quality can be achieved.

<u>Overall conclusions and further analysis</u>

From the analysis so far, the most benefit is gained when carrying out all the improvement works. However, the improvements to cane quality are longer term and more complex to implement, with more stakeholders involved. Having highlighted the significant potential benefits, it is probably sensible to treat this as a separate project. Otherwise, there is a clear benefit to be gained in improving mill and process house operations and expanding the factory for an increased crushing rate, and the recommendation is to pursue this option whilst attempting to mitigate the risks identified in the sensitivity analysis. There is a question mark over whether to include the new cogeneration boiler, as the analysis showed there was an average positive benefit, but with the possibility of a negative return. It was considered worthwhile to investigate this option further by running one extra simulation on two models in parallel. The first model represents the works excluding the boiler, and the second model includes the boiler. By comparing the two, we can see more clearly the probabilities of success and the risks/opportunities. Figure 8 below shows the probability distribution of the predicted benefit in extending the improvements to include the new cogen boiler.

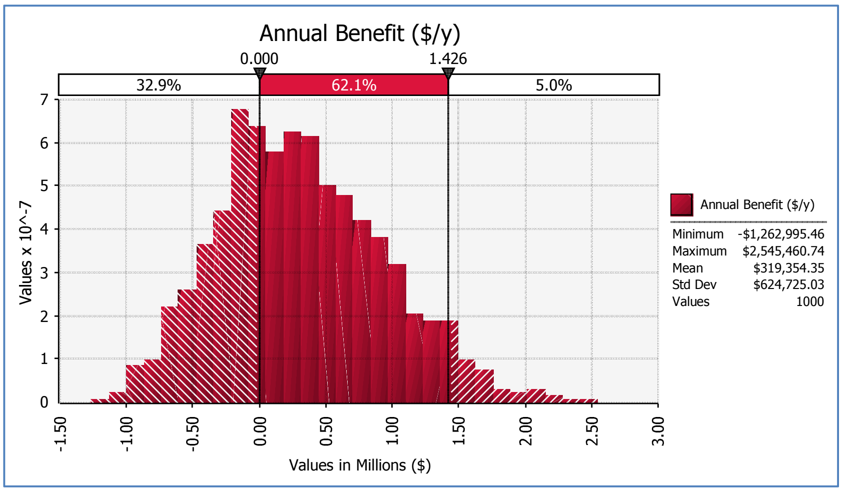

Figure 8: Probability distribution of annual benefit from installing new cogeneration boiler.

This shows that although there is a mean predicted benefit of $320K/y, there is a one in three chance of a negative return. This probability is too high for the new boiler to be recommended at this stage. Instead, efforts should be focussed on mitigating the new risks identified in figure 7, i.e. the electricity price and the exchange rate. If these risks can be managed (such as by long-term price agreements or currency hedging), the analysis could then be carried out again using new input ranges.

There are two important points to note, however:

1. If the cane quality improvement works are to be carried out, then the above analysis repeated shows that the mean benefit from the cogeneration boiler is much greater with 0% probability of a negative return, i.e. the boiler project would be recommended. This is mainly due to the increased cane fibre content.
2. If the new boiler project is not carried out (i.e. there is no condensing turbine and no export of electricity) then there is an excess of HP steam (or bagasse). The thermal efficiency improvements could be relaxed, or the excess bagasse could be sold for other uses.

Comparison with payback time

It is of interest to compare the above results with the predicted payback time (based on the mean predicted increase in cash flows). Figure 9 below shows payback time for the cumulative implementation of the various stages of improvements. It indicates that the implementing any works (i.e. new boiler and improved cane quality) beyond the increase in crushing rate would result in a longer payback period. This highlights the limitations of relying on payback as a tool for assessing investment potential. It does not take account of the cost of money (interest rate) or the economic lifetime of the project, and so the potential long-term benefits of the new boiler and improved cane quality projects are missed.

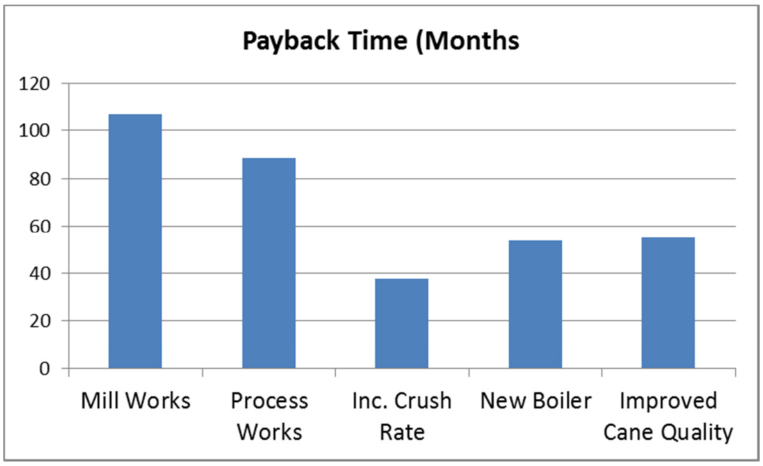

Figure 9: Predicted payback time for cumulative implementation of the various stages of improvements.

Conclusions

Rigorous modelling using Monte Carlo simulation to take into account uncertainty can provide valuable analysis to assist decision-making in the cane sugar industry. In this example:

1. Each stage of the improvement works was assessed via a single measure of financial benefit taking into account the cost of investment, providing a clear basis for comparison. This highlighted that expanding the mill for an increased crush rate provided a much greater benefit than mill and process house improvements alone.
2. The careful and rigorous definition of uncertainty in the input parameters provided visibility of the likely range of outcomes, identifying the risk of and likelihood of negative financial returns.
3. Sensitivity analysis identified the key risks/opportunities for each stage of works, providing guidance as to where future work should be focussed. It also highlighted the potential gains from investing in improvements in cane quality.
4. Analysis of the mill, factory, utilities and economic conditions as a complete system highlighted the limited benefit of undertaking mill improvements alone without corresponding improvements in process energy efficiency, and potential excess of bagasse or steam if cogeneration is not included.

Appendix

	Mill Works	Process Works	Inc. Crush Rate	New Boiler	Imp. Cane Quality
Costs					
Cane	$0	$0	$10,694,283	$10,843,954	$10,843,954
Water	$1,761	-$1,630	$6,958	$3,045	$8,586
Heat Fuel	$319,859	-$450,156	-$450,156	-$450,156	-$450,156
Chemicals	$18,189	-$28,122	$194,564	$279,662	$417,530
Cost of capital	$651,601	$1,303,202	$2,246,912	$4,407,991	$5,935,787
Insurance	$60,000	$120,000	$206,894	$405,885	$546,573
Effluent/waste disposal	$338	$559	$110,820	$110,820	$132,108
Electricity	-$124,384	-$123,663	-$121,914	-$124,384	-$124,384
Bagging/packing materials	$38,787	$52,951	$704,318	$704,318	$857,728
Total increase in costs:	**$966,600**	**$873,676**	**$13,598,447**	**$16,029,166**	**$18,165,649**
Revenues					
Raw sugar	$886,852	$1,211,256	$16,111,607	$16,111,607	$19,619,149
Electricity	$0	$0	$0	$2,759,387	$3,197,357
Molasses	$115,065	-$1,369	$1,980,744	$1,980,744	$1,525,836
Total increase in revenues:	**$1,001,917**	**$1,209,887**	**$18,092,352**	**$20,851,739**	**$24,342,343**
Net annual benefit:	**$35,317**	**$336,211**	**$4,493,905**	**$4,822,574**	**$6,176,694**

Table A1: Cumulative predicted change in costs and revenues throughout the improvement stages. All values are relative to the Baseline model, and are mean values from 1000 simulations.

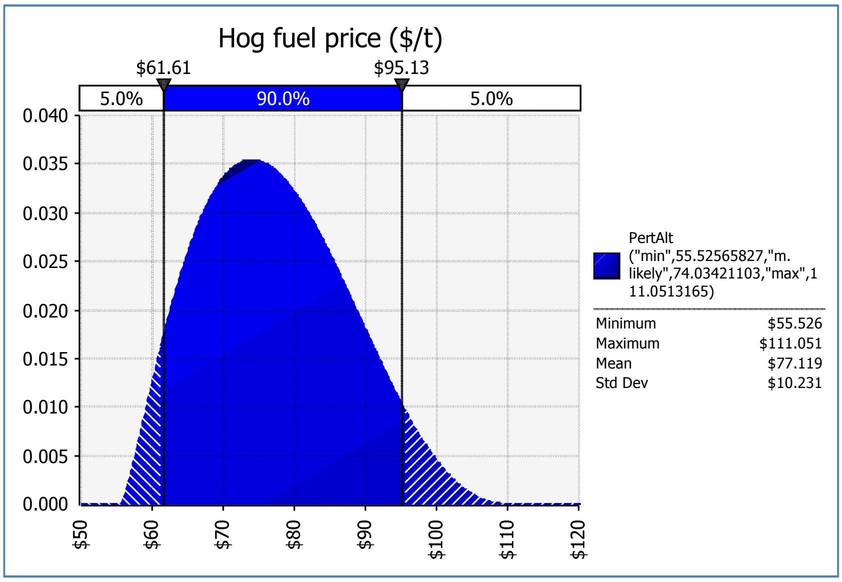

Figure A1: Example of a probability distribution describing potential future variations in hog fuel price. The distribution was generated via a three-point estimate: an estimation of the minimum, most likely and maximum values.