CHEMECA 2013 Quantifying Product Variation in Milk Production Using a Monte Carlo Analysis

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***Abstract*—Milk powder is typically fortified during processing by the addition of several ingredients. At the powder plant studied, one particular ingredient showed significant concentration variation in the final product, of which the causes were not well understood. Hence, a Monte Carlo uncertainty analysis was used to predict the output concentration distribution based on the typical variations of processing conditions observed in the actual plant. The purpose was to find if the observed output variability could be attributed to either variation during processing, due to a poor analytical measurement procedure, or something else. The strategy was also used to quantitatively establish if changes in the operational procedure could further reduce the variation in final product quality. The variation in final quality parameter due to processing conditions was found to be of the same magnitude as the analytical technique, meaning that both contribute to the final product variation, and hence a reduction in processing variability will reduce the overall variation. Furthermore the model suggests that the product is more likely to be out of specification on the upper limit, than on the more important lower limit given typical process variation, which was also seen in the measured results. Thus, powder out of specification above the upper limit is likely to be caused by process variation; however powder out of specification on the lower limit is not. A concrete recommendation from this analysis is that ratio control of ingredient addition was shown to significantly reduce the final product variation, and could prevent out of specification on the upper limit.**

Keywords-milk powder; monte carlo; uncertainty analysis

I. INTRODUCTION

Many processing industries have recently seen a shift away from process control to maximise production to a focus on quality, and process analytical technology (PAT) has come to stand for the assessment and control of product quality. Fonterra have recently been looking to accelerate the development and use of PAT tools for what they have classified as 'real time quality' (RTQ), to combine the benefits of advanced process control (APC) with an explicit focus on quality [1].

Milk powder is typically fortified during processing by the addition of several ingredients in tiny, but carefully controlled quantities. The exact composition and concentration of these additions depend on the customer's requirements, some of whom are exacting. The plant identified variability of a particular ingredient in the milk powder to be a major quality issue of interest. Currently the concentration of the ingredient which is the focus of this paper in the powder shows low predictability, especially with unexpected out-of-specification results on the lower specification limit. The overall aim of this work was to systematically assess the sources of variation in the ingredient dosing system and use a Monte Carlo approach to carry out an uncertainty analysis. Specifically the aim of this study was to evaluate if the ingredient variation due to processing parameter variation during normal operation exceeds, or is even of the same order as the variability found in the analytical technique. If the variation in the processing exceeds (or is of the same order as) the variation of the analytical method, then further analysis can be used to establish if changes in the process can be used to make the final ingredient concentration more predictable, such as by development of an online tool for quality management and for improved operator support.

II. REVIEW OF CURRENT SYSTEM AND OPERATION

The current process of ingredient addition can be broken down into two stages:

1. Dosing tank make-up — where the ingredient dosing solution is made up by dissolving a dry powder.
2. Dosing — where the ingredient solution is dosed directly into the milk evaporator feed line.

The ingredient dosing tank is made up by filling the tank manually with water and then tipping the pre-weighed ingredient powder into the tank. The tank is filled to a volume specified by a marker painted on the inside of the vessel. Two tanks are used during dosing, one for making up the solution and one for dosing.

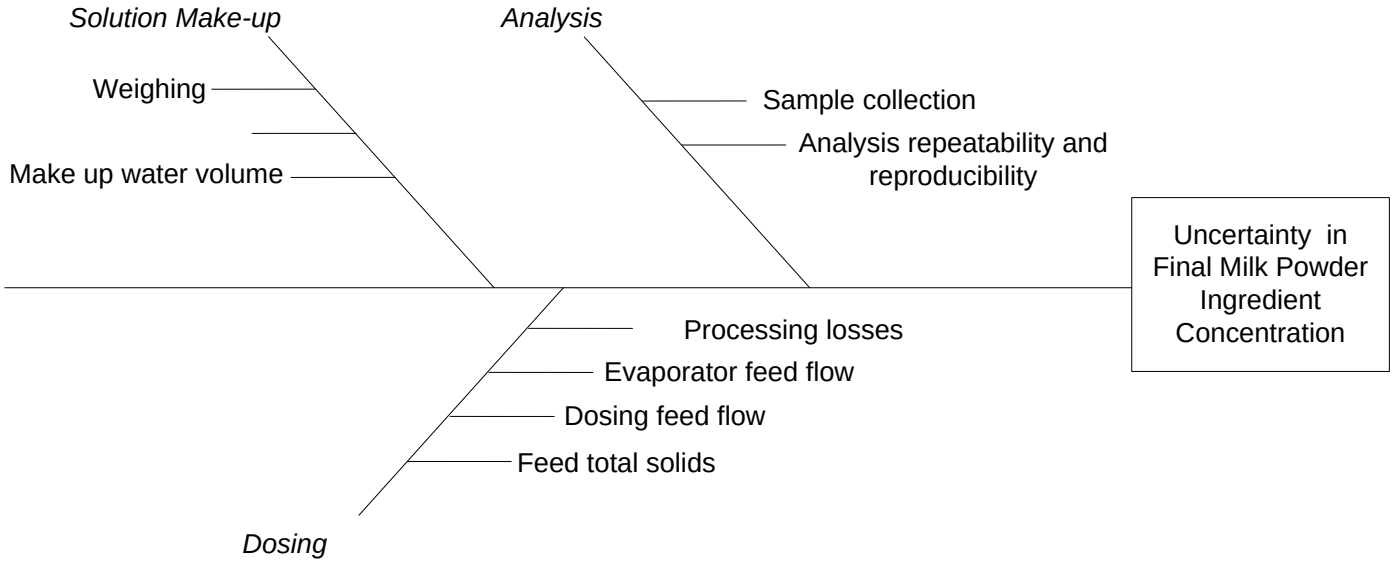

Fig. 1: Sources of variability in the final concentration of the in the milk powder.

The ingredient powder is weighed in dedicated preparation room. A mass balance is used for calculating the mass of ingredient to dissolve in the dosing tank, using the following information:

1. Target concentration of the ingredient in the final milk powder specification. The tank is designed to empty in 4 hours at a constant flow rate (and varies).
2. Constant milk feed flow rate, total solids and moisture content, which is based on the specification being produced.
3. Assumed losses during processing – a fixed 12% for the ingredient at the plant studied based on earlier investigations.

The dosing is carried out at a constant volumetric rate, even though the concentration of total solids, and the milk feed flowrate, vary throughout the production run.

A fishbone cause and effect diagram, shown in Fig. 1, was constructed from a review of the current system operation to identify the sources of variation in the final ingredient concentration.

III. The Monte Carlo Strategy

A Monte Carlo uncertainty analysis was used to quantify the variation in concentration of the ingredient in question in the final milk powder due to processing. A Monte Carlo strategy develops an estimate of the statistical distribution of the output by sampling (or evaluating) a model many times given a representative sample of the inputs [2], as shown in Fig. 2. Such a procedure is simple (although computationally expensive), and can be used to estimate the output distributions through complicated nonlinear dynamic systems without excessive approximation.

A simple mass balance was used to model the output concentration of the ingredient in the final milk powder since the ingredient does not react, and the dispersion is assumed negligible. The model used was the same as that used by the plant for calculating the mass of powder to dissolve in the dosing tank. The concentration of the ingredient in the final powder is given by

$$C = \frac{F_D P[100 - M]}{V F_E S}\left[1 - {}^{L}/_{100}\right] \quad (1)$$

where C is the concentration of the ingredient in the final powder, F_D is the dosing flow rate, P is the mass of ingredient powder dissolved in the dosing tank, L is the ingredient losses during processing, V is the volume used to dissolve the ingredient powder, M is the moisture content of the final milk powder, F_E is the flow rate to the evaporator and S is the total solids content at the dosing point.

As different product specifications demand for different ingredient upper and lower concentration limits and different operating conditions, it was only possible to investigate one specification at a time. Furthermore, since the plant operation changes throughout the day, therefore several days of data for the single specification have to be used to understand the normal input process variations. Data from the same product specification produced during nine different production runs was used for assessing the input variation. Measurements of the final product concentration of the ingredient were available for all production runs used as simulation inputs. The data were checked for continuity, runs excluded which had abnormal operations such as mid-run stops or interruptions, which were unlikely to be representative of typical operation.

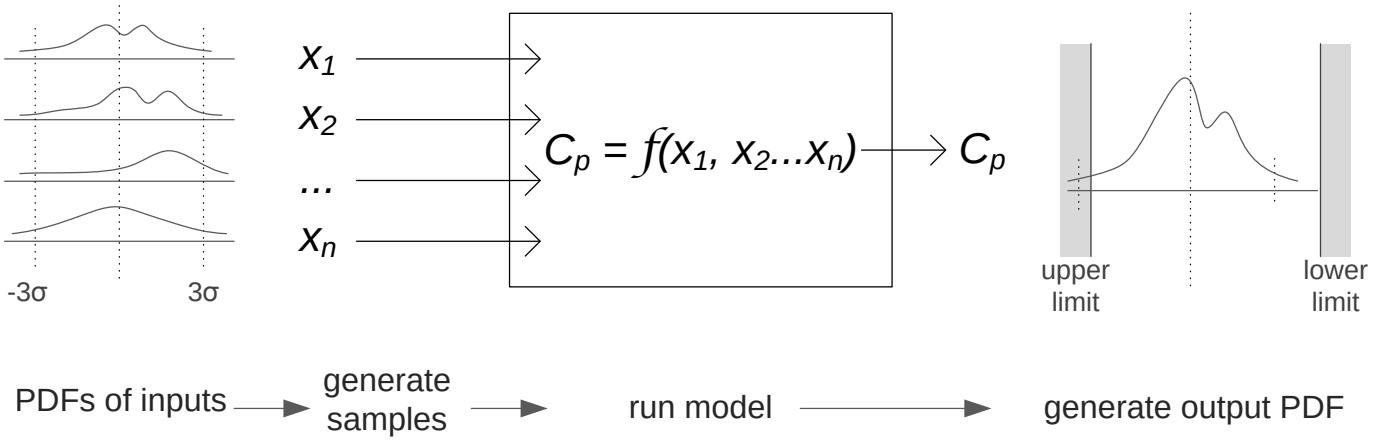

Fig. 2: Schematic diagram of the Monte Carlo method showing samples being generate from input probability density functions (PDFs) and then propogating these through the model to generate and output PDF.

Probability density functions (PDFs) were used to characterise the distribution of each input variable. Random sampling was used by passing uniformly distributed random numbers through the inverse cumulative distribution functions (CDFs) to generate the samples for that input with the observed PDF.

The data used for building the probability density functions (PDFs) of the dosing tank fill volume, flow rate to evaporator and dosing flow rate was extracted from the plant historian. The mass of the ingredient used for dosing tank make-up for at the plant was maintained constant for that specification with an expected normal three-sigma variation of 0.5%, based on previous work carried out by the plant. However, this does not account for any ingredient losses during tipping, only during weighing, and thus the actual variation is likely larger.

No information was available as to the variability of the processing losses and thus for the purpose of the analysis they were assumed to be constant, at 12% based on previous estimates.

IV. Results and Discussion

After establishing representative input PDFs and CDFs, several scenarios were examined to assess the uncertainty of the final ingredient concentration. The first scenario evaluated the concentration variation due to normal process parameter variation, and this was used as the base case to compare against. The control scenarios tested were a) constant dosing tank fill volume b) ratio control of dosing flow rate with the evaporator flow rate and c) effect of expected weight of the ingredient used on the final ingredient concentration in the milk powder. All simulations used a sample size of 50,000 for each input. All processing variable values and associated units have been removed and/or normalised for confidentiality reasons.

A. Generating Suitable Input Distributions

The dosing tank fill volume PDF was built using the most recent fill level data, and was extracted between the dates of 1-September 2012 to 31-January 2013. The PDF of the tank fill level can be found in Fig. 3(a), and shows a bi-modal distribution, as two tanks were used (one being re-filled whilst the other tank was being drained). The two modes are most likely due to a slightly different fill level being marked in each tank. The fill level varies by up to 14%, and is always higher than designed for. Therefore the dosing solution used is actually more dilute than expected. From the cumulative distribution function in Fig. 3(a) it was found that approximately 50% of the time, the tank is overfilled by 10% or more and that 95% of the time the tank is overfilled by at least 6%.

Fig. 3(b) shows the PDF and CDF functions for the evaporator feed total solids. The total solids data was extracted from a historian entry that calculates the total solids using a correlation between the feed density and temperature. The evaporator feed and dosing flow rate PDFs and CDFs are shown in Fig. 3(c) Fig. 3(d). The dosing flow rate follows the evaporator feed flow, most likely due to a pressure feedback mechanism. The evaporator and dosing flow rates have a Spearman's correlation coefficient of 0.84, and this was used in the Iman-Conover method [3] to generate a correlated sample for the analysis.

B. Current Variation of Ingredient Concentration

The first case assessed was the current likely uncertainty in the milk powder of the ingredient concentration for a particular product specification based on current operational procedures; the results are presented in Fig. 4. This was carried out to evaluate the current performance, and as a baseline for comparison with other dosing operation scenarios. The standard deviation was found to be 4.7% of the mean (or 13.1% for 2.8 standard deviations). The repeatability of the analytical measurement is 10% within 2.8 standard deviations, which is similar in magnitude to the variation due to processing. Therefore a reduction in the variation in either the processing or the analytical method will decrease the variability of the measured ingredient concentration in the milk powder.

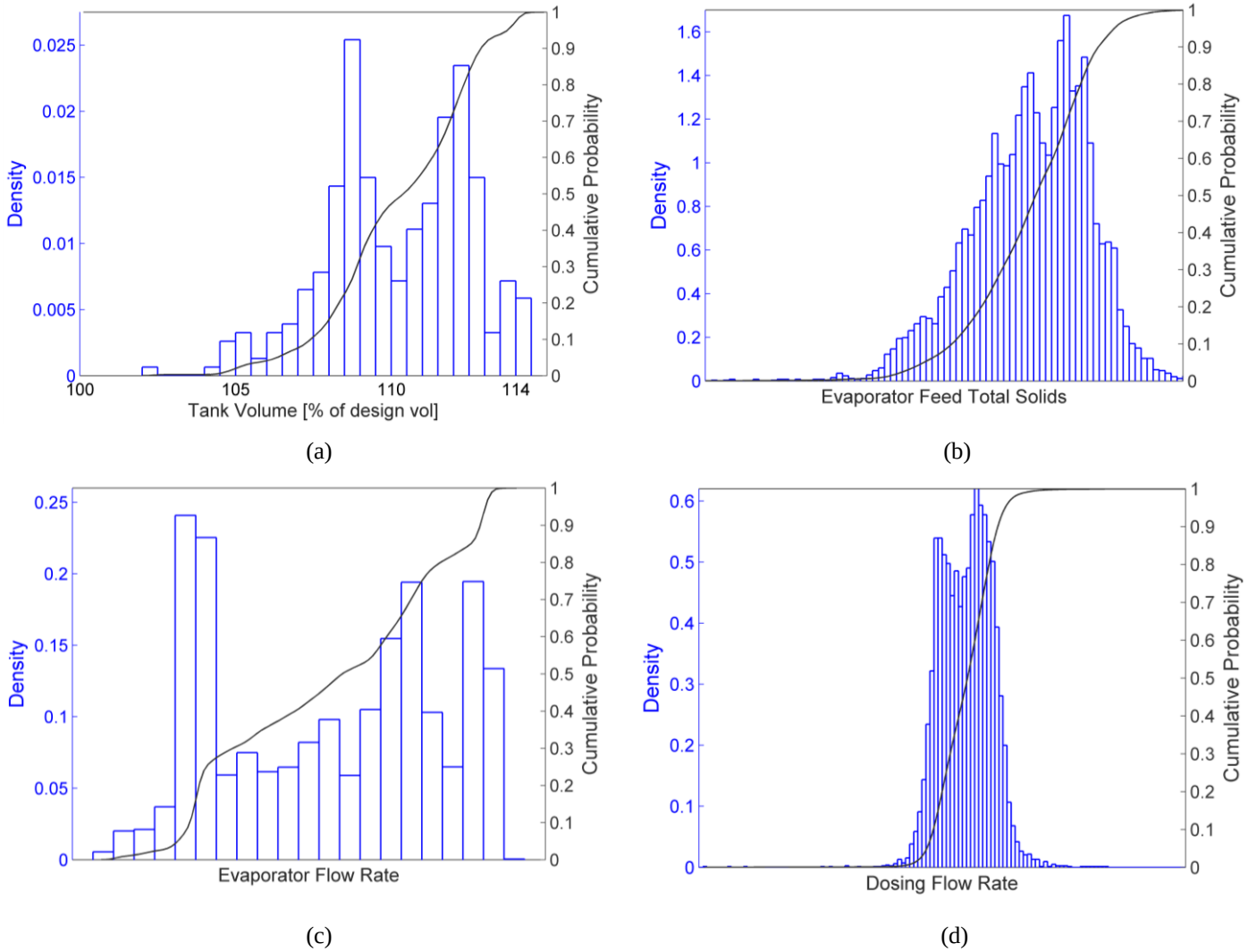

Fig. 3: Probability and cumulative density functions for a) dosing tank fill volume b) evaporator feed total solids c) evaporator flow rate and d) dosing flow rate.

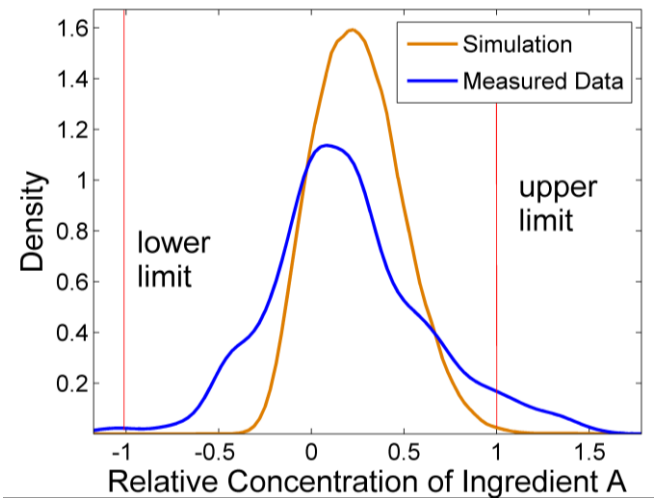

Fig. 4: Comparison of the distribution of output concentration in the simulation with the measured distribution of data from the five previous years production in normalised units. Note that the actual distribution includes data from all specifications.

Fig. 4 shows a comparison between the simulated ingredient concentration distribution and the actual measured data distribution over the last five years production. The measured concentration includes all specifications, as the data pool for a single specification is insufficient to draw a distribution from; therefore this data has been normalised against the specification limits. Both distributions are similar in that the majority of the data lies above the mid-specification value (normalised to zero), and the concentration is more likely to be out of specification on the upper limit than the lower limit. However, the measured concentration distribution is significantly flatter, which could be due to the extra variability introduced by the analytical method, which cannot be accounted for in the simulation.

C. Effect of Dosing Tank Fill Volume on Ingredient Concentration Variation

The scenario above described was compared with what the distribution would look like if the dosing was filled to a constant a) 106% of the designed volume (currently 95% of the time the tank volume is above 106% and b) 100% (the volume

that the tank was designed to be filled to). The results of these are shown in Fig. 5, with some measured ingredient concentration results for a number of production campaigns. However, if the tank volume was filled as intended in the ingredient addition calculation, then it is likely that a significant portion of the powder, ~16%, would be out of specification with respect to the maximum allowable ingredient concentration. If the tank is overfilled by 6%, then less than one percent of the powder produced might be expected to have a concentration of the ingredient in excess of the maximum limit. This implies that the plant processing losses (assumed to be 12%) may not be as high as previously calculated by the plant, and that the current over-dilution compensates for this i.e. that some of the losses are not encountered during the processing so much as by miss-dilution. Therefore, either the tank volume fill procedure should be made more accurate or the dosing flow rate should be adjusted based on the actual volume of water used to dissolve the ingredient.

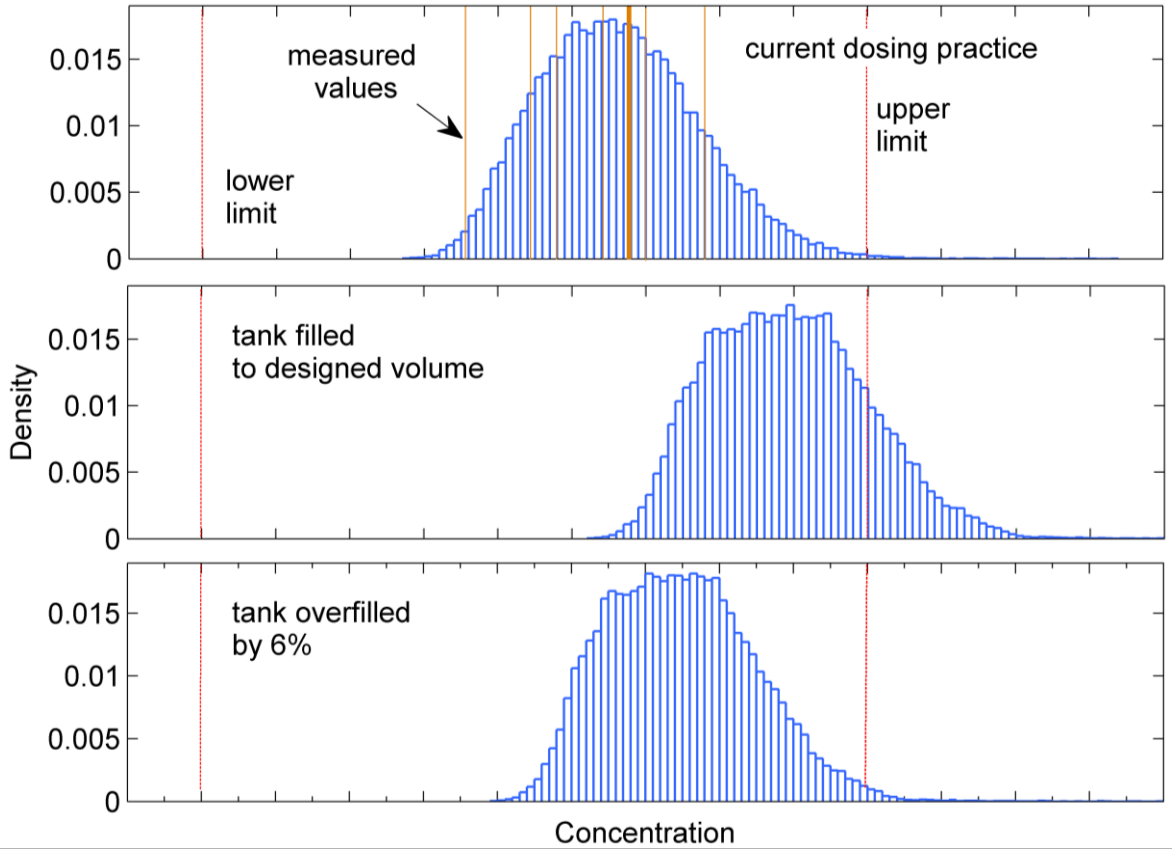

Fig. 5: Comparison between the likely distributions of the ingredient concentration in the milk powder with variable dosing tank fill volume and if the tank was filled to the designed volume or overfilled by 6%.

D. Effect of Ratio Control on Ingredient Concentration Variation

Ratio control is a strategy often employed with ingredient addition to maintain a constant concentration of an ingredient in the final milk powder. It involves changing the dosing flow rate in ratio to feed flow rate; hence and increase in the feed flow rate results in a proportional increase in the dosing flow rate and vice versa.

Fig. 6 shows a comparison of what impact the implementation of dosing flow rate controlled in ratio with the evaporator flow rate would be expected to have on the distribution of the concentration of the ingredient in the powder. With the use of ratio control the distribution becomes significantly narrower, whether the dosing tank is filled to a consistent level or not. The standard deviation decreases significantly with increasing control, as shown by Fig. 6, with a shift in the mean closer to the maximum concentration limit of the ingredient in the milk powder. The implementation of ratio control and a consistent tank fill volume would decrease the variability of the process and allow the plant to be run closer to the upper limit. This may make it possible to compensate for unexpected losses that may occur downstream (e.g. during processing and/or storage) as a larger portion of the powder now has a higher concentration of the ingredient. The distribution of the ingredient in the milk powder now mirrors the total solids distribution (Fig. 3(b)), and therefore if ratio control is implemented for the evaporator flow rate, it should be in ratio to total solids flow, rather than total flowrate, to reduce the variability further.

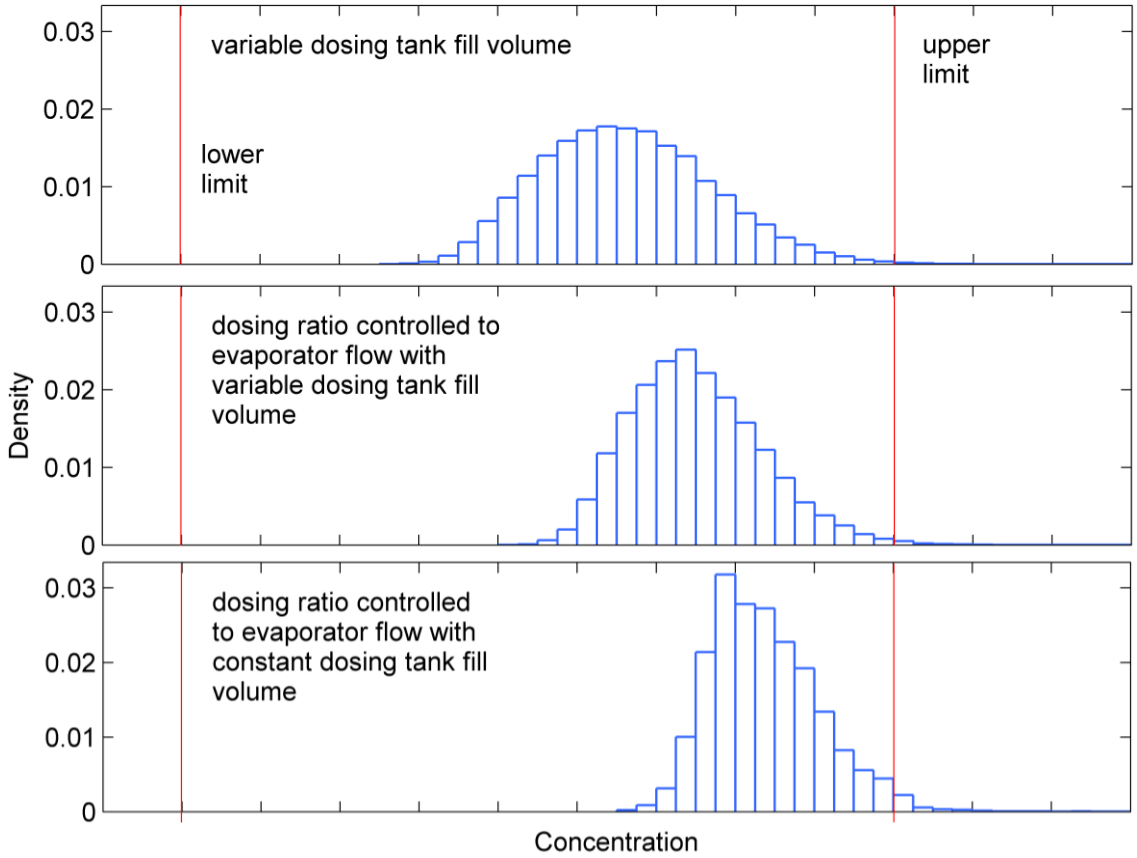

Fig. 6: Effect of implementation of ingredient dosing ratio control to the evaporator flow rate on the ingredient concentration, with variable dosing tank fill volume and with a constant tank volume of 106% of designed value.

TABLE I. EFFECT OF RATIO CONTROL OF THE DOSING FLOW WITH THE EVAPORATOR FLOW RATE ON THE MEAN AND STANDARD DEVIATION OF THE INGREDIENT CONCENTRATION, WITH VARIABLE AND CONSTANT TANK FILL VOLUME (UNITS REMOVED AND VALUES NORMALISED AGAINST TOP ROW).

Simulation	Mean Concentration	Standard Deviation	Ratio to max standard deviation
No ratio control and variable dosing tank fill volume	100.0	4.8	1.0
Ratio control with variable dosing tank fill volume	103.9	3.7	0.78
Ratio control with a constant dosing tank fill volume of 106% of designed volume.	107.7	3.1	0.66

E. Effect of Mass of Ingredient Powder Used on Ingredient Variation

Fig. 7 shows the effect of the mass of powder dissolved in the dosing tank on the concentration of the ingredient in the milk powder, assuming ratio control and constant volume (tight control scenario). The mass of powder was assumed to be normally distributed about the measured value with three standard deviation limits of + 0.5%, as described before. Provided as long as the mass of powder weighed into the dosing tank is maintained within these limits, it will have little impact on the concentration of the ingredient in the milk powder. It should be noted that this does not account for any powder lost during tipping into the tank e.g. spillage.

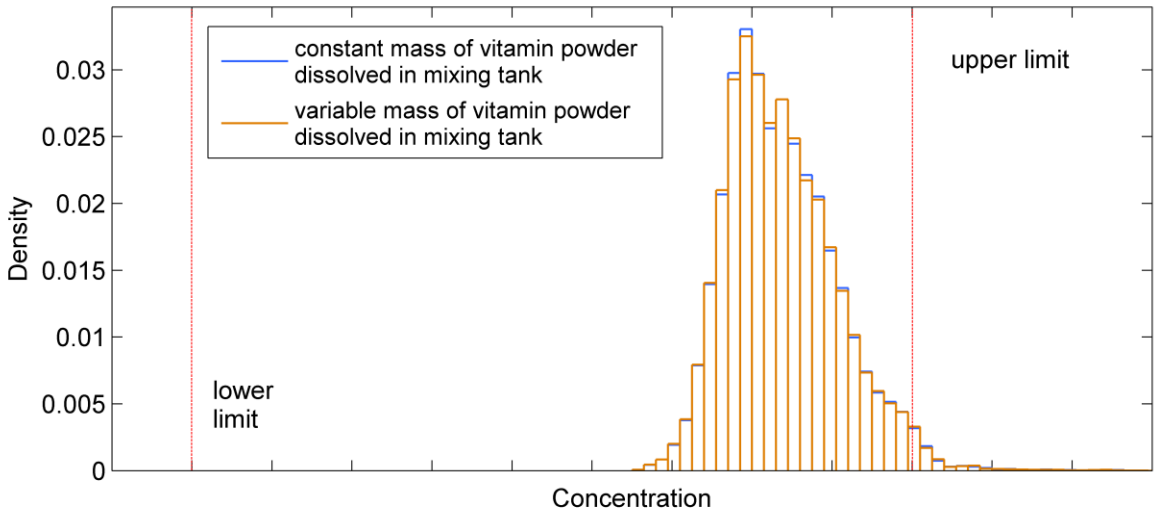

Fig. 7: Effect of variation in the mass of ingredient powder dissolved in the dosing tank on the concentration of the ingredient in the powder produced, with ratio control and a constant tank volume of 106% of designed volume.

V. Conclusions

A Monte Carlo uncertainty analysis was used to assess the variation in an ingredient addition dosing system at a milk powder production plant. It was found that the variation of the concentration of the ingredient in the final product introduced due to the processing is of similar magnitude as the anticipated variation introduced by the analytical technique. Consequently, a reduction in the processing variability would be expected to reduce the variability in the final measured ingredient concentration, and so therefore it is prudent to investigate ways to reduce this variation introduced by the current operation. The out of specification results are more likely on the upper limit than on the lower limit for the ingredient, as suggested by the simulations and validated by the observed data. Out of specification on the upper limit is likely caused by normal process variation; however this is unlikely for milk powder out of specification on the lower limit. The Monte Carlo simulations indicate that the following measures can be taken to reduce the variability of concentration of the ingredient in the milk powder:

1) Ratio control of the dosing flow rate should be implemented with the evaporator feed flow rate and total solids.

2) The concentration of the ingredient in the dosing tank should be recalculated based on the volume used at the time and the dosing flow rate adjusted accordingly.

A reduction in the variability of the concentration of the ingredient in the milk powder could make it possible to run closer to the upper allowable limit and thus provide a greater buffer for any unpredictable losses during processing, storage and handling, and improve product quality.

While this paper described a particular investigation, the methodology of assessing where the key sources of variation come from in a highly interconnected processing operation using input samples drawn from the actual measured distributions, and a physical model delivers a reliable analysis of variance that is awkward, if not impossible to obtain by any other means. This information can then be used to quantify the value of, and hence rank competing process improvement projects.

Acknowledgement

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