REFEREED PAPER

DYNAMIC SIMULATION ON A SPREADSHEET AS A TOOL FOR EVALUATING OPTIONS FOR MIXED JUICE FLOW CONTROL

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Abstract

Dynamic simulation is a powerful tool for both predicting and interpreting the behaviour of systems that change with time. This is particularly true for understanding and optimising the performance of feedback control loops. A spreadsheet program is a powerful, simple and widely available tool that allows dynamic simulations to be generated and operated.

The use of a mixed juice tank as buffer storage to smooth out flow fluctuations and provide a more stable mixed juice flow to the juice clarifiers is an example of a dynamic system where there is no clear agreement on the best strategy to implement. Dynamic simulation provides a method for objectively comparing different strategies under varying operating conditions.

A simple method for creating dynamic simulations using an Excel spreadsheet is described. Alternative mixed juice flow control strategies are described and simulated on a spreadsheet. An example of a control strategy that performed poorly at a particular factory is simulated, demonstrating the cause of the problem and allowing suggested solutions to the problem to be evaluated.

Keywords: spreadsheet, modelling, simulation, dynamic, flow control

Introduction

There are numerous instances in sugar engineering where computer simulations of factory performance can be of considerable value. Most commonly, these simulations are steady state simulations which can be used for design or evaluation. Two examples, relating to multiple effect evaporators and continuous pans respectively, are described by Hoekstra (1981) and Hoekstra (1985). More recently, the commercial simulation package Sugars™ has become a tool of choice for many sugar engineers who want to develop steady state simulations of sugar factories or is used as a bench-mark for alternative simulation approaches (e.g. Starzak and Davis, 2016).

Dynamic simulations are less common and often involve the use of specialised software for handling mathematical problems, such as MATLAB. Examples are the work done on the control of multiple effect evaporators at Triangle by Smith et al (2001) and the investigation into juice flow control at Gledhow by Melrose (2003). The lack of wider use of dynamic simulations within the sugar industry is probably due to the perceived difficulties in undertaking these simulations. An obvious barrier is the expense of the specialised software and the likelihood of a steep learning curve with a significant time commitment before it is possible to make effective use of the software.

As a possible alternative to specialist software, Microsoft Excel is readily available to most computer users. The absence of any extra cost, combined with familiarity, ease of use and flexibility make it a tempting option as a tool for conducting simulations. Locally, Loubser (2004) has reported on the use of a spreadsheet for steady state factory mass balances.

Clearly, there is also the potential to use an Excel spreadsheet for dynamic simulations of sugar factory operations.

Digital Simulation of a Dynamic System

Dynamic systems are those where the properties of interest vary with time. As such, the mathematical description of their behaviour ideally requires calculus and the use of differential equations. To provide a viable description of the real system the mathematical representation needs to be based on the fundamental laws of chemistry and physics and thus requires a clear understanding of the system being simulated. Examples of this approach applied to a relatively simple system are the simulations developed for investigating the dynamics of pan feed control, described by Love and Chilvers (1986), and Love (2001).

A full mathematical description of a dynamic system will produce a differential equation which, in some instances, may be solved analytically. Alternatively, standard numerical techniques are available for solving differential equations (Press et al 1989), eliminating the complexities and limitations of analytical solutions. These numerical techniques represent continuously changing real systems by samples at fixed time intervals, creating "difference" equations that approximate the "differential" equations that properly describe the real system.

Fortunately, some systems are simple enough to be modelled by a simple, practical, approach using reasonable judgement, as will be demonstrated in the examples relating to mixed juice flow control described later in this paper. Relatively simple dynamic systems can demonstrate complex behaviour that can be difficult to either predict or understand based on simple conceptual mental models. This observation provides both the incentive and justification for building and using effective dynamic models.

Using a spreadsheet for digital simulation

A major challenge in computer programming is to create a program that is easy to understand, debug and modify. There has been much argument about the most appropriate language for programming different computing tasks, with programming that takes place within a spreadsheet environment (either using a macro programming language or the VBA language provided within Excel) often regarded as a poor choice.

The approach described in this paper avoids programming as such by using the standard functions provided within Excel. This generally meets the need for a clear specification for the calculations that are required to model a dynamic system. Unfortunately, the "if ( )" function within Excel can be cumbersome when compared with the "if, then, else" structures of conventional computer languages. Carefully documenting this part of the specification can greatly help with clarity.

Appendix B describes how to construct an Excel simulation of a mixed juice buffer control problem, based on the mathematical representation of the system described in Appendix A.

The challenge of mixed juice flow control

The terminology "mixed juice flow control" is generally used to describe the selection of an appropriate strategy for smoothing the flow of juice from the extraction plant before it enters the juice processing plant. The term "mixed juice" is correctly only applied when the extraction plant is a milling tandem or a first mill followed by a bagasse diffuser. In these instances there is a primary juice stream that is combined with a secondary juice stream to create mixed juice. When the extraction plant is a cane diffuser, there is only one juice stream from the extraction plant and this is more properly termed draft juice. More recently,

with the development of the "direct clear juice process" a new term, "direct clear juice", has been coined to describe the juice leaving the extraction plant that uses this new process. Despite the rationale for using different terminology depending on the extraction process, the term "mixed juice" is still commonly used to describe the juice from the extraction plant regardless of the particular type of extraction plant. Perhaps in future it will be more convenient to refer generically to the juice leaving the extraction plant as "raw juice", as done by Meadows (1996).

With continuous processing in the juice processing plant (clarification and evaporation) there is a need for a stable flow of juice into the juice processing plant to achieve the best possible capacity and performance from this section of the plant. Flow stabilisation is achieved by having a buffer tank (the mixed juice tank) with sufficient volume to accommodate fluctuations in the flow from the extraction plant whilst allowing a smoothed flow out of the tank to feed the juice processing plant. This flow stabilisation challenge is not unique to the sugar industry and the generic challenge of "buffer tank control" is experienced in many process industries and is consequently discussed in a number of technical publications.

Possible strategies for mixed juice flow control

Meadows (1996) provides a useful summary of strategies that were in use in the South African sugar industry at the time of his paper. He characterised these strategies as falling into four groups viz.:

Flow control;
Level control;
Gap action and
Cascade, as shown in Figure 1.
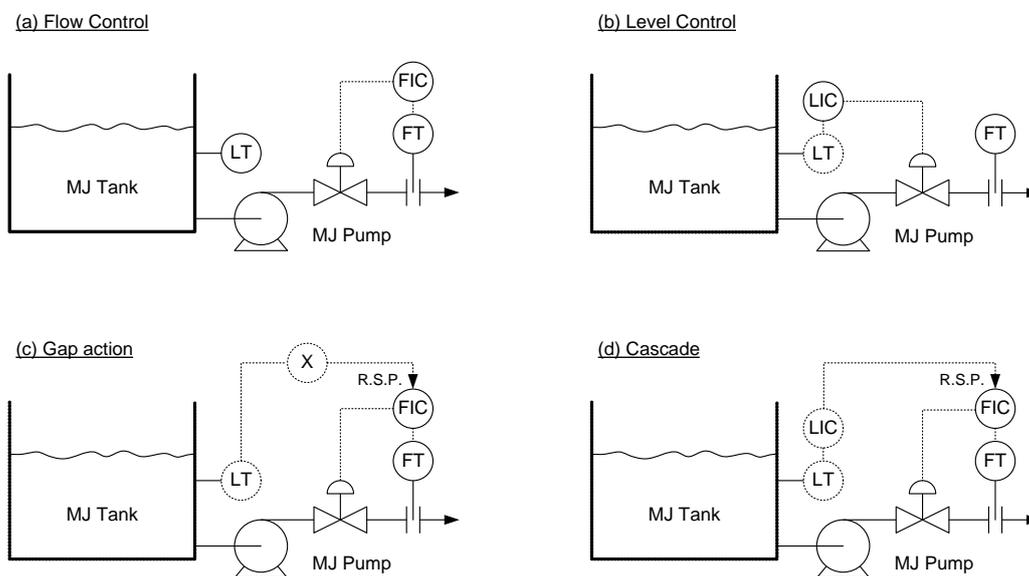
Figure 1. Strategies for mixed juice flow control based on Meadows (1996)

The strategies reported by Meadows (1996) are specific to the sugar industry but can be compared with the more general recommendations of Shinskey (1979) in his standard text on practical control engineering for the process industries. Love (2002) provides a review of published buffer control strategies, both for mixed juice flow control and as a more generalised flow stabilisation strategy, whilst also deriving a new strategy based on the principles of optimal control. The review did not provide any startling insights from outside of the sugar industry and demonstrated that some of the very detailed mathematical treatments that have been published were of very little practical value.

Based on pre-publication communication of the review and the new flow stabilisation strategy, Smith (2000) investigated the application of the new strategy to smoothing the juice flow into an evaporator train at Triangle. Melrose (2003) subsequently investigated the use of the strategy at Gledhow.

Ideally, each factory should evaluate potential control strategies appiled to the specific situation at that factory. In the first instance this could be an investigation into what could be achieved with an alternative strategy implemented using equiment that was already installed and available. At the next level of investigation this could evaluate the benefits of installing new equipment to implement an improved buffer control strategy. In any event, most of the more sophisticated strategies have "tuning parameters" that need to be adjusted to achieve the best possible flow smoothing for the particular variations in juice inflow encountered at the factory, and this is a valuable use of dynamic simulations.

Simple comparisons of buffer strategies using a spreadsheet simulation

To give an indication of the utility of spreadsheet simulations to evaluate and compare alternative control strategies, it is possible to use simulated variations in the flow rate of juice from the extraction plant into the mixed juice tank. Appendix A describes the simple mass balance that forms the basis of the simulation of the dynamics of a mixed juice tank used to buffer variations in juice flow. Appendix B describes the techniques necessary to implement the simulation on an Excel spreadsheet using simple spreadsheet functions without the need to resort to progamming using macros or the available VBA programming language available within Excel.

The simulation described in Appendix B and used for the two examples below is based on an installation with the following characteristics:

      Volume of mixed juice tank   :   50 m^3
      Maximum flow out of tank   :   450 m^3/hr

The simulated flows used in these examples were created by using the random number generator available as an Excel function and then scaling and filtering the result (using simple digital first order filters) to generate a plausibly variable juice flow.

Elementary "gap action" control.

An elementary form of "gap action" control, as described by Meadows (1996), is to simply vary the remote set-point to the flow controller linearly from zero when the tank is empty, to maximum flow when the tank is full. The results of a simulation of this type of control are shown in Figure 2. The simple linkage between the juice flow out of the tank and the level within the tank is clearly evident as these two signals move in unison over the full length of the simulation. There is a clear smoothing of the flow evident by comparing the variability of the flow out with the variability of the flow in. However, it was evident that more smoothing of the flow could have been achieved if a larger portion of the available buffer volume had been used.
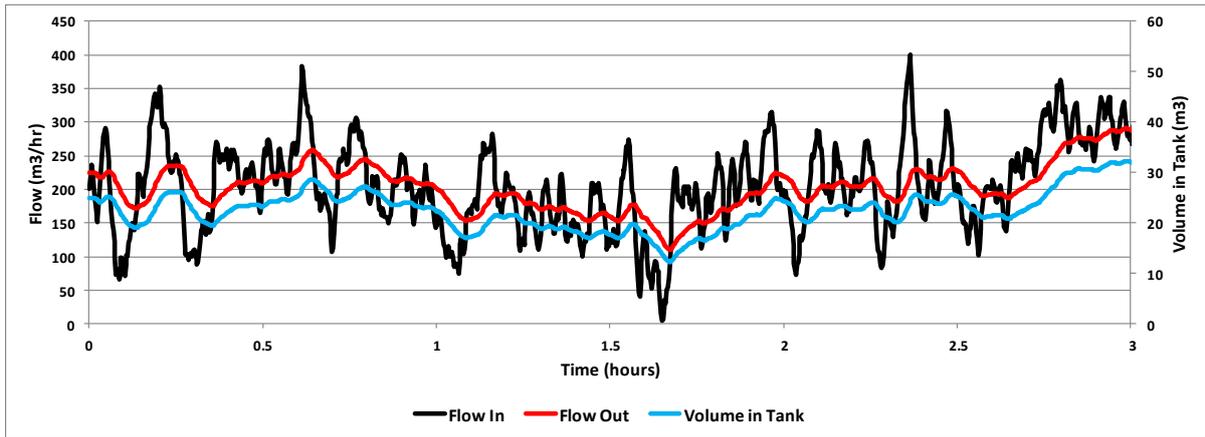
Figure 2. Simulation results when using an elementary "gap action" control

Conventional "gap action" control

The more conventional form of "gap action" is to have a non-linear form of variation in the set-point to the flow controller of the form shown in Figure 3.
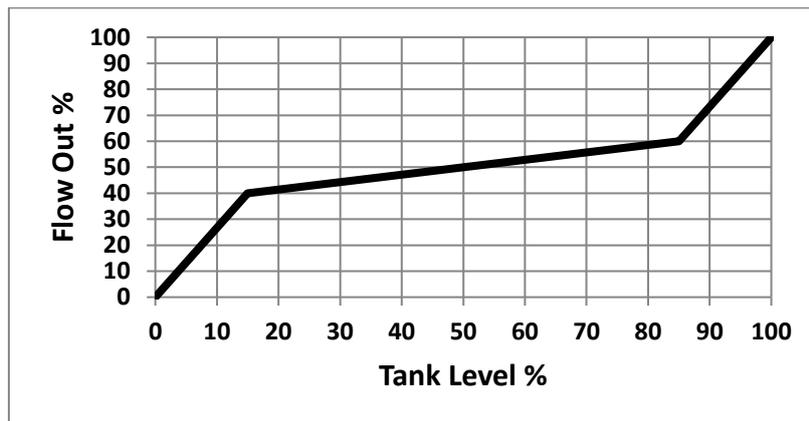

Figure 3. Conventional "gap action" control

The intention of this strategy is that the outlet flow should vary only slightly if the tank level is in a "centre zone", with the gap around 50 %, but will vary more radically if the tank level enters "end zones" as it approaches either empty or full. This controller is defined by the position of two break points and thus requires four parameters for its specification (or only two parameters if it is designed to be symmetrical around the half-full condition).

Appendix B describes how this strategy is implemented within a spreadsheet simulation. The results of a simulation of this type of control are shown in Figure 4.

The simulation results show that for most of the time there is a much better smoothing of the juice flow out of the tank when compared with the elementary "gap action" control. However, it is clear that when the tank level dropped into the lower "end zone", around and just after 1.5 hours, a radical drop in flow out was necessary to prevent the tank from running empty.
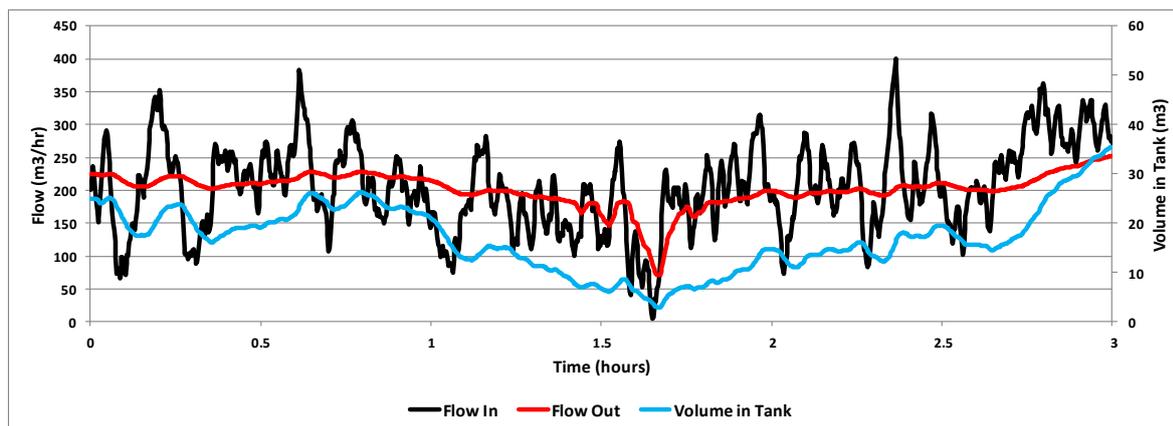
Figure 4. Simulation results when using a conventional "gap action" control

If real trends of the variability of juice inflow with time were available, a range of simulations could be run to evaluate how best to tune the conventional "gap action" control by adjusting the positions of the two break points that specify the control action.

Investigating a specific mixed juice flow stability problem using a spreadsheet simulation

It is not uncommon, in relation to automatic control systems, to receive a report that a control loop "performs badly" and "can only be run on manual". The fact that the operators and even the factory engineers may not be able to describe the nature of the problem in ways that are helpful to properly understand it, does not mean that the problem is not real. Extensive factory testing can help elucidate the nature of the problem, particularly if comprehensive data logging is available to allow subsequent analysis. Time, resistance from operators (to using a failing system) and possible process disruptions are all factors against using this approach. As an alternative approach, dynamic simulation provides an opportunity to investigate the nature of a control problem without encountering operator resistance or risking any process upsets as indicated in the following example.

A gap action control on a mixed juice tank was reported to perform "very badly at times" and the factory process engineer believed that part of the problem was that the mixed juice tank was too small. Could it be shown that the control problem was caused by an undersized mixed juice tank and, if so, would the planned replacement of the mixed juice tank with a larger one solve the problem?

To properly understand the reported problem, the simple model of the buffer system described earlier in this paper is insufficient. It is necessary to include a model of the mixed juice scale as part of the simulation. The paper by Keir (1980) provides a useful summary of the operation of a standard juice scale that weighs the juice leaving the extraction plant in batches, each of which is discharged almost instantaneously into the mixed juice tank.

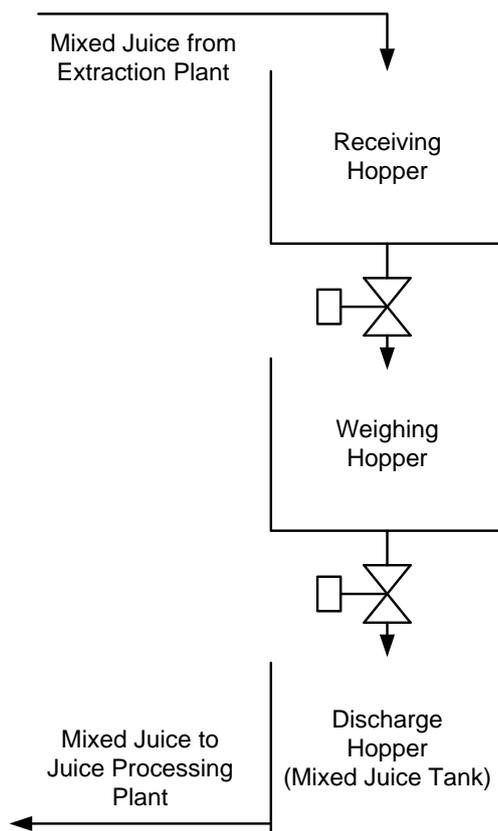The arrangement of conventional batch juice scale is shown in Figure 5.

Figure 5. Schematic representation of a juice scale based on Keir (1980)

As a reasonable first approximation, the scale can be represented in a simulation as a single scale tank that accumulates the flow into it (rather than the two tanks, shown in Figure 5). In the simulation, if at any time instant the quantity in the tank is greater than the capacity of the scale, a volume equal to the capacity of the scale is immediately transferred into the mixed juice tank, leaving the balance of juice in the scale tank.

Simulating a conventional "gap action" control on the combined scale and juice tank system yielded the results shown in Figure 6. The mixed juice (MJ) tank had a volume of 27 m³ and the scale had a tip capacity of 3.5 tons. The maximum juice flow out of the tank was set at 306 tons/hr. The gap action controller was configured with end zones below 15 % full and above 85 % full. At 15 % full the flow was set at 44.3 % and at 85 % the flow was set at 55.7 %.

What is clear from this simulation is that the scale tips have an undesireable effect on the smoothness of the mixed juice flow out of the tank. When the mixed juice tank level is in the centre zone (between 15 % and 85 % full) the scale tips have a small and acceptable effect on the flow. However, when scale tips result in the level entering or leaving one of the end zones (below 15 % or above 85 %) there are large and rapid changes in the juice flow from the mixed juice tank. Although this is a function of the settings of the gap action control, it is largely due to the fact that an individual scale tip corresponds to a change in tank level of approximately 10 %. A larger tank where the size of a scale tip is a much smaller proportion of the total tank volume would greatly reduce this undesirable effect, providing added justification for the planned replacement of the mixed juice tank with a larger one at the factory where this problem was experienced.
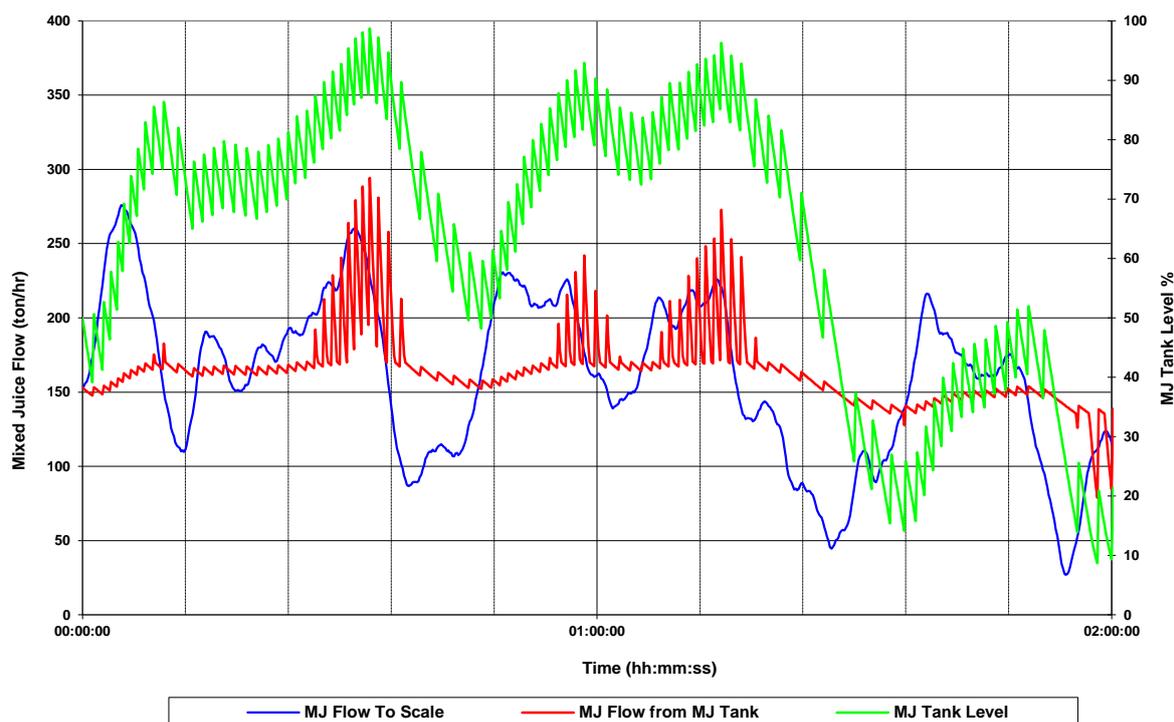
Figure 6. Simulated dynamic behaviour of combined MJ scale and MJ tank

The results of the simulation suggest some possible modifications to improve the control strategy. There is an option to filter the mixed juice flow signal from the gap action controller before it is pased through as a remote setpoint to the flow controller. This would be particularly helpful in removing the higher frequency variations in flow due to scale tips in the centre zone. If it was possible to get a signal from the juice scale that gave a continuous reading of the mass of juice held up within the scale, this could be added to the tank level signal to provide an "effective tank level" signal with much of the variability due to scale tips removed.

Conclusion

Dynamic simulation is a very useful tool for investigating and optimising the time behaviour of processes within a sugar factory. An Excel spreadsheet is a convenient and flexible tool for generating and using dynamic simulations.

Acknowledgements

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APPENDIX A

Definition of a standard buffer tank problem

Description of the buffer tank problem

The standard buffer control problem is essentially the question of how best to use the installed volume of a buffer tank to smooth out fluctuations in flow into the tank to produce a more stable outlet flow. This has to be achieved whilst also ensuring that the tank never ran empty or overflowed. This is shown diagrammatically in Figure A1 below.
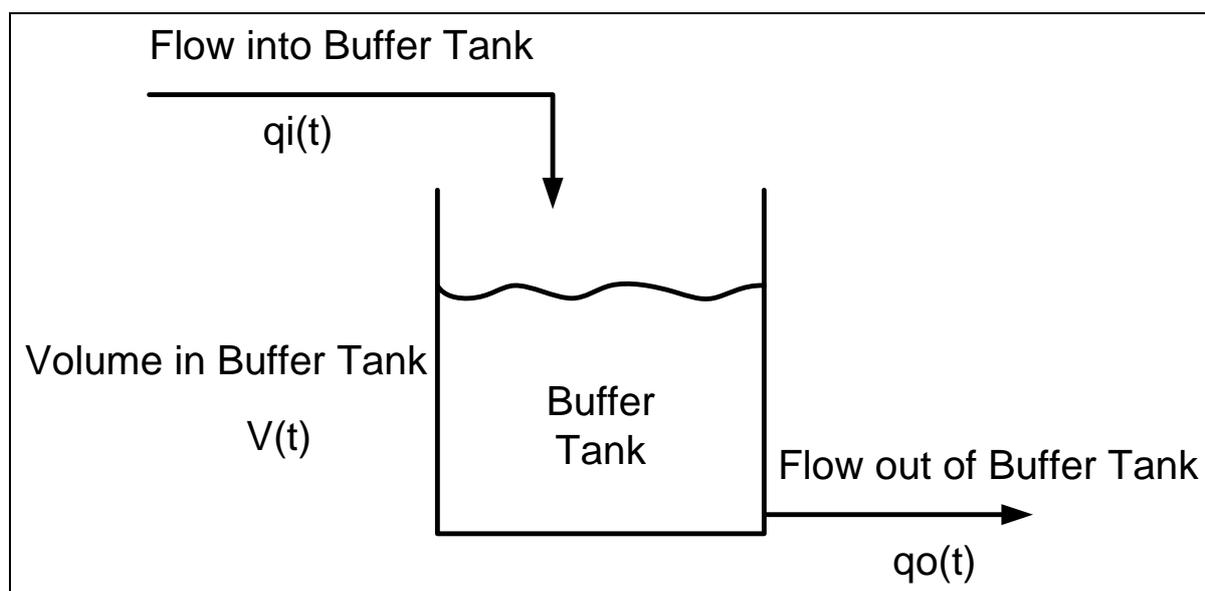

Figure A1: Pictorial representation of the standard buffer control problem

Mathematical formulation of the buffer tank problem

The buffer tank behaviour can be described mathematically by using the standard mass balance relationship of:

Flow in = Flow out + accumulation.

Which yields:

$$qi(t) = qo(t) + \frac{dV(t)}{dt}$$

The challenge in the buffer control problem is to define the control strategy that makes the "most appropriate" adjustment to the outlet flow $qo(t)$, based on the current value of both the outlet flow and the volume within the tank $V(t)$. It may seem that it would be helpful to use a measurement of the flow into the tank $qi(t)$ as part of the control strategy but the mass balance equation means that the inlet flow can be derived from a knowledge of the outflow and the variation with time of the volume within the tank and therefore does not provide any extra information.

The differential equation above can be approximated as difference equation as follows:

$$qi(t) = qo(t) + \frac{\Delta V(t)}{\Delta t}$$

And rearranged to give:

$$\Delta V(t) = qi(t) * \Delta t - qo(t) * \Delta t$$

Now:

$$V(t + \Delta t) = V(t) + \Delta V(t)$$

Thus:

$$V(t + \Delta t) = V(t) + qi(t) * \Delta t - qo(t) * \Delta t$$

Using the subscript k to represent a series of values sequential measurements, each one time step, Δt, apart, it is possible to write the difference equation as:

$$V_{k+1} = V_k + qi_k * \Delta t - qo_k * \Delta t$$

This is what one would calculate from the following simple analysis:
Assume that at time instant *k* we know the volume in the tank, V_k,
We assume that the flow in and flow out at this instant, qi_k and qo_k over the next short time increment, Δt
The accumulation of liquid within the tank over this time interval is then given by:

$$qi_k * \Delta t - qo_k * \Delta t$$

Adding this accumulation to the volume in the tank at the beginning of the time step, V_k, gives the volume in the tank at the end of the time step, V_{k+1}.

APPENDIX B

Basic components of a system for Dynamic Simulation using an Excel spreadsheet

The basic components that are required to simulate the dynamics (characteristics that vary with time) of a system using an Excel spreadsheet are described below, referring where necessary to the layout shown in Figure B1.
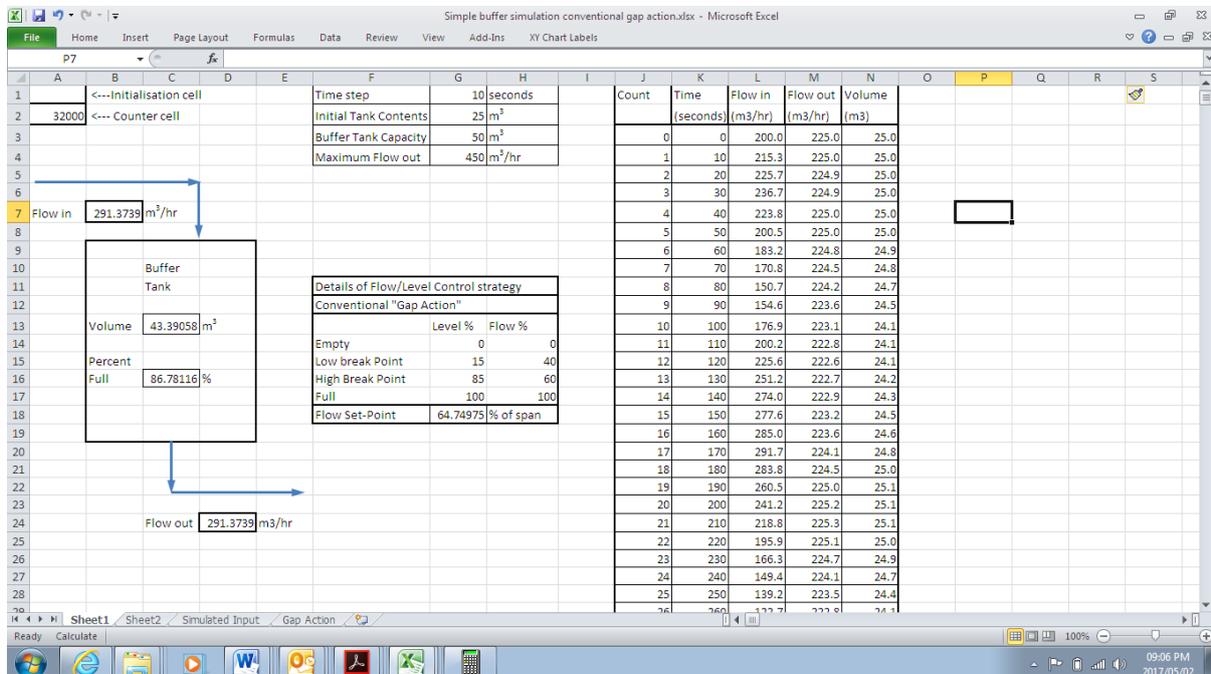

Figure B1: Excel spreadsheet showing the layout used for the simulation of mixed juice flow control strategy.

A clear definition of the dynamic system to be simulated

It is important to have a clear definition of the dynamic system that has to be simulated. This definition needs to be formulated in mathematical terms that allow the behaviour to be approximated as a difference equation. Appendix A gives an example of this approach applied to a simple buffer tank problem.

The use of circular references

A very useful feature of spreadsheets is the ability to use "circular references". This is a feature that allows the calculation within a cell to reference the value existing within the cell itself. In a spreadsheet that is not set up to accept circular references an error message is usually displayed as this "self-referencing" is normally indicative of a mistake in conventional spreadsheet calculations. Within Microsoft Excel 2010, circular references are set up by following the menu items File, Options, Formulas, to reach the screen shown in Figure B2:
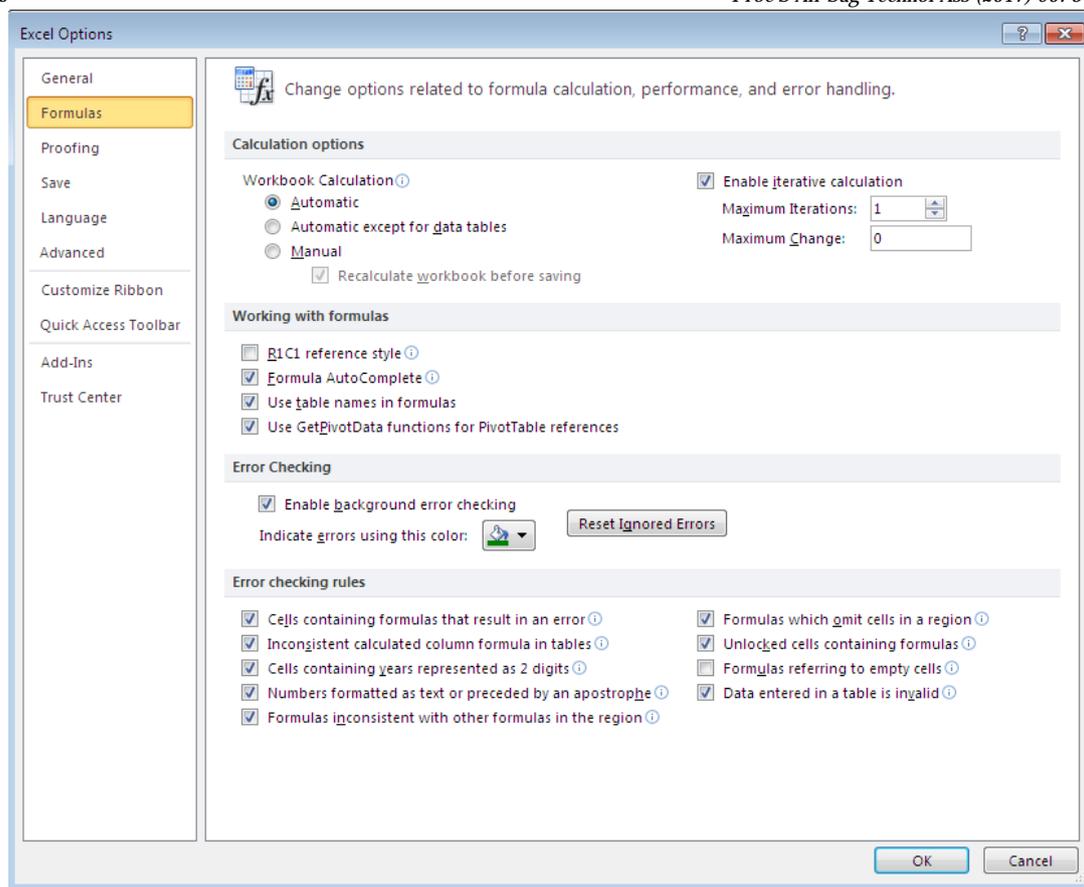
Figure B2: Excel window for enabling iterative calculation with circular references

On this screen the "Enable iterative calculation" box needs to be checked.
"Maximum Iterations" needs to be set to an appropriate value. Setting this to 1, as shown in Figure B2, will update the circular references once each time the spreadsheet is recalculated, which will happen after a manual change to any value in the spreadsheet or when the F9 key is pressed. It is convenient to set "Maximum Iterations" to 1 when first testing out a new simulation so that the calculations can be carefully monitored by watching changes each time the F9 key is pressed. However, it is normally more convenient to set "Maximum Iterations" to a large number, say 1 000, to enable the full simulation to be updated with just one or only a few presses of F9.

It is important to provide a feature that allows the circular references to be initialised when required. A means for doing this is described below, under the section on the use of a counter to track time increments.

The use of a counter to track time increments (Cell A2)

In a digital simulation, continuous time is approximated as a sequence of discrete time steps, short enough to provide a reasonable approximation of continuous time. A simple circular reference can be used to track time increments. Assume that cell A1 is used to initialise the counter, to zero, if it contains the letter "I". A counter can then be implemented in cell A2 by entering the formula:
=IF(A1="I",0,+A2+1)
If the time increment for each step is specified by a variable named deltaT, then the prevailing time for the simulation (in seconds elapsed from the start of the simulation) is given by:
= $A$2 * deltaT

Defining the Fixed parameters used in the simulation (Block F1 to H4)

The simulation will require a number of fixed parameters to be specified. The values specified in Figure B1 are those that adequately describe the mixed juice flow control problem being simulated.

Specifying a control strategy (Block F11 to H18)

Many dynamic simulations require the simulation of some form of feedback control. The example shown in Figure B1 uses a conventional "gap action" control to set the required flow out of the tank as a function of the level within the tank. The relevant portion of the spreadsheet used to define the control action is shown enlarged in Figure B3.

	F	G	H
11	Details of Flow/Level Control strategy		
12	Conventional "Gap Action"		
13		Level %	Flow %
14	Empty	0	0
15	Low break Point	15	40
16	High Break Point	85	60
17	Full	100	100
18	Flow Set-Point	64.75	% of span

Figure B3: Portion of spreadsheet used to define a conventional "gap action" control.

The data points in the block G14 to H17 define the graph (shown in Figure 3 within the main text of the paper) that gives a useful visual representation of the control action.
To describe the control action mathematically it is necessary to consider three possible conditions viz.:
The level within the tank (cell C16) is below the Low break point level (cell G15)
In this condition, the flow set-point (as a % of span) is given by:

$$C16/G15*H15$$

The level within the tank (cell C16) is above the High break point level (cell G16)
In this condition, the flow set-point (as a % of span) is given by:

$$(C16-G16)/(100-G16)*(100-H16)+H16$$

The level within the tank (cell C16) is between the two break points (cells G15 and G16)
In this condition, the flow set-point (as a % of span) is given by:

$$(C16-G15)/(G16-G15)*(H16-H15)+H15$$

These three conditions can be combined into one expression that is entered into cell G18 viz.:

=IF(C16<G15,C16/G15*H15,IF(C16>G16,+(C16-G16)/(100-G16)*(100-H16)+H16,(C16-G15)/(G16-G15)*(H16-H15)+H15))

Creating a "Data Logger" and Input Definition Area (Block J1 to N2000)

The results of a dynamic simulation are easily captured by creating a table of columns that are filled with results as they are generated. The same table can be used to provide the input signal for the simulation. In the example shown in Figure B1, simulated values for the flow into the mixed juice tank at each time interval are entered in column J.

The "Data Logger" is created in columns M and N where the current values of the simulation are entered into the correct row as the simulation progresses when the circular references are updated. The formula in cell M4 demonstrates how this is achieved:

=IF($A$1="I",0,IF(J4=$A$2,$D$24,M4))

This formula first checks to see whether the spreadsheet is in initialisation mode and then, if so, sets the value of the cell to zero. This is convenient for demonstrating that all old values are cleared from the data logger before a new simulation is initiated. Otherwise, a check is made to see if the current iteration number (cell A2) is equal to the iteration number, count, of this row as shown in column J (cell J4). If so, the value of cell M4 is updated with the current value of the juice flow out of the tank (cell D24), otherwise it is left unchanged from its current value. The use of the $ symbol is to ensure that this formula remains correct when copied into all the cells within column M.
A similar approach is followed for the cells in column N with the formula in cell N4 given by:

=IF($A$1="I",0,IF(J4=$A$2,$C$13,N4))

A discrete time simulation of the dynamic system (Block A5 to E24 and F16 or H22)

It is convenient to lay out the discrete time simulation in a format that approximates a flow diagram. Figure B1 shows how this can be done for the example of the mixed juice buffer control problem. The juice input flow to the tank (cell B7) is updated at each time interval by comparing the current time step (cell A2) with the time steps in column J and then retrieving the flow from the value on the same row from column L. This uses VLOOKUP function of Excel in the following formula that is entered into cell B7:

=VLOOKUP(A2,J3:L1175,3)

The mass balance outlined in Appendix A is entered into Cell C13 as:

=IF(A1="I",G2,+C13+B7*G1/3600-D24*G1/3600)

This initialises the tank level to value specified in cell G2 if the spreadsheet is set to "Initialise" mode by entering the letter "I" into cell A1. Otherwise, it increments or decrements the volume within the tank by the difference in the quantity of juice that flowed into and out of the tank over the current time interval.
The flow out of the tank (cell D24) is given by the formula:

=G18/100*G4

Which simply converts the output of the flow control strategy (cell G18), which is given as a percentage of span, into a flow rate in m^3/hr by using the specified maximum flow rate (cell G4).

The tank volume expressed as a percent full (cell C16) is given by the formula:

$$=+C13/G3*100$$

Which simply relates the actual volume in the tank (cell C13) to the maximum volume of the tank (cell G3).

Running the simulation

The simulation is run by switching off the initialisation functionality (following the example described above, this would be achieved by setting cell A1 to any value other than the letter "I") and then pressing the F9 key enough times until the value of the counter displayed in cell A2 is large enough to have covered the period of time being monitored for the simulation (as defined by the largest value in column J).

Graphs can easily be set up on a separate page to display the results of the simulation in a convenient format of the type shown in Figures 2, 4 and 6.