Sensitivity analysis for solid/liquid separation equipment selection using an expert system

PUBLISHER

Filtech Exhibitions / The Filtration Society

VERSION

NA (Not Applicable or Unknown)

SENSITIVITY ANALYSIS FOR SOLID/LIQUID SEPARATION EQUIPMENT SELECTION USING AN EXPERT SYSTEM

R.J. Wakeman[1] and E.S. Tarleton[2] (e.s.tarleton@lboro.ac.uk)
[1]Separation Processes Centre, University of Exeter, Exeter EX4 4QF, UK.
[2]Department of Chemical Engineering, Loughborough University, Loughborough LE11 3TU, UK.

ABSTRACT

All processing systems are designed and built to solve a particular problem, and it is rare for the problem to be defined explicitly in the statement of the design requirements. A sensitivity analysis may need to be carried out at the equipment selection stage of the design process to take account the inexactness of the problem specification and to establish the suitability of potential choices of equipment. 'What if?' and other questions should be raised at the equipment selection stage, and the answers can have an impact on capital costs of a project, as well as on running costs and equipment effectiveness. Effects of basic system and operational properties on equipment selection can he explored with the help of a computer based expert system such as p^{C}-SELECT. Examples relating to problems of equipment selection for both batch and continuous processes are discussed.

INTRODUCTION

A filter is part of a processing system. Whilst considerable attention has been given to the detailed design of the filter, little cognisance has been given to interactions between different parts of the filter cycle or to the performance of the filter in relation to upstream or downstream processes. The need to correctly specify ancillary equipment such as pumps, instruments, feed and effluent tanks and so on was recognised long ago[1], and the simultaneous optimization of all parts of a filtration system at the design stage has been advocated[2,3]. The former is a well accepted fact, but the latter appears to be rarely practised. This may be due in part to a general lack of fundamental knowledge of the variables that affect cake formation, consolidation, deliquoring and washing and their interactions. Many of these variables are affected by upstream processes. For example, the size distribution of the particles fed to the filter may be determined by reaction conditions in a reactor or precipitator, or by the use of pretreatment chemicals, or by the operation of a crystallizer. This fundamental variable in turn affects all stages of the filter cycle including the ease of cake discharge, as well as having a significant role in determining the performance of downstream units such as dryers, pelletisers, or reslurry tanks.

Filtration and separation technology contains numerous heuristics, evidenced by consulting industrial reference books such as Solid/Liquid Separation Equipment Scale- Up[4]. A majority of industrial process engineers need to possess wide ranging knowledge covering many unit operations and rarely have the opportunity to gain in-depth specialist knowledge of filtration and separation technology. Consequently the large number of heuristics that have evolved in the technology can lead to confusion for the non-expert.

Solid/liquid separation technology selection or design is most effectively handled with software designed to run interactively, so that the engineer can input data and receive a result rapidly. An expert system such as p^{C}-SELECT[5] can be used to ensure the correctness of input data as far as this is possible, and it can utilise interactive graphics facilities to show effects of changes in variables or to allow the engineer access to calculations to make value judgements. To be most effective the software must be a well-chosen mix of algorithms, expert systems, and information input by the engineer[6].

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.

There exist a number of charts which serve as a guide to the approach to equipment selection, the better ones of which consider a variety of possible eventualities and indicate where decisions must be made. These charts generally have been devised by experts to be fairly comprehensive and are of value to the solid/liquid separation expert. They also illustrate the near impossibility of combining comprehensiveness with usability when so much interacting information is presented in written form. Purchas[4] introduced a general guide for the non- specialist, which is a valuable aid to one confronted with this confusing and complex area: that guide is adopted, suitably extended and adapted, for use in p^C-SELECT.

SCOPE OF PROCESS FILTER PROBLEMS

To illustrate how important some variables might be in the entire filter cycle, without looking into details of the precise effects of each variable, consider a filtration unit on which the following sequence of operations are carried out: cake formation, consolidation, deliquoring, washing and discharge. All filter cycles are composed of combinations of some or all of these elements, sometimes with an element being carried out more than once within the one filter cycle. Table 1 lists the variables involved in the various stages: for there to be an unequivocal design solution equations (either empirical or fundamental) would be needed which linked all the variables. Heuristics may also be used, and generally must be, to account for the effects of parameters which are affected by filter type and the choice of filter medium.

Like most engineering problems, filter system design can involve a certain amount of trial- and-error calculation as there are generally more variables to be determined than there are linking equations; this gives the engineer scope to make choices or to exercise design skills. Whenever a design variable is specified to complete the definition of a problem (i.e. to obtain an equal number of equations and unknowns), the design variable must correspond to an optimisation problem. Identification of the optimum values for the specified variables requires an analysis of the trade-offs that exist between the costs that increase and those that decrease as the value of the design variable is changed in a given direction.

COMPUTER BASED APPROACH TO EQUIPMENT SELECTION

The essential steps in solid/liquid selection are shown in a simplified form in Figure 1. There are three principal sets of data which characterize the problem. The first set describes the requirements of the separation in the process environment, the second set concerns the data obtained from leaf and/or jar tests to characterize the filtration and/or sedimentation behaviour of the slurry, and the third set constitutes a data bank which holds information about available solid/liquid separation equipment.

Contained in the p^C-SELECT data bank is information associated with more than fifty categories of equipment. These data are analysed using public knowledge, heuristics and decision making techniques. Results from the analyses are in the form of data sheets which detail both experimental and calculated results from tests, and a list of recommended equipment which satisfies the process requirements and slurry characteristics. The list may be sorted and ranked according to various relative operational performance criteria or product quality demands. Other screens displayed during the analysis also may be printed for inclusion in reports. p^C-SELECT allows entry into its rule based selection procedures at various levels. The level of entry is determined by the amount and type of information available, and there are two important entry points:

a) The first is the ability to enter for an initial list of equipment without any form of test data, but with a knowledge of the process. Here a list can be produced, but against each item in the list

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.

will be one or more warning messages indicating the need for additional data of a particular type

b) The second entry point is after the analysis of leaf and/or jar test data, the results from which will enable a more reliable and shorter list to be drawn up than was possible at the previous entry level.

Entry into the expert system with a low level of data (excluding any test data) will lead to a long list of equipment which might be capable of achieving the separation. The list is divided into three parts: (i) a summary of the information fed into the selection procedure; (ii) a list of the selected equipment that indicates for each item, through selection warnings, what further action should be taken to check the equipment suitability and what limitations the equipment may possess; and (iii) the relative performance of the selected equipment based on various criteria, including solid product dryness, liquid product clarity, washing effectiveness and the tendency of the equipment to cause crystal breakage.

The suitability of the equipment is related also to typical particle size ranges and feed concentrations. Although the latter information has been used in the selection, the values have been implied through the use of other data such as settling rates and it is at this point that the engineer can check the equipment information against other measurement data. The relative performance criteria for the selected equipment are based on a scale from 0 to 9, with larger numbers indicating better performance and showing whether the solid is generally discharged in cake (C) or slurry (S) form. Selection warnings marked against any item in the list reflect uncertainty about the suitability of the particular equipment or because of a shortage of input data which has led to a 'best approximation' being made to some point in the analysis.

The procedures outlined above enable the non-expert to make rational decision based on expert knowledge, without the need to consult an expert in the earlier stages of solving his problem. This is important in solid/liquid separation, not least because the expert is often a representative of an equipment manufacturing company whose job it is to sell a particular type of separator. Taking filters as an example, many types usually will be capable of carrying out a particular filtration, but probably only a few general types will be most suited to the task. It is wise to have an insight into which types these axe before consulting an expert. Software such as p^C-SELECT enables the rapid analysis of data and exploration of alternatives. It puts the engineer in a position to ask more penetrating questions of whichever expert he or she may consult, and reduces expenditure on unwarranted pilot scale testwork. These advantages are gained without the need for extensive computer knowledge or high speed/capacity computers.

As an example to illustrate the general method of approach to equipment selection using computers, consider in the following: identify a preliminary list of equipment to produce dewatered (unwashed) solids from a slurry continuously fed to the separation plant at about 10 $m^3\ h^{-1}$. Leaf test data indicates a likely cake growth rate of about 1 cm min^{-1}, and a jar test shows a settling rate of 0.5 cm s^{-1} to give a clear supernatant liquor and a final sludge volume of about 10% of the starting suspension volume. These data lead to the preliminary selection shown on Figure 2.

The sensitivity of equipment selection to changes in process performance can also be assessed. For example, if the particle size distribution were to change such that the mean size was halved, the settling and filtration rates could be expected to reduce by a factor of 4 and a cloudy supernatant may result. If this were to happen a pusher centrifuge would clearly become a non-viable option, the choice of a decanter centrifuge would be less desirable due to the reduced settling rate, but the suitability of a variable volume filter for the task would be increased.

CREATION OF PROCESSING SYSTEMS

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.

All too often the choice of solid/liquid separation equipment is perceived to be between alternative separator types - for example between a centrifuge and a rotary vacuum filter. In fact the situation is considerably more complex as many equipment items up- and down- stream of the separator are frequently interdependent, and all ancillary equipment must be included in the analysis. The ancillary components vary according to the type of separator, the choice of which depends on other units in the process. It is often possible to devise a multiplicity of solutions leading to alternative process flowsheets, and formal methods exist[2,3] to sort these so that detailed designs need not be carried out on an the alternatives. It is implied, therefore, that interactions exist between plant items.

Where interactions exist 'local' and 'global' trade-offs are identifiable[3]. Local trade-offs affect single items of equipment, whilst effects of global ones manifest themselves on the design of a large number of equipment items. Consequently the latter are of considerable importance to defining optimum design and operating conditions for the process as a whole. Considering the elements of the filter cycle shown on Table 1, it is clear that several variables are global for the filter (those marked 'x' against all stages in the cycle). In terms of an overall process these may or may not have a global effect, dependent on other processes in the flowsheet. A simplified flowsheet to recover particles from an evaporative crystalliser is shown on Figure 3. In this example particle size and temperature are the major global variables, and the effect of increasing the value of either variable on the unit operation costs is[3]:

	Evaporative crystalliser	Solid/liquid separator	Dryer
Particle size	£↑	£↓	£↓
Temperature	£↓	£↓	£↓

Here, two different effects of global variables are observed. Increasing the particle size usually enables easier separation and less moisture in the discharged cake, resulting in reduced costs for both separation and drying - but the crystalliser size and cost is increased, hence an ‘optimum' particle size may be sought (when size is not governed by market criteria or heuristic aspects of equipment performance). Increasing the temperature, on the other hand, leads to lower costs in all three unit operations - hence the 'best' temperature will be one close to the temperature of an available utility such as steam.

On Figure 3 minor global variables can also be identified between two equipment items. Operating at high slurry densities in the crystalliser take-off can reduce the size of both the crystalliser and the separator. Producing a drier filter cake tends to increase mechanical separation costs, but reduce thermal dryer costs. Hence an optimum cake moisture content may be sought.

SENSITIVITY OF EQUIPMENT CHOICE IN BATCH PLANTS

In batch plants where several products are manufactured in small to medium quantities the same filter may be required to perform several different separations. A good deal of heuristic information is needed with some detailed knowledge of a wide variety of separators in order to shortlist appropriate separators - an initial selection is readily carried out using an expert system like p^C-SELECT. Consider a plant manufacturing four products in batches, the equivalent feed rate of each being in the order of 10 $m^3\ h^{-1}$, where each product has the following characteristics:

	Product 1	Product 2	Product 3	Product 4
Solids product objective	dewatered	dewatered	dewatered	washed/dewatered
Settling test data				
Settling rate (cm s^{-1})	<0.1	<0.1	<0.1	0.1-5
Clarity of supernatant	poor	poor	good	good
Sludge volume (%)	<2	>20	>20	2-20

Filtration rate data Cake growth rate (cm min^{-1})	<0.02	<0.02	0.02-1	0.02-1

The test results above clearly show that the separation characteristics of each product are quite different, but the problem remains to identify a single separator suitable to recover the solids as a cake. From using p^C-SELECT the filters which may be appropriate for each individual separation can be identified, and these are listed below. The numbers listed under the headings 'D' or 'W' indicate the likely relative performance index of the equipment as a solids dewatering device or as a cake washing device respectively (better performance is associated with greater index values), whilst '-' indicates that the equipment is not suitable for the particular separation.

Filter type selected:	Product 1	Product 2	Product 3	Product 4	
	D	D	D	D	W
Horizontal belt, pan or table filter	7	7	7	7	9
Plate and frame filter press	6	6	-	-	-
Pressure Nutsche filter	6	6	6	6	8
Tubular element pressure filter	5	-	-	-	-
Vertical element pressure filter	5	-	-	-	-
Horizontal element pressure filter	-	-	-	5	8
Membrane plate and frame filter press	-	8	8	8	8
Vacuum leaf filter	-	6	6	6	8
Variable volume filter (e.g. tube press)	-	8	8	8	4
Basket or pendulum centrifuge	-	9	9	9	6
Peeler (plough) centrifuge	-	-	9	9	6

The equipment list above indicates that only horizontal belt, pan or table filter types and pressure Nutsche filter types are likely to be suitable for all four products. Of these it would be anticipated that the belt, pan or table filters will show a slightly superior performance. However, the expert might expect the pressure Nutsche to give a better clarity liquid product, although any improvement may be marginal and a final selection will depend on other factors.

CONCLUSIONS

Manufacturers of different equipment types tend to use different heuristic approaches to equipment sizing, making it very difficult for a user engineer to check that the correct equipment is being specified for the separation and that the size of the equipment is appropriate. Computer software could be of considerable assistance not only in the areas identified above, but also in design and scale-up[7].

Formalised approaches to the design of solids separation processes must consider the process system as a whole, with interdependencies between individual plant items fully accounted for during their design and specification. The process design must take due cognisance of likely variations in feed concentrations and throughput and environmental conditions, the safety of life and property, product quality, the reliability and redundancy of the equipment and the process, and the plant economics.

Generalised process stage models that would allow an amount of process optimisation prior to the selection of specific types of equipment for the various processing steps require further development. These would provide a powerful tool for the engineer, allowing the maximum economic potential of new or alternative process structures to be estimated prior to any significant expenditure. The vast range of equipment types for solids processing makes this a difficult task, as do the problems associated with identifying suitable capital and revenue costs.

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.

The widespread use of heuristics, the lack of standard approaches to most aspects of design and the limited information available to the design engineer in texts gives rise to several requirements in solid/liquid separation. There is a need to

- standardise small scale tests
- rationalise the analysis of the data which come from the tests, and
- formalise the approaches to process design and scale-up of equipment.

REFERENCES

1. F.M. Tiller, *Chemical Engineering*, McGraw Hill, 1956.

2. D.C. Freshwater, A new approach to the design of filtration systems, *Filtration and Separation*, **13**(3), 244-248, 1976.

3. A.P. Rossiter and J.M. Douglas, Design and optimisation of solids processes, *Chem. Eng. Res. Des.*, **64**, 184-196, 1986.

4. D.B. Purchas and R.J. Wakeman, *Solid/Liquid Separation Equipment Scale-up*, Uplands Press & Filtration Specialists, 1986.

5. E.S. Tarleton and R.J. Wakeman, *Solid/Liquid Separation Equipment Simulation & Design*: p^{C}-SELECT, Personal computer software for the analysis of filtration and sedimentation test data and the selection of solid/liquid separation equipment, Separations Technology Associates, 1991.

6. R.J. Wakeman and E.S. Tarleton, Solid/liquid separation equipment simulation and design - An expert systems approach, *Filtration & Separation*, **28**(4), 274, 1991.

7. R.J. Wakeman and E.S. Tarleton, Modelling, simulation and process design of the filter cycle, *Filtration & Separation*, **27**(6), 412-419, 1990.

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.

FIGURES AND TABLES

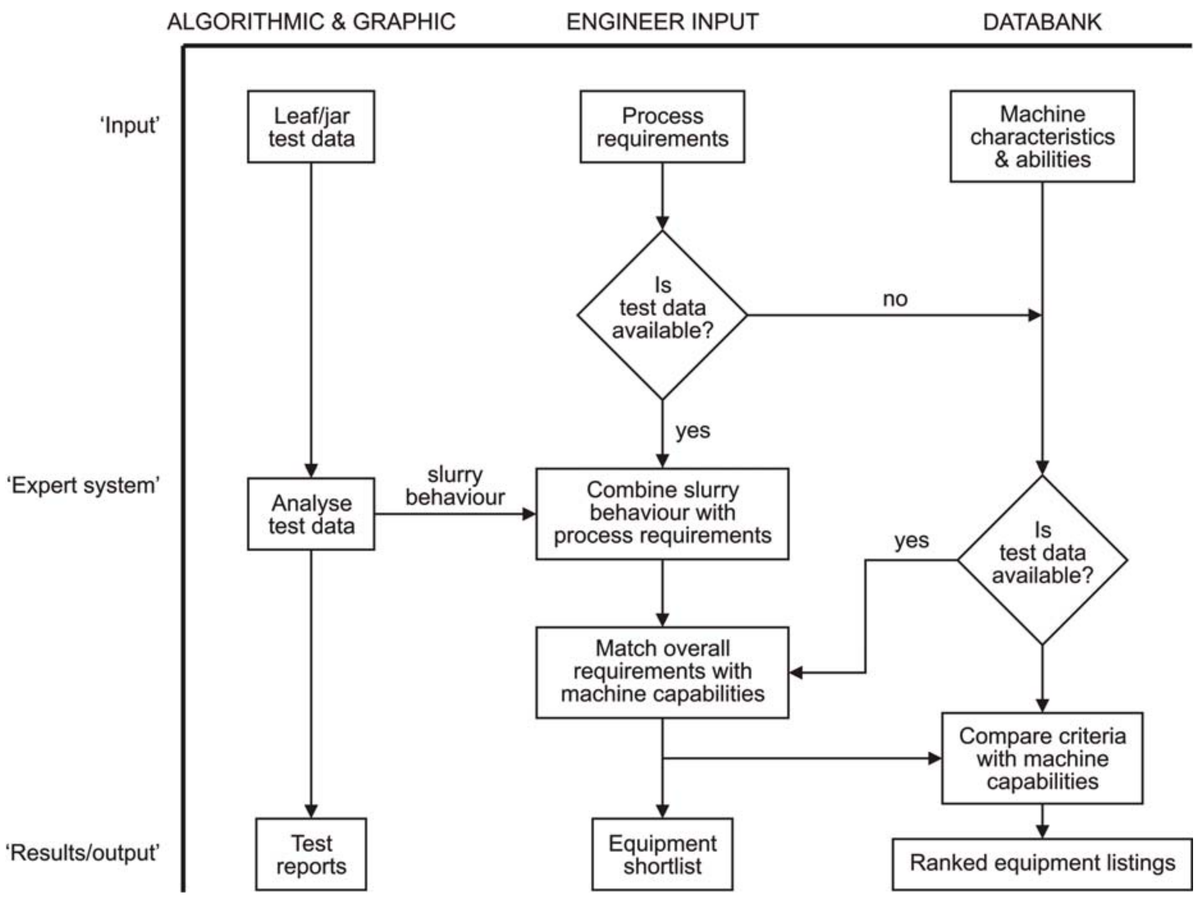

Figure 1: The approach to equipment selection used by p^C-SELECT[5].

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.

DATA SHEET FOR EQUIPMENT SELECTION

Specifications

Duty	Scale:- medium (10 m^3/hr) Operation:- continuous Objective:- dewatered solids recovery
Settling	Rate:- medium (0.1-5 cm/s) Overflow clarity:- good Sludge proportion:- medium (2-20% vol)
Filtration	Cake growth rate:- medium (0.02-1 cm/min)

Selected equipment description	Selection warnings	Particle size (μm)	Feed conc (% v/v)
Horizontal belt, pan or table filter	None	20-80,000	3-40
Bottom fed drum filter, knife dis.	None	1-200	3-30
Bottom fed drum filter, roll dis.	None	1-50	3-30
Bottom fed drum filter, string dis.	None	1-70	3-30
Continuous pressure filter	None	1-100	0.01-30
Variable volume filter	1iB	1-200	0.1-25
Pusher centrifuge	None	40-7,000	4-40
Disc filter	None	1-700	3-30
Scroll (decanter) centrifuge	1i	1-5,000	4-40

Selected equipment description	F3: index	F4: index	F5: index	F6: index	F7: index
Horizontal belt, pan or table filter	7C	7	9	8	31
Bottom fed drum filter, knife dis.	6C	7	7	8	28
Bottom fed drum filter, roll dis.	6C	7	7	8	28
Bottom fed drum filter, string dis.	6C	7	7	8	28
Continuous pressure filter	6C	7	6	7	26
Variable volume filter	8C	7	4	7	26
Pusher centrifuge	9C	4	5	4	22
Disc filter	4C	6	0	8	18
Scroll (decanter) centrifuge	4C	4	3	3	14

F3 index:- Solid product dryness
F4 index:- Liquid product clarity
F5 index:- Washing performance
F6 index.- Crystal breakage
F7 index:- Overall performance

Equipment listed in order of overall performance rating

Figure 2: Equipment selection by p^C-SELECT.

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.

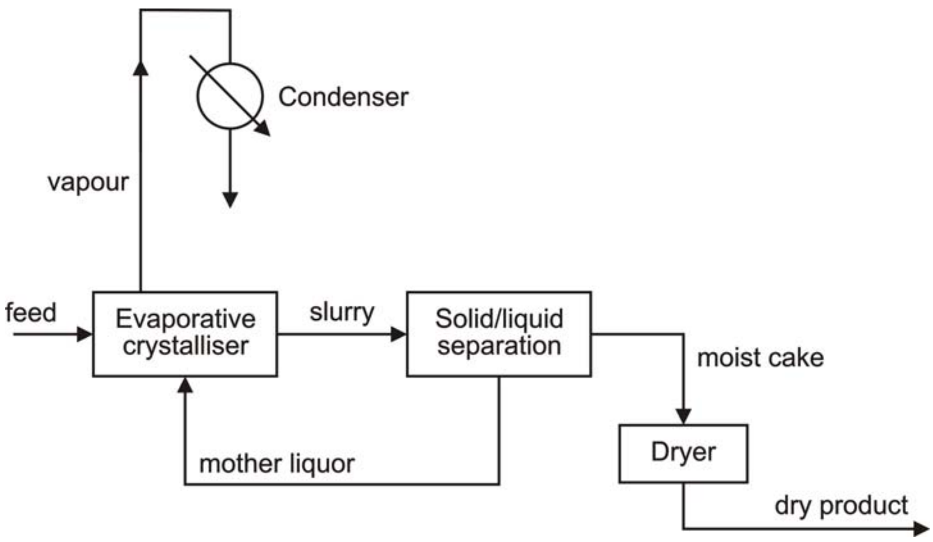

Figure 3: Possible simplified flowsheet structure for particle production.

	Formation	Consolidation	Washing	Deliquoring	Discharge
Filter type	x	x	x	x	x
Filtration pressure	x				
Consolidation pressure		x			
Washing pressure			x		
Deliquoring pressure				x	x
Filter area	x	x	x	x	x
Medium resistance	x	x	x	x	x
Cake formation time	x				
Consolidation time		x			
Washing time			x		
Deliquoring time				x	x
Feed liquid viscosity*	x	x	x		
Feed solids concentration	x				
Wash liquid viscosity*			x	x	
Solute diffusivity*			x		
Interfacial tension*				x	
Deliquoring gas viscosity*				x	
Particle size distribution	x	x	x	x	x
Particle interactions	x	x	x	x	x
Cake porosity	x	x	x	x	
Cake thickness		x	x	x	x
Cloth/particle interactions					x

*these variables are functions of temperature

Table 1: Variables involved in solid/liquid separation by filtration.

Cite paper as: Wakeman R.J. and Tarleton E.S., 1993, Sensitivity analysis for solid/liquid separation equipment selection using an expert system, *Proc. Filtech Conference*, pp.43-52, The Filtration Society, Karlsruhe.