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Synergies from spreadsheet LP used with the theory of constraints—a case study

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This paper describes a case study relating to a food-processing plant. The methods used to address the case include spreadsheets combined with Goldratt's Theory of Constraints (TOC), both of which are accessible to practising managers. The paper demonstrates how standard spreadsheet optimisation tools can be used in combination with a TOC framework to provide effective decision aids. The results from the case study indicate real productivity improvements are possible from even small models of a situation. The paper explores the interrelationships and complementaries between Linear Programming and Theory of Constraints frameworks, and details the steps involved in using them in combination. We argue that traditional LP practice should be modified in light of the ease with which LPs can be solved, and suggest that the Theory of Constraints approach provides a useful framework to guide LP use. We share some of the insights gained both by the analysts and by the company.

Keywords: linear programming; theory of constraints; spreadsheets; production; management; case study

Introduction

This paper draws on three areas and their integration: firstly, the operations research/management science methods of linear programming and simulation; secondly, the production-inventory management field, especially the theory of constraints;[1–5] and thirdly, the application of action research in management education programmes. While production-inventory management and operations research have well known links developed in part through the field of operations management, there have nevertheless been debates about the relative merits of various approaches, for example, the recent debate concerning theory of constraints and LP.[6–11] All but the last author frame the debate as a competition between LP and TOC, while Mabin[11] argued that LP and TOC are mutually beneficial and should be used together to achieve synergistic results.

Luebbe and Finch[7] also link the five steps of the TOC approach to the LP approach, as recommended independently by Mabin.[11] However, the former authors still portray it as a comparison—a contest—in contrast to the present paper which argues for a multi-methodology approach as defined by Brocklesby.[12] Furthermore, the first three of these papers[6–8] portray LP as a specialist tool, while Mabin[11] argues that LP is universally available through spreadsheets, and is a powerful tool that can be used by non-specialists.

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This paper provides evidence of the benefits of combining TOC with spreadsheet LP in practice, based on a case study originally written as an assignment for MBA students. The students learnt a great deal from the exercise, as have the authors in the process of continuing to work with the case. In addition, the company on which the case was based benefited beyond expectation. The company was already very aware of a major bottleneck (constraint) in the production process, but using TOC intensified their focus on this constraint. The company acknowledged gaining additional insights into the strategic and operational problems they were facing, and in particular, gained a better understanding of the relative values of resources, their espoused priorities, and, consequently, how to make the best use of their scarce resources. As a result, they were able to quickly adapt current practices to gain a more realistic perception of resource expansion options and priorities, and to make more effective use of existing resources. In particular, TOC and LP helped them to make use of existing equipment more effectively, to produce more without investing in expensive equipment, and to eliminate the problems of lost sales opportunities and unscheduled overtime.

In the remainder of this paper, we will describe the case study, its analysis using the combined TOC/LP approach, and discuss the insights gained both by the analysts and by the company.

The case study

Description

Goulds Fine Foods is a medium-sized, Wellington-based company manufacturing and selling bacon, ham, smallgoods and other convenience food products. It had experienced significant growth in the previous two year period, resulting in the construction of a new plant in Petone (the old one had come to the end of its useful life). The machinery however was relatively old and was being replaced as the cash position of the firm allowed, with priority being given to areas of the operation experiencing the most growth in volume. The case focuses on the production of manufacturing hams (used in commercial products and sandwiches) and pre-cooked sausages.[13] The following extracts describe the production process and demand environment.

> The ingredients for the two products (manufacturing hams and pre-cooked sausages) are mixed separately, using their own dedicated mixing facilities, but both use the same filling operation. The products are then cooked after filling, taking some four hours for the hams, and aound one hour per batch of sausages. Each cooker is two cubic meters in volume which can take a maximum of 500 kg of product, so hams are cooked in half batches. It is normal practice to cook 350 kg of sausage (1 batch) at a time. There are four cookers available. After cooking, the batches need to be chilled, prior to packing and despatch. Hams take 10 hours to chill, while sausages take only two hours. The chillers are quite large, and can handle any quantity made. The packing line has four people usually, each working a 40 hour week. The main time involved on packing and despatch is for sausages, as they need shrink-packaging in small packs for retail sale, while hams are sold in the plastic packs they have been cooked in. Both products require packing in outer cartons, and despatch documentation. Each packer can repack approximately 50 kgs of sausages per hour, so that it takes seven person-hours to pack and despatch a 350 kg batch of sausages. However packers are happy to do overtime or work Saturdays if needed. The two separate mixing processes are able to mix a 1000 kg batch of ham mix in five hours, while sausages take 30 minutes to prepare. Filling takes place at a rate of 125 kg per hour for hams, and one hour per batch of sausages. The current weekly demand for hams is in the vicinity of eight batches per week, though that varies by up to 35%. Likewise sausage demand equates to roughly 20 batches per week, plus or minus 100%. The profit margin (gross or product margin) on a batch of hams is roughly six times that of a batch of sausages.

Profit margins are not stated precisely for confidentiality reasons. For teaching purposes, the case poses the hypothetical question of whether or not Goulds should purchase more filling and cooking capacity. (Although hypothetical, this was certainly a realistic situation, given the prevalence of plant closures at the time, and Gould's expansion programme.) It is estimated that this equipment might give perhaps 50% more capacity than presently available. Given that the demand is certainly more than they can meet at their current production, it appears the extra equipment would be worthwhile.

Analysis

The information in the above case description can be used to derive the following process flowchart, process times, and demands, as shown below in Figures 1 and 2. The information contained in the case can be represented as a spreadsheet model, as shown in Figure 3, with linear formulae representing resource use. This representation includes several assumptions: that the constraints are linear, and that average demand will be met as a first step in the analysis if possible. These assumptions are discussed further in Mabin.[13] Note also that in the case, chiller capacity is not given explicitly, but is said to not be a problem, and the nature of chilling is such that it is a volume constraint rather than a flow constraint, so the RHS has been set to an arbitrary large number. Likewise the case is purposefully vague about the exact time it takes to pack hams, so an initial guesstimate is included here. It is intended that students would use a guesstimate for the initial analysis, check whether it was important, and if so, investigate further, as an experienced OR practitioner would do.

Figure 3 shows that it is not possible to meet even average demands given the current usage and availability of resources. However if they could, they would make 68 'units of profit' per week, where 1 unit of profit is equivalent to the gross margin on a batch of sausages.

A traditional LP approach would be to formulate this as a product mix problem:

1. to determine the product mix that maximises the profit, and
2. to use sensitivity analysis to find out what the extra filling or cooking capacity would be worth, if either were added to the line. Based on this information, the managers would know whether to make the purchase of extra capacity or not.

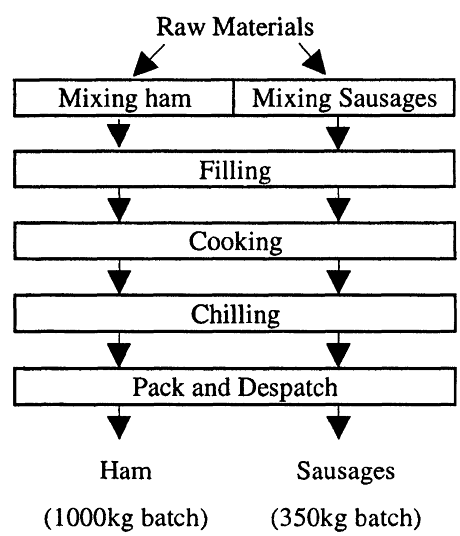

Figure 1 Process flowchart.

Process times (hrs/batch)	Hams	Sausages	Total Process Time Available (hrs/wk)
Mixing (Ham)	5.0	0.0	40
Mixing (Saus)	0.0	0.5	40
Filling	8.0	1.0	40
Cooking	8.0	1.0	160
Chilling	10.0	2.0	200
Pack & Despatch	1.0	7.0	160
Average Demand (batches/wk)	8	20	

Figure 2 Process times and demands.

	A	B	C	D	E	F
1	**Spreadsheet Model of Goulds' Production Problem**					
2			**Hams**	**Sausage**		
3	**Decision Variables:**	**No. Produced**	8.0	20.0		
4	**Constraints:**				**Required**	**Available**
5	**Production**	Mixing (Ham)	5.0	0.0	40.0	40.0
6		Mixing (Saus)	0.0	0.5	10.0	40.0
7		Filling	8.0	1.0	84.0	40.0
8		Cooking	8.0	1.0	84.0	160.0
9		Chilling	10.0	2.0	120.0	200.0
10		Pack & Despatch	1.0	7.0	148.0	160.0
11					**Sold**	**Demand**
12	**Demands**	Hams/wk			8.0	8.0
13		Sausage/wk			20.0	20.0
14					**Total**	
15	**Objective function:**	**Profit**	6.0	1.0	68.0	

Figure 3 Spreadsheet model.

However better results can be obtained by combining Linear Programming (LP), with the theory of constraints, in particular the five focusing steps which are part of Goldratt's process of on-going improvement,[4,5] and the 'Drum-Buffer-Rope' scheduling method of TOC.[1,2,5] In the rest of this paper, the TOC philosophy will be described, and then the combined TOC/LP approach will be demonstrated.

The theory of constraints

Goldratt's theory of constraints is underpinned by a system improvement philosophy. It is a collection of system principles, concepts, prescriptions, and tools or methods for tackling the problem of improving overall system performance. Some of these, such as Throughout Accounting and the 'Drum-Buffer-Rope' approach to production control, popularised through Goldratt's novels,[1,14,15] are generic enough to have broad application to many businesses and agencies well beyond those specific companies in which they were originally developed.[16] Yet Goldratt's theory of constraints remains relatively unknown,[5] particularly within the established 'systems' communities such as OR and systems science. Furthermore since the TOC approach developed from a real manufacturing problem solved by providing a scheduling technique, many people may mistakenly believe it has no relevance outside manufacturing. In addition to these applications, there are the TOC logic tools: five distinct logic trees and their rules of logic which govern how they are constructed. These tools are applicable anywhere. However until recently there has been no step by step guide to their use within a TOC framework, and how to implement it. Recent books help to fill those gaps.[5,16]

Some key concepts are that a system is 'like a chain, or network of chains, and no matter how much effort goes into improving parts of the system, only the improvements to the weakest link will result in any detectable system improvement. The weakest link is the constraint. And Goldratt's TOC is the paradigm he's created to manage the living daylights out of these weakest links, with the end result that systems improve much more quickly than they would otherwise have done.'[16]

Dettmer[16] further argues that TOC differs from other continuous improvement philosophies in that where they almost all focus on continuous improvement of processes, TOC acknowledges the effects of interdependence or linkages between processes. The success or failure of an organisation depends on how well component processes interact with each other. Continuous improvement does not just mean incremental improvement: the methods can be used to re-engineer a business as well.

The five steps of ongoing improvement are part of the wider TOC framework, and are eminently suited to focusing improvements in systems where the constraints are easily identified. In more complex systems, or larger, messier problems, the major constraints are often policies, and Goldratt's thinking processes (logic trees) provide a systematic approach to answering three basic questions about change that every manager needs to know:

1. What to change? (Where is the constraint?)
2. What to change to? (What should we do with the constraint?)
3. How to cause the change? (How do we implement the change?)

A full description of the TOC five focusing steps of on-going improvement is given elsewhere.[3–5,16] A brief summary is provided below for those unfamiliar with the approach.

Five focusing steps in the process of on-going improvement

Step 1: *IDENTIFY the system constraint(s)*
Identify the constraint(s) that is/are preventing the system from achieving its goal. What part of the system constitutes the weakest link? (note: that when using the five step process we assume that the goal of the organisation has already been determined, although this is part of the question 'what to change?'.)

Step 2: *Decide how to EXPLOIT the constraint*
Decide how to use the constraint to wring every bit of capability out of it. What can we do to get the most out of this constraint without committing to potentially expensive changes or upgrades?

Step 3: *SUBORDINATE other activities to the decisions made in step 2*
Do not let other activities stop the constrained activities from actually producing their best. We may need to de-tune some parts, and rev up other parts to make the system as a whole as productive as possible. Is the constraint still a constraint? If so, continue; if not, this constraint has been eliminated, and we skip to step 5.

Step 4: *ELEVATE the constraint(s)*
Remove the constraint or make it less constraining by adding or upgrading capacity

Step 5: *If anything has changed, GO BACK to step 1*
Do not let inertia become a system constraint!

Sometimes we can proceed through these steps without difficulty, but sometimes the constraint is a policy. Often, all we can see is an interrelated tangle of symptoms, and in these latter cases the logic trees (thinking process tools) are needed to diagnose the nature of the illness (core problems), prescribe appropriate remedies and institute a treatment program. The remainder of the paper deals with the application of the TOC 5 step method to the Goulds case directly, without needing recourse to the logic trees.

Combining LP with a TOC framework

In using the two methods in combination, we will view the LP model results within the theory of constraints (TOC) 5-step framework following Mabin.[11] A similar approach has also independently been used by Luebbe and Finch.[7] Such a combination leads to the following interpretation:

(1) *Identify the constraint(s).* The first step in using TOC is to identify the major constraint(s) which are preventing Goulds from reaching their goal. In this case the goal would be to maximise profit. If we try to make the most profit possible, by filling market demand, we can see from Figure 3 that the constraint is the filling process (we need 84 hours of filling to meet market demands, but only 40 hours are available per week).

In this type of so-called 'product mix' problem, formulated as an LP, there will usually be more than one constraint. In the Goulds case, market demand for sausages is also a constraint. Goldratt[4] would generally argue that one of these is more critical than the others, and that we should focus actions on the most critical constraint. In LP also, this is possible; note, Goldratt's definition of the term 'constraint' is more specific than the LP definition: 'constraints' in TOC equate to 'binding constraints' in LP.

Using spreadsheet optimisation the LP can be solved. We used the solver optimisation tool in Microsoft Excel®, but other modern spreadsheet packages have equivalent optimisation facilities. Excel outputs include an 'Answer Report' and a 'Sensitivity Report', shown below in Figures 4 and 5, and will be discussed shortly. The LP formulation is stated in the answer report: the target cell is the objective function, the adjustable cells show the decision variables, and the formula column specifies the constraints, using cell references from the spreadsheet model in Figure 3.

(2) *Exploit the constraint(s).* This step says we should make the most of the constrained resources: for example, ensure every minute of the filler is utilised, and that sausage demand is filled to the maximum.

Given that it is not possible to make everything demanded, it is necessary to decide which product should receive higher priority. (This presupposes that the best profit in this type of situation will be obtained

Target Cell (Max)

Cell	Name	Original Value	Final Value
$E$15	Profit Total	68.0	35.0

Adjustable Cells

Cell	Name	Original Value	Final Value
$C$3	No. Produced Hams	8.0	2.5
$D$3	No. Produced Sausage	20.0	20.0

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$E$5	Mixing (Ham) Required	12.5	$E$5<=$F$5	Not Binding	27.5
$E$6	Mixing (Saus) Required	10.0	$E$6<=$F$6	Not Binding	30.0
$E$7	Filling Required	40.0	$E$7<=$F$7	Binding	0.0
$E$8	Cooking Required	40.0	$E$8<=$F$8	Not Binding	120.0
$E$9	Chilling Required	65.0	$E$9<=$F$9	Not Binding	135.0
$E$10	Pack & Despatch Requirec	142.5	$E$10<=$F$10	Not Binding	17.5
$E$12	Hams/wk Sold	2.5	$E$12<=$F$12	Not Binding	5.5
$E$13	Sausage/wk Sold	20.0	$E$13<=$F$13	Binding	0.0
$C$3	No. Produced Hams	2.5	$C$3>=0	Not Binding	2.5
$D$3	No. Produced Sausage	20.0	$D$3>=0	Not Binding	20.0

Figure 4 Excel answer report.

by completely filling the market demand for one product and producing less than market demand for the other product, rather than cutting back on both products. This assumption will be discussed later.) In order to establish priorities between the products, Goldratt[3] provides a rule, sometimes referred to as the TOC rule, which in simple cases produces the best product mix. This rule is based on the ratio of profit to constraint use for each product, and is calculated as follows:

First the ratio of 'gross profit per constraint hour' (GP/CH) is calculated for each product. Since the filler is the resource constraint, GP/CH for Hams is 0.75 (=6 units of profit per batch/8 hours of filling per batch) and for Sausages is 1.0 (=1/1). Then rank these products in decreasing order of the GP/CH ratio, (namely, Sausages and then Hams) to determine priorities. This ranking is used, together with resource availabilities and other constraints such as market demand, to determine the actual production quantities of each product.

Given the ratios computed above, the TOC decision rule would direct us to 'make Sausages first (as many as can

Changing Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$C$3	No. Produced Hams	2.5	0.0	6	2	6
$D$3	No. Produced Sausage	20.0	0.0	1	1E+30	0.25

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$E$5	Mixing (Ham) Required	12.5	0.00	40	1E+30	27.5
$E$6	Mixing (Saus) Required	10.0	0.00	40	1E+30	30
$E$7	Filling Required	40.0	0.75	40	44	20
$E$8	Cooking Required	40.0	0.00	160	1E+30	120
$E$9	Chilling Required	65.0	0.00	200	1E+30	135
$E$10	Pack & Despatch Required	142.5	0.00	160	1E+30	17.5
$E$12	Hams/wk Sold	2.5	0.00	8	1E+30	5.5
$E$13	Sausage/wk Sold	20.0	0.25	20	2.55	20

Figure 5 Excel sensitivity report.

be sold), then Hams, until all filling capacity is used up', acknowledging the filling, resource, and market constraints. The actual amounts produced would vary depending on the particular market demand at the time. For an average demand of 20 batches of Sausages, the TOC rule says to make 20 batches of Sausages, and use the rest of the filling capacity to make Hams, in which case 2.5 batches of Ham could be made.

Solving the LP shows the product mix is 2.5 batches of hams and 20 batches of sausages, maximises the profit (at 35 units of profit weekly), subject to the constraints. The LP will give the same outcome as that resulting from the application of the TOC rule in simple cases such as this. In more complicated cases, where there are several (binding) resource and demand constraints, the TOC rule becomes less straightforward,[17,18] and LP has clear advantages.

To allow for variable demands, one can interpret the LP solution in terms of the basic variables in the Simplex sense, rather as the particular product mix (20 Sausages and 2.5 Hams), and again generalise this rule to 'make Sausages first, then Hams'.

Note that regardless of whether LP or the TOC rule is used, the presupposition we made earlier holds true, namely that we will make all of a product up to the point where a constraint becomes binding. This accords with LP theory, namely, that the optimal point will occur at a corner point.

TOC additionally encourages further actions to be taken which squeeze more throughput from the filler and sausage market constraints, such as ensuring the filler is never idle due to machine stoppages (planned or unplanned) or shortage of material. Nor should we waste any of the filler's precious capacity by working on sub-standard raw materials. We should also include, under this step, actions which check whether the filler constraint coefficients are correct, and whether any procedures can be changed without committing to expensive changes or upgrades, in order to increase the output through the filler. Such procedures should include standard operating policies and practices. In doing so, the left-hand side coefficients (LHS) may well be changed. If the constraint is still the filler, we proceed to step 3.

(3) *Subordinate other activities to the decisions made in step 2.* This step says we should subordinate everything else to the decisions we have made in step 2. For example, it would be tempting to run all processes at their maximum capacities in a bid to make efficient use of resources, but if subsequent processes are limited in capacity, such action will result in an accumulation of inventories. Goldratt[1,3,4] shows such actions aimed at increasing local efficiencies to be futile in the system-wide context: no extra production will result from a large build-up of inventory in the system, and indeed production may suffer. Instead, we should limit production on non-constraint resources to the rate that best suits the constraint, that is, run mixing to feed the filler, while ensuring the right inventory buffers to protect against uncertainty and variability.

Luebbe and Finch[7] asserted that an LP approach does not provide help on subordinating. However, we would argue that it does. The LP answer report shows how much time is required on each process, and the slack, that is, unused capacities. This allows us to subordinate the processes with slack, to the constraints. For example, the sausage mixing machine has 30 minutes unused. There is little point using this spare capacity to mix more sausage mix because any extra cannot be processed by filling.

There is a subtle but significant difference between the interpretation of the slack under LP and TOC frames. Under LP, the slack is spare capacity that we need not use; under TOC, we should avoid using this slack capacity (except to build a small buffer, but this is a timing rather than quantity issue).

The LP also helps identify constraints with a small amount of slack, such as pack and despatch, which although not a (binding) constraint, could easily become one if it is not scheduled carefully. Our initial guesstimate of the time taken to pack hams should be verified, but also efforts to reduce the times for packing would also ease the situation and should be encouraged.

While this is as far as the LP solution goes, the TOC frame encourages us to consider how the static plan would be operationalised. In the spreadsheet model, we assume set-up times are fixed, regardless of batch sizes, and the LP model is static rather than dynamic. These are issues the TOC frame can address.

The TOC 'Drum-Buffer-Rope' scheduling method provides a framework within which to account for the dynamic aspects, and the effects of different batch sizes (both transfer and process batches), see for example Goldratt and Fox.[2] Under 'Drum-Buffer-Rope', the rate of throughput is governed by the 'drum' (in this case the filler and sausage demand); there should be a 'buffer' of material maintained in front of the drum so it is never idle; and the 'rope' is a control system that limits new material entering the process to a rate that best suits the constraint(s). In Goulds' case, it would be advisable to use some of the spare capacity at mixing to build up a modest buffer to ensure filling is never waiting for work, as any time lost at filling will cost the company through lost revenue or overtime. The Drum-Buffer-Rope schedule would also consider the pack and despatch operation, to ensure it does not become a constraint. The distinction between *transfer* and *process* batches[4] is also a key to developing successful schedules.

(4) *Elevate the constraint.* If the previous three steps have not resulted in breaking the constraint, then it may be

desirable to expand capacity by purchasing some of the cooking and/or filling equipment that is available for purchase. The LP approach provides useful quantitative information for this TOC step. (Note that if anything has been changed, the initial LP solution may be invalid, in which case it is necessary to proceed to Step 5, rather than use the initial LP reports.) The LP sensitivity report gives answers to the relevant 'what if' questions:

- what is it worth to add extra resources?
- how much extra resource is needed?

In doing this, the focus is on the (binding) constraints: additional capacity is apparently worthless elsewhere since other processes have spare capacity already (though as just noted, pack and depatch may become a constraint from time to time, and extra capacity may be needed if the schedule cannot be adjusted to suit). Sensitivity analysis tells us that an extra hour of filling time is worth 0.75 units of profit. (It is no coincidence that this is the same as the GP/CH for Hams calculated under Step 2, since any extra time available, after satisfying sausage demand, will be used to make extra hams.)

A key point is that LP sensitivity analysis conditions us to look at the *right hand side* (RHS) coefficients, but it is often far more effective and cheaper to look at the coefficients on the *left hand side* (LHS) of the constraints, namely the production or yield coefficients. For example, if the time to fill a batch of Hams could be reduced from 8 hours this would have an immediate impact on production throughput. TOC encourages us to look at the way the operations are performed, and attempt to change these key elements, rather than take them as given as with an LP approach. In reality, Goulds installed a double nozzle on the filler which reduced the time to fill a batch by about 50%, with immediate gains in effective capacity at very little cost.

(5) *If anything has changed, go back to Step 1—do not let inertia become a system constraint.* When something changes, the LP spreadsheet can be amended, and re-solved, enabling the process to start from step 1 again, so Goulds can continue to improve profits. Depending on the new constraint, the spreadsheet model itself may become inappropriate, and other methods may be needed; for example if the market became the constraint, the thinking processes would be of more use than the spreadsheet model.

The product mix frame may well lead us to be satisfied with our optimised 35 units of profit since this is the optimal profit subject to the constraints. Good users of LP would undoubtedly seek to explore capacity expansion options, as indeed TOC would do under Step 4: Elevate. However TOC additionally encourages us to consider changes to the LHS coefficients, and subordination through scheduling, in Steps 2 and 3 prior to this increase in capacity.

Discussion

As the above section shows, TOC and LP complement each other, and can be integrated in a straightforward fashion. LP provides quantitative output, while TOC adds guidance on the most effective use of the LP information, considers operational aspects, and takes a pro-active stance. However there are a number of issues that warrant discussion.

The role of traditional sensitivity analysis

The first issue is the role of sensitivity analysis. Savage[19] pointed out that LP tableaux and sensitivity analysis are relics from the days of batch processing, when it took large boxes of cards often run on remote computers, with several hours or overnight to get the LP results back. Applying TOC, we can see that in those days, the constraint was the time and effort to perform a run. The use of sensitivity analysis was a clever way of exploiting that constraint as in Step 2 of TOC, that is, getting every last scrap of information out of a single run. However, now that LPs can be solved virtually instantaneously, the solution time is no longer a constraint, and we should change our approach accordingly. We should not let traditional ways govern our thoughts and actions, or we will be falling victim to Goldratt's fifth step by letting intellectual 'inertia become a system constraint'!

The spreadsheet alternative

So what should be done in place of sensitivity analysis? Savage[19] argued that users should experiment by making changes directly to the spreadsheet. Rapid spreadsheet optimisation allows us to freely change the model and re-solve, allowing us to explore many possible scenarios, such as:

> The impact of reducing the time to fill hams, a key factor, can be explored by changing the coefficient for filling time for Hams to 4 hours, say, and re-running the model. We find that our optimal decision rule has changed to 'fill Hams first, then Sausages'; an exact reversal of priorities to those identified earlier. Filling time is still a constraint, but extra equipment is not needed. Rather, overtime and double shift on that operation will be cheaper in the short term. In this way, spreadsheets allow quick exploration of alternative scenarios, and will be much more enlightening than traditional sensitivity anlaysis.

Savage[19] also argued that spreadsheet models should not be represented as an LP tableau. For those who are not familiar with LP, this may well be true, but we would argue that users familiar with LP may well find the LP structure leads to helpful insights. However, the spreadsheet does allow a relaxation of conventions necessary for LP models which both users and non-users of LP alike may find more attractive in making models more readable. We would also argue that traditional sensitivity analysis can still provide a first step, but users should definitely not be content to stop there. Both LP tableaux and sensitivity analysis may help guide the exploration of the spreadsheet model. We would highly recommend the TOC steps as a guide to that process of exploration.

Caution when using spreadsheets!

While solving an LP using a spreadsheet package can be relatively straightforward, spreadsheet models require particular care. With a spreadsheet, the formulation will be represented via formulae connecting the changing cells (decision variables) to the resource requirements; in particular, the cell representing the LHS of each constraint, for example resource required, must depend directly or indirectly on the changing cells (production quantities). As with traditional LP, great care needs to be taken to ensure that the formulation is correct, but here the spreadsheet formulation is not as transparent, thus requiring perhaps more care. Care is also required in interpreting the Excel reports. For example, default formatting may suggest that a particular reduced cost or shadow price is zero when it is in fact non-zero. However, as the reports are themselves spreadsheets, they can be edited and columns reformatted to display the required precision.

Advantages of spreadsheets

The main advantage of spreadsheets is their universality,[19] and while managers are often not equipped to use LP or interpret LP output correctly, the spreadsheet is at least a familiar medium. They can gain an understanding of what is happening in a simple spreadsheet model by experimenting with the changing cells (decision varaibles) manually, observing the consequent outputs (resource usages and profits), and checking them against their intuition, before Solver is used to generate an optimal solution to the LP model.

Simple can be powerful

As Patterson[6] found, even very simple representations of a situation can lead to insights. Even though managers may be extremely familiar with their business, it is important to take time periodically to develop a different perspective. In the Goulds case, the real situation was simplified, and given a particular decision focus by setting it in the wider context of plant closures that were prevalent at the time, and posing the question of whether or not Goulds should purchase some of the equipment that had become available. Goulds found the situation that was modelled was still accurate enough to be very insightful. In this regard it can also be said that sharing the problem with outsiders (the second author was both an MBA student and production manager with Goulds at the time) as advocated by action learning[20] can also assist in developing alternative perspectives and perhaps seeing the problem more clearly, because outsiders are less burdened by the detail of the real situation.

Another aspect of simplicity is the choice of a linear model over other methods. The LP provides a simple and effective model to use as a starting point, and the benefits of simplicity and power of LP outweigh the advantages of a more complex model.

The advantages of using spreadsheet LP

The advantages of LP are several: The LP does all the 'number crunching' and generates an optimal solution fast (to the basic static problem). It also provides a wealth of 'what if' information through the sensitivity analysis. Now that most spreadsheet packages have user-friendly optimisers which include user-friendly LP solving facilities, and given the benefits of LP and spreadsheets, as listed above, spreadsheet LP has many advantages, particularly for small or pilot LPs. The use of spreadsheet models also allows more adaptations to consider operating realities such as sequencing, simulations, buffer stocks, as well as being more accessible to managers.[11,21]

Why not just LP without TOC?

We endorse the views of Luebbe and Finch,[7] that the TOC approach in general, and in particular the TOC-derived rule based on the Gross Profit per Constraint Hour (GP/CH) ratio, has more intuitive appeal than a non-graphical LP approach.

Furthermore, we highlight a major disadvantage of using LP in isolation, which can be seen in the way LP frames the original question: 'what is the product mix that maximises the profit subject to the constraints?' This is the wrong question.

Firstly, the LP frame encourages us to think we have optimised the use of our resources, when we have acquiesced to the constraints, by taking them as given. TOC, on the other hand, encourages us to change the constraints by changing the input/output or yield coefficients on the left hand side, not just the right hand side, by effectively changing the way we do things. Under TOC, this is done before adding more resources (that is changing the RHS), and is often a far simpler and cheaper way of improving the process and profits. In contrast, the LP provides justification for the addition of more resources, before questioning the real need. Zeleny's[22] excellent article uses a fable to show the shortcomings of a blinkered LP modelling approach to logistics problems, challenging traditional LP frames of the product mix problem, but fails to challenge the technological coefficients, that is the LHS coefficients, and in doing so, misses a golden opportunity. While experienced practitioners may argue that they routinely and actively seek changes in the LHS, this notion is nevertheless absent from the vast majority of OR/MS texts on LP. If this is indeed standard LP practice, then it should be reflected in standard OR texts. If not, then perhaps TOC can help to formalise such good practice.

Secondly, what we should be asking, is not 'how to maximise profit subject to the constraints' but 'how can we remove/change/manage the constraints so we can achieve our goal?' for example supply all of the market demand. Once this is done, we should go back to Step 1 and ask, 'What is the new constraint?' If it is now the market demands, we may ask how can we exploit the existing demand, and so on. We may seek to increase market demand and fill that new demand. This is not the same as goal programming: goal programming encourages us to set prioritised goals and meet them by varying resource availabilities, but again, subject to the same production or yield coefficients on the LHS. The TOC approach offers much more scope for real improvement by questioning whether these 'givens' can be changed.

Thirdly, given the normal statistical fluctuations that occur in process times, and the dynamic rather than static nature of the production process, it is often difficult to justify the constraints as being linear. While the LP provides a good starting production plan, we must adapt this static plan into a robust operational plan that can withstand the impacts of variability and sequential operations, and can do so by using the TOC 'Drum-Buffer-Rope' scheduling method.

Synergy is gained from integrating the two methods: Spreadsheet LP and TOC

The spreadsheet LP optimisation does the number-crunching quickly and effectively, to produce an optimum solution, fast, and also provides a wealth of additional information about the problem. TOC complements the LP approach by guiding the LP use to encourage a pro-active, continuous improvement approach, and extends the LP to consider variability and workflows, and how to operationalise plans.

Barriers to achieving such synergies

But how easy is it to achieve such synergies? We would like to address two related issues: firstly whether the approach is applicable to larger models, and secondly whether such combined approaches are achievable in practice.

The approach has worked for small problems, and there is some evidence that it could be adapted to larger models. Godfrey[22] has recently looked at the feasibility of using TOC and LP together in the oil industry, where the use of very large LP models is well established. He has identified four areas where it would appear that TOC could fruitfully be used: mantaining model accuracy, maintaining model credibility, analysing and using LP results, and in detailed plant scheduling. He states that 'industries already using LPs for production planning should be able to move to a TOC framework reasonably easily, but the cultural changes required means that this will be more difficult than it first appears.'

This brings us to the second related issue: part of the cultural change involves a paradigm shift between traditional LP thinking and TOC, in order to achieve synergies. This paper has attempted to make it appear straightforward, and many of the insights did indeed come quickly. However, some of them have emerged more slowly as we have worked with the case over a two year period. As Brocklesby[12] pointed out, it is difficult to transcend paradigms and be truly integrative in our approaches to problem solving. The case analysis no doubt benefited from the ready acceptance by the students of a multi-perspective approach as a result of our pedagogical approach which has been to encourage an eclectic mix of models and frameworks. But if OR/MS is the favoured (first trained) paradigm, problems of this kind tend to be framed as a product mix LP even in the knowledge of TOC, and we have to be very determined to see past the product mix frame. Furthermore, as discussed earlier, we should not let traditional LP formulations, solutions and sensitivity analysis constrain our thoughts and actions.

Lessons that Goulds learnt

Goulds benefited beyond expectations from their involvement with this case. Goulds' managers and staff knew their resource constraints intimately, but as is often the case, daily pressures and complexity in the business place conspired so that they did not act to get the best from that knowledge. As in many organisations, there was a general tendency to jump straight from Step 2: Exploit, to Step 4: Elevate. Under this frame of mind, production shortcomings tend to be blamed on a lack of capacity. Since working with the TOC/LP approach, Goulds' managers have been mindful of the need to acknowledge the importance of the constraints, and to focus on the operational management of all factors contributing to the constraints. Instead of wishing for more capacity (and viewing their problems as being due to the lack of it!), they are now using their existing capacity far more effectively. In addition to the product mix decision discussed under step 2 of TOC above, Goulds have taken many other actions to improve their usage of the constraints, such as speeding up the filling process, reducing both set-up and running times, and reducing machine down-time. In this way, they were able to exploit their constraints better, and subordinate other activities to them, rather than simply wishing they could elevate them. Their ongoing problems of lost sales opportunities through non-availability of stock, and unscheduled overtime, were eliminated. They doubled their output in this area of their business with the same staff, and lastly, but by no means least, there was reduced stress on management.

Conclusions

In this paper, we have demonstrated how TOC and spreadsheet LP approaches can complement each other, and may be integrated in a straightforward fashion. We have argued that this is an appropriate way to model, and transform, so-called 'product mix' problems. Each of the methods has its own advantages, plus synergies from being used together. Spreadsheet LP offers advantages of flexibility, universality, combined with speedy LP solution, considerable 'what if?' information, and the ability to make changes quickly and easily. The LP provides a good starting point for the production plan. TOC provides a philosophy within which to use the LP to gain extra advantages: it encourages us to be more innovative in exploring the static LP, both in the ways we conduct sensitivity analysis, and the pro-active approach to seeking improvements to the system. The TOC 5 step process of ongoing improvement in particular encourages more rigour in exploiting the constraints fully before subordinating other activities to suit the constraint, and before adding new capacity. It encourages us to be active in seeking changes in the 'input–output' LHS coefficients, and to ensure we embed the LP in a wider process of continuous improvement. In addition, the TOC Drum-Buffer-Rope scheduling approach allows the static LP to be adapted to a robust operational plan to cope with sequential and variable operations. The wider TOC thinking processes could be used to addresss more complex issues.

It is acknowledged that it is difficult to transcend paradigms and be truly integrative in our approaches to problem solving. Now that LPs can be solved virtually instantaneously, we should not let traditional LP formulation, solution, computational requirements and sensitivity analysis still direct our thoughts and actions. If they do, we run the risk of falling victim to Goldratt's fifth step by 'letting inertia become a system constraint', and achieving far from optimal results.

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