The performance of the theory of constraints methodology

Analysis and discussion of successful TOC applications

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Abstract *The theory of constraints (TOC) is a multi-faceted systems methodology that has been developed to assist people and organisations to think about their problems, develop breakthrough solutions and implement those solutions successfully. This paper describes a literature-based research project examining the results of TOC applications reported in the literature. In particular, it presents here the results of a meta-analysis of over 80 successful TOC applications, based on available quantitative data, which showed that significant improvements in both operational and financial performance were achieved as a result of applying TOC. Despite extensive searches, the research found no reports of failures. While reports are mainly from manufacturing organisations, the findings may be generalisable to other types of organisations, particularly to their operational aspects. The paper concludes with an agenda for future research on the use of TOC in operations and production management.*

Introduction

This paper ensues from a literature-based research project examining the theory of constraints (TOC) methodology and reports of its performance. In late 1996, we started compiling a database of published works on TOC. We were surprised to find no published attempts to summarise or integrate the literature: that is, no major literature reviews had been published (this remained true until late 1998). This observation led us to undertake several

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further projects, including the collection of the diverse elements of the TOC methodology, developed over its 20-year history and scattered throughout the literature, into one integrated review of TOC (Balderstone, 1999) and the publication of an annotated bibliography (Mabin and Balderstone, 2000). In 1998, a review of TOC was published by Rahman (1998) with over 60 references. This provides a good overview of the literature and the methodology at that time, but concludes that "although several papers have referred to the application of TOC in actual business settings, very few cases so far have been reported" (Noreen *et al.*, 1995, p. 353). Thus while Rahman's paper provided a much-needed review of the methodology, a review of applications was still absent. Our own search over a four-year period produced over 400 items, a significant proportion of which comprised reports of applications of TOC, although we still found no overview or summary of the general effects of applying TOC.

The purpose of this article is therefore to provide an overview of the effects of TOC on organisational performance, based on a meta-analysis of these reported applications, using a case survey method (Larsson, 1993). From the reported applications, we collected data on changes in operational performance measures (inventory, lead time, cycle time and due date performance (DDP)) and financial performance measures as a result of applying TOC, and the reported performance of TOC was then analysed using exploratory data analysis methods.

In this paper, we first provide a short overview of TOC, followed by a brief review of the TOC literature in terms of what has been published, where and when. The major portion of this article is then devoted to a description of our meta-analysis of the reported performance of TOC. We close with a discussion of the issues raised by the research and, in particular, a suggested agenda for future research on TOC applications.

TOC

TOC is a multi-faceted systems methodology that has been progressively developed to assist people and organisations to think about problems, develop breakthrough solutions and implement those solutions successfully. Developed primarily by Dr Eliyahu M. Goldratt, it has been popularised through novels such as *The Goal* (Goldratt and Cox, 1992), *It's Not Luck* (Goldratt, 1994), *Critical Chain* (Goldratt, 1997) and *Necessary But Not Sufficient* (Goldratt *et al.*, 2000). Descriptions of the TOC methodology and its components can be found in a number of books (see for example Goldratt, 1990a, b; Noreen *et al.*, 1995; Dettmer, 1997, 1998; Cox and Spencer, 1998; Scheinkopf, 1999), or book chapters (Chase and Aquilano, 1995; Finch and Luebbe, 1995). Outlines and histories of the approach are provided elsewhere (Goldratt, 1996; Cox and Spencer, 1998, pp. 12-21; Corbett, 1998). The following overview is an attempt to represent the various aspects of TOC, including recent developments, in a coherent framework.

Although conceived in the 1970s in a manufacturing context as a scheduling algorithm, TOC has now been developed into a powerful and versatile management theory, as a suite of theoretical frames, methodologies, techniques and tools. It is now a systemic problem-structuring and problem-solving methodology which can be used to develop solutions with both intuitive power and analytical rigour in any environment. The changes of name from Optimised Production Timetable (1979) to Optimised Production Technology (OPT) in 1982 and then to TOC at the beginning of 1987 signalled a major change in emphasis, first, from rule-based scheduling logic to the applications software tool OPT and later to a focusing/iterative process of ongoing improvement. The addition of the thinking processes (TPs) in the 1990s broadened the scope to an organisation-wide perspective and the changes in people's thinking and behaviours required in any change process. While many of the early principles foreshadowed systemic and behavioural issues, the later frameworks have made these issues more apparent and more amenable to managerial analysis and action. TOC is increasingly being applied to situations outside the manufacturing context, including distribution, marketing, project management, accounting – in fact any situation involving change to a system.

The TOC approach epitomises systems thinking: a philosophy that recognises that the whole is much more than the sum of its parts, and that a complex web of interrelationships exist within the system. As Goldratt *et al.* (2000) stressed recently in a keynote speech, "We must never lose sight of the global picture". While everyone is aware of this obvious truth, it is also apparent that many of our day-to-day business practices lead us directly away from this objective. A distinctive feature of Goldratt's systems perspective is the recognition that there are always limitations to the performance of the system of interest, and that despite the tangled web of relationships, these limitations are caused by a very small number of elements in the system, usually just one, which he terms the "constraint". The constraint may be a physical constraint – such as a machine with limited capacity, raw material, but more often it is either a policy or behavioural constraint. Policy constraints often arise when the environment that a company exists within changes while the policies of the company remain unchanged. Most significantly, policy constraints are usually within the control of the management of the organisation. Behavioural constraints occur when performance measures or policies lead to behaviours that, even after policies or measures are changed, are ingrained and constrain a system's performance: "Old habits die hard". TOC contains a range of tools and techniques for addressing physical, policy and behavioural constraints.

The TOC body of knowledge can be organised into the following components:

(1) Performance measurement: sound financial and operational performance measures to measure the performance of the system relative to its goal, however that has been defined.

(2) Performance improvement using one of the following:
   - Constraint management using the five focusing steps in the process of ongoing improvement, including the notions of buffer management.
   - Problem solving/TPs: tools for problem solving.

The performance measures and the two improvement processes, which are described further below, have been used to develop several specific applications:

- Performance measurement-based guidelines (including product mix decision rule, inventory and throughput measures and the TIE rule).
- Focusing steps/buffer management-based solutions for production, distribution and project management.
- TP-based solutions for marketing, sales and strategy.
- TP-based tools for day-to-day management issues.

Performance measurement. A key to maintaining a global perspective is to avoid the use of local measures which encourage local thinking at the expense of global objectives and measures. Most of our traditional measures are local based: local efficiencies; unit costs (e.g. for batch size decisions); and standard costs. These have been demonstrated to be often in conflict with global measures and to lead to erroneous decisions (Goldratt, 1990a; Corbett, 1998; Smith, 2000). In a for-profit organisation, TOC's performance measures centre on achieving excellent results on the three financial measurements, rofit, return on investment (ROI) and cash flow, together with a set of three operational measures that provide a simple and effective way of relating local actions to the overall organisation's financial health. The operational measures are:

- throughput (T) defined as sales revenue less totally variable costs;
- inventory (I) defined as total money invested in the business which is to be or could be sold; and
- operating expense (OE) defined as all non-variable costs associated with turning inventory into throughput.

Net profit (NP) is then calculated as throughput less operating expenses ($T - I$), and ROI is net profit divided by inventory (NP/I). Cash flow incorporates the timing of income and expenditure. In not-for-profit organisations, careful thought is needed to define the appropriate definitions for the above three operational performance measures, but then the same principles apply. In either situation, performance will be improved if T increases, I reduces and/or OE reduces, timing issues aside. Two other measures, throughput dollar days and inventory dollar days, measure backorders and inventory respectively as a product of both their monetary value and length of time backordered or held. Although mentioned in earlier books, these gain prominence in Goldratt's fourth novel (Goldratt *et al.*, 2000, Ch. 17).

These measures address the need to "make operations decisions and design measures to drive actions that are aligned with the strategic objectives of the company and maximise return on investment" correcting for the failings of cost accounting (Smith, 2000, p. 29). Although there are similarities with other methods such as variable costing, there are major differences with other accounting conventions, which have been well covered in the literature, especially recently (e.g. Corbett, 1998; Schragenheim, 1999; Ptak and Schragenheim, 2000; Smith, 2000; Balderstone and Keef, 1999). Other alternatives to cost accounting have been suggested, such as activity-based costing and balanced scorecard, but they differ in that TOC seeks to make decisions based on their effect at a global level, rather than local level. TOC makes it easier to make sensible decisions in areas such as product emphasis (product mix), product pricing, capital investment and process improvement expenditures, and product addition/deletion decisions that are in alignment with corporate goals (Smith, 2000, p. xvi; 26; 115 ff).

Constraint management, the five focusing steps and buffer management. Most of the early development of TOC pertained to manufacturing and it was in this context that the operations management principles, strategies and tools were developed. This is the part of TOC that was used in most of the applications studied in our case survey. Although there are various components within this branch, the five focussing steps embraced in a process of ongoing improvement provide the underpinning rationale: a five-step method to identify and exploit successively the constraint, subordinate other actions in line with the constraint, elevate the constraint and repeat the process. The drum-buffer-rope method, used to schedule operations, allows one to set the pace of the process (drum); provide an allowance for "Murphy" (buffer); and control material release (rope). Buffer management was found to be key to effective production scheduling, and the concept of buffer is central also to distribution and project management, for which specific solutions have been developed using TOC. Further information on this can be found in Goldratt and Fox (1986); Goldratt and Cox (1992); Stein (1996); Cox and Spencer (1998); Goldratt (1997); and Goldratt *et al.* (2000).

The problem solving/TPs. The TPs are a codified suite of five logic-based tools which allow managers to analyse problematic situations and to identify, enhance and implement win-win solutions appropriate to the situation. Users identify sufficiency (cause-and-effect) relationships and necessity relationships, and use these to construct diagrammatic representations of the situation and its solution. Both types of relationship use box and arrow diagrams but have their own sets of rules to audit the logic. These thinking and representational tools can be used in any context: manufacturing, services, personal, or professional. They help any manager address the questions of managing change: "What to change?", "What to change to?" and "How to cause the change to happen?". Descriptions of the tools and examples of their use are provided in books such

as Goldratt (1994); Dettmer (1998); Scheinkopf (1999); Schragenheim (1999); Cox and Spencer (1998); and Kendall (1998).

The TOC literature

An extensive search of the literature using both hard-copy and Web-based resources, uncovered over 400 books, journal articles, conference papers and Web articles on TOC in the 1990s. A list of summaries of these items, together with an overview of the published literature, trends and issues, is already available (Mabin and Balderstone, 2000).This paper builds on that material and provides further analysis and discussion of the case material summarised in the book.

The literature search indicates a considerable growth in publications in recent years. In particular, since the beginning of 1998, we have seen a dramatic increase in the number of books published on TOC, with more than 20 new books including Corbett (1998); Cox and Spencer (1998); Kendall (1998); Newbold (1998); Scheinkopf (1999); Schragenheim (1999); Leach (2000); Ptak and Schragenheim (2000); Smith (2000); Lepore and Cohen (1999); Mabin and Balderstone (2000); Goldratt *et al.* (2000). This takes the total number of books on TOC to nearly 50 since the first release of *The Goal* (Goldratt and Cox, 1984), indicating growing recognition of the area.

Publications have appeared in over 100 journals, and display a pattern consistent with the Pareto principle. About 60 journals featured a single article on TOC, accounting for about one-sixth of the articles. These "solo" articles appear to have a significant element of outreach, aiming to introduce TOC to readers in disparate areas. At the other extreme, a significant number of articles have been concentrated in a few journals, mostly influential industry journals. For instance, APICS publications have carried more than 90 papers about TOC, and *Industry Week* has published over 15 articles. Prominent academic journals, such as the *Harvard Business Review*, have contributed to the body of literature on TOC to a lesser – but growing – extent, perhaps paralleling TOC's inclusion in hundreds of university courses. Discussion has predominantly focused in areas such as manufacturing, and opportunities exist to transfer and apply the principles of TOC to other areas.

The TOC literature spans theory and practice as well as addressing a diverse range of issues relating to accounting, scheduling, performance measurement, product mix, quality, and project management and application areas. Application areas include manufacturing, re-manufacturing, non-manufacturing/services, IS/software, military and education. The military, in the USA and Israel, were early adopters of the logistics and scheduling techniques of TOC, and now use the techniques extensively. The US Air Force has used the TPs in its logistics and medical environment. According to Cox and Spencer (1998), it has contributed substantially to developments of TOC in these areas, and in the use of the TPs in not-for-profit and medical

environments more generally (Roadman *et al.*, 1995). In addition to contributions related to teaching TOC, there have been notable achievements in the application and development of TOC methods for use in education (for example, Suerken, 1995).

Reported applications. In the literature reviewed, there were over 100 descriptions of applications of TOC, the majority of which were based in the manufacturing sector, and most of these focused on the manufacturing operations of each organisation. However, there were several instances of application to non-manufacturing, administrative or service functions (Mabin and Balderstone, 2000). Within the manufacturing sector, there are significant clusters of applications in the aerospace, apparel, automotive, electronics, furniture, semi-conductor, steel and heavy engineering industries. The great majority of applications reported in the literature were conducted in North America. A number of European applications were reported, with only a few cases emerging from the UK and Australasia. The range of organisations reported on includes some of the world's largest and most successful organisations: Boeing, General Motors, Ford Motor Company, Lucent Technologies, to name just a few. At the other extreme, there are reports of applying TOC in very small organisations (Adelman, 1995; Demmy and Demmy, 1994).

The case survey methodology

In order to draw general conclusions about the results of applying TOC, we used the case survey methodology (Larsson, 1993), which draws on published case studies relevant to the field of study. In some instances the literature contained only case vignettes, rather than complete case studies. These vignettes were considered to be still of use providing they contained information about the results of a TOC application. Before describing the analysis, we will briefly review the strengths and weaknesses of the case survey methodology.

The strengths of the case survey methodology

Lucas (1974) claims the benefits of the methodology are that "the case survey is an inexpensive and potentially powerful method of identifying and statistically testing patterns across studies". Larsson (1993, pp. 1517-18) outlines the strengths of the case survey method, summarised as follows:

- Case surveys tap prior research efforts reported in a vast number of cases that contain managerially relevant data.
- The case survey method overcomes major drawbacks of single case studies, namely their inability to examine cross-sectional patterns and to generalise to large populations.
- The method capitalises on the idiographic richness of case studies that derives from their ability to study more complex phenomena than more superficial nomothetic surveys can study (Tsoukas, 1989).

- Case surveys can be replicated since both their coding schemes and case study reports are available to other researchers.
- The case survey method avoids premature exclusion of studies based on a priori judgements about their research designs, publication status and age, all of which often plague research reviews.
- The inclusion of case studies from different time periods also enables the analysis of patterns of complex phenomena over time; for instance, possible effects of organisational learning might be detected.
- From a broader perspective, the case survey method provides a valuable bridge between quantitative and qualitative methods and positivistic and humanistic paradigms and approaches (Lee, 1991).

Larsson (1993) indicates that technological advancement has facilitated case surveys. Hunter *et al.* (1982) acknowledge the impact of technology on meta-analysis, saying that the recent proliferation of electronic on-line databases enables a researcher to identify and obtain a large number of studies relatively quickly and easily. The points which Hunter *et al.* (1982, pp. 38-39) make about statistically based meta-analysis also apply to the case survey method: "Valuable information is needlessly scattered in individual studies ... A young behavioural or social scientist today with the needed training and skills can make major original discoveries and contributions without ever conducting a single primary research study – simply by mining the rich untapped veins of information in accumulated research literatures". Such ability to tap into the published research allows organisations to turn the data contained therein into useful information.

Limitations of the case survey methodology

As with any method, there are some limitations, which Larsson (1993, p. 1519) identifies as follows:

- The number and representativeness of available, relevant case studies may be insufficient to allow theoretical and statistical generalisation of results.
- Case study reports often restrict the information available for case surveys by leaving out much of the collected data because of space or other limitations.
- The quality of the case survey can be no better than the quality of the case studies and their data.
- Coding procedures can strip complexity and unduly simplify the complex phenomena under investigation.

The case survey methodology is also prone to another limitation, a positive reporting bias – the tendency to report "successes" rather than "failures", and to provide retrospective justification for the application of a management

methodology (also termed the confirmation bias (Bazerman, 1998)). Case studies of troubled organisations are occasionally published, providing valuable insight, as exceptions to this general tendency. Recent research into the effectiveness of business process re-engineering (BPR) and total quality management (TQM) by Giroux and Landry (1998) and Lu and Yeh (1998) respectively, claim the literature relating to these topics has uncovered many reported "failures". However, despite this, we must remain alert to the literature being possibly biased towards reports of successes.

On balance, the case survey methodology was considered to be appropriate for the proposed meta-analysis, that is, to tap into data that already existed on TOC applications, and which had remained significantly under-utilised.

The meta-analysis

The literature contains many references to spectacular results achieved by organisations applying TOC principles, procedures and tools, and we uncovered many case studies reporting impressive results. However we could find no sources providing aggregate or omnibus findings on applying TOC, except for Noreen *et al.* (1995), who studied 20 organisations that had applied TOC – but even this lacked an analytical summary of the results achieved. Additionally, while books on TOC tended to draw on many case studies to illustrate points, the cases themselves were often reported in piecemeal fashion. Consequently, this research set out to provide a summative quantified meta-analysis of the impacts of applying TOC as reported in the literature. We concentrated on the material published in the 1990s in order to evaluate the expanded TOC methodology as it was then, rather than the earlier OPT technique.

The case studies and vignettes reported in the publicly-available literature were collated and analysed. Data on changes in the following measures were extracted and tabulated: lead time, cycle time, DDP, inventory, revenue, throughput, and profitability. Any data were converted wherever possible to comparative terms, i.e. percentage improvements, so that results could be collated. Some cases reported such improvements directly, such as "Due-Date Performance improved by 80 per cent." Others might state that DDP improved from 50 per cent to 90 per cent, which could be converted to an 80 per cent improvement; but others stated simply that it improved, or that it improved to 90 per cent, which information was insufficient for the statistical analysis part of the study. This reduced the number of cases providing data suitable for the statistical analysis down to 81. A representative sample of this data is shown in Table I (the full set is given in Mabin and Balderstone (2000)).

The usefulness of the results of the meta-analysis will be dependent on the quality and quantity of available case reports. Before discussing the findings, there are a few observations to make about the data as a whole. As expected there was a significant positive reporting bias: indeed, despite extensive

Table I. A sample of the data on reported changes in operational and financial performance measures (expressed as percentage improvements)

Source	Organisation	Cycle time	Lead time	Due date performance	Inventory size	Revenue or throughput	Profitability
Callahan and Morgan (1989)	General Motors (Windsor)	94			50		
Reimer (1991)	Valmont ALS			20			600 (over 4 yrs)
Keller and Devlin (1991)	BHP – Coated Products Division		20		20		
Andrews and Becker (1992)	Alko Lighting		88	30	−4	20	42
Simons and Moore (1992)	Modine Manufacturing Co.		75		70		
Libby (1994)	Cochrane Furniture	64	78		38		
Murphy and Levinson (1995)	Harris Semi-conductor	50			40	28	
Shoemaker (1995)	Zycon Corporation	80			50	100	
Wayman (1996)	Morton International Automotive		50	28-47	50	+	
Danos (1996)	Dixie Iron Works			100	50		300
Wilson (1997)	Ketema A&E		30-60		40		
Gallagher (1997)	ITT (Night Vision Division)	50				200	
Wilson *et al.* (1998)	BHP (Malaysia)		86	+	50		
Gronseth and Ray (1998)	Nystrom Inc. (Cesco Products)					570 (3 yrs) 190 ave.	470 (3 yrs) 156 ave.

Note: + denotes unspecified positive improvement

searching, no failures were found to be reported in the literature (an early reported failure referred to the use of the OPT software, not to TOC as such).

In order to provide an indicator of the quality of case reports, we have analysed the nature of the authorship as well as the publications of the various case reports. First, with respect to authorship, we have categorised the authors of the articles into four categories: academic, consultant/TOC expert, company representative, and reporter. The number of authors in each of these categories is shown in Table II.

The academic classification includes both full- and part-time academics, but does not include former academics who had changed affiliation at the time of writing the papers. We found that over 40 per cent (55/130) of authors were academics. These authors can be expected to provide a critical and independent review of the process and results. Of particular note in this category is the extensive and thorough paper by Andrews and Becker (1992) of the Graduate School of Business, University of Chicago, reporting on the Alkco Lighting Company and "its journey to Goldratt's *Goal*". This contains a wealth of information in terms of both specific details of the case, and sound advice for others.

Company representatives are those reporting on their own company's implementation of TOC. We observed that about three-quarters (22/29) of these authors listed tertiary academic and/or professional qualifications. A total of 16 held academic qualifications including PhDs and MBAs, as well as Bachelor and other Masters degrees. In addition, many held professional qualifications such as CFPIM and CPIM, CPA and Jonah. The remainder held positions of high responsibility in their organisation and while qualifications may well have been held, they were not provided for the particular publications (some do not publish author biographies or state qualifications).

Company representatives displayed a desire to share their experiences, and given that they have experienced the situation first hand, are able to provide very genuine reports. There may be some element of hyperbole – evangelical fervour even – but the need to maintain credibility within the company and industry will in the main temper any desire to overstate results.

The remaining articles were divided equally between consultant/TOC experts, and reporters both at 18 per cent (23/130 each). The former have their own "barrow to push" and are likely to be the most biased but knowledgeable about the methodology, while reporters provide an independent but not necessarily knowledgeable perspective.

Table II.
Authorship of the published case reports

Author	Academic	Consultant/ TOC expert	Company representative	Reporter	Total
Number	55	23	29	23	130
Percentage	42	18	22	18	100

Turning now to the status of the publications in which the case reports were published, we characterised the publications into eight categories as shown in Table III.

A variety of publication types were used to report on the cases, as would be expected for write-ups intended to inform a variety of interested parties, including academic audiences and industry groups. Two cases were reported in more than one publication. Nearly half the reports were published in either refereed academic journals or conference proceedings (23 per cent each). Next highest categories were reports in books and Web pages, at 15 per ent each. magazines for industry and sectors were used too, at 13 per cent and 8 per cent respectively. At least three of the papers were for work that had won prizes.

Another characteristic of the data – indeed of the case survey method – is that authors used a variety of definitions and measurements. This is not surprising given the different emphasis of the articles in different publications, the differing backgrounds of authors, and the newness of the field. Such differences occurred especially for measurements concerning throughput and inventory for which TOC has its own definitions. In addition, inventory sometimes meant WIP inventory, and at other times total inventory. In many cases, definitions were not clearly provided. As a consequence, the general thrust of the results will be more meaningful and relevant than their numerical values.

After tabulating the data, we were initially concerned at the many missing data elements. On reflection, however, we realised that there were several valid reasons for the missing data, and while undesirable, it was not necessarily an indicator of negative results being deliberately unreported. The most obvious reason is that until results are collated in a table, such omissions are often not even realised: such "missing" data, which can be highlighted in tabular form, are easily overlooked when cases are presented in the usual narrative form. Thus a spinoff from this research could be a recommended list of performance measures to be used when reporting future applications. However, the issue of a minimum set of performance measures is itself a matter for debate, as TOC measures would arguably be more effective for decision making, though they are not as widely recognised. At this stage, we would recommend a combination of the measures used in this paper, which includes the TOC measures (*T*, *I* and OE), together with normal operational measures and accounting/financial reporting measures.

Table III. Publication type for the published case reports

Publication	Refereed journal	Conference proceedings	Book	Industry (broad)	Sector magazine	Internal news-letter	Web page	News-paper	Total
Number	19	19	13	11	7	1	13	1	84
Percentage	23	23	15	13	8	1	15	1	100

Another reason for "missing" data is that some of the performance measures can be regarded as substitutes for each other: for example lead times, cycle times and DDP all refer to the organisation's ability to respond speedily to customer needs, and many case studies reported only one of the three. Financial performance was often not reported, and even less often quantified, probably for commercial sensitivity reasons. Furthermore, it is often difficult and time-consuming to measure the effects of changes, and this may not be a high priority for action-oriented managers. To calculate percentage changes (which we required) requires both before and after figures, and people may not bother to take such measurements, or they may be too hard to collect, particularly if they have changed the way they measure or value inventory, for example, and are now using the TOC definitions rather than traditional accounting definitions.

Overall, when taken in context of the articles themselves, it is apparent that the authors considered the application of TOC to be a success. We note also that some journals, such as the *Production and Inventory Management Journal*, require confirmation from an independent and senior company official of the results claimed.

For all these reasons, not too much of a negative nature can be read into the gaps in the data. They are a limitation, but not overly problematic. On balance, we believe that the 81 case studies provided data of sufficient quality, at least for the purposes of obtaining summary statistics of the performance measure changes reported by these organisations. Owing to the limitations of the data, however, it would be unwise to attempt too complex an analysis, as that may lead to spurious claims or overconfidence in the results. For this reason, the core of the analysis relied on exploratory data analysis (used to plot and understand the data and derive summary statistics), and simple statistical tests of significance.

Summary of reported results

Over half of the organisations that provided usable information on the impacts of applying TOC, mentioned improvements in revenue, throughput or profits. Over 80 per cent mentioned improvements in lead times, cycle times, DDP and/or inventory, and of these, over 40 per cent also mentioned improvements in financial performance (revenue, throughput and/or profits). This may well be an underestimate of the actual performance. For the reasons given earlier, there are likely to be many cases where improvements went unreported. The following analysis is limited to those reports which provided sufficient data to allow us to calculate percentage changes, which we will refer to as "quantified performance changes".

Summary statistics for all quantified performance changes are provided in Table IV. (The reader is referred to Balderstone (1999) for a full description of

	n	Min	LQ	Mean	Median	UQ	Max
Lead time	34	20	50	70	75	86	98
Cycle time	14	24	50	65	66	80	97
Due date performance	13	15	30	44	50	90	166
Inventory[a]	32	−4[b]	40	49	50	68	80
Revenue	20	10	21	83	39	66	600
Throughput	4	28	30	65	65	100	100
Profitability	7	37	42	116	100	156	300

Notes:
[a] Excludes two datapoints expressed in US$ and unable to be converted to per cent
US$600 million decrease in inventory for Proctor & Gamble
US$100 million decrease in inventory for Ford Motor Co Electronics Division
[b] This figure was recorded at Alkco Lighting Company, which underwent major restructuring as reported by Andrews and Becker (1992). The next lowest reported inventory improvement was 17 per cent

Table IV.
Summary of quantified reported changes (percentage improvements)

the exploratory data analysis performed, including graphical presentations of the data.)

Operational performance measures

First we detail the three indicators of speed/flexibility, namely lead time, cycle time and DDP:

(1) *Lead time.* Just under half (34/81) of the case studies provided sufficient data to calculate quantified lead time changes, and all of these were reductions, while a further six indicated unspecified reductions. The median reduction in lead time of 75 per cent (mean 70 per cent) for the sample of 34 indicates the substantial improvements achieved. Over 85 per cent of the organisations reported reductions in lead time of over 50 per cent. Given that almost half (40 out of 81) the organisations reported an improvement in lead time, and the magnitude of four in five of those improvements, the issue of missing data would appear to have negligible impact on our findings. To produce a nil effect overall, i.e. for TOC to have no positive effect, the size of detrimental results would have to be extremely large. Thus we can safely say that TOC had a positive effect on lead times.

(2) *Cycle time.* One in six organisations (14/81) reported changes in cycle time, with an average of two-thirds reduction. The highest was a 97 per cent reduction. The lowest reported a reduction by one-quarter, and the interquartile range was 30 per cent indicating only a small degree of spread. Applying TOC thus yielded a positive reduction in cycle time for the organisations reporting changes in this variable, but the small sample size reduces the confidence with which we can generalise this result.

(3) *DDP.* A total of 30 organisations reported improvements in DDP, but less than half of these (13/30) provided sufficient numerical data. These 13 showed a median increase of 50 per cent, with a mean improvement of 44 per cent, and an interquartile range of 60 per cent, indicative of a wide spread in the reported results. This spread is likely due not only to the small sample size, but also to the nature of the data: because DDP is unbounded, unlike lead times and cycle times which cannot decrease by more than 100 per cent. Indeed the maximum improvement for DDP was 166 per cent, and occurred at MK Electric, with a concomitant decrease in lead time of 80 per cent. From these findings we can conclude that many organisations applying TOC techniques and reporting results, have experienced improvements – sometimes very large – in DDP.

Inventory level. Over half the cases (42/81) reported that their inventory had reduced, and 34 organisations provided actual data. However, two substantial results could not be expressed in relative terms, and so were excluded from the analysis. Proctor and Gamble reduced their inventory by US$600 million, and Ford Motor Co Electronics Division reduced theirs by US$100 million (Gardiner *et al.*, 1994). The median reduction for the remaining 32 organisations was 50 per cent (mean 49 per cent), with three-quarters of the organisations experiencing improvements of over 40 per cent. The reported results showed relatively little spread, as indicated by the narrow interquartile range, and close mean and median values. We noted that a large number reported either 40 per cent or 50 per cent improvements, probably due to rounding. One organisation that implemented TOC's drum-buffer-rope method (Alkco Lighting, see Andrews and Becker (1992)) reported a 4 per cent increase in inventory as a result of creating a pre-constraint buffer, but this enabled them to decrease their lead time by 88 per cent. Overall we can conclude that the application of TOC techniques did yield reduced inventory levels, with an average improvement of around 50 per cent reduction for the organisations providing comparative data.

Financial performance measures

Over half the case studies reported improvements in financial performance. However, usable quantitative data for financial performance were provided in only 31 cases, and then was expressed variously as sales, revenues, profit, profitability and/or throughput. Additionally, the TOC definition of the term throughput is different from most cost accounting definitions in use, and it is not always clear which definition has been used. The following section makes no assumptions about the definitions used, and incorporates "sales" figures under revenue.

Revenue. The organisations that applied TOC and reported changes in Revenue (or sales), indicated that they achieved moderate to large increases. Again, there are no theoretical limits to the level of improvements possible.

Some 30 organisations reported changes, all of which were increases, but only 20 provided usable data. These 20 organisations gave a median of 39 per cent mean improvement, and a mean of 83 per cent, due to one outlier that increased revenue by 600 per cent. Over one-quarter of the organisations experienced revenue increases of over two-thirds. A group of six organisations (several from the semi-conductor/electronics industry) experienced improvements of less than 30 per cent. We can conclude that organisations applying TOC techniques and then reporting changes to revenue did experience significant improvements; however the range of increases is very large.

Throughput. Throughput was reported for four organisations only. Reported increases ranged from 28 to 100 per cent, with both a mean and median increase of 65 per cent.

Profitability. For profitability, a very small sample of case studies provided quantitative data. Just under one-quarter (19/81) of the organisations reported increases in profitability. However only seven of the 19 organisations reported quantified results. This low level of quantitative reporting for profitability (in comparison to the operational performance measures) is possibly due to the need for sensitivity in competitive commercial environments. Increases in profitability, as with other measures, are unbounded, and were indeed observed to cover a great range from 37 up to 300 per cent with a mean of 116 per cent and median of 100 per cent. Overall, 19 organisations applying TOC did report improvements to profitability, but the numerical results are based on a sample of seven, so are indicative only.

Operating expense (OE). Very few cases reported changes in OE the third of the TOC performance measures. TOC emphasises efforts to increase throughput rather than reduce inventory or OE, for the reason that inventory and operating expense both have a finite bottom limit beyond which further reductions quickly start to hurt the organisation's performance. On the other hand, throughput improvements have no theoretical limits, and actual limits that do exist appear to be due to company rules and policies (Covington, 1996, p. 12).

In the absence of quantitative data on OE, it can be argued that any reductions in OE gained in addition to the reported results would strengthen the findings. What would be of concern is if companies increased their OE without an accompanying increase in throughput or reduction in inventory.

We therefore sought out evidence from other sources:

- Noreen *et al.* (1995, p. 144) investigated 20 actual applications of TOC and reported that "Managers at almost all of the sites we visited claimed that they had been able to reduce or keep operating expenses constant despite increased volumes and variety." This would suggest that an adverse change in OE in the present sample is rather unlikely, and the effect on OE can be expected to be small. Noreen *et al.* (quoted in Corbett, 1998, p. 113) go on to say "This fact is surprising given the assertions made in

the ABC literature concerning the effects of volume and variety on overhead costs."

- The TOC Center (2000) reports that: "Our experience indicates that organisations can typically gain 25-100 per cent of additional output without any notable increase in operating expenditure or investment."

Comparison with other reports of results

Since our analysis of the 81 cases, we have found some Web sites which provide summary statements on the results of the application of TOC by TOC experts/consultants, for example, see Chesapeake Consulting (2000) and Innovation Architects (2002). The results of TOC application reported on these sites are generally consistent in their magnitude and direction with the results of our secondary research. In relation to some metrics, the results of our research are actually conservative in comparison with the reported results of the TOC experts/consultants.

Relationships evident from reported results

The relationship between lead time reduction and inventory reduction. It has been claimed (Goldratt and Fox, 1986) that lead time will generally reduce at a similar rate as inventory, as a result of applying TOC. This effect has been shown to apply experimentally[1] (see for example Cook, 1994; Chakravorty and Atwater, 1996; Lambrecht and Segaert, 1990), and occurs because as inventory is removed from the system, there is less material clogging the pipeline, and work can flow through faster. (Inventory does have a place, though – if strategically located to guard against fluctuations which might otherwise jeopardise throughput.) While recognising that these effects are meant to apply to a particular system, we analysed the inventory and lead time data to see whether we could detect any connection between the reductions in lead times and inventory over this sample.

Almost half (37/81) the organisations reported improvements in, on the one hand, lead times, cycle times and/or DDP, and on the other, inventory reductions. Quantitative data on both lead times and inventory were provided in 15 cases. The plot of these cases is shown in Figure 1. Both a regression analysis and a Spearman's Rank Correlation were performed[2]. This suggests a good correlation may exist. The regression gave R^2 of 0.36, significant at the 2.5 per cent level, and the Spearman gave a rank correlation r_s of 0.47, significant at the 5 per cent level.

Furthermore, the order of magnitude of reduction in lead time was greater than that of the reduction in inventory levels, in 93 per cent of the observations. Two-thirds of the organisations reported reductions in lead time to within 13 per cent of the reduction in inventory level. Thus, we can conclude that both inventory and lead time tend to be reduced concurrently as a result of applying TOC techniques.

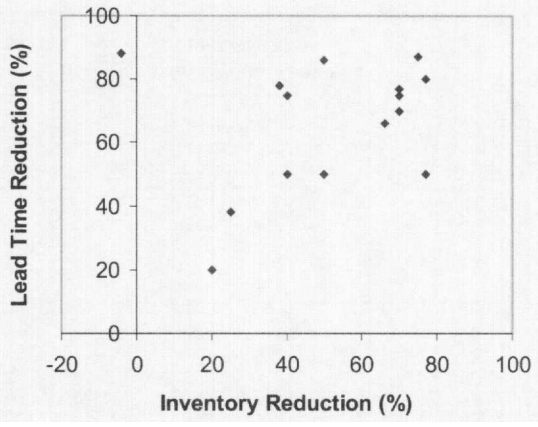

Figure 1.
Lead time and inventory reductions

Research into the application of the just-in-time (JIT) methodology has so far been unable to reveal or confirm that these two performance measures exhibit a similar relationship as a consequence of JIT. Corbett *et al.* (1992) surveyed Australasian manufacturers and received responses from over 200 organisations. The Corbett *et al.* (1992) data indicate that organisations applying JIT did increase inventory turnover, at a greater rate than for a non-JIT sample. However, there was no significant difference in lead time reduction between the two groups. Both groups reported a 3-5 per cent reduction in manufacturing lead time. White (1993) reports on a major survey of US manufacturers that implemented JIT. An average reduction in throughput-time (analogous to lead time) of 59.4 per cent was reported, (see the 70 per cent in our analysis.) White does not provide any data on any corresponding reduction in inventory levels. Hence further investigation is required to establish whether there is a correlation between lead time and inventory reductions in instances of JIT implementation.

Relationships between financial and operational performance measures. In addition to the above analyses, we also conducted an analysis of all reported results, both qualitative and quantitative, pertaining to the performance measures. We tabulated reported improvements on two dimensions: the first was reports of improvements in lead time, cycle time and/or DDP. This dimension captured the notion of faster response to the customer. The second dimension was improvement in either inventory levels, or financial performance (throughput, revenue or profitability). The breakdown of the 81 cases is provided in Table V. Over half of the organisations (45/81) reported an improvement in both areas simultaneously. Almost half reported an improvement in one or other area. This suggests a highly non-random effect. Using a Chi-square test shows that we can reject the hypothesis that organisations reporting an improvement on one dimension do so at the expense of an improvement on the other dimension (significant at the 5 per cent level).

	Improvement in inventory and/or financial performance measures	No reported improvement in inventory or financial performance measures
Improvements in LT, CT and/or DDP	45	14
No reported improvement in LT, CT and/or DDP	22	0

Table V.
Relationship between performance changes

Notes:
Abbreviations: LT = lead time; CT = cycle time; DDP = due date performance

The relationship between inventory and profitability. Goldratt and Fox (1986) argue that profits will also be indirectly positively influenced by decreases in inventory. Unfortunately there were only three cases for which data for both profit and inventory were available. More data are needed to test this hypothesis.

Intangible changes

The case studies also contained comments on many other changes that are less tangible or measurable than the ones listed earlier. These include: an improvement in morale; reduction of chaos and stress; better team functioning and employee involvement; people acting more "as one"; improved flexibility and responsiveness; improved customer satisfaction; and improved quality. Many of these changes can be explained by TOC's focus on global performance, while other improvements, in say flexibility and quality, often result from a reduction in WIP inventory which means that less is in the pipeline, and changes/corrections to schedules or procedures can be enacted faster. We have not attempted to code and analyse these intangible factors, but would recommend that an analysis of such intangible factors would be a worthwhile area for future study, particularly as the number of TP applications increases.

Summary of the findings – quantitative results. TOC provided a source of competitive advantage for manufacturing organisations reporting results of TOC application, as evidenced by this research which concludes that the application of TOC techniques yielded substantial reductions in lead time (median 75 per cent); cycle time (median 66 per cent); and inventory (median 50 per cent). Improvements (increases) in DDP (median of 50 per cent) were based on a small sample. Financial improvements were also considerable, with median 39 per cent improvement in revenue. Unfortunately, very few case studies reported increases in profitability, but those that did had a median improvement of 100 per cent. In relation to lead time and inventory performance measures, it can also be concluded that the hypothesis that reductions in lead time and reductions in inventory levels are positively correlated (Goldratt and Fox, 1986, p. 65) is confirmed by the statistically

significant regression and Spearman rank correlation results. Finally, financial and/or inventory improvements were often gained at the same time as improved response to customers (lead time, cycle time or DDP); one did not occur at the expense of the other.

Limited use of the full range of TOC techniques. The TOC approach embraces many principles, guidelines, processes, techniques, methods and tools. The literature search, data collection and meta-analysis revealed that none of the applications used the full arsenal of TOC techniques, methods, tools, etc. The most common components applied were the five focusing steps in the process of ongoing improvement, and the drum-buffer-rope scheduling system. Reported applications of the TOC TPs were less commonly reported, not surprisingly as this component of TOC is a fairly recent development. While many of these TP applications describe very successful applications, often the results were not reported in terms amenable to aggregation or synthesis to this present study (e.g. Dettmer, 1998, pp. 126-8). The literature does not yet report sufficient results to enable us to evaluate the value of the TPs as a means of guiding system improvement.

The finding that no applications used the full TOC arsenal, indicates that only a portion of the full power of TOC was utilised. Furthermore, like any methodology which is evolving, the tools and techniques used in the early 1990s are likely to be different from the tools used later in the decade. Each case is different and each application is unique in its combination of tools used, and the ways in which those tools are interpreted and applied. The application of TOC in such a variety of cases is thus likely to be of variable quality and to yield variance in results. This provides another justification for the choice of the case survey method. In situations where there is such variability, it would be fallacious to examine only a small number of cases to assess performance. By drawing on a larger sample, the case survey method is better placed to make this assessment.

Furthermore, with such diversity, and with limited data on particular aspects of TOC applied, it was not considered worth testing whether the results are correlated with particular components. However, this may be a question worth pursuing in future, especially to compare the relative success of applications using the TP's versus those not using them. Evidence to date suggests that organisations can potentially experience greater operational and financial improvement if they were to apply the TPs and gain the full weight of the methodology. However, the lack of empirical evidence of the value of applying the TOC TPs means we can not make categorical statements about the additional benefits to be derived from their application, prior to the adoption of the operations strategy techniques.

Positive reporting bias. All of the reported case studies found in the search were success stories. However, there have been failures, as instanced an early widely publicised failure in the mid-1980s where Mars sued Creative Output

because of poor performance, but this related to the use of the OPT software package rather than the broader TOC methodology. None of the surveyed applications of TOC could be described as failures: even the single instance of a 4 per cent increase in inventory was explained as being due to the implementation of buffer management which provided more reliable delivery to customers and enabled lead times to be reduced by 88 per cent. Negative data may have been omitted from case reports, providing a biased view, yet the cases themselves were clearly portrayed as success stories.

We could find no published evidence to support the assertion by Noreen *et al.* (1995, p. 148), that "as with other improvement programs, such as TQM, the failures (of TOC applications) probably outnumber the successes in the sense that improvements fall short of expectations". At the sites they visited, managers were generally happy with what they had done, but usually felt they should have used TOC more Noreen *et al.* (1995, p. xxii). This view was particularly true with regard to the TPs, and many of the sites that Noreen *et al.* (1995) studied were using the TPs. In contrast, the majority of cases in our literature review used the "production solution" (drum-buffer-rope, focusing steps, buffer management), and this may account for much of the difference in judging the success of TOC. Noreen *et al.* (1995, p. 149) state that in job shops, "efforts will be rewarded with almost immediate improvements in operations and in profits at virtually no cost. However such efforts ultimately will lead to failure unless management outside of manufacturing is willing to embrace TOC or evaluate manufacturing performance using TOC measures." While they give no data to support their claims, the claim about immediate improvements tallies with what we found, while their cautionary note echoes our perceived need for future research on the long-term impacts of TOC, with one of the research gaps that we identified being a lack of longitudinal studies on the application of TOC.

In light of this unknown positive reporting bias, we need to be a little cautious when drawing conclusions beyond the scope of the present study.

Implications of the research

Implications for managers of manufacturing operations

This research clearly indicates from the available evidence that TOC thinking, methods, tools etc. have been a source of competitive advantage for the manufacturing organisations which reported results. Such a conclusion leads us to speculate about the replicability of the results in other manufacturing settings. We cannot assert that the results presented above are typical results of applying TOC, as the bias associated with reporting results (as previously discussed), and the lack of control over the sample, preclude such assertions being made. We can assert, however, that organisations that apply TOC can and did achieve the results outlined above. Therefore, managers in other

manufacturing organisations can take some confidence from the results achievable if they make effective use of the TOC methodology.

In interpreting the results, we also recognise that the improvements are relative to a base state for each individual organisation prior to the application of TOC. One might expect that companies that have already streamlined their operations have less to gain and may show less startling results from using TOC, than those whose operations have not already been improved. It may be a comparatively simple task for an experienced and well-educated improvement specialist to produce significant improvements – using any of the well-known improvement methods – in a poorly-managed organisation, whereas gaining improvement in a comparatively well-managed business would be a lot more difficult. The impressive results of TOC implementation may benefit from such so-called "low hanging fruit" in some instances. However, the organisations reporting results include a number of major international businesses, such as Ford, General Motors, Boeing and Proctor and Gamble, so this may be ruled out as a valid explanation of all the successes. For example, Ford Electronics obtained a 90 per cent reduction in cycle time using TOC, on top of a 40 per cent reduction they had already achieved from applying JIT and TQM (Dettmer, 1998). From the available evidence, we cannot determine the extent to which the impressive improvements reported represent the "picking of low hanging fruit". It would be useful in future if organisations could indicate previous improvements.

With regard to the TOC TP tools, it could be argued that the benefits from these applying are not necessarily subject to the same limitation – the benefits could be much larger because much more fundamental assumptions and policies are being tackled, and changes to these areas can have major impacts. Thus the TPs are often used to attack thornier issues, which can hardly be regarded as "low-hanging" fruit.

The TOC frameworks offer an approach to management that reflects a systems-oriented holistic paradigm. The success of the approach must raise questions about the continued appropriateness of the existing methods consistent with the dominant functionalist paradigm (specifically: high inventory MRP systems, Cost and ABC accounting). Managers must ask the question: "Are the current dominant paradigms producing satisfactory operational and financial results?". Managers need to assess the performance of their organisations as a whole, and consider if a new source of competitive advantage is desirable. Managers then must consider what sources of competitive advantage are open to them, and assess whether TOC is a viable option. Recent texts such as Corbett (1998), Smith (2000), and Swain and Bell (1999) provide considerable discussion of these issues, demonstrating the superiority of the TOC approach on theoretical grounds as well as citing numerous examples. This research may also aid that assessment by summarising the reported evidence of TOC in practice.

As discussed above, the reports of TOC applications are overwhelmingly favourable. The lack of criticism associated with the use of the TOC methods, particularly when compared with BPR, TQM and JIT, could indicate its superiority over other methods, or it could just indicate that the downsides have yet to be identified. Consequently, users must think for themselves about possible negative effects. They can, however, take comfort in the fact that TOC is founded on systems principles, and as such considers both the big picture as well as the impact of local practices/measures/constraints on overall performance. It contains tools that are designed specifically to address and manage these global and local issues, and any potential negative side effects and successfully negotiate a way through the change process to improve operational and financial performance.

Implications for other areas of business

There is now a small but growing body of literature describing applications to areas other than manufacturing, which may provide future researchers with fertile material for study. Managers in other areas of business can find good examples of the diversity that can be handled with the TOC approach (see Dettmer, 1998; Kendall, 1998; Fritz, 2000; Leach, 2000; McClelland, 1998; Newbold, 1998; Scheinkopf, 1999; Schragenheim, 1999; Mabin *et al.*, 2001).

Implications for O&PM researchers

In attempting to draw conclusions from this research, we recognise that there are obviously many areas where more research could be done, such as a rigorous critique of the TOC methodology; longitudinal studies of organisations in which TOC has been applied; success factors for the use of TOC; as well as further development of the approach itself and theoretical issues.

For a more rigorous assessment of the effects of TOC, we could first, revisit the cases in this present study and seek independent confirmation of the effects of applying TOC. This could perhaps be turned into a longitudinal study. There is a dearth of longitudinal studies on the performance of TOC over time. Such studies could provide valuable insights into the prerequisites for success and failure at various stages of TOC implementations. Contextual information should also be supplied: specifically, we need to know whether and what other improvement approaches had previously or since been applied. This information may perhaps shed some light on the question of whether any change, not just TOC, might have led to improvements.

One of the pressing issues identified in this paper, though, is the need for more complete and more consistent reporting of case results: a standard set of measures should be used to provide the required information and to facilitate summaries such as the present survey. For the cases summarised in this paper, the inconsistencies in performance measure definitions was an issue that may be able to be addressed by returning to the original organisations, although

from our experience the data may simply not be available for the required measures. If future case write-ups used a standard set of measures, this issue could begin to be addressed. At a minimum, the changes in throughput, inventory and operating expense measured according to TOC definitions would provide adequate information to calculate financial performance improvement. Traditional performance measures, including the operational performance measures listed earlier, would also be valuable, where appropriate. Both before and after data, or data showing improvements as a percentage of the original, are essential to allow compilation of summaries across cases.

With more applications coming from outside manufacturing, including the not-for-profit sector, we will need to resort more to *T*, *I* and OE, and softer intangible measures. Reports should also include details on the size of the organisation, and the part(s) in which TOC was employed. The strengths and weaknesses of TOC in its broadest sense, and the intangible effects of its application, should be reported. Notwithstanding the comments earlier about the diversity of TOC applications, there is a need for clearer reporting of which aspects of TOC (thinking, methods, tools, techniques) were employed, if links between methods used and results achieved are to be made.

Both case surveys and surveys of users would be worthwhile sources of information on the performance of TOC. However, even where case reports did include the above data and did provide more information, likely variation in definitions and interpretations would limit the power of the results. A survey of TOC users may be better able to control for such variability, but there is still likely to be some degree of variability in the bases of interpretation.

The links between the TOC and other systems theories are yet to be examined. Multi-methodologies formed by combining TOC with other methods have been popular and will no doubt continue as a research focus. One of most recent of these is The Decalogue: a ten-step method combining Deming's and Goldratt's teachings (Lepore and Cohen, 1999). Other growth areas are project management (critical chain), supply chain management, enterprise resource management, and the application and further development of the TPs to meet new perceived needs. However any such research faces a serious challenge in that it needs to be carefully framed to maximise its currency and to avoid lagging behind the developments continually being made to TOC itself.

Concluding discussion

The TOC has been employed in a range of manufacturing and other organisations for the past 20 years. Over this time, the methodology has developed a dedicated following among those familiar with the approach. The body of literature addressing TOC has accumulated steadily, with over 400 articles and 45 books published on the topic in the last ten years. Our research has indicated that the rate of publication on TOC is steadily increasing. The

literature contains many case studies or case vignettes of the application of TOC to manufacturing organisations. Numerous success stories are reported, but hitherto no overall assessment of the impacts of applying TOC has been available. This research exercise has attempted to address this gap by posing the question of whether TOC provides manufacturing organisations with a source of competitive advantage.

Data gathered using the case survey methodology were used to address the question. Organisations applying TOC and reporting results gained considerable improvements in important performance measures such as lead time, cycle-time, and revenue, indicating that TOC did provide a substantial source of competitive advantage for these organisations.

TOC has evolved and expanded over time. The majority of the applications reported on did not employ the TOC TPs – the systems-thinking-oriented process improvement approach which is now the core of TOC. The advent of the TPs not only broadens the range of applications of TOC, but also broadens the areas of applications. This work suggests that Goldratt's broader TOC methodology can be usefully and effectively applied beyond the manufacturing organisations, that initially inspired the earliest TOC methods and concepts, to the wider commercial and not-for-profit sectors.

Notes

1. Such experimental evidence partially meets the possible criticism of the case survey method that there is no control group.
2. $n = 14$. Both of these were performed with one outlier excluded (the case with an 88 per cent decrease in lead time and a 4 per cent increase in inventory can be seen in Figure 1 to not fit the general pattern).

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