International Journal of Industrial Engineering and Management (IJIEM), Vol. 7 No 1, 2016, pp. 15-23
Available online at www.iim.ftn.uns.ac.rs/ijiem_journal.php
ISSN 2217-2661

UDK: 005.1 658.5

Theory of Constraints (TOC) Production and Manufacturing Performance

Roberto Panizzolo
Associate Professor, University of Padova, Department of Engineering and Management,
Via Venezia, 1 - 35131 Padova, Italy, roberto.panizzolo@unipd.it

Received (16.10.2015.); Revised (28.01.2016.); Accepted (17.02.2016.)

Abstract

This paper is based on an empirical study of the relationship between Theory of Constraints (TOC) production and operational performance in manufacturing plants. The study uses a survey questionnaire to collect data from a sample of 61 European firms which have implemented the TOC approach. Analysis of variance (ANOVA) technique and regression models have been employed to test the research hypotheses. The results detect many differences and similarities in adoption of TOC practices across the countries and suggest that manufacturing managers should consider adopting some TOC practices instead of others. In particular the Drum-buffer-rope methodology, the development of a Master Production Schedule based on constraints and the use of Non-constraint resources with excess capacity are among the most important practices to enhance competitive performance of manufacturing plants.

Key words: *Empirical research, International comparison, Manufacturing Performance, Theory of Constraints*

1. INTRODUCTION

Since the 1980s, Theory of Constraints (TOC) has been a critical theme in operations management research. This theory suggests that improvement in the global performance of organizations may be obtained by focusing on a few leverage points of the system. According to Goldratt [1], the TOC approach recognizes that every organization must be understood as a system with a goal, and so, every action taken by any part of the system must be judged by its impact on the whole system goal. When applied to production processes, TOC describes the idea of identifying and managing the bottlenecks in the manufacturing process and introduces a method of creating a finite production schedule for the bottleneck operations. These approaches for production planning and control area are called Drum-Buffer-Rope and Buffer Management [2] [3] [4].

While many scholars suggested that TOC production significantly impacts organizational performance, there is still little agreement on how to successfully implement TOC production in manufacturing organization. This paper empirically investigates the difference and similarity in the implementation of TOC production practices and their impact on different dimensions of operational performance of manufacturing plants among the countries.

The study is based on the measurement scales concerning with TOC production processes. The data were collected from 61 manufacturing plants located in Spain, United Kingdom, Germany, Italy and France through an extensive questionnaire survey which has been conducted in 2014.

Seven measurement scales have been proposed to measure different aspects of TOC namely 1) *Drum-buffer-rope methodology*, 2) *Time-Buffer Management*, 3) *MRP for optimised schedules*, 4) *Material movement with transfer batches smaller than production batches*, 5) *Master Schedule optimized for constraint resource*, 6) *Non-constraint resources with excess capacity*, and 7) *Backward and forward scheduling*. Using these scales, we investigated the similarity and difference in the adoption the TOC production practices and the effect of this adoption on five dimensions of manufacturing performance: 1) *Manufacturing unit cost*, 2) *Due-date performance*, 3) *Lead-time*, 4) *Inventory level* and 5) *Cycle time*.

Analysis of variance (ANOVA) technique and regression models have been employed to test the hypotheses. The results indicate that the TOC practices are being adopted in different ways across the countries. Some practices such as *Drum-buffer-rope methodology*, *Non-constraint resources with excess capacity*, and *Master Schedule optimized for constraint resource* were found as the most effective approaches to improve manufacturing performances.

The remaining of this paper is organized as follows: firstly, we make a brief literature review of TOC concept; secondly, the analytical research framework is presented; thirdly the research methodology we adopted for data collection, measurement testing and hypothesis testing is described. Finally, the last section discuss the findings and limitations to this research, and give final conclusions.

2. OVERVIEW OF TOC EVOLUTION

In 1979 a manufacturing planning and control system named OPT Optimized Production Timetables was presented by Goldratt [5]. The system was later known under the commercial name of Optimized Production Technology which consists of four major software components: Buildnet, Serve, Split and Opt. Opt and Serve contain the algorithm for scheduling production while Buildnet and Split collect and arrange data in the required format.

The distinguishing attribute of OPT system when compared with the MRPII system is the importance of recognising and managing resources as bottleneck (constraints) and non-bottleneck. Production planning and scheduling in the OPT system is structured around constraints: the organization of data is carried out to efficiently generate master production schedules for bottleneck resources and, based on this constraint schedule, the scheduling algorithm backwards schedules production at non-bottleneck resources and determines the release of non-constraint materials.

From this initial phase, the overall concept gradually moved from the production floor to encompasses all the departments and processes of a company and became later known as the Theory Of Constraints (TOC). As reported in the article of Watson *et al*. [6], the evolution of TOC may be segmented into five eras:

- The Optimized Production Technology Era – the secret algorithm.
- The Goal Era – articulating drum-buffer-rope scheduling;
- The Haystack Syndrome Era – articulating the TOC measures.
- The It's Not Luck Era – thinking processes applied to various topics.
- The Critical Chain Era – TOC project management.

Nowadays TOC is viewed as "an overall theory for running an organisation". A constraint "is anything that limits a system from achieving higher performance versus its goal" [7].

The theory highlights that every system must have at least one constraint. If it were not true, then a real system such as a profit making organisation would make unlimited profit. The main constraints in most organizations may be not only physical but also managerial-policy. However, contrary to conventional thinking, TOC views constraints as positive, not negative as the existence of constraints represents opportunities for improvement. Constraints determine the performance of a system, a gradual elevation of the system's constraints will improve its performance.

To address the constraints and effectively implement the process of on-going improvement, TOC has evolved into a suite of integrated management tools spanning numerous operations management sub-disciplines [8]. Consequently, there has been a huge increase in number of manuscripts published. Most of the books, dissertations, academic articles, magazine articles and conference proceedings on TOC had been written since '90s. This surge of interest in the TOC seems to stem from the potential benefits available from the implementation of TOC practices. From this point of view, to measure an organisation's performance in achieving its main goal, i.e. generate profit, two sets of measurements have been prescribed by Goldratt and Fox [9]:

- operational measurement

  (1) Throughput (T), (2) Inventory (I), (3) Operating expense (OE)
- global (financial) measurements

  (1) Net profit (NP), (2) Return on investment (ROI), (3) Cash flow (CF)

Many authors have investigated the relationships between TOC implementation and firm's performance. In the beginning, these studies were mainly based on personal views rather than facts or research and put into evidence that TOC techniques could result in increased output while decreasing both inventory and cycle time [10] [11] [12]. Subsequently, more accurate scholarly testing proved those early findings revealing that manufacturing systems employing TOC techniques exceed the performance of those using Manufacturing Resource Planning (MRP-II) [13] [14] [15]. These studies showed that TOC systems produce greater levels of output while reducing inventory, manufacturing lead time, and the standard deviation of cycle time. In particular, Noreen *et al*. [16] studied the implementation of TOC to a typical production environment and they stated its capability to quickly yield substantial improvements in operations and in profits.

One of the most interesting work about the relationship between TOC and performance is the article of Mabin and Balderstone entitled "*The performance of the theory of constraints methodology*" [17]. The empirical analysis of a sample of firms showed that TOC adoption lead to a 70% mean reduction in order-to-delivery lead time, a 65% mean reduction in manufacturing cycle time, a 49% mean reduction in inventory, a 63% mean increase in throughput/revenue, a 44% mean improvement in due date performance.

3. RESEARCH FRAMEWORK

The main purpose of this study is twofold. Firstly, we study whether TOC practices are adopted in different ways across firms belonging to some European countries. After having identifying the differences and similarities in the adoption of TOC, we investigate the impact on the performance of manufacturing plants deriving from the adoption of TOC practices. As explained later, this study considers TOC in the narrow view meaning that we refer to a suite of integrated management tools applied to the operations

management/production area only. For this reason, hereafter we will use the term "TOC production".
In order to carry out the study three hypotheses have been established. The first is defined as follows:

H1: There is no difference between TOC production practices across the countries.

In manufacturing firms, TOC could be implemented using a paradigmatic approach or a contingent one. In the first case it is assumed that there is one best way of organising manufacturing based on TOC principles which means adopting a specific set of tools and methodologies. Thus, TOC production should be adopted and implemented in an almost identical similar style across different manufacturing plants. On the other hand, the contingency theory of the firm [18] [19] [20] suggests that every company can design its own TOC production strategy in terms of organisation and management.
The next hypothesis concerns with the linkage between TOC production and performance, i.e TOC production is considered a key determinant for firm's performance. We consider only the operational measures of manufacturing plants, judging unrealistic to analyse the impact on the financial measures in view of the heterogeneity of the sample (firms belonging to different industries and countries). The second hypothesis is defined as:

H2: TOC production practices significantly contribute to manufacturing performance.

The last argument is about the similarity in the impact of TOC practices across the countries. We are not only interested in evaluating whether the adoption of the TOC production practice has an impact on firms' operating performance but even if this impact manifests itself differently among companies belonging to various countries. The third hypothesis is defined as:

H3: There is no difference on the impact of TOC production practices on manufacturing performance across the countries.

In order to test the three hypotheses so far defined, first of all we need to develop appropriate scales measuring different aspects of TOC production.
As said before, although conceived in the 1970s in a manufacturing context as a scheduling algorithm, TOC has then been developed into a powerful and versatile management theory as a suite of theoretical frames, methodologies, techniques and tools. Rahman [21] observed that TOC has two major components. One of these is usually referred to as TOC's logistics/production paradigm which deals with the principle of TOC applied to the operations management area. The starting point are the five focusing steps developed by Goldratt [22] which can be summarised as follow:

1) Identify the system's constraint(s). In the operations management area these may be materials, machines, people, demand level and so on.

2) Decide how to exploit the system's constraint(s). Exploitation of the constraints seeks to achieve the highest rate of throughput possible. This requires to manage non-constraints resources so that they just provide what is needed to match the output of the constrained resources.

3) Subordinate everything else to the above decision. Since the constraints are keeping us from moving toward our goal, all the resources are applied that can assist in breaking them. This means that resource synchronisation with the constraint provides the most effective manner of resource utilisation. Moreover, non-constraint resources must contain productive capacity (capacity to support the constraint throughput) and idle capacity (capacity to protect against system disruptions and capacity not currently needed) [23].

4) Elevate the system's constraint(s). If we continue to work toward breaking a constraint (also called elevating a constraint) at some point the constraint will no longer be a constraint. The constraint will be broken.

5) If in any of the previous steps a constraint is broken, go back to step 1. Do not let inertia become the next constraint. This fifth step recommends to consider TOC a continuous process and remarks that no solution is or correct for all time or in every situation.

If the five steps are the working principle of TOC which provide a focus for a continuous improvement process, the base foundation of TOC's production is the scheduling software called optimised production technology (OPT) which in turn, is grounded on the following nine rules [24]:

- Balance flow, not capacity.
- Level of utilization of a non-bottleneck is determined not by its own potential but by some other constraint in the system.
- Utilization and activation of a resource are not synonymous.
- An hour lost at a bottleneck is an hour lost for the total system.
- An hour saved at a non-bottleneck is just a mirage.
- Bottlenecks govern both throughput and inventory in the system.
- A transfer batch may not, and many times should not, be equal to the process batch.
- The process batch should be variable, not fixed.
- Schedules should be established by looking at all of the constraints simultaneously. Lead times are a result of a schedule and cannot be predetermined.

The effective application of these nine rules is made possible by the DBR methodology and the use of time buffers [3] [24] [25] [26] [27]. Drum-buffer-rope is a manufacturing execution methodology, named for its three components. The *drum* is the physical constraint of the plant: the work centre or machine or operation that limits the ability of the entire system to produce more. The rest of the plant follows the beat of the drum making sure that the drum has work and that anything the drum has processed does not get wasted.

The *buffer* protects the drum from the effects of disruptions at non-constraint resources. Buffers in DBR have time as their unit of measure, rather than quantity of material. This makes the priority system operate strictly based on the time an order is expected to be at the drum. Traditional DBR usually calls for buffers at several points in the system: the constraint (constraints buffers), synchronization points (assembly buffers) and at shipping (shipping buffers) [23]. The use of time buffers as an information system to effectively manage and improve throughput is referred to as buffer management.

The *rope* is the work release mechanism for the plant. Orders are released to the shop floor at one "buffer time" before they are due. Putting work into the system earlier than this buffer time is likely to generate too-high work-in-process and slow down the entire system.

The implementation of the DBR methodology requires significant changes in the general architecture of a manufacturing planning and control system (MPCS). These changes occur at all the three levels (i.e. Front-end, Engine, Back-end) which traditionally shape an MPCS in accordance with the model of Vollmann *et al*. [28].

In particular, at the front-end level, master production scheduling (MPS) in a theory of constraints (TOC) environment requires a different focus and understanding than under classical material requirements planning (MRP) systems. Under TOC, the MPS is shifted to plan the constraint(s). This means that the development of the MPS consists of the following [8]:

- determine the constraint(s) using capacity analysis,
- determine which components are routed across the constraint(s)
- determine production priorities per constraint(s)
- use priorities to build up the MPS so that the constraint(s) is fully exploited
- schedule any items that do not contain components routed across the constraint(s) evenly in the MPS
- develop a material release schedule by back scheduling from the constraint(s) and create the constraint buffer
- develop the shipping schedule by forward scheduling from the constraint(s) and create the shipping buffer.

In summary, the MPS under TOC contains only components routed across the constraint; however, the MPS accounts for all end items in the shipping schedule. There is only one MPS under TOC but it drives a series of subordinate schedules for material release, final assembly and shipping to orchestrate production.

A second important change affects Material Requirements Planning (MRP). Swann [29] in his conceptual contribution entitled "Using MRP for optimised schedules" compares specific components of the TOC and MRP and reports MRP shortcomings in a TOC production environment. While the main objective of TOC is to determine ‘an optimised schedule’, the main objective of MRP is to determine ‘net requirements of the parts and components’. In other words, the MPS is fed into the MRP module for the material requirements calculations. The MRP is thus "reduced" to a simple calculation of requirements for raw materials or for components to be purchased; as a consequence, only purchasing orders, not production orders, are issued. The MRP system does not produce prioritised schedules which are instead generated by the DBR methodology. Thus, a case is made to view "little" MRP as an information system and DBR as a shop floor scheduler.

Moreover, as pointed out by Panizzolo and Garengo [30], the rope mechanism releases material in accordance with the finite schedule at the bottleneck and materials flow through the shop as required to support the bottleneck buffer. Thus, a first-come-first-serve priority often ensures that no orders are delayed. The input of materials into the shop based on usage by the control point assures that work in process inventories and lead times are controlled. In this manner, raw materials are pulled into the shop, not pushed. After being released, materials are processed in a first-come-first-served priority and are pushed between all operations.

Consequently, in a TOC environment the material movement control system can be described as a combination of push/pull logic. More specifically, the downstream operations are finite forward loaded based upon the capacity of the CCR resource. The upstream operations are back scheduled from the CCR.

Starting from the considerations made so far, to test the research hypotheses listed above we propose seven scales measuring different aspects of TOC production as follows:

1) Drum-buffer-rope methodology (DBRM): assesses use of the DBR methodology as it is described in the literature;

2) Time-Buffer Management (TBUM): evaluates whether different time buffers are used to protect the drum from the effects of disruptions at non-constraint resources;

3) MRP for optimised schedules (MRPO): ascertains whether the firm makes use of a modified MRP procedure to determine net requirements of materials;

4) Material movement with transfer batches smaller than production batches (MAMO): measures whether transferring units of product from one process step to another is made in small quantities in order to reduce the time for a batch of parts to get through a system;

5) Non-constraint resources with excess capacity (NCEC): examines if non-constraint equipment has some degree of excess capacity which enables smoother operation of the constraint(s);

6) Master Schedule optimized for constraint resource (MPSO): inquiries if the Master Production Scheduling (MPS) is developed taking into account the constraints;

7) Backward and forward scheduling (BFSC): measures if an hybrid push/pull logic is used to scheduling production.

As regards the impact of TOC practices on the performance of manufacturing plants, this study employs five indicators as follows:

1) Manufacturing Cost (MFCS)
2) Due-Date Performance (DUDP)
3) Lead-time (LETI)
4) Inventory Level (INLE)
5) Cycle Time (CYTI)

Figure 1 illustrates the research framework of the study.

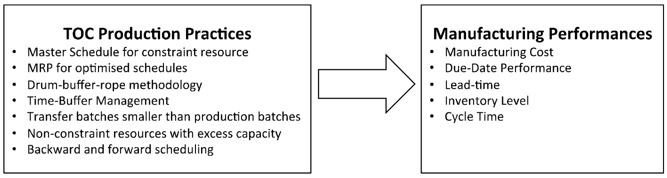

Figure 1. The research framework.

4. DATA COLLECTION AND MEASUREMENT ANALYSIS

This study analyses the data collected from 61 manufacturing plants in Spain (8 plants), United Kingdom (12 plants), Germany (14 plants), Italy (13 plants), and France (14 plants) through an extensive questionnaire survey which has been conducted in the 2012. The plants belong to one of the following industries: aeronautic, electronic, mechanical, machinery, automobile, pressure equipment, textiles and clothing.

In each plant, degree of implementation of TOC practices were evaluated by seven individuals including supervisors, production control manager, production planning manager, inventory manager, supply chain manager, plant manager and controller. The degree of implementation for each TOC practice has been evaluated in seven points Likert scale (1: Strongly disagree, 4: Neither agree nor disagree, 7: Strongly agree).

Finally, the five operational measures of manufacturing plants were subjectively judged by the supply chain manager, plant manager and controller. Each manager was asked to indicate his/her opinion about how the plant compares to its competitors in the same industry on a global basis on a five-point Likert scale (1=Poor or low end of the industry, 2=Below average, 3=Average, 4= Equivalent to competitor, 5=Superior or top of the industry).

The first step of analytical process is the analysis of reliability and validity of seven measurement scales. In this study, Cronbach's alpha coefficient was calculated for each measurement scale to evaluate its reliability.

Table 1 shows that the alpha value for all of the seven scales exceeded the minimum acceptable value of 0.60 for the pooled sample and country-wise samples. Most the scales have alpha values above 0.75, indicating that the scales were internally consistent.

Table 1. Measurement analysis of TOC measurement scales

Measurement Scale	Min.	Max.	Mean	S.D.	Cronbach's alpha	Eigenvalue (Percentage of variance)
Drum-buffer-rope methodology (DBRM)	2.350	6.561	4.552	0.883	.660	2.33 (52)
Time-Buffer Management (TBUM)	1.730	6.450	4.939	0.875	.760	2.43 (58)
MRP for optimised schedules (MRPO)	1.750	6.128	3.302	0.834	.780	2.36 (52)
Material movement with transfer batches smaller than production batches (MAMO)	1.700	6.786	4.386	1.203	.850	2.22 (53)
Nonconstraint resources with excess capacity (NCEC)	3.830	6.450	5.451	0.698	.730	2.50 (47)
Master Schedule for constraint resource (MPSO)	3.575	6.950	4.299	0.732	.740	2.33 (49)
Backward and forward scheduling (BFSC)	3.563	7.330	5.797	0.695	.780	2.85 (55)

As regards construct validity which ensures that all question items in a scale measure the same construct, within-scale factor analysis was conducted with the three criteria: uni-dimensionality, a minimum eigenvalue of 1, and item factor loadings in excess of 0.40. The results of measurement analysis shown in Table 1 prove that all scales have satisfactory construct validity. All of the scales have an eigenvalue of more than two. The factor loadings of question items are more than 0.40, mostly ranged between 0.70 and 0.90.

5. DATA ANALYSIS

Firstly, we examine the country effect on the implementation of TOC production. One-way ANOVA was used to identify the similarities and differences in TOC production practices across the countries. The last two columns of Table 2 show the value of the *F*-statistic and the corresponding significance level. If we set the significance level at 5%, the ANOVA test suggests that all of the TOC practices are significantly different across the countries except MRP for optimised schedules.

Table 2. TOC production practices across countries

Measurement Scale	SPA	UK	GER	FRA	ITA	Pair wise Difference	F	Sig.
DBRM	4.858	4.858	4.003	5.123	4.455	(SPA-GER), (UK-GER), (UK-FRA), (UK-GER), (ITL-FRA)	12.444	.000
TBUM	4.333	4.434	3.564	4.900	4.598	(SPA-GER), (UK-GER), (FRA-GER), (ITL-FRA)	11.556	.000
MRPO	3.899	3.456	3.965	4.200	3.900		1.234	.423
MAMO	4.003	4.765	3.099	5.198	4.189	(SPA-GER), (SPA-FRA), (UK-GER), (UK-FRA), (GER-FRA), (GER-ITL), (FRA-ITL)	35.845	.000
NCEC	5.423	4.834	4.993	5.394	4.864	(UK-FRA), (GER-FRA), (FRA-ITL)	5.043	.002
MPSO	4.544	5.102	4.675	5.102	4.834	(UK-GER), (GER-FRA)	3.789	.005
BFSC	5.456	4.944	5.399	5.206	5.100	(SPA-UK), (UK-GER)	4.205	.001

SPA = Spain; GER = Germany; UK = United Kingdom; ITL = Italy; FRA = France

In addition, Tukey pairwise comparison tests of mean differences were conducted to identify how TOC practices differ between each pair of countries. This comparison detected several important aspects of TOC practices as they are universally adopted in different countries.

The largest difference across the countries exists in *Material movement with transfer batches smaller than production batches* and *Drum-buffer-rope methodology*. Generally, Spanish and French plants exhibit higher scores in every TOC scale than German, Italian, and British plants. German and Italian plants tend to show lower scores than other countries except *Backward and forward scheduling.* French respondents tell that every TOC practice is important. The similarities were found between United Kingdom and Italy and between Spain and France (except *Material movement with transfer batches smaller than production batches*). The results also indicate the most important aspect of TOC production for each country: M*aterial movement with transfer batches smaller than production batches* (Spain, Germany, and Italy)*, Master Schedule optimized for constraint resource* (United Kingdom), *Non-constraint resources with excess capacity* (France). In contrast, *MRP for optimised schedules* was found unpopular to those countries. In summary TOC practices vary widely among countries. Each country evaluated the importance of TOC in different ways. As the result we would like to reject the hypothesis H1 and state that there is significant difference in TOC practices across the countries.

Next, simple correlation coefficients are shown in Table 3 to identify the relationship between TOC production practices and operational performances. Table 3 has 35 cells, each corresponding to a pair of one TOC production practice and one performance indicator. Each cell includes the abbreviated name of the countries for which significant correlation was found between the TOC production practice and the performance indicator. It is found that correlations between TOC practices and performance indicators appear differently across the countries. The TOC practices are considerably connected with high performance at British plants. Setting the significant level at 0.5% as suggested in the literature, the number of pairs of significant correlation for the British sample is 22 out of 35. This number is 9, 5, 6, and 2 for France, Italy, Germany, and Spain respectively.

Table 3. Correlation between TOC production practices and performance

Measurement Scale	Manufacturing Cost	Due Date Performance	Lead-Time	Inventory Level	Cycle-Time
DBRM	UK,FRA	GER,ITL	FRA	UK	UK
TBUM	UK	UK,SPA	UK,FRA	UK	UK
MRPO	FRA	GER,ITL	FRA	UK	
MAMO			ITL,UK	UK	UK
NCEC	UK	GER,UK	GER,ITL,UK,FRA	UK	UK
MPSO	GER,UK,FRA	ITL,SPA	UK	UK	UK
BFSC	GER	FRA	UK,FRA		

SPA = Spain; GER = Germany; UK = United Kingdom; ITL = Italy; FRA = France

In general, TOC practices are more or less associated with every operational performance measure. Especially, every TOC practice significantly correlates with *Manufacturing cost, Due-date Performance*, and *Lead-time* in all of the five countries. In addition, all the TOC practices are significantly related with *Inventory level* and *Cycle time* for the British sample. The most popular TOC practices may be attributed to *Drum-buffer-rope methodology, Non-constraint resources with excess capacity* and *Master Schedule optimized for constraint resource,* while *Material movement with transfer batches smaller than production batches* can be effective in British and Italian plants only. *Lead-time* and *Inventory level* are the performance indicators that are benefited most from adopting TOC practices for the pooled sample, while an evidence of the effect of TOC production on the reduction in *Inventory level* and *Cycle time* can be found for the British sample only.

To better testing the second and third hypotheses, regression analysis was conducted for the pooled sample with utilization of four dummy variables representing four countries: SPA (Spain), GER (Germany), ITL (Italy), and FRA (France). These four dummy variables were include because the effect of country need to be removed before evaluating the impact of TOC production practices on operational performance that can be generalized across countries. Table 4 shows the results. If significant level is set at 5 % by using two-tailed test, the regression results suggest the significant contribution of TOC practices to *Due-date performance*, *Lead-time* and *Inventory level*. They also reveal the significant differences in the determinants of manufacturing performance among five countries.

For example, there are considerable differences in the impact of *MRP for optimised schedules* on *Due-date performance* (between United Kingdom and Italy) and the impact of *Backward and forward scheduling* on *Inventory level* (between Spain and United Kingdom).

Table 4. Regression on the effect of TOC production practices on performance using dummy variables.

	Manufacturing Cost as Dependent Variable	Due Date Performance as Dependent Variable	Lead-Time as Dependent Variable	Inventory Level as Dependent Variable	Cycle Time as Dependent Variable
R^2	0.432	.425	.393	.394	.286
Adjusted R^2	0.123	.225	.218	.149	.023
F and p	1.323 (.075)	1.854 (.020)	2.181 (.004)	1.545 (.046)	1.132 (.403)
df.	144	144	144	144	144
(Constant)	-0.274 0.870	.371 .811	-.635 .632	-.516 .753	.309 .832
SPA	0.211 0.854	-.120 .912	2.363 .027	.180 .873	.001 .999
GER	-0.159 0.896	-.716 .532	1.843 .099	1.117 .348	1.001 .428
FRA	-0.184 0.882	-.046 .969	-.684 .550	.099 .936	.645 .623
ITL	1.668 0.197	-.283 .817	.526 .657	.888 .485	.199 .883
DBRM	0.181 0.593	-.492 .130	.090 .774	.236 .479	-.098 .782
TBUM	0.177 0.625	.745 .032	.494 .142	.326 .359	.432 .256
MRPO	-0.309 0.185	-.195 .378	-.436 .044	-.204 .374	-.181 .458
MAMO	0.551 0.100	.086 .786	.319 .301	.536 .107	.492 .160
NCEC	0.318 0.415	.021 .954	.372 .302	-.013 .973	.280 .495
MPSO	0.117 0.813	.447 .344	.029 .949	.458 .347	.197 .705
BFSC	-0.226 0.364	.069 .772	.087 .706	-.432 .084	-.196 .455
SPA * DBRM	0.088 0.945	.324 .788	-.419 .721	-.009 .994	.193 .884
SPA * TBUM	0.195 0.847	.353 .713	-1.151 .218	-.766 .442	-.136 .897
SPA * MRPO	0.000 1.000	-.130 .799	1.067 .032	-.711 .179	-.146 .791
SPA * MAMO	-0.714 0.266	-.057 .926	-.589 .319	-.199 .752	-.545 .417
SPA * NCEC	-1.833 0.174	-.083 .948	-1.127 .363	.611 .644	.441 .750
SPA * MPSO	0.354 0.804	-.101 .941	.062 .962	-1.615 .250	-.115 .938
SPA * BFSC	1.706 0.117	-.036 .972	-.113 .910	2.905 .008	.365 .745
GER * DBRM	-0.270 0.806	1.615 .125	.043 .966	-.513 .636	-.207 .857
GER * TBUM	-0.226 0.751	-1.313 .055	-.763 .246	-1.235 .080	-1.632 .030
GER * MRPO	0.486 0.374	.789 .131	.500 .322	.639 .237	.730 .204
GER * MAMO	-0.488 0.337	.234 .628	-.843 .074	-.416 .408	-.361 .497
G ER* NCEC	-1.429 0.267	.647 .596	-.048 .968	.141 .911	-.264 .844
GER * MPSO	0.247 0.876	-2.520 .098	-.220 .881	-.291 .852	.403 .809
GER * BFSC	2.399 0.126	1.541 .300	-.112 .938	1.333 .387	.824 .614
FRA * DBRM	1.321 0.435	3.614 .026	1.766 .259	-2.045 .215	-.652 .710
FRA * TBUM	-0.459 0.698	-1.923 .089	.027 .980	1.655 .150	.465 .703
FRA * MRPO	1.565 0.107	.863 .348	1.778 .048	1.435 .137	1.763 .087
FRA * MAMO	-0.478 0.659	-.977 .344	-1.370 .172	.047 .965	.172 .880
FRA * NCEC	-4.022 0.027	-.987 .563	-2.166 .192	-2.230 .224	-1.446 .458
FRA * MPSO	1.073 0.566	-2.777 .120	-2.014 .244	-2.570 .157	-1.350 .485
FRA * BFSC	1.087 0.492	2.350 .120	2.398 .102	3.584 .023	.230 .889
ITL * DBRM	-1.056 0.327	1.157 .264	-.205 .837	-.490 .643	.945 .402
ITL * TBUM	0.289 0.745	-1.422 .093	-.875 .285	-1.076 .219	-1.088 .242
ITL * MRPO	0.314 0.547	1.085 .032	.362 .455	.511 .321	.249 .648
ITL * MAMO	0.150 0.845	.141 .847	.238 .738	-.958 .207	-.588 .465
ITL * NCEC	-0.999 0.361	-.120 .909	-.070 .945	.357 .740	-.395 .729
ITL * MPSO	0.131 0.933	-1.108 .458	.162 .911	-1.066 .486	-1.158 .479
ITL * BFSC	-0.259 0.831	.410 .721	-.223 .842	2.037 .092	1.773 .166

To confirm these findings additional regression analysis have been performed to check whether the coefficients in a particular regression model are the same for the samples of different countries, after dividing the pooled sample into five sub-samples representing each country. We need to compare an estimated regression model including measurement scales as independent variables for the pooled sample with the corresponding model applied for five sub-samples. In doing this no restrictions are imposed on the values of regression coefficients so that they can take different values for different countries. In this way we enable regression coefficients to take different values by an F test [31].

The results of regression analysis of five manufacturing performance indicators are shown in Tables 5, 6, 7, 8, and 9.

Table 5. Impact of TOC production practices on manufacturing cost

	SPA	UK	GER	FRA	ITL	Pooled Sample
R^2	.269	.429	.196	.586	.324	.169
Adjusted R^2	-.016	.263	.009	.405	.062	.127
F and p	.945 (.497)	2.577 (.039)	1.048 (.420)	3.241 (.024)	1.234 (.335)	4.000 (.001)
(Constant)	.285 (.909)	-.235 (.881)	-.560 (.759)	-.670 (.682)	3.585 (.079)	.265 (.709)
DBRM	.180 (.617)	.178 (.577)	.062 (.783)	.560 (.082)	-.305 (.280)	.102 (.397)
TBUM	.176 (.606)	.130 (.621)	.054 (.806)	-.054 (.842)	.273 (.219)	.041 (.685)
MRPO	-.252 (.331)	-.381 (.150)	-.031 (.871)	.414 (.084)	-.138 (.577)	-.090 (.335)
MAMO	.025 (.913)	.407 (.093)	.160 (.399)	.161 (.465)	.499 (.053)	.114 (.239)
NCEC	-.242 (.360)	.298 (.398)	-.189 (.411)	-.965 (.005)	-.124 (.600)	-.106 (.296)
MPSO	.227 (.466)	.098 (.792)	.221 (.349)	.474 (.120)	.167 (.467)	.274 (.007)
BFSC	.314 (.264)	-.188 (.349)	.296 (.230)	.115 (.660)	-.305 (.160)	.159 (.087)
Chow Test: F = 6.487 p=0.000						

Table 6. Impact of TOC production practices on due-date performance

	SPA	UK	GER	FRA	ITL	Pooled Sample
R^2	.529	.225	.369	.454	.413	.162
Adjusted R^2	.345	.008	.221	.215	.197	.120
F and p	2.885 (.033)	1.036 (.432)	2.502 (.038)	1.898 (.137)	1.914 (.123)	3.868 (.001)
(Constant)	.064 (.968)	.676 (.722)	-.595 (.705)	.474 (.799)	-.554 (.794)	.628 (.366)
DBRM	-.366 (.213)	-.424 (.253)	.157 (.434)	.817 (.031)	.019 (.940)	.073 (.542)
TBUM	.781 (.010)	.547 (.079)	.055 (.775)	-.366 (.251)	.030 (.877)	.065 (.517)
MRPO	-.297 (.159)	-.194 (.512)	.233 (.181)	.116 (.658)	.502 (.035)	.121 (.192)
MAMO	.096 (.607)	.080 (.767)	.223 (.188)	-.317 (.217)	.091 (.683)	.044 (.644)
NCEC	.010 (.961)	.003 (.994)	.279 (.174)	-.281 (.421)	-.035 (.867)	.103 (.305)
MPSO	.438 (.090)	.273 (.526)	-.495 (.023)	-.455 (.190)	.120 (.571)	-.027 (.790)
BFSC	.091 (.682)	.056 (.806)	.317 (.150)	.770 (.019)	.127 (.521)	.210 (.025)
Chow Test: F = 8.205 p=0.000						

Table 7. Impact of TOC production practices on lead time

	SPA	UK	GER	FRA	ITL	Pooled Sample
R^2	.088	.477	.336	.669	.289	.223
Adjusted R^2	-.267	.331	.181	.524	.027	.184
F and p	.247 (.967)	3.260 (.013)	2.166 (.067)	4.623 (.005)	1.104 (.400)	5.743 (.000)
(Constant)	3.718 (.025)	-.568 (.668)	2.644 (.045)	-2.006 (.190)	-.080 (.972)	1.355 (.022)
DBRM	-.114 (.776)	.109 (.718)	.142 (.489)	.593 (.043)	.052 (.851)	.156 (.176)
TBUM	-.048 (.899)	.388 (.126)	.157 (.430)	.274 (.270)	.062 (.768)	.023 (.812)
MRPO	.281 (.330)	-.444 (.076)	-.186 (.295)	.307 (.146)	-.245 (.326)	-.085 (.342)
MAMO	-.011 (.967)	.251 (.261)	-.325 (.065)	-.215 (.278)	.235 (.345)	-.175 (.061)
NCEC	-.037 (.899)	.337 (.316)	.462 (.032)	-.263 (.335)	.370 (.123)	.372 (.000)
MPSO	.090 (.795)	-.025 (.943)	-.065 (.762)	-.531 (.057)	.108 (.641)	-.023 (.809)
BFSC	.099 (.748)	.062 (.742)	-.006 (.979)	.614 (.017)	.010 (.965)	.112 (.209)
Chow Test: F = 8.335 p=0.000						

Table 8. Impact of TOC production practices on inventory level

	SPA	UK	GER	FRA	ITL	Pooled Sample
R^2	.347	.564	.158	.377	.224	.096
Adjusted R^2	.093	.437	-.039	.086	-.078	.050
F and p	1.365 (.279)	4.439 (.003)	.803(.592)	1.296 (.317)	.743 (.640)	2.077 (.050)
(Constant)	-.094 (.968)	.055 (.968)	2.454 (.204)	-.070 (.977)	.979 (.600)	.875 (.238)
DBRM	.202 (.554)	.282 (.312)	.111 (.629)	-.234 (.533)	.124 (.678)	.114 (.361)
TBUM	-.091 (.778)	.272 (.233)	-.377 (.100)	.629 (.080)	-.194 (.409)	-.097 (.360)
MRPO	-.553 (.032)	-.209 (.345)	.139 (.484)	.213 (.478)	.136 (.608)	.011 (.908)
MAMO	.323 (.153)	.434 (.045)	.151 (.437)	.260 (.346)	-.118 (.651)	.098 (.333)
NCEC	.170 (.494)	-.043 (.890)	.063 (.788)	-.542 (.172)	.172 (.500)	.099 (.352)
MPSO	-.191 (.516)	.259 (.431)	.326 (.181)	-.286 (.443)	.279 (.260)	.054 (.608)
BFSC	.478 (.080)	-.354 (.053)	-.154 (.538)	.598 (.093)	.113 (.616)	.140 (.151)
Chow Test: F = 8.324 p=0.000						

It is noticed that the significant level for regression coefficients is set at 5% with two-tailed test and that the results of Chow test have been presented at the bottom of each table. The hypothesis H2 is accepted for the pooled sample, the Spanish sample (if taking *Due-date performance* as a dependent variable), the British sample (if taking *Inventory level* as a dependent variable), and the French sample (if taking *Lead-time* as a dependent variable). Because the results from the Chow test show the highly significant level of F statistic, we should reject the hypothesis H3 and state that the determinants of TOC performance are largely different across the countries.

Table 9. Impact of TOC production practices on cycle time

	SPA	UK	GER	FRA	ITL	Pooled Sample
R^2	.233	.319	.344	.127	.171	.121
Adjusted R^2	-.082	.129	.191	-.281	-.151	.076
F and p	.739 (.643)	1.674 (.161)	2.249 (.058)	.311 (.938)	.532 (.799)	2.683 (.012)
(Constant)	.543 (.765)	.692 (.642)	2.446 (.076)	1.805 (.477)	.772 (.711)	1.879 (.003)
DBRM	-.004 (.991)	-.068 (.843)	-.111 (.584)	-.159 (.719)	.292 (.348)	.068 (.584)
TBUM	.211 (.565)	.316 (.269)	-.604 (.004)	.328 (.421)	-.113 (.641)	-.250 (.018)
MRPO	-.267 (.330)	-.230 (.408)	.235 (.186)	.393 (.273)	-.009 (.974)	.080 (.407)
MAMO	.119 (.628)	.354 (.167)	.150 (.381)	.239 (.462)	.072 (.789)	.060 (.551)
NCEC	.395 (.164)	.227 (.551)	.187 (.367)	-.198 (.665)	.102 (.697)	.220 (.036)
MPSO	.127 (.698)	.099 (.805)	.319 (.139)	-.164 (.708)	-.107 (.671)	.115 (.270)
BFSC	-.125 (.669)	-.141 (.512)	-.013 (.952)	-.012 (.977)	.230 (.331)	.017 (.856)
Chow Test: F = 7.333 p=0.000						

6. DISCUSSIONS AND CONCLUSIONS

Seven TOC production measurement scales have been proposed and utilized in this study to test the impact of TOC practices on operational performance. We obtained the mixed results when those TOC practices were compared across five countries. There are two important findings that should be highlighted.

Firstly, statistical analyses indicate that TOC production has been adopted and implemented in different ways. TOC production is relatively important in French and Spanish plants while it is not so important in German and Italian plants. In between those are British plants where TOC production has been adopted earlier than other countries. However, the close connection between high manufacturing performance and TOC practices indicate that British plants are effectively utilizing TOC practices to improve operational performance in term of *Inventory level*. Spanish plants are successful to implement TOC production to improve their *Due-date performance*, while French plants have introduced TOC practices to enhance their *Lead-times*. In contrast, German and Italian cases prove that high manufacturing performance can be achieved by other means rather than TOC production. This indicates that each country should find its own path for improving the performance depending on its specific context and competitive environment. Secondly, this study highlights importance of specific TOC practices. *Drum-buffer-rope methodology*, *Non-constraint resources with excess capacity* and *Master Schedule optimized for constraint resource* are regarded as the most effective approaches to improve manufacturing performance of their plants.

As regards the link between TOC and performance a first interesting finding of the study is that one particular TOC practice can simultaneously associate with several performance indicators. In particular, *Drum-buffer-rope methodology, Master Schedule optimized for constraint resource* and *Time-Buffer Management* are the practices that have an impact on all the different manufacturing performance. A second outcome is that there is difference in the impact of specific TOC practice on performance indicators across countries. This difference may be attribute to the effect of two different set of factors: external factors such as different geography and industry sectors, and internal factors related to number of employees, ownership, manufacturing strategy, level of automation and so on. All these factors would play important roles on the effective implementation of TOC production.

Despite of some limitations in term of sample size and the utilization of subjective performance measures, this study significantly contributes to the literature by providing an empirical evidence for the impact of TOC production on manufacturing performance. The results of a series of statistical analyses support the contingency perspective which suggests that the relationship between TOC practices and plant performance is contingent (dependent) upon the internal and external situation of the firm.

7. REFERENCES

[1] Goldratt, E.M. (1990), The Haystack Syndrome: Sifting Information from the Data Ocean?, North River Press, Croton-on-Hudson, NY.

[2] Goldratt, E.M., Cox, J. (1984), The Goal. North River Press, Croton-on-Hudson, NY.

[3] Umble, M., Srikanth, M.L. (1990), Synchronous Manufacturing: Principles for World Class Excellence, Spectrum Publishing Company, Wallingford, CT.

[4] Stein, R. E. (1996), Reengineering the Manufacturing System: Applying the Theory of Constraints (TOC), Marcel Dekker, New York.

[5] Goldratt, E.M. (1980), “Optimized production timetables: a revolutionary program for industry”, in APICS 23rd Annual International Conference, APICS, Falls Church.

[6] Watson, K. J., Blackstone, J. H., & Gardiner, S. C. (2007), “The evolution of a management philosophy: the theory of constraints”, Journal of Operations Management, Vol. 25, No. 2, pp. 387-402.

[7] Goldratt, E.M. (1988), “Computerized shop floor scheduling”, International Journal of Production Research, Vol. 26, No. 3, pp. 443-55.

[8] Spencer M. S., Cox J. F. (1995), “Master production scheduling development in a theory of constraints environment”, Production & Inventory Management Journal, Vol. 36, No. 1, pp. 8-14.

[9] Goldratt, E. M., Fox, Robert (1986), The Race, North River Press, Croton-on-Hudson, NY.

[10] Aggarwal, S.C. (1985), “MRP, JIT, OPT, FMS?”, Harvard Business Review, Vol. 63 No. 5, pp. 8–16.

[11] Johnson, A. (1986), "MRP? MRP II? OPT? CIM? FMS? JIT? Is any system letter-perfect?", Management Review, Vol. 75, No. 9, pp. 22–27.

[12] Koziol, D.S. (1988), “How the constraint theory improved a job-shop operation”, Management Accounting, Vol. 69, No. 11,pp. 44–49.

[13] Ramsay, M.L., Brown, S., Tabibzadeh, K. (1990), “Push, pull and squeeze shopfloor control with computer simulation”, Industrial Engineering, Vol. 22, No. 2, pp. 39–45.

[14] Fogarty, D.W., Blackstone, J.H., Hoffman, T.R. (1991), Production and Inventory Management, South-Western Publishing Co., Cincinnati, OH.

[15] Cook, D.P. (1994), “A simulation comparison of traditional, JIT, and TOC manufacturing systems in a flow shop with bottlenecks”, Production and Inventory Management Journal, Vol. 35 No. 1, pp. 73–78.

[16] Noreen, E., Smith, D. and Mackey, J. (1995), The Theory of Constraints and Its Implications for Management Accounting, North River Press, Great Barrington, MA.

[17] Mabin, V.J., Balderstone, S.J. (2000), The World of the Theory of Constraints: A Review of the International Literature, St. Lucie Press, Boca Raton.

[18] Lawrence, P., and Lorsch, J. (1967), "Differentiation and Integration in Complex Organizations", Administrative Science Quarterly, Vol. 12, pp. 1-30.

[19] Galbraith, J. R. (1973), Designing Complex Organizations, Reading, MA: Addison-Wesley.

[20] Galbraith, J. R. (1977), Organization Design. Reading, Addison-Wesley, MA.

[21] Rahman, S.U. (1998), “Theory of Constraints: a review of the philosophy and its applications”, International Journal of Operations & Production Management, Vol. 18, No. 4, pp. 336-55.

[22] Goldratt, E.M. (1990b), What is This Thing Called Theory of Constraints and How Should it be Implemented?, North River Press, New York, NY.

[23] Lockamy III, A. and Cox, J. F. (1991), “Using V-A-T analysis for determining the priority and location of JIT manufacturing”, International Journal of Production Research, Vol. 29, pp. 1661-1672.

[24] Goldratt, E.M. and Fox, J. (1986), The Race, North River Press, New York, NY.

[25] Lambrecht, M. and Decaluwe, L. (1988), “JIT and constraint theory: The issue of bottleneck management”, Production and Inventory Management Journal, Vol. 29, No. 3, pp.61–65.

[26] Schragenheim, E. and Ronen, B. (1990), “Drum-Buffer shop floor control”, Production and Inventory Management, Third Quarter, pp. 18-22.

[27] Gardiner, S.C., Blackstone, J.H. Jr and Gardiner, L.R. (1994), “The evolution of the theory of constraints”, Industrial Management, May-June, pp. 13-15.

[28] [28] Vollmann T.E., Berry, W.L. Whybark, D.C. (1997), Manufacturing planning and Control System, Irwin/McGraw-Hill, New York, NY.

[29] [29] Swann, D. (1986), “Using MRP for optimized schedules (emulating OPT)”, Production and Inventory Management, Second Quarter, pp. 30-77.

[30] Panizzolo, R., Garengo, P. (2013), “Using Theory of Constraints to Control Manufacturing Systems: A Conceptual Model”, Industrial Engineering & Management, Vol. 2, No. 111, pp. 2169-0316.

[31] Chow, G. (1960), “Tests of equality between sets of coefficients in two linear regressions”, Econometrica, Vol. 28, pp. 591-605.

Teorija ograničenja (TO) i proizvodne performance

Roberto Panizzolo

Primljen (16.10.2015.); Recenziran (28.01.2016.); Prihvaćen (17.02.2016.)

Apstrakt

Ovaj rad se zasniva na empirijskom istraživanju odnosa između teorija ograničenja (TOC) proizvodnje i operativnih performansi proizvodnih pogona. Istraživačka studija bazirana je anketnom upitniku za prikupljanje podataka od evropskih firmi koje su primenile TO. Broj ispitanih proizvodnih sistema iznosi 61. Takođe, analiza varijanse (ANOVA) i modeli regresije korišteni su za testiranje hipoteze istraživanja. Dobijeni rezultati ukazuju na mnoge razlike i sličnosti u primeni TO u praksi širom EU i ukazuju na to da menadžment proizvodnje treba da razmotri usvoji koje TO prakse može I treba da primeni. Takođe, "Drum-buffer-rope" metodologija, razvoj master plana proizvodnje na osnovu ograničenja i upotreba neograničenih resursa sa viškom kapaciteta, nameću se kao najinteresantnije prakse za poboljšanje konkurentske performanse proizvodnih pogona.

Ključne reči: *Empirijsko istraživanje, Međunarodna poređenja, Proizvodne performanse, Teorija ograničenja.*