
Teaching Theory of Constraints in 10 hours using open-source simulator

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Abstract: In this paper, the use of a graphical simulator called TOCNUN is presented. It helps users to understand plant operations conducted under the philosophy of Theory of Constraints (TOC) developed by Goldratt. TOCNUN is an alternative tool developed to support the teaching of TOC in just six or seven steps, which correspond to six or seven, 90-min learning sessions, including theory. This paper illustrates the structure for practical sessions that should be carried out with the simulator. Finally, validation input from undergraduate students and company managers is presented.

Keywords: engineering learning; Theory of Constraints; simulation-based learning; operation management education.

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1 Introduction

The teaching of operations management (OM) has traditionally been accompanied by learning aids such as games, case studies and simulations. This common practice is based on the concept of learning as a cycle, suggested by Kolb (1984). This theory describes learning as an iterative process of which experimenting and experiencing are an integral part.

Simulation games give the student the opportunity to experience some degree of reality of the subject i.e. being studied (Haapasalo and Hyvönen, 2001), thus helping to complete the learning cycle. Moreover, this experience can be attained without the risk of failure in actual experimental activities (Smeds, 2003) and in a controlled and evaluated scenario.

A significant number of games to teach OM principles have been proposed and, despite the fact that there is no evidence suggesting that simulation games are better learning aids compared with role-playing games or case study exercises (Basnet, 1996), the simulation component seems to give the advantage of ease in data management. Furthermore, simulation provides game registry and clear feedback of results stemming from decisions taken during the simulation. In addition, simulation provides a gaming context. All of these reasons have spurred the use of simulation in many recent games (Lewis and Maylor, 2007), even though most simulation tools continue to be used for various applications other than training and education (Jahangirian et al., 2010, Table 4).

A study by Lewis and Maylor reported that more than 25% of revised games were concerned specifically with aspects of manufacturing production control such as scheduling and inventory management (EOQ, MRP), thereby reflecting an interest in aiding the learning of these subjects. However, there are no reports of any simulation games focused on the Theory of Constraints (TOC – a theory that includes strategies and

tactics for scheduling and inventory management), apart from the original game developed by Goldratt, which must be purchased.

Therefore, while striving for an easily accessible tool for TOC learning, we have developed a simulator along with a plant editor to aid in the teaching of TOC concepts in 10 hr. This simulator and editor package will be presented in this paper along with pilot test results from the simulator.

2 TOC and its simulation software

Proposed by Eliyahu M. Goldratt, TOC recognises that most companies have one resource that limits the capacity (capacity constrained resource (CCR)) of the system to generate the desired outcome. Therefore, proper management of that resource will lead the company to reach its goal (Goldratt, 1993), i.e. maximising its profits. TOC consists of five steps:

- 1 identify system constraints
- 2 decide how to exploit system constraints
- 3 subordinate everything else to that decision
- 4 elevate system constraints
- 5 if constraints are no longer present, go back to step 1.

With the objective of helping companies achieve that goal, Goldratt describes the DBR (Drum-Buffer-Rope) methodology (Goldratt and Fox, 1986), which is the application of TOC to the production function using three procedures to follow these five steps.

TOC is commonly included in OM courses as a stand-alone topic, generally included in the methodologies used for planning and scheduling production. Some books covering OM (Chase and Aquilano, 1995; Dominguez et al., 1995) even have a complete chapter dedicated to this theory.

Considering the previously explained topics, the Goldratt Institute developed a MS-DOS-based simulator called Selfsim (Goldratt, 1996) to aid in the understanding of TOC concepts. This simulator was later updated to a more graphical and easy-to-use tool (Goldratt, 2003).

However, these tools were developed with longer courses in mind, which are not ideal for company managers who usually demand shorter training times. Furthermore, Goldratt's simulator did not include an option to create customised plant models, which could help the instructor to partially simulate the company's manufacturing process.

In the beginning of 2007, a group at Tecnun, supported by the local government (Diputacion Foral de Gipuzkoa), decided to develop a didactical open-source simulator based on the experience acquired from the use of Goldratt's simulator since 1996. The use of the simulator can be complemented by watching Goldratt's film based on the book.

2.1 The goal

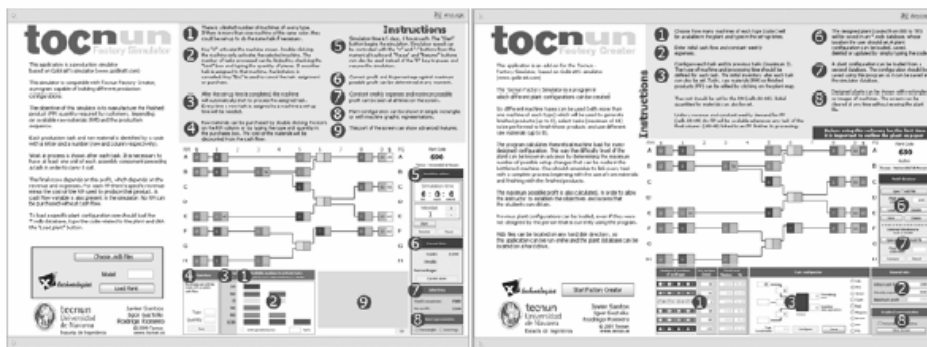
The premises used to build this tool were the following:

- it is important to have a measure to compare performance among participants
- the graphic interface should be improved by adding mouse interactivity
- it should be easily and freely accessible to everyone, without the need to install specific software on the user's end
- some simulator features that are not used in practice will not be included, such as process batch, variable processing times or machine breakdowns
- an easy interface to load data to the simulator should be considered, including a Microsoft Excel connection
- the simulator should be supported by an application capable of easily and graphically developing and sharing customised models of production plants.

The resulting project was named TOCNUN (Figure 1), which delivered two different applications: the simulator (TOCNUN Factory Simulator) and the production plant editor (TOCNUN Factory Creator).

Before building this tool, it was decided that both applications were to be available via the internet and the best developing language to use was Java because of its support of graphical and internet features. Therefore, both applications were developed in the Java 1.6 programming language using Anylogic software (Borshchev and Filippov, 2004), an application used to develop simulation models and transform them into web applets. Anylogic was chosen based on three reasons: the ease of acquiring an educational license to use the software, the development platform that supports it (Open Source Eclipse) and the possibility of using a visual development environment.

Figure 1 TOCNUN Factory Simulator presentation screen



3 TOCNUN Factory Simulator

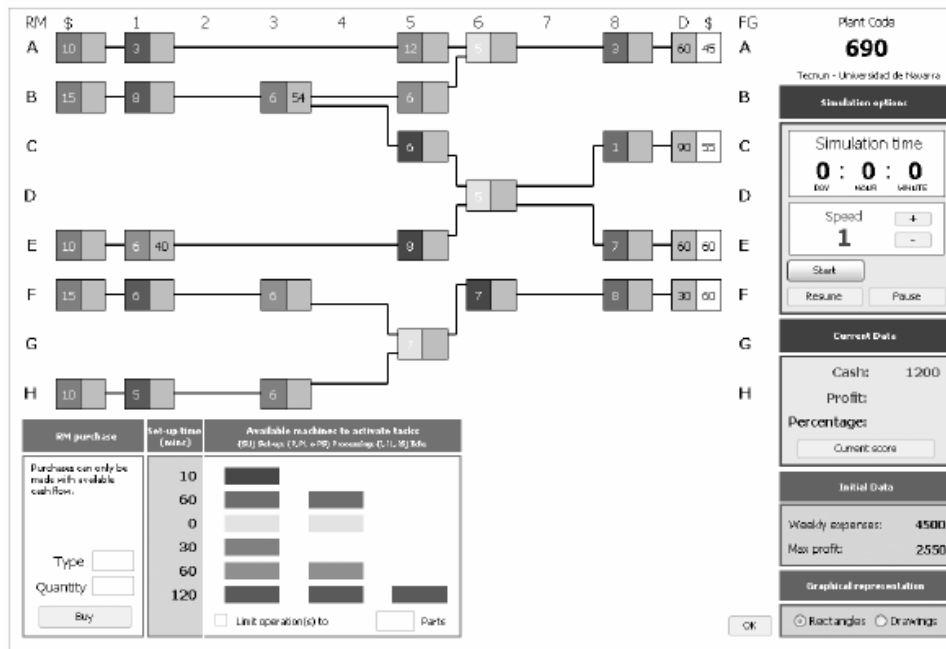
With the TOCNUN Factory Simulator, students are able to graphically view how their decisions affect the total profit of a production run and can also recognise the importance of the correct use of the CCR. The simulator is able to either control machinery in real time or set processing sequences beforehand from a Microsoft Excel input. The basic instructions of the software are described in Appendix A.

Figure 2 shows the main screen of the simulator. The objective is twofold: to produce the quantity of finished products (FP) required by customers dependant on available raw materials (RM) and with the specific task routing for the FP and to obtain the best possible profit in the simulation trial. The basic instructions of the software are described in Appendix B.

The grids are labelled with letters and numbers in order to locate tasks and RM. The number on each coloured square represents the processing time of the task.

The work in process inventory is shown in a grey square just after the coloured square. At least one unit of all required components must be used in a task in order to start it. A score is tracked and depends on the total profit, which is the revenue generated by the FP minus the cost of purchased RM and constant weekly expenses. The cost of each raw material is shown in the dark grey squares next to the RM column.

Figure 2 TOCNUN Factory Simulator main screen



4 TOCNUN Factory Creator

TOCNUN Factory Creator allows for the design of different plant configurations with options for various RM and FP. Processing and setup times and initial stock levels can also be customised. It includes the common save and load feature of any desired configuration.

The plant editor (Figure 3) allows the user to design a plant with up to six different types of machines (with a maximum of three machines of the same type/colour) employed to process the different operations needed to complete different FP (maximum of eight) with an option for various types of raw material purchases (limited to eight).

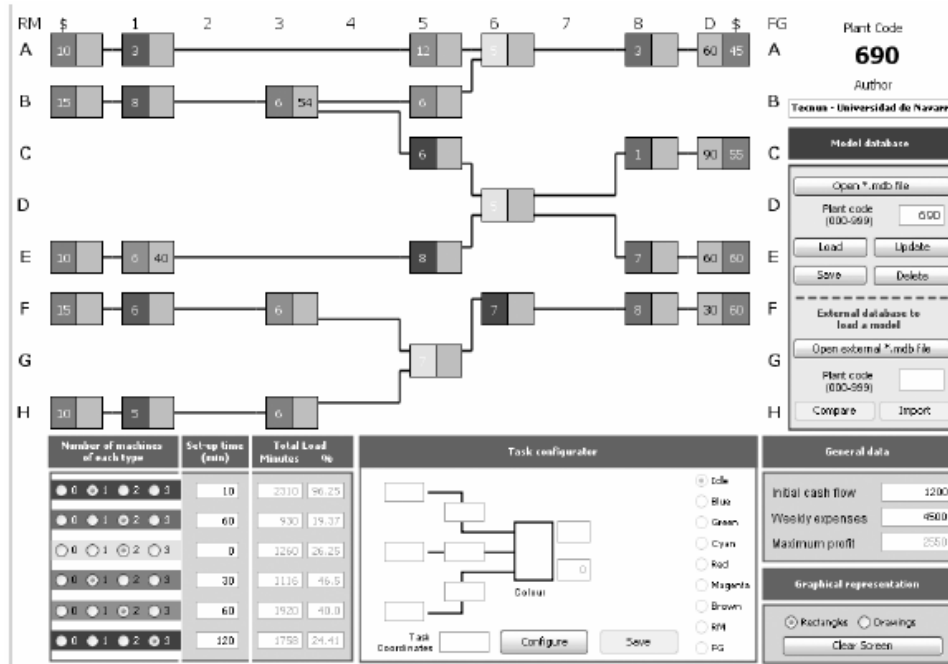
The program calculates the load of every machine with every plant configuration. This allows for the difficulty level of the plant to be known in advance by recognising the maximum number of set-ups that can be made before exceeding CCR capacity. Special attention should be paid to the completion of the fabrication route and all RM and FP should be accounted for.

This application also has the feature of calculating the maximum possible profit that can be reached with the designed plant, a feature that allows knowing beforehand which objectives are attainable when simulating a production run with the created configuration.

Moreover, plant configurations created by other people can be loaded in the program to be modified and added to the plant library. The simulator includes the name of the plant designer. Microsoft Access databases are used to support this characteristic.

These databases can be saved on any computer, allowing the use of a web application of the editor and simulator but with local files containing plant configurations.

Figure 3 TOCNUN Factory Creator main screen



5 Use of the simulator by instructors

Five, 1.5-hr sessions, (including a short theoretical explanation) followed by a final evaluation session, will be used to teach TOC. Based on our experience with Selfsim, we feel that simulations should be performed with pairs of students.

Since the objective of this development is to teach TOC, and not simulate real plant conditions, there is no option for variability in the processing time or machine breakdowns.

5.1 Step 1 Using intuition

In this session, there is no time to think about strategy. The simulation plant is number 100. The company produces three different products with different levels of demand and income. Students usually fail to realise that there is not enough capacity to produce the weekly demand. The basic instructions of the software for this test-run appear on the presentation screen (Figure 1) and are described in Appendix A.

A brief simulation is carried out during the first 15 min of the trial run in order to get accustomed to the program's interface. This is followed by a full simulation which will be evaluated depending on the profit obtained.

During the theoretical explanation included in the session, the concepts of capacity, TOC and CCR are presented as well as the possible problems that can arise.

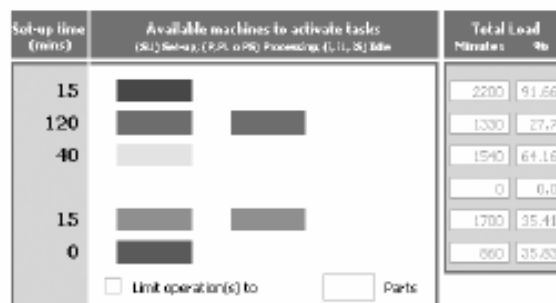
5.2 Step 2 Taking capacity into account

At the beginning of the trial run, a review of the first two steps of TOC is given as well as the methods to identify the CCR. Since not all resources are equally important, the resource with the highest workload must be recognised.

To prevent students from investing too much time in calculating resource capacities, an option has been created in the program that shows actual workloads of every machine of the simulated plant configuration, depending on work in process inventory. This option can be accessed by pressing the 'Q' key (Figure 4).

In this simulation, students will attempt to reduce the idle time of the CCR. This is an important run because students will learn the importance of focusing on just one resource to establish the scheduling program, resulting in improved results.

Figure 4 Machine workload according to simulated plant configuration



5.3 Step 3 Decide the product mix

During this activity, students will try to avoid CCR idleness by deciding the best way to exploit such machine. To achieve the aforementioned objective, a minimum number of set ups should be set because the total load in the CCR is higher than the available capacity.

On the other hand, students must decide the product whose demand will not be completely fulfilled due to the lack of capacity. Students usually decide to reduce the production of the cheaper product in terms of benefit. The plan is prepared to teach another Goldratt concept: the most profitable product is the one which offers a better relationship between incomes and use of CCR (quotient between product profit and time required in the CCR).

It should be expected that the results will be better compared to the second exercise. However, because a local strategy has been followed, the maximum possible profit will not be reached without paying attention to the time required in the CCR to produce each final product.

5.4 Step 4 Assuring component availability

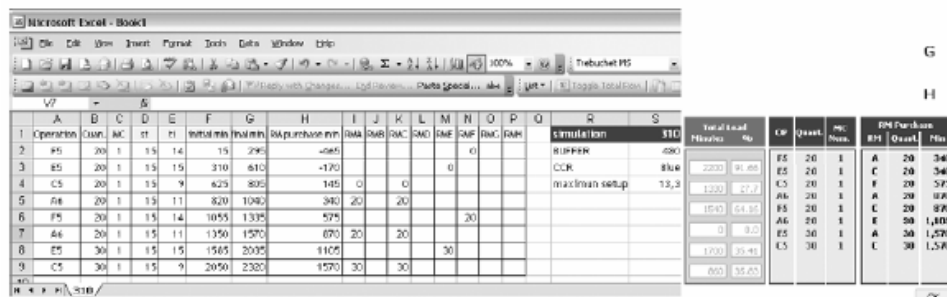
The DBR methodology, following the recommendation made in step three of TOC, suggests creating a time buffer to support constant work for the CCR. A possible cause that could prevent students from reaching the maximum profit is that, although they were concentrated on the CCR capacity and its management, materials needed for process operations in the CCR were not available or could not arrive to that resource on time. Another possible explanation could be that material purchases have not been made in a timely fashion or have been totally forgotten.

Therefore, material releases (raw material purchases) should be planned in advance to cover a time buffer of 8 hr (or a complete working day) for the CCR.

These calculations should be done using the Microsoft Excel template provided with the TOCNUN Factory Simulator (Figure 5) so that, once the sequences and required purchases have been determined, the data can be loaded into the simulator by pressing the 'Y' key. The simulator is able to define the sequence of each machine, but it is recommended that just the sequence of the CCR be established.

After this simulation, the results obtained should reach the maximum possible profit if the students decide to produce the most profitable product according to the time required for the CCR.

Figure 5 Simulator integration with Microsoft Excel



5.5 Step 5 Increasing capacity and using acquired knowledge

Steps 4 and 5 of TOC seek to increase the capacity of the CCR once it has been correctly managed. A new plant configuration with the same productive structure as that previously used will be loaded in order to grasp the concepts of these steps (Figure 6), such that the original CCR is no longer constrained and that the complete process must be executed again. In the example given in this paper, a new Type 1 machine has been added (Type 1 machine is located in the first row in Figure 4).

To facilitate learning, it is recommended that the new CCR only be one resource. The strategy proposed in Excel should include more than the minimum number of set ups.

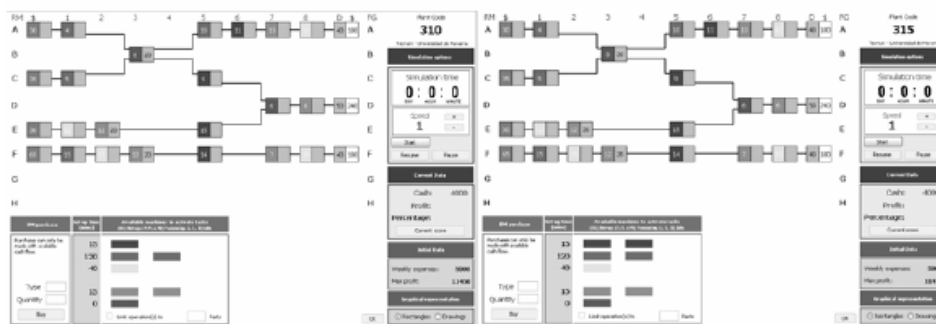
This run usually takes less time than others and students frequently end the run before time while achieving maximum profit. In those cases, plant number 118 is prepared, where product demand has increased. In this case, it is possible to increase profit up to 15%, according to Goldratt's film.

At the end of this fifth step, students will be able to repeat all the previously learned methods with one of the several defined plant configurations in the simulator, a number that could increase if students voluntarily design new configurations.

5.6 Step 6 Evaluation test

The instructor will load an unpublished plant configuration to assess student learning. A possible evaluation grade could depend on the percentage of profit obtained by the student out of the maximum possible profit for that plant model. After instantly receiving their grades upon the end of the simulation, the pair of students could choose to run another simulation or accept (partially or totally) the grade obtained with the previous simulation. With this option, the negotiation skills of the students are encouraged, which can turn these practices into a personal challenge for the practitioners. This final step can be eliminated in professional courses where grades are not necessary.

Figure 6 Plant configurations number 100 and 115 prepared to follow the suggested practices in this paper



6 Validation in undergraduate and professional courses

The proposed steps were validated through two different courses:

The first course, for professionals, was conducted in March 2009. About 12 students attended the two-day training course. Most of the attendants were production or logistics managers.

The second validation took place during a regular course in the Industrial Engineering undergraduate program at Tecnun. The course included 44 students and the TOC was explained over the course of six classes (as described in this paper). This validation study includes the data only for the student pairs who attended every class.

Tables 1 and 2 summarise the results from the pairs according to the first five simulations, which correspond to the same structure laid out previously.

Tables 1 and 2 show how the average value grows from simulation to simulation, despite the fact that some student pairs reduce, rather than increase, their profit during consecutive simulations. It is worth noting that the theoretical maximum profit in simulations 1–4 is 18,075 while in simulation 5 it jumps to 21,600 due to the increase in capacity.

TOCNUN was initially developed in Spanish and published on the internet at the end of 2008. To date, 15 universities (from Spain, Argentina, México, Colombia, Peru, Ecuador and Bolivia) are studying the possibility of including TOCNUN in their classes. This demonstrates how easy it is for instructors to use the simulator as a learning tool.

Table 1 Professional results

<i>Professionals</i>	<i>Sim 1</i>	<i>Sim 2</i>	<i>Sim 3</i>	<i>Sim 4</i>	<i>Sim 5</i>
1	11,235	13,965	16,665	17,140	21,600
2	750	10,030	15,750	16,195	–
3	15,975	16,395	1,590	18,075	21,600
4	9,970	12,660	13,610	13,140	20,795
5	6,880	11,220	16,565	14,550	20,385
6	7,500	14,635	15,375	14,550	9,100
<i>Average</i>	<i>8,718</i>	<i>13,151</i>	<i>13,259</i>	<i>15,608</i>	<i>18,696</i>

Table 2 Student results

<i>Students</i>	<i>Sim 1</i>	<i>Sim 2</i>	<i>Sim 3</i>	<i>Sim 4</i>	<i>Sim 5</i>
1	10,670	13,100	5,400	14,280	16,805
2	10,865	11,220	13,700	17,605	21,600
3	4,945	7,500	13,385	12,200	21,600
4	14,550	15,975	16,900	18,075	21,600
5	13,176	14,635	14,558	17,605	21,600
6	17,550	11,235	15,725	18,075	21,600
7	11,005	13,610	15,725	14,550	21,600
8	14,850	13,140	15,255	17,605	21,600

Table 2 Student results (continued)

<i>Students</i>	<i>Sim 1</i>	<i>Sim 2</i>	<i>Sim 3</i>	<i>Sim 4</i>	<i>Sim 5</i>
9	8,715	13,610	16,665	15,255	21,600
10	15,725	16,395	16,665	17,605	21,600
11	14,550	15,975	13,845	16,900	21,600
12	14,475	15,975	13,845	16,195	20,790
13	9,065	9,970	15,255	17,605	21,600
14	16,375	15,750	16,900	17,840	21,600
15	4,015	7,500	11,260	17,605	21,600
16	12,435	13,965	16,195	17,840	21,600
17	9,470	9,100	16,665	17,605	21,600
<i>Average</i>	<i>11,908</i>	<i>12,862</i>	<i>14,585</i>	<i>16,732</i>	<i>21,270</i>

7 Conclusions

The TOCNUN Factory Simulator and Creator achieve their objective: to teach the TOC methodology in a manufacturing plant in a practical and simple manner. It is a very useful tool for instructors because it can simulate many different situations that could be faced in a plant. Since it has been developed using educational software licenses, this application can be used and published for free.

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Appendix A

Basic TOCNUN simulator instructions

The simulator allows one to include up to six types of machines and three machines for each type (18 machines). If there is more than one machine of the same type (colour) they could be used to process the same task.

Pressing the 'A' key of the keyboard accesses the machine control screen (Figure A1). Double clicking a machine-coloured square lets the user input the desired task to be processed in that machine after pressing the 'Enter' key.

The total quantity of products processed in a set task can be limited by checking the option 'Limit' and writing the number of products that should be processed. If the task processed by that machine is changed, the limitation is cancelled. The 'ESC' key cancels raw material purchases and machine activation.

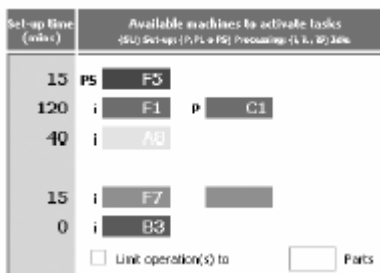
Each machine will start to process the required products after the setup time (showed on the left part of the machine control screen) is completed. While the machine is being set-up, it will be tagged 'SU'. A setup time will be required for every time a different task is assigned to a machine.

While the machine is processing a task it will be tagged 'P', 'PL' if the number of products to process is limited and 'PS' if the sequence has been previously planned and set. In the case that not all components for the task are available, either an 'i', 'iL' or 'iS' will appear to show the inactive state of the resource.

RM can be purchased by pressing the 'M' key and typing the material type and quantity, or by clicking the specific material in the graphical representation of the plant and typing the required quantity. When a purchase is made, cash flow is accordingly reduced in the simulation.

Simulation time lasts one week (Five 8-hr days). The 'Start' button starts the simulation. Simulation speed can be controlled with the '+' and '-' buttons or with the '+' and '-' keys of the numerical keyboard. Pausing the simulation can be done with the button 'Pause-resume' or with the 'P' key.

Figure A1 Screenshot of the machine control screen



The maximum possible profit for the simulation week can be determined at any moment, as well as the actual percentage of profit attained, along with weekly expenses.

Appendix B

Basic TOCNUN Creator instructions

Initially, the number of machine types should be chosen as well as their setup time. It would be also convenient to enter constant weekly expenses and initial cash flow at this stage.

Next, all operations should be defined by setting their preceding operations (limited to three), the machine type that will process them and their processing time. The number of finished jobs for each operation can be set as work-in-process inventory. Such jobs can be used initially by the machine processing the subsequent task in the product route. The row-column location of the operation can be written in the text box labelled 'Task configuration' or the plant configuration map can be clicked to activate the operation (or raw material or finished product) to be configured.

A price should be set for raw materials (locations A0–H0). An initial raw material inventory can be established. Weekly demand and unitary revenue should be defined for final products (A9–H9). Column 8 (cells A8–H8) should always be attached to a finished product belonging to the same row.

Designed plants (coded from 000 to 999) should be saved in a Microsoft Access file, which should be loaded every time the editor is started. A plant design can be loaded, saved, deleted or updated by simply using the plant code. A plant from another database can also be imported. If it is saved, however, it will be recorded in the default database.