Utilization of System Dynamics for Comparing Traditional and O.P.T. Production Systems

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Abstract

In the study presented here we have modelled a firm with various production sections managed along traditional lines. We also include in the model the structural changes necessary for the company to be managed according to OPT. It is possible to work with the two philosophies alternately. We have thus created a tool which allows us to check the validity of the various basic rules from which professor Goldratt works in developing his theory, and also to stablishs its strengths and/or possible weaknesses for different business situations.

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1. INTRODUCTION

The study presented here falls within one of the principal lines of research of the University of Seville's G.I.D.E.A.O group, which aims to improve our knowledge of, and training in, the various aspects and problems associated with Business Management, taking advantage of the new possibilities the use of computers offers in research and training processes. Within this line we devote particular attention to aspects connected with the production subsystem of firms, where recent decades have witnessed the development of new methods such as MRP and the Japanese "Just in Time" philosophy, which have clearly contributed towards improving the results obtained in this subsystem within the overall management of a firm and securing competitive advantages for it.

So much so, that this last approach sparked off a real revolution in Japanese businesses, in reducing to the minimum the level of in-plant inventories and achieving high-quality, low-price products, leading western businesses to witness an invasion of Japanese products which they feared would threaten their own market share. The most recent production planning and control method is that known as OPT, which aims, according to its creator, E. Goldratt, to ensure that western countries do not lose the competivity race and become second-rate powers. This method, based principally on balancing the production flow and on management focussed on *bottle-neck* resources, is being successfully applied in numerous western firms, achieving results which can be described as spectacular. We thus find a decrease in stocks of 75% in General Motors, 40% in Bendix France, etc. Moreover, these results are usually accompanied by significant increases in output (15% in M&M), reduced production time and, correspondingly, shortened delivery deadlines (Wheatley, 1986), etc.

The fact that OPT is the most recent theory, and perhaps the least well-known in the teaching sphere, and also that its workings are deliberately "hidden" to a great extent, prompted us to consider as a research objective the generation of an instrument which would not only enable us to establish the validity of its basic principles but would also be of use in the teaching of these principles.

Within GIDEAO, this instrument takes the form of the generation of business models and games developed by means of systems dynamics. As we have explained on previous occasions (Machuca J.A.D., Machuca M.A.D., Ruiz A., Ruiz J.C., 1993) we are convinced that these models and games retain the advantages of the methods used up until now in Business Management training, that is **traditional teaching, the case method and traditional black-box business games**, but they go a long way towards correcting their drawbacks.

The present paper is a brief summary of a research project that has been carried out over two years (Ruiz A., Machuca J.A.D., Machuca M.A.D., 1994).

2. AIMS OF THE RESEARCH

The aims pursued in our project can be summarized as follows:

* to carry out a theoretical study and generate a model, using systems dynamics, which would make it possible to establish the validity of the basic principles of the OPT theory.
* to construct a training tool which, by permitting different situations to be simulated, would increase the degree of motivation and learning which could be achieved starting from a purely theoretical position.

However, having started the research we realized that the fact that some of the basic rules of the OPT theory referred to behaviour observable in firms run under a traditional approach imposed upon us a preliminary phase of **creating a model that would represent a classically-managed production system** and would resemble this business reality as closely as possible. Throughout this paper we shall refer to this model as the Basic Model (in addition to the model's aim of permitting comparison, we considered the possibility that it should exist in its own right, thus making it easier to understand the general workings of a traditional production system). Once both models had been generated they were used to try out different policies, observing the effect that each of these had on the future behaviour of the models' principal variables. In addition, detailed comparisons have been carried out between the behaviour observed in the two models, obtaining various conclusions and lessons on the modes of management they represent.

3. DEVELOPMENT OF THE MODELS

We will begin by briefly describing the theoretical business, run in the classic manner, which will serve as a basis for the development of the Basic Model and which we will later transform in order to accommodate it to an OPT line of management.

3.1. The Basic Model

3.1.1.-Production sections structure.- As can be seen in figure 1, the firm was designed with four sections, the last one devoted to assembly tasks. This design will later enable us to observe all the possible relationships which, following the OPT approach, can be established between "bottleneck" and "non-bottleneck" sections. Moreover, in itself it involves greater complexity than the majority of production models that are generally used in business simulation models, which normally have just one section or, at most, a number of sections linked by a single line.

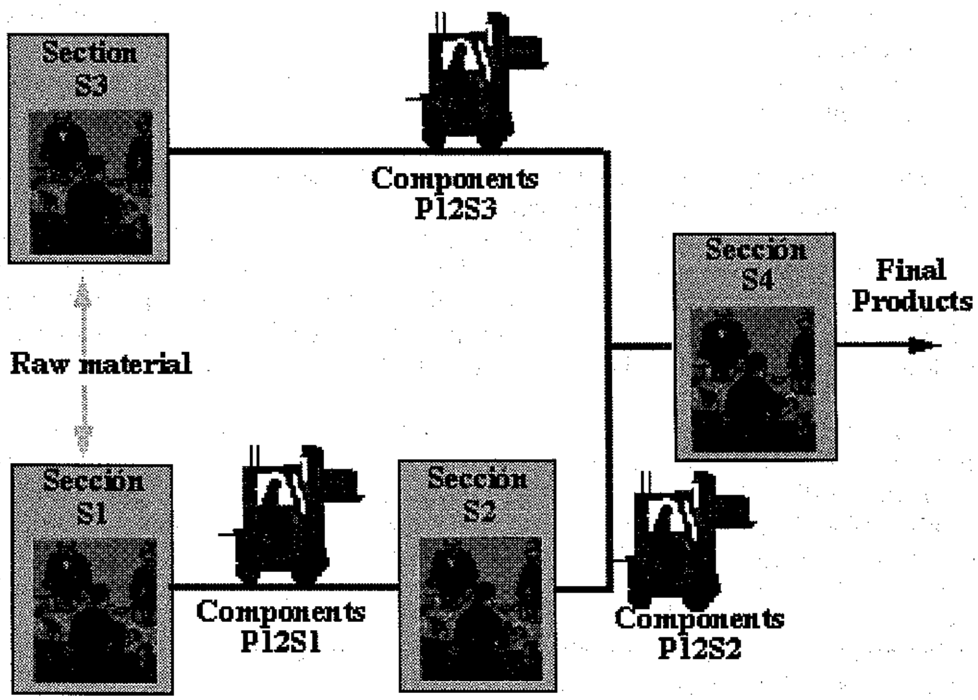

Figure 1. Scheme of Production Subsystem.

3.1.2.-Production planning.- It is possible to simulate different types of demand, which is transformed by a process of adjustment into a certain value of **expected Orders**. Working from this basis and taking the example of section S4, which bases its planning process on establishing the desired production for the following period, this production being calculated as the sum of two components: **expected Orders + Inventory correction.** With the second element the aim is to adjust the possible differences between the value of the section's actual inventory and the desired security stock.Once the desired production level for certain products is known, this figure is used to calculate the requirements of components to be supplied by the other sections.

3.1.3.-The production process.- We would stress that the modelling process has resulted in the design of a set of versatile equations, in the sense that it not only allows a certain type of continuous production to be represented, but also the main characteristics of batch production.

3.1.4.- Labour.- We have studied all processes connected with the hired labour force, focussing on its possible modifications and its effect on the capacity of the firm. For the system of hiring and firing we have created a set of equations which will enable us to detect any imbalance in manpower and we have detailed the correction process. The main characteristic of this set of equations is its flexibility when factors such as the following are considered:

* We have assumed that the manager or decision-maker can give himself a certain time, *during which continual imbalances in manpower are occurring*, before adopting a final decision on hiring or laying-off.
* For certain reasons, whether purely managerial or legal, the decision-maker might not apply his decision to hire or lay off to the total labour imbalance diagnosed, but only to a certain percentage.
* We have also tried to be consistent with reality in introducing a delay between the instant when a hiring decision is made and the moment when the workers are fully active in their section (administrative formalities and training process). The same thing happens in the case of dismissals (legal requirements concerning notice).
* The model incorporates the possibility of working overtime, which is subject to a series of restrictions and is also flexible, since it can be manipulated by the user:
    • We have assumed that there is a trade union presence in the firm, as a result of which, and by means of collective negotiation, the working of overtime is restricted.
    • The second limitation is defined by legal considerations, which can be assumed to prevent overtime being worked beyond a certain annual limit.

3.1.5.- Production capacity: Standard capacity in each of the sections is calculated as the lowest figure defined by either the production permitted by the work-force or the availability of equipment. To this standard capacity is added the capacity achieved through overtime to determine the real capacity of the section. In addition, in an attempt to reflect a traditional policy in many western firms, we have assumed that the total available capacity will be used, with the idea of achieving hypothetically high performances. Accordingly, in our Basic Model the production flow of any given section is equal to the real capacity available.

3.1.6- The market: Discontinuity in the stocks of finished products involves the loss of a certain percentage of demand. We are aware that this aspect, penalization by the market when demand is not fully satisfied, may in reality be subject to great variations. This reason prompted us to create a set of variables which makes it possible, through changes in the parameters included in the model, to test a great variety of situations, for instance:

* markets with varying degrees of sensitivity to disruption in stockouts of finished products.
* market reactions of varying rapidity to poor customer service.
* differing possibilities concerning the recovery of lost demand.

3.1.7.- Financial aspects: Although our research was focussed on areas concerning the production subsystem of firms, we felt it appropriate to include certain elements which would allow us to analyse a number of financial consequences of the various steps or policies tried out on any of our models. In particular, we have included a figure for "operating margin", calculated on the difference between income from sales and all the costs resulting merely from production tasks. To complement the description offered, we include, by way of example, the simplified causal loop diagram for section S4 (see figure 2). In our study we have carefully analysed, in the structure of the firm represented, certain feedback loops which we assumed to be of key importance in understanding the behaviour of the Basic Model (Ruiz, A., Machuca, J.A.D., Machuca, M.A.D., 1994).

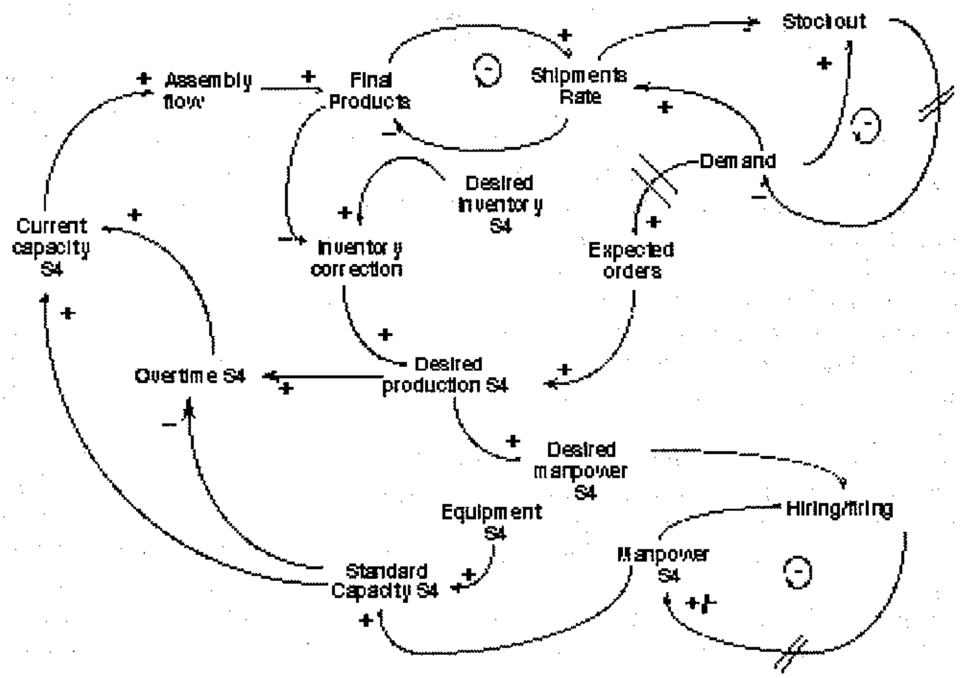

Figure 2: Causal loop diagram for section S4.

3.2.- Changes introduced to obtain the OPT Model

Once the Basic Model had been conceptualized and developed, we had to make the appropriate changes to adapt its working to an OPT management model. These changes involved converting into equations the principles set out in the now-famous basic rules of OPT, which we repeat here (E.Goldratt, 1986 and 1989):

* Balance the flow, not capacity.
* Constraints determine *nonbottleneck* utilization.
* Activation is not always equal to utilization.
* An hour lost at a *bottleneck* is an hour lost for the Entire System.
* An hour saved at a *non-bottleneck* is a mirage.
* *Bottleneck* govern throughput and inventory.
* Transfer batch should not always equal a process batch.
* Process batches should be variable, not fixed.
* Set the Schedule by examining all the constraints simultaneously.

First of all we had to **define a new situation for the balancing of the production plant in the OPT Model**, since it was obvious from the first of its rules that it could not be the same as the situation designed for the Basic Model, in which the capacity of each section was balanced with demand. The solution proposed by E.Goldratt corresponds to the concept of "unbalanced plant" (E.Goldratt, 1981): in relation to market demand, the various sections must be allotted excess capacity, which will be all the greater the nearer it is to the end of the production process. In order to introduce this solution in our OPT model we created a series of variables termed **Buffer capacity percentage**, with which the user can decide, with great flexibility, the **ideal initial capacity** of the different sections or else the capacity towards which each of them should subsequently aim, again bearing in mind the previous recommendations.

In addition, given that **OPT bases the management of the production subsystem on the existence of bottlenecks**, a system was designed to detect this situation in the structure of the firm modelled. This took the form of a set of equations which enable the possible *bottlenecks* to be identified, whether they are within the firm itself or exterior (the result of demand). Besides, given the advantages that could foreseeably be obtained from an early determining of the limitations of the system, mechanisms were designed to give warning that a specific section will soon form a *bottleneck*; this last aspect is limited to certain controllable situations like a deliberate change of capacity, where such planning is possible.

Once we were familiar with the basic principles of the OPT theory and had established the system to identify the *bottlenecks*, we were in a position to introduce the changes which would affect the business modelled as a result of the complete **introduction of DBR** which, as is well known, is the alternative system of production programming and control advocated by the OPT theory and which consists of three elements: the drum, the buffer and the rope.

As regards **the drum**, the need for it stems from the conviction that it is *bottleneck* resources that define the capacity of the whole production plant, and that therefore our principle must be that of balancing the production flow of *non-bottleneck* resources with the real capacity able to be developed by the saturated resource; this will work like a drum, marking the rhythm of production scheduling. The formulation of this variable consisted in making it coincide with the value of the real capacity of the bottleneck resource which held at any given moment in the structure of the business being modelled.

Given that, in spite of the introduction of the drum, the system may not work if the other production resources attempt to obtain maximum individual performance ignoring the sound of the drum, Goldratt proposes a second element: **the rope**, with which the entry of raw materials into the production system is tied to the *bottleneck* element; in other words, no more raw materials will be introduced than are necessary to maintain the production determined by the *bottleneck*, thus avoiding the temptation to produce more than is needed in those resources with excess capacity. The introduction of the rope into the model was a little more complicated than that of the drum, since the existence of *floating bottlenecks* had been introduced into our model. Thus, if we assume that section S2 is the only saturated resource in our firm, it is clear that in order to work according to the DBR system, the entry of raw materials from sections S1 and S3 must be "tied" to S2 (see figure 1), formulating the entry of raw material as equalling the amount necessary to cover real capacity. But if section S3 were to become a bottleneck in place of S2, the ties on the raw materials would have to be changed and linked now with the capacity of S3. This prompted us to create a **multifunctional rope**, for which we generated the variable **real system capacity** which, taken as the smallest of the real capacities of each section, always coincides with the value of the capacity of the *bottleneck*. In this way, if we limit the entry of raw material from the different sections in accordance with the value adopted by this variable, we can be sure that the rope will always work, preventing the sections in question from processing more components than are needed.

As regards the third element, **the buffer**, it consists in placing a series of security stocks in certain key places in the production process (more precisely, before the *bottlenecks* and the assembly sections which use their parts). The *bottleneck* resource can thus always be guaranteed to work at full capacity, and its parts used immediately in the assembly section. The formulation of this aspect for each of the sections is carried out by answering two basic questions: in the first place, In what circumstances should there be security stock in the section being examined?, and secondly, What should the volume of such stock be? If, for instance, we analyse section S1 (see figure 1), the answer to the first question will be that section S1 should only maintain security stock when the *bottleneck* is located in section S2. As for its volume, we knew that it had to be such that the work of the bottleneck at full capacity would always be guaranteed. In order to formulate it, we had to work through the following steps:

* We created the variables **Maximum disruption S1 MP**. These reflect the maximum number of periods that, according to estimates, any disruption may last, from the point when raw materials are delivered to the moment when the components produced by section S1 are obtained.
* The number of cover periods desired, **Cov Periods S1**, was made to coincide with the value of the variable **Maximum disruption S1 MP** in those cases where it was necessary to maintain security stock in section S1.
* Finally, we formulated the equation of security stock required by section S1 as **Sec stock requ S1 = real cap sys * Cov Periods S1**. With the above formulation we can be assured that even at worst, if the supply from S1 and S2 were zero, the *bottleneck* would continue to function.

4.- SENSITIVITY ANALYSIS

Once the formulation stage was over we carried out the **analysis and evaluation of the models developed**, in an attempt to establish whether their behaviour was consistent with the system dynamics hypotheses incorporated, and thus have data to work on when determining their validity in representing real behaviour. As a preliminary validating instrument a wide-ranging **sensitivity analysis** was carried out, with the following aims:

a.- To establish the influence which varying values of their parameters might exert on the behaviour of the models; to this end we extended the analysis to cover all the parameters present in their structures.

b.- To deepen our knowledge of the system, submitting the parameters to extensive variations.

c.- To increase our understanding of the relationship between the structure and behaviour of the system; here, we related the behaviour observed with that expected on the basis of the relationships established in the causal loop diagrams. Given the scope of the analysis and the great quantity of data obtained, we shall only mention here those conclusions we judge to be most significant since, among other things, they help in validating the models developed, coinciding as they do with models from other studies or with actual experience (Ruiz A., Machuca J.A.D., Machuca M.A.D., 1994, chapters 4 and 8):

- Delays present in the structure of the system give rise to phenomena which oscillate in their behaviour, but they can be mitigated by incorporating negative feed-back loops of a lesser order
- Attempts to take intense corrective action when there are discrepancies between the objectives and manpower or inventory related results lead to the opposite of the desired effect, giving rise to more oscillations and worse financial results. If the corrective steps taken are less drastic, they improve the results obtained, contrary to what might be assumed intuitively.
- There is an inverse relationship between the volume of stocks held in the plant and the economic results obtained.
- A clear connection has been established between any test improvement in productivity figures and the achievement of better results.

The first two observations coincide with the results of other studies, such as the classic "Causes of oscillations" by J.Sterman (D-33721, System Dynamics Group) or the Beer Game. The other two observations are absolutely realistic.

5.- REACTIONS OF THE MODELS TO INCREASE AND DECREASE IN DEMAND

As a **second phase in the validation** of the models developed and in improving our knowledge of the system, we analysed their behaviour in response to possible variations in demand. Specifically, with a *sudden increase in demand* of ten percent, the most significant reactions observed were the following:

* In both models the firm had to fall back on their reserve stocks in order to avoid stockouts.
* An increase in demand led to the desired production of the different sections increasing gradually, which produced an expansion of their capacity. Use was made of overtime; however, the **amount of overtime worked in the OPT Model was significantly lower** due to the overcapacity with which this model worked in each section.
* Subsequently, when the rise in demand was confirmed as being stable, the different sections went on to *increase* their *staff*. However, the behaviour observed was completely different in the two models: in the **Basic Model the adjustment was carried out by an oscillatory process** because of the presence of delaying factors in the structure of the system, which led to periods when manpower was greater or less than necessary. On the other hand, the manner in which the **OPT Model** carried out this process was **progressive** and **not in the least oscillatory** due to the action of the rope on the manpower negative feed-back loop.
* **In the OPT Model, a closer correspondence** was observed **between the desired inventories** in the different sections **and those actually held,** with no great accumulation of unnecessary stocks, as in the Basic Model. This, in conjunction with the

different conception of security stocks in the two forms of management represented, meant that throughout the simulation of **the OPT Model maintained an overall inventory** of approximately **75% less that of the Basic Model**

* Finally, **as regards the financial results** we should stress that at the end of the simulation the operating margin of the Basic Model stabilized above the rate that had been normal before the increase in demand, with an increase of over 10.5%, to be more exact. As for **the OPT Model**, it **maintained** at all times **a favourable differential with respect to the Basic Model, being around 7%** .

For a *sudden decrease in demand* of ten percent, the following significant behaviour was observed:

* In both models there was the logical drop in sales.
* Again, the behaviour observed was completely different: **in the Basic Model,** corresponding perfectly to a possible real situation, **inventories were well above the desired levels.** Two main reasons can be given for this accumulation of stocks: first, the hypothesis by which any available capacity is fully used and, secondly, the delays inherent to the process of capacity adjustment. As a result, all personnel are kept in production tasks until there is a staff restructuring. **With the OPT Model, this accumulation was practically insignificant.** Having analysed the causes of this difference, we established that they were due precisely to the incorporation into the structure of the recommendation to balance the flow of production and not capacity, which makes it possible, among other things:
    • to make a rapid adjustment to the volume of production in the new *bottleneck,* without incurring as a result unnecessary stock accumulation, while offering a rapid response to the immediate environment.
    • to avoid oscillatory phenomena by short-circuiting the labour regulation loop.
* In relation to this last aspect, the **OPT Model** carried out the process of **staff restructuring in a stable manner,** while **in the Basic Model oscillatory phenomena were again observed,** due to the delays inherent in the structure; this held up the process of achieving a new balance and also increased the costs involved.
* The **OPT Model showed better financial results in the face of falls in demand,** since it incurred lower maintenance costs and because, by making the labour adjustments in a stable manner, there was no need to bear the costs of overtime or new hiring, etc., which resulted in an operating margin clearly higher than the Basic Model throughout the simulation.

To conclude our comments about the validation of the models, we would stress that, in general, the results achieved for the Basic Model have, in our view, been logical and expected and that they therefore helped to increase our confidence in the model's capacity to simulate real behaviour. As far as the OPT Model is concerned, the behaviour observed is consistent with the hypotheses built into the OPT approach (balancing of production flow and not of capacity, a different approach to security stocks, a different outlook on labour, etc...), thus also helping to strengthen our confidence in its ability to represent behaviour characteristic of a system run under this approach.

6.-SIMULATION

After satisfactorily concluding the stage of model validation, we went on to check the new rules of OPT on them. Since we do not have the space here to show the method of verification, we shall limit ourselves to giving a **brief** idea of how we achieved the arguments which made it possible. The process used was always the same: creating a reference situation with which to check, on the Basic Model, the occurrence of those events envisaged by the rules of OPT, and subsequently submitting the OPT model to the same situation and immediately comparing the results obtained. To illustrate this, we shall mention the process which enabled the validation of the **sixth rule of OPT,** which maintains that it is the *bottlenecks* that determine the inventories and throughput of a firm. The reference situation created for this purpose can be resumed in the following points:

* Negotiation of the collective agreement on working conditions gives rise to labour problems in section S2 during part of March and April.
* In June there is a machinery breakdown in section S4, reducing its capacity.

* In August a new production method is introduced in section S3, which achieves an increase in the productivity of its workers.
* At the end of the year there is another machinery breakdown in section S4.

In the results obtained it can be seen that the standard capacity of each of the sections is clearly affected by the events listed above (see figure 3).

* Stock accumulation in section S1 corresponds to the times when section S2 constituted a bottleneck (see figure 4) ; this happened because the section continued to use its full capacity in production tasks while the flow of consumption decreased (see figure 5).
* Sales are affected by *bottlenecks* when security stocks run out (see figure 6).

After this type of analysis in all the sections, and in different situations, we established that in all of them there was a clear relationship between the existence of *bottlenecks* and stock accumulation phenomena, while the latter also had a decisive influence on the quantity sold.

Applying the reference situation mentioned to the OPT Model, we can see that the behaviour generated by it is completely different; fewer stocks are accumulated, due to the fact that at all times the production flow of the different sections equals the capacity of the different bottlenecks appearing in the structure of the firm (see figure 5, 7 y 8).

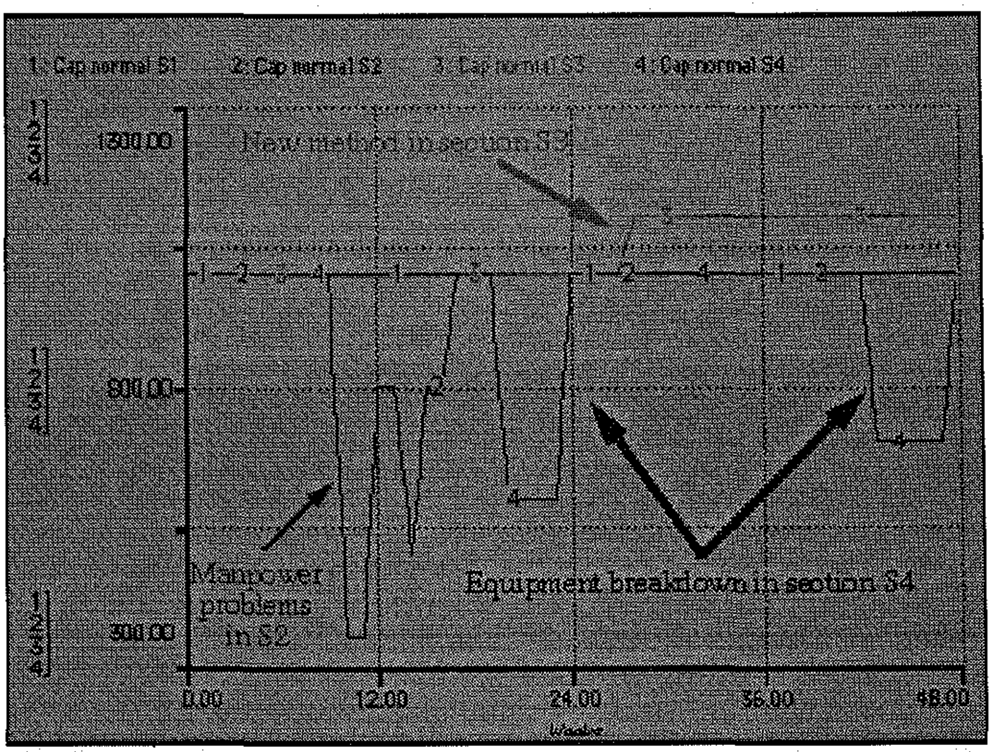

Figure 3: 1, 2 ,3 ,4: Standard cap. S1, S2, S3, S4

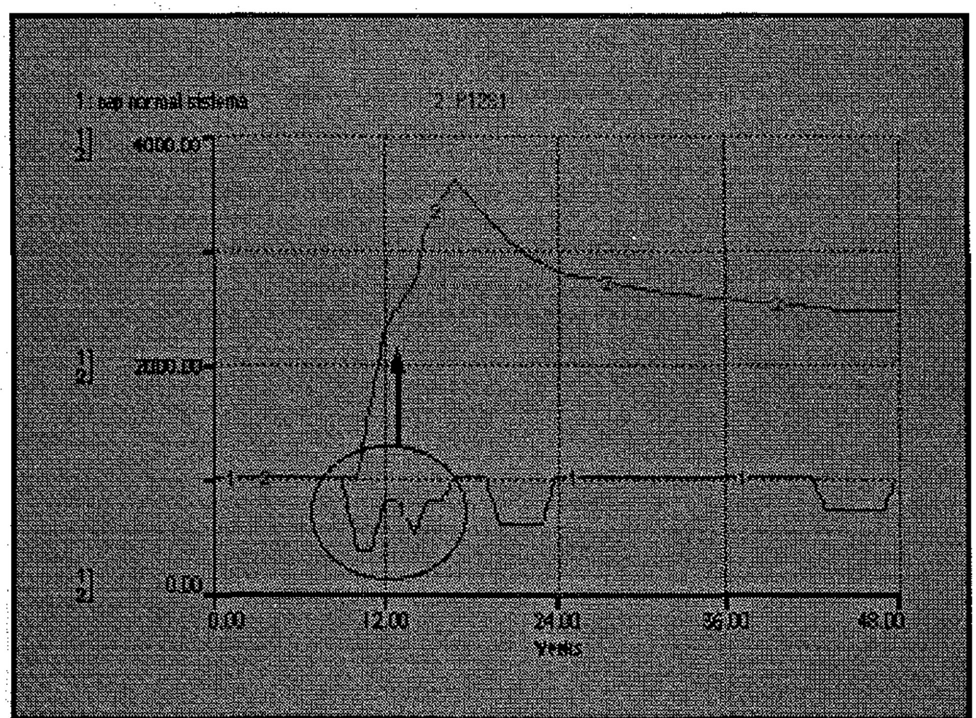

Figure 4: 1: Standard system capacity; 2: P12S1

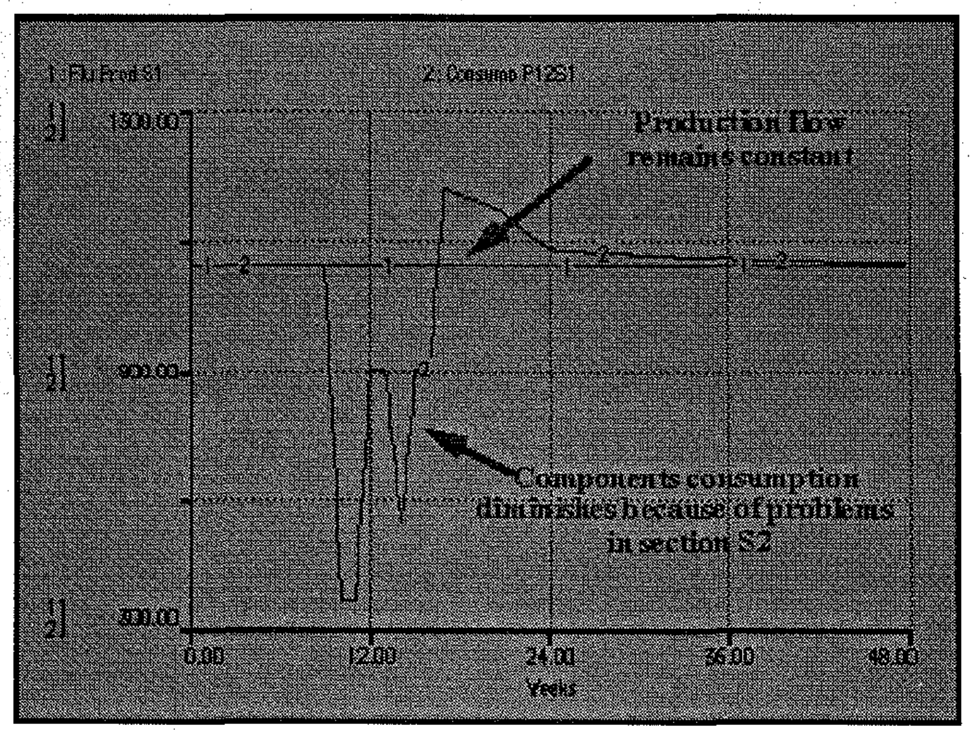

Figure 5: 1: S1 Prod. Flow; 2: P12S1 Consumption

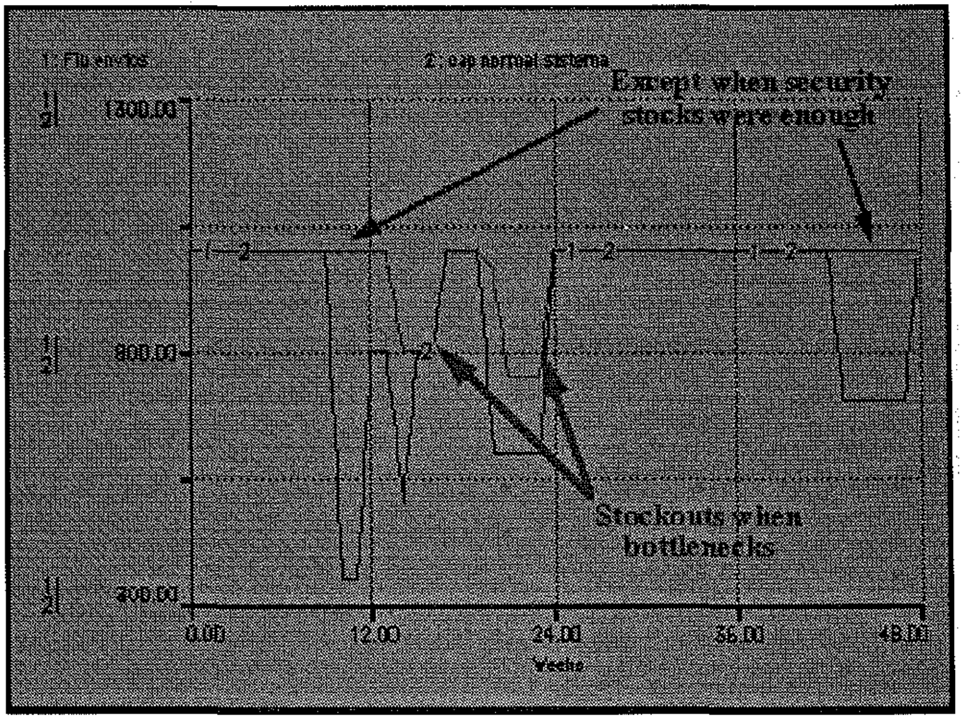

Figure 6: 1: Shipments; 2: Standard system capacity

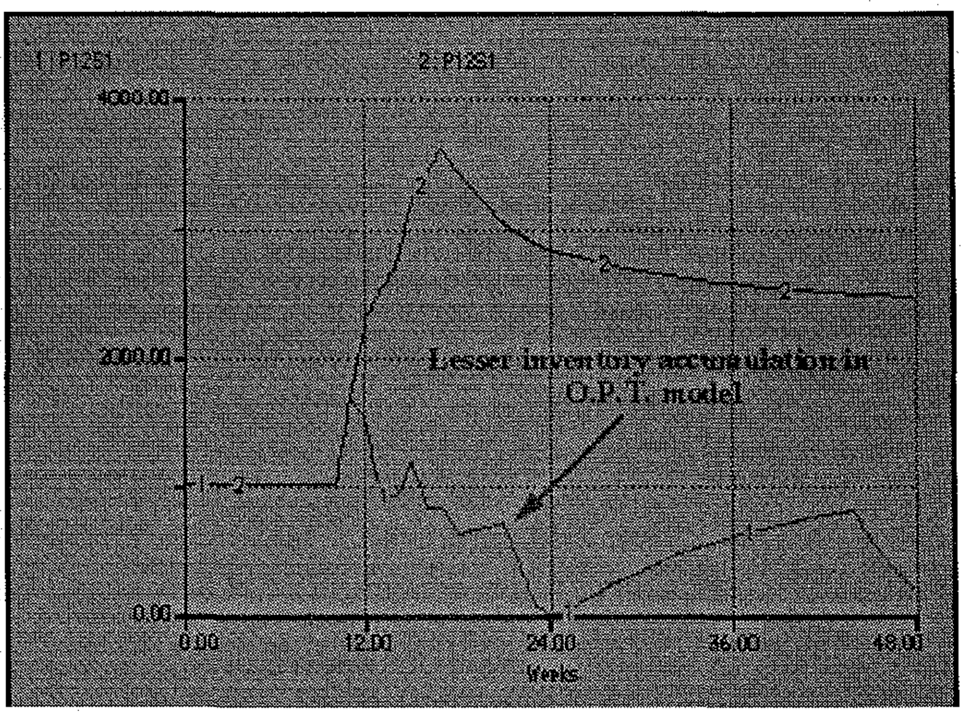

Figure 7.

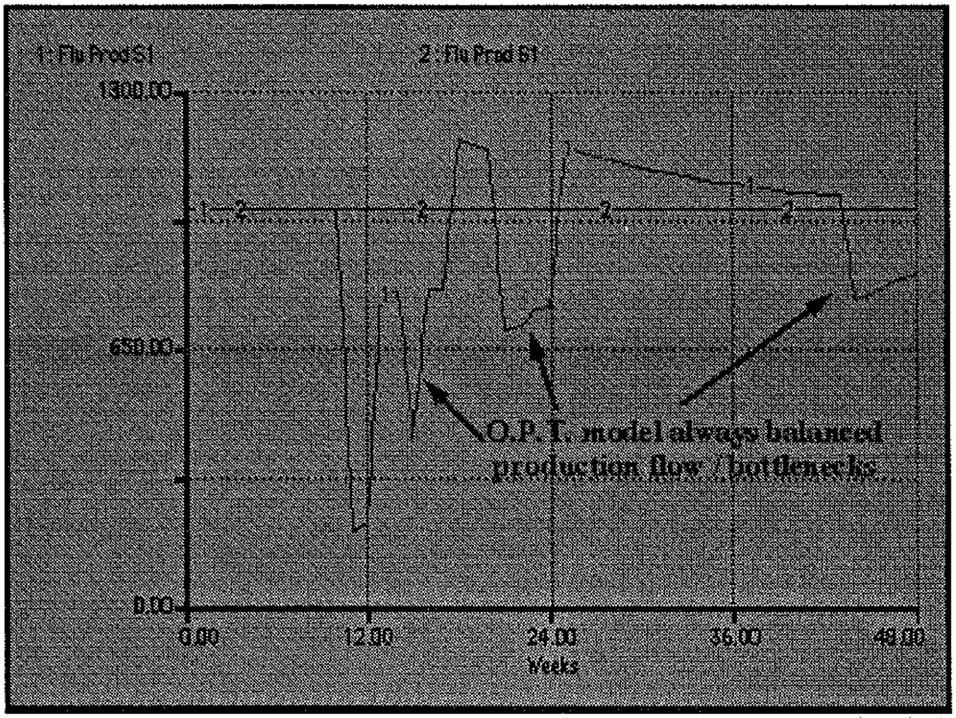

Figure 8: 1:Prod. flow S1; 2: Prod. flow S2

CONCLUSIONS

In this presentation of conclusions we shall only emphasize some of those contained in our research:

1.- The Basic Model reflects the main characteristics of a traditionally-managed production system.

2.- The OPT Model is valid for representing the most important qualitative behaviour of a production system managed following this approach.

3.- Simulations carried out with the Basic Model confirm that its behaviour is determined by their internal structure. This conclusion was reinforced by the fact that the changes brought about in the structure of the system for the introduction of OPT gave rise to behaviour that was characteristic and different from that previously observed for the Basic Model.

4.- Since the results obtained from the various simulations carried out, as well as from the respective sensitivity analyses, proved satisfactory, they have served to increase our confidence in the models developed as being representative of reality.

5.- Both models match the ideas of substance, simplicity, transparency and flexibility with which we began the modelling process. In addition, because of the characteristics of the software used, they clearly go beyond the "ceteris paribus" qualification. In this sense we consider both to be suitable for use in training processes, either in System Dynamics modelling or in the teaching of the OPT approach.

6.- From the simulations carried out on the OPT Model the validity of each of its basic rules can be inferred for the cases under study.

7.- The theoretical study on which our research is based and the results we have obtained enable us to state that OPT methodology represents a systemic and integrated approach for the running of the production subsystem in particular and for the firm in general. This approach is one of the fundamental reasons for the better results obtained by the OPT Model.

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