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Capacitated Material Requirements Planning considering Delivery Constraints*

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1. Introduction

In 1977, was published what is claimed to be the first paper in English on the principles of the Toyota Production System (Sugimori et al., 1977) The authors of that paper stated the basic production planning levels that a supply chain using a JIT approach is requiring. On the same paper Sugimori and his colleagues stated that the use of computer systems for organizing production logistics would introduce unnecessary cost and uncertainty.

As the overall production system has become more complicated, and the Information Systems Technology has improved its performance and reduce the cost, the usual lean practices are converging into hybrid production systems (Riezebos et al., 2009). Many Lean companies now use ERP/MRP methods to communicate demand through the supply chain and hybrid situations have become common within the automotive industry.

And this is the basis of the following case study. Traditional MRP methods, only consider the availability of materials when organizing demands, ignoring factors such as capacity limits and alternative configurations.(Chern y Hsieh, 2007). Supply Chain Planning in JIT environments, such as the automotive sector, requires not only the consideration the material and resources planning but also the consideration of alternative Bill of Materials with minimizing the transportation cost by utilizing at maximum each transport system. (Feischmann et al., 2005).

Operations Planning at these Supply Chains is a core activity but it is usually performed in a human-supported and distributed manner. To centralize and automate this activity large mathematical models must be used and complicated heuristic algorithms must be applied to the process(Erenguç et al., 1999). Such problems are so large that usually they must be split into several submodels. (Kreipl y Pinedo, 2004)

A number of papers have dealt with portions of the problem. Due to space limitations of this abstract a large state of the art is not presented and we refer, as an example, to (Mula et al., 2008). The specific characteristics of considering delivery constraints have been considered in a number of papers such as (Hernández et al., 2008), (Sarker y Diponegoro, 2009).

This paper proposes a MILP model that deals with the issues extracted from a real problem. The model has been developed, tested and implemented at an engine factory. The paper also states some general considerations from the real case where it has been implemented.

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The remainder of the paper will be organized as follows. The next section points out the problem from the operations perspective of the factory. Then a MILP model to manage with the problem has been created and is described in section three. The fourth section is devoted to the Information System where the model has been implemented and finally a set of conclusions are provided. And further research topics are presented.

2. Problem Statement

2.1. The Product and the clients.

An internal combustion engine is an assembly product, composed of a variety of components that are manufactured and assembled in an assembly line (Wang y Sarker, 2005). Although there are many other parts that are also assembled in the final product, the most relevant components are cylinder blocks, cylinder heads, crankshafts, connecting rods and camshafts (known as 5C's).

The main clients of an engine assembly line are the car assembly lines. The cost of backlogging those clients is very high since without an engine the car cannot be assembled. Other clients of the engine plant are mainly Spare Part Distribution systems. and customized car builders (among those the R+D departments). These clients hold very low demand and their backlogging costs are not that expensive.

In order to be stored and transported, engines have to be placed on expensive and specific racks. They have to be carefully prepared for transport, and in a standard container about a maximum of 150 engines can be transported.

Components can also be sold elsewhere. The main external clients are other engine plants and the Part Spare Operations System. The same criteria applies to them.

Depending on the product and on the clients, the shipping can be done by truck or by ship using a FTL strategy. Such strategy implies the consideration of what has been named as Negative Backlogs.

2.2. The Production Process and the supply base.

The engine assembly line is a mixed model assembly line. The component lines did not evolve from the multi-model assembly line concept, and there setup costs are very relevant.

The raw material for each one of the five main components is bought directly from different foundries with long lead times. The transformation process is quite complex and highly automated and so is usually located close to an engine assembly line.

The supply that a simple engine plant requires has to consider not only the foundries that deliver the five units that are the raw material for the 5C lines, but also some plastic components and other subassemblies. Some of the suppliers are local, but in other cases, the transit time goes to more than 10 weeks, due to the use of global suppliers for some components, (for instance, Mexico to serve to a Spanish factory, with a lead time of 8-10 weeks). Those times can be unreliable due to customs, shipping transport and so on.

2.3. Operations Planning Process. The infrastructure

The plant level decisions are related mainly with the flow of raw material, semi-finished and finished products. They have to plan flows inside the plant, but also to and from the whole network. Those operational decisions are easily modified in the short term, even changing decisions that have been taken on the upper level, such as the transportation mode (Cordeau et al., 2006).

Since the engine is an assembled product, it seems clear that traditional production planning methods, such as material requirement planning (MRP), will be useful. However over the years it has been claimed that the application of Lean principles and the use of IT are incompatible (Riezebos et al., 2009).

Traditional production planning methods, such as material requirement planning (MRP), consider only the availability of materials when organising demands. They totally ignore factors such as capacity limits and supply chain configurations. For this reason, MRP cannot provide feasible production plans. To cope with these challenges, advance planning and scheduling (APS) methods were developed (Chern y Hsieh, 2007).

But nowadays most automakers and their suppliers are still working in a manual and decentralized way. Each user gets from the ERP the demand requested from clients, copies it into a personalized excel type spreadsheet, and creates a new production plan. Then delivers back to the ERP system its new proposal. That procedure is repeated on each level.

If on a given level a problem arises with the requirements, it is communicated with the upper level to see if something can be changed on the requirements.

That negotiation effort will work both backwards and forwards once a plan is considered feasible it is transmitted to the people that are closer to the factory problems, that will try to adapt the plan to the shorter term, considering more constraints, and information that it is not available to everyone. Since the process requires too much effort to work with on a daily basis, it has evolved to a once per week plan with daily minor updates.

In the case studied On Monday a four week plan is released trying to freeze the first two weeks. During the week reality is becoming apparent, and minor adjustments have to be done, continually checking the fulfilment of strong constraints, such as material availability. The system is driven trying to reach the plan as soon as possible. Only if it is seen as impossible, is a new plan released.

That sort of decentralized MRP-CRP explosion, that runs in parallel with the JIT efforts and Kanban practices, works reasonably well under certain conditions, the main one being stability.(Hüttmeir et al.,) The computational capability of the human being doing that job is limited, and therefore, what was calculated the previous day should be similar to the present day, and similar to the following.

However it could be seen as strange that the process is quite spread. (Choi y Hong, 2002) expresses clearly what our experience says, the fax or telephone information before (and after) the ERP effective delivery has released its latest change.

This way of working (general at the Automotive Industry) has certain disadvantages. One of them is the lack of real data control, since all those adjustments happen outside of IT.

But also it has certain advantages such as reducing the quantity of data to be transferred and allows different and contradictory objectives and fuzzy information.

To some extent the reality is similar to the theory presented in (C.Schneeweiss, 2003) when considering that information about inventory and capacity is at certain level unknown or even stochastic.

2.4. Data from the Company ERP

The inventory levels from the database of the company, of each product are known. Although a forecast has to be considered since the inventory adjustment are done daily with a gap of more than 4 hours, and some uncertainties might happen due to quality control issues.

The Bill Of Materials of all products are given, although it has to be considered that engineering changes happen almost every day, and they should be managed at the scheduling level.

The working calendar is different not only for the suppliers and clients but also for the each production line, since capacities are not adjusted. Specific attention should be given to the so-called “stock piling process”. The shipping plan depends on the product and on the client. When it deals with an engine, the transport is by truck or container.

The plant has to produce enough engines to fill the specific rack for each type of engines, and combine the production to fill the truck or container. The component production and shipping is quite atypical since the company performs quality tests on all components made and in some cases products with the same name have different characteristics and this has to be considered.

Each line is characterized by its production, its daily rate of production according to the shift concerned. The cost of the different types of set-up is known. But since it is an opportunity cost, the production department states a number of setups that can be considered as maximum and forces the production scheduling department to plan by batches. The setup is sequence dependent

3. Model Formulation

3.1. Notation

The parameters used is presented at Table 1.

$C^{Y}_{i,t}$: cost of holding a unit of i during day t	C^{BN}_{i} : cost of negative backlogging a unit of i on day t.
C^{BP}_{i} : cost of positive backlogging a unit of i on day t.	$C^{set1}_{t,\xi}$:cost of a difficult setup on day 1 at line ξ
$C^{\Delta X}_{i,t}$:cost of the instability of product i on day t	$C^{S}_{k,t}$:cost of producing the stroke k on day t
$SS_{i,t}$:safety stock of i on day t	$SM_{i,t}$: maximum stock level of of i on day t
$SM_{\xi,t}$: maximum stock level for every product i been produced at production line ξ on day t	L_{ξ} : set of products produced at line ξ
U_{k} : use of resource that uses the stroke k	$KAP_{\xi,t}$: capacity of line ξ on day t
W_{i} : number of products i that the rack is holding.	V_{j} : number of racks that can be hold in a container to client j
$N_{i,k}$: number of units of i that generates a stroke k	$M_{i,k}$: number of units of i that requires a stroke k
T^{CY}_{k} : Cycle tyme for stroke k	$DER_{\xi,t}$: Number of derivatives allowed at line ξ
$PLR_{i,t}$: Planned reception of product i on day t	DS set of products (i1,i2) with difficult setup

Table 1. Parameter Notation

The variables used are presented at Table 2, except otherwise noted variables are always positive integers.

$y_{i,t}$: stock level of product i at day t	$v_{i,j,t}$: delivery of product i to client j at day t
$\mu_{i,j,t}$: numbers of racks of product i to client j at day t	$\varpi_{j,t}$: numbers of containers to client j at day t
$x_{i,t}$: production of product i at day t	$z_{k,t}$: number of strokes k at week t
$\beta^{+}_{i,j,t}$: positive backlog of product i for client j at day t	$\beta^{-}_{i,j,t}$: negative backlog of product i for client j at day t
$\theta^{set1}_{\xi,t}$: {0,1} if a large setup is at day t on line ξ	$\gamma_{i,t} \in R^{+}$: instability for product i between two consecutive days

Tabla 2. Variable Notation

3.2. Objectives

Creating a plan that satisfies the requirements of the logistics department together with the production department are complicated, since each department has different objectives, and in some cases these are expressed as constraints and in others as goals.

During the modeling phase a set of 4 goals were settled: 1) Maximize Delivery Performance. 2) Production Stability, 3) Reduce Setup costs 4) Reduce Inventory and production costs.

The overall objective is always said to be minimize total costs, although in general those costs are unknown. The model was designed to hold them all, and at the implementation phase a parameter tunning was heuristically performed. The whole objective function is presented as formula (1)

$$\min \left\{ \begin{array}{lr} \sum_{i,j,t} C^{BN}_{i,j,t}\beta^{-}_{i,j,t} + \sum_{i,j,t} C^{BP}_{i,j,t}\beta^{+}_{i,j,t} + & (1.1) \\ \sum_{i,t} C^{\Delta X}_{i,t}\gamma_{i,t} + & (1.2) \\ \sum_{k,t} C^{\Delta X}_{k,t} z_{k,t} + & (1.3) \\ \sum_{\xi,t} C^{set1}_{t,\xi}\theta^{1}_{t,\xi} + \sum_{\xi,t} C^{set2}_{t,\xi}\theta^{2}_{t,\xi} + & (1.4) \\ \sum_{i \notin RM,t} \left(C^{Y}_{i,t}\left(y_{i,t} - SS_{i,t}\right)\right) & (1.5) \end{array} \right\} \quad (1)$$

The objective of optimizing delivery fulfillment was modeled by a summatory (1.1) that tried to minimize the backlog costs both positive (the classical) and the negative (serving in advance). Costs of backlogging are different depending on the product, the client and the time. Not every client is similarly relevant, not every product and not every day. In fact backlogging costs were classified in two different levels high and low, and all were settled to low levels. When the users started using it the rationality appeared easily, when they were expressing their requirements… Low demand products are less relevant, no assembly line clients were less relevant, and backlogging in the third or fourth week was not relevant, since extra-days could be added if necessary.

Summatory (1.2) is used to minimize the instability on production levels for each product. The idea is to reduce to an acceptable minimum the volatility of the production, even if demand is volatile.

Summatoy (1.3) will allow selecting the cheapest possible alternative bill of materials.

The objective of minimizing setup costs was addressed on a special way (summatory 1.4). A penalty is created when two products (with large sequence dependent setup costs) are to be on the same day or on consecutive days. This way of modeling the setup cost, due to the special characteristics of the system modeled (no more than two products per day), will generate a feasible schedule, avoiding the complexity of setting a sequence for the problem.

Finally the objective of minimizing the inventory cost deserves an explanation. From a realistic point of view the inventory levels cannot be reduced since the production rate is fixed, and so it's the demand.

But the inventory cost are used to keep an inventory, as balanced as possible. Therefore the model applies a penalty for the stock over the safety stock levels, and as the penalty is so the system will prefer to run as produce smoothly as possible to avoid the penalty enough.

3.3. Constraints

The constraints of the model are presented at this section. When not stated specifically the constraints apply to the whole set represented by the index.

Storage capacity constraints are (2) and (3) For any product and component, inventories at any time should not exceed the storage capacity but not be less than the defined safety stock, these constraints might be relaxed if the problem has not a solution.

$$SS_{i,t} \leq y_{i,t} \leq SM_{i,t} \tag{2}$$

Constraints (3) limit the overall capacity of stock, this constraint might be relaxed if necessary.

$$\sum_{i \in L_\xi} y_{i,t} \leq SM_{\xi,t} \tag{3}$$

The continuity constraint hold for manufactured units. The main particular case on the model presented at this paper is the us of the concept of stroke, to plan the operation, as a mean to create the production and requirements of the different products. The stroke concept allows to separate the material requirements planning from the operations planning, and allows the introduction of alternative BOM.

The basic idea on the concept is the following. Each product i, can be produced using a set of strokes k (in such case $N_{i,k}$ will be a positive number). To produce such stroke a set of components i might be required, in such case (in such case $M_{i,k}$ will be a positive number). This stroke concept adds complexity to the conventional MRP models, but allows to consider alternative and inverse BOM. In the case here introduced allows the use of the "so-called" puntos azules". Products that, although passing quality controls are only used on certain models, due to its specific tolerance limits.

$$y_{i,t} = y_{i,t-1} - \sum_j v_{i,j,t} + \sum_k N_{i,k} z_{k,t} - \sum_k M_{i,k} z_{k,t-T_k^{CY}} + PLR_{i,t} \tag{4}$$

Therefore the quantity of product i to be produced is a multiple of the strokes that produce it.

$$x_{i,t} = \sum_k N_{i,k} z_{k,t} \tag{5}$$

A further advantage of the use of strokes is that it allow to plan production independently of the delivery of the product. Production capacity constraints are expressed in constraints 6(6). The total production at each line should be equal to the capacity. Therefore the use that the different strokes do to the line they are assigned is limited by the capacity of the line for a given period.

$$\sum_{k \in P_{\xi}} U_k z_{k,t} = KAP_{\xi,t} \tag{6}$$

Each day, the shipping quantity of each product has to be less than the stock at the beginning of the day, but also it should fill the container. In fact that constraint might be relaxed for the first day of planning, but this operates on a very short term basis, and it is not object of this model.

$$\sum_{j} v_{i,j,t} \leq y_{i,t-1} \tag{7}$$

Each product has a certain Lead Safety level, therefore initial backlogging also considers the demand of the first LS days. Since it is a lead *safety* level, this is a characteristic that may be relaxed if on a first run we are not able to solve the problem. Reducing the LS level for each product and client, will help to find a feasible solution.

$$\beta_{i,j,0} - \beta^{-}_{i,j,0} = B_{i,j} + \sum_{t=1}^{LS_{i,j}} D_{i,j,t} \tag{8}$$

Backlog constraints are also special. Backlog is usually considered to be a delay. As long as racks and containers should be filled the negative backlog is required. The continuity constraint applies

$$\beta^{+}_{i,j,t} - \beta^{-}_{i,j,t} = \beta^{+}_{i,j,t-1} - \beta^{-}_{i,j,t-1} - D_{i,j,t+LS_{i,j}} + v_{i,j,t} \tag{9}$$

The units to be send should be multiple of the capacity of the rack that is going to hold them.

$$W_i \mu_{i,j,t} - v_{i,j,t} = 0 \tag{10}$$

And the number of racks sent to a single client should fill the capacity of the truck

$$V_j \varpi_{j,t} - \sum_{i} \mu_{i,j,t} = 0 \tag{11}$$

The purpose of constraint (12) is to stabilize the production of engines, therefore it only applies to those products that are produced at the assembly line. Moreover, we are not interested on reaching an absolute balancing level (the MMAL sequencing problem that it is solved on reality, will tend to do it). That is the reason why under a 5% of deviation over the total production for a given product is considered. It is worth to remember that this only applies to those products with positive demand on the two days considered.

$$\gamma_{i,t} \geq \max\left(\frac{x_{i,t} - x_{i,t-1}}{\sum_{j} D_{i,j,t}} ; \frac{-x_{i,t} + x_{i,t-1}}{\sum_{j} D_{i,j,t}} ; 0.05 \right) \tag{12}$$

The number of derivatives should be limited per line and day and constraint (13) helps to count them and constraints (14) limit them

$$x_{i,t} - MM_{i,t} \times \chi_{i,t} \leq 0 \tag{13}$$

$$DER_{\xi,t}^{\min} \leq \sum_{i \in L_\xi} \chi_{i,t} \leq DER_{\xi,t}^{\max} \quad (14)$$

The reduction of number of derivatives reduces naturally the number of setups. The clients have required to to limit the possibility of difficult setups. In order to do so a proper sequencing process should be carried out, but since the problem has sequence dependent setups a different approach has been used. This approach is useful in the context here presented because the number of derivatives per day is settled to be less than four per week (less than two per day in most cases). Users of the system generates the list of each pair of products i1 and i2 that will require a difficult setup on line ξ. Then a penalty will be assigned.

$$\chi_{i1,t} + \chi_{i2,t} - \theta_{\xi,t}^{1} \leq 1 \quad \forall (i1, i2) \in DS \quad (15)$$

$$\chi_{i1,t} + \chi_{i2,t-1} - \theta_{\xi,t}^{2} \leq 1, \chi_{i1,t-1} + \chi_{i2,t} - \theta_{\xi,t}^{2} \leq 1 \qquad \forall (i1, i2) \in DS \quad (16)$$

4. Implementantion

4.1. Implementation System

This model is part of a more general DSS, and in particular was devoted to develop a 4 week delivery, production and material requirements plan.

Since the company has an ERP (so called CMMS3) the main data should be gathered from there. But the data on this software that is reliable enough, is that related to deliveries and working calendars.

Therefore parallel systems had to be developed. Such systems rely on a “SQL Server” database, that it is accessible to the normal users, using standard internet browsers, since a proper interface has been carefully developed.

Once the user adapts the data that he considers should be changed (inventory levels or production capacity constraints), the same interface creates a XML file that is sent to the system, the model which has been described on this paper. Once the solution is reached an XML file is released with the results, and then the system creates the different files that are required from the users. Most of these files are XML files that can be opened using MSExcel © spreadsheets similar to those that were created previously, including formula on them, so they can keep on changing the results and check what happens.

The model has been tested against a CPLEX 9.0 engine and such software can easily solve it. The system is a Java-based code that uses as a free solver engine LP-Solve. The use of LPSolve software makes the resolution method extraordinarily complicated for this problem where the number of constraints overpasses easily the 100.000. Therefore a heuristic process was developed that reduced the size of the modelling has been used. The process (presented at figure 1) also allows to “relax” constraints to cope with the information deficiency problems that had to be faced.

On a first stage the model is solved considering only the delivery constraints for the engines, and constraints are added to guarantee that the model will be feasible on subsequent stages. The soft constraints as safety stocks and backlog levels might be also relaxed. Once the trucks are filled, the results obtained have generated a demand for the assembly line and the Production model (taking into account sequence dependent setups) is solved. Then using the production plan results as demand, the requirements plan is solved.

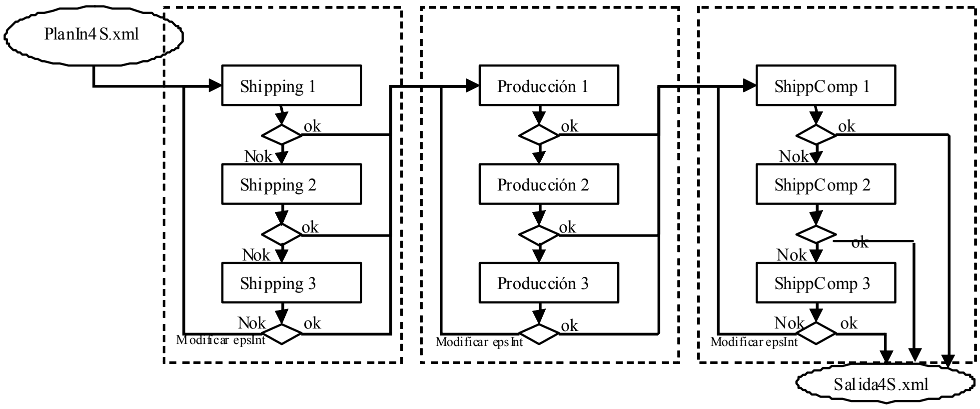

Illustration 1. The resolution procedure

That method of solving reduces the optimality of the whole process by 10-20%, but since the operations managers are more interested on fulfilling than on optimized, was accepted. To guarantee stability on the production, the models solves the problem for 6 weeks, although the users only received the results for 4 weeks. The latest 2 weeks had most of the constraints (such as filling trucks) relaxed.

4.2. Implementation Process

As with all change, some opposition from the workers affected could be expected. In the present case, there were 3 people directly affected by the change, and their boss, was in fact the one supporting the implementation is not subsequent results. When the model started being used an expected concern arose. Against the opinion of the responsible for the project that strongly believed that the data was reliable, it was not

Moreover, the affected people did not like the system considering too much information. In fact we found that, reasonably, the 4-week plans were not considering all the variety, since they do not consume a lot of resources. Thus, strange products, were not planned but only executed.

Since the new system required all the data available several changes had to made on procedures. The process of modeling started on April 2008, just before the 2008 financial crisis started, and from September onwards the instability was so severe that is disrupted the whole process.

Their process of planning relied heavily on stability, and due to the market situation the pressure to have the software running, counterbalanced the initial opposition. In fact it can be said that developing and launching the project “

5. Conclusions and remarks.

The above outlined model is part of a more extended Decision Support System that has been created to help the Supply Chain and Operations Activity at a real engine factory.

This paper aims to describe the Master Planning tool based on a MILP model developed for the company. In the system implemented at the plant, the novelty is found in the entire supply chain performance optimized as shipping planning at the production site, production planning, inventory management and purchase management are simultaneously considered in the same model.

In order to implement an efficient system approved by the planners, the system had been validated using a step by step approach and a mathematical model, the core of the system, has been created in various spin-off to respond to the cautious approach of the different departments involved. The system is modeled as a mixed-integer linear model with multi-objectives using discrete-time representation. To tackle the complexity of this case study, the quantity of data to process and moreover the use of a free software, different optimization-based solution models had been proposed so as improve the CPU time, the stability of the plans and solution quality. The developed approach showed only the entire model macro-level with the three levels of planning.

Future research should be driven to reduce the gap between the optimum solution and the solution reached through the heuristic procedure here presented.

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