

**A Modified Hierarchical Production Planning
System for Make-to-Order
Integrated with MRP**

by

Sertaç Kanlı

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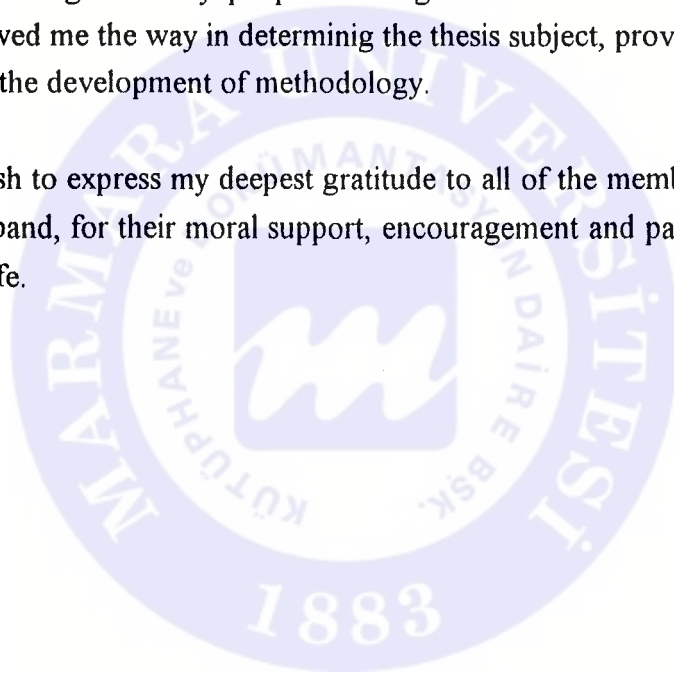
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ABSTRACT

Due date setting is a difficult task for make-to-order companies and requires efficient capacity and lead time management. In the literature, production planning for make-to-order companies is tackled by using shop floor scheduling algorithms coupled with simulation. However, capacity management cannot be realized through shop floor scheduling which actually represents the last phase of planning. As many researchers point out, capacity should be managed at the aggregate level where loads can be smoothed over time resulting in reduced shop congestion, late deliveries and overtime.

A linear aggregate master scheduling model is proposed for dealing with problems of capacity management. Orders are conveniently grouped into product families so that the proposed model becomes tractable in terms of practical problem sizes. Capacity constraints are included in the model which covers a number of future periods. The objective is to minimize total backorder and overtime costs. An order is assumed to be backordered if it is delivered some weeks later than that of its arrival. Actually, the time during which an order is backordered represents the production lead time for that order. Furthermore, the production lead times of all orders are limited by a certain period determined as a company policy. The output of the model conveys weekly order release and delivery times which serve as order due dates. Hence, lead time management and due date setting are both achieved by the aggregate model.

The aggregate model does not take set-up times into consideration in order to preserve its linearity. However, including the set-up times in the production plan generated by the model often leads to capacity violation. To remedy this situation, an iterative algorithm which tends to smooth out capacity loads over the time periods is proposed. The iterative algorithm compensates the exclusion of set-up times from the model.

The proposed model and iterative algorithm are applied for planning production in a manufacturing company which makes/assembles custom kitchen cupboards. Results are compared with the actual production plan and a considerable decrease is observed in total costs.

ÖZET

Sipariş üzerine üretim yapan firmalarda, müşteriye teslim tarihi verme olgusunun zorluğu pratikte bilinmektedir. Literatürde, bu konu ile ilgili olarak önsüre yönetimini sağlayacak olan girdi/çıkıtı kontrolü gibi yöntemlerle karşılaşmaktadır. Bu çalışmada ise, sipariş üzerine üretim sistemleri, ürün sınıflandırması yapılarak hiyerarşik bir yapıda ele alınmakta ve haftalık üretim planları, kapasite sınırlarının da dikkate alındığı bir doğrusal programlama modeli yardımı ile elde edilmektedir. Geliştirilen modelin ürün ailesi bazında olması, kullanılan değişken ve kısıt sayılarını minimuma indirmektedir. Teslim tarihleri ise modelin çözümü sonucunda doğal olarak ortaya çıkmaktadır. Ancak, planlamacı, verilebilecek maksimum teslim sürelerini saptama esnekliğine de sahiptir. Modelin çözümü, fazla mesai ve ardışıklama maliyetlerinin toplamı açısından eniyelenmiş bir Ana Üretim Çizelgesi oluşturmaktadır.

Ürün ailelerinin geçişleri arasındaki hazırlık süreleri Ana Üretim Çizelgesine dahil edildiğinde bazı kapasite aşımına yol açmaktadır. Bunun engellenmesi amacı ile, normal kapasite sınırlarının revize edildiği iteratif bir algoritma önerilmiştir. Bu algoritmanın amacı, haftalararası yükü dağıtarak hazırlık sürelerine yer açmaktır.

Önerilen model ile iteratif algoritma, bir mobilya fabrikasında üretimin planlanması amacı ile uygulanmış ve elde edilen sonuçlar gerçekleşen planlama ile karşılaştırılmıştır. Bu karşılaştırma sonucunda, toplam maliyetin önemli ölçüde azaldığı ve haftalararası yükün dengelendiği görülmektedir.

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I. INTRODUCTION

In the production planning area, the researches have concentrated mostly on the make-to-stock companies. Production planning in make-to-order companies is more difficult as compared to make-to-stock companies due to the fact that it is not possible to forecast future demand. A wide product spectrum that is essential for today's environment of world-wide competitive market further complicates the production planning task.

The major issue in make-to-order companies is determining due dates for customer orders, and delivering the orders at these determined due dates. An order due date depends on the production lead time that can be defined as the time span between the order arrival and order delivery. The production lead time, on the other hand, depends on the current and future available production capacity, and on the material handling. To remain competitive, especially after entering Customs Union, it is desired to quote short lead times and produce high quality products at a reasonable cost. Competition generally will increase, with multinational companies competing in a single European market. The pressure will place demands on management to review their manufacturing strategies and to optimise their uses of tools and resources. On the other hand, quoted lead times should be adhered to in order to secure the customer.

As it is not possible to forecast the future demand, controlling the inventory levels and the material handling becomes impossible. Unfortunately, assumptions according to previous data does not cover the demand changes, which increases stock costs. Solving this problem may be topic of an other study, it will be not included in this study.

Customer satisfaction, the *magic* word of today's world, is also more important in make-to-order companies compared to make-to-stock companies and very important to solve any complain of customers.

The subject of concern in this thesis is to develop a new mathematical model is to be solved for obtaining a MPS, the model constraints and variables must be of aggregate form so that the model remains to be tractable for problems of practical size. The objective is the minimisation of backorder and overtime costs. Penalising backorders enforces shorter production lead times. However, overtime is also a cost factor and in the optimal solution the trade-off between short lead times and overtime is optimised.

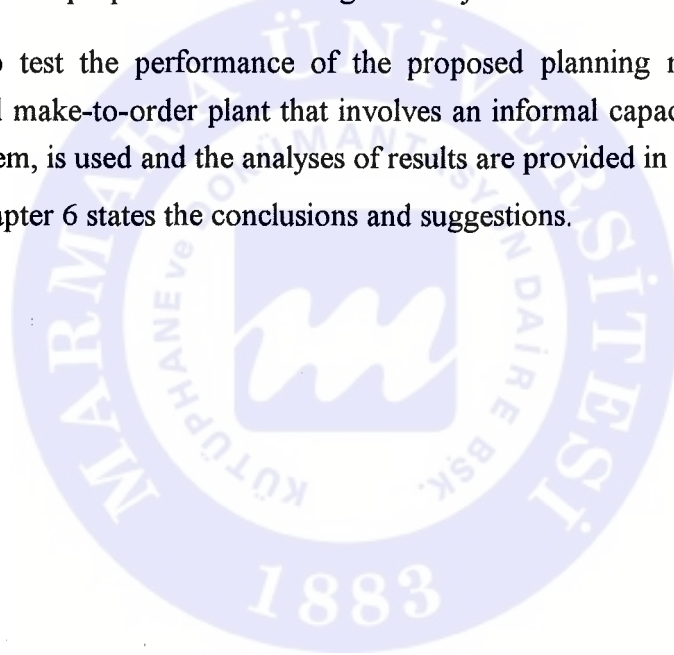
The sources of the problem related to existing planning systems and aggregate planning approach are reviewed in detail in Chapter 2, which presents literature survey. During modelling to obtain a MPS, the model constraints and variables must be of aggregate form so that the model remains to be tractable for problems of practical size.

The proposed planning model, which is developed on an actual model with the reasons and expected results, is given in Chapter 3. Current order and process flow are provided also in this chapter.

A MPS is required for planning the production of the bottleneck department is given in Chapter 4. The plan will trigger production in upstream departments. A mathematical model is proposed for obtaining a weekly MPS in this chapter.

In order to test the performance of the proposed planning model and MPS module, an actual make-to-order plant that involves an informal capacity and due date management system, is used and the analyses of results are provided in Chapter 5.

Finally, Chapter 6 states the conclusions and suggestions.



II. LITERATURE SURVEY

As mentioned before much of the research in the production planning area has concentrated on the make-to-stock companies. Maruchek and McClelland (1986), who outlined some of the strategic issues facing the latter group of manufacturers, in contrast to those facing make-to-stock companies. **Table 1** compares some of the characteristics of the two groups [L.C. Hendry and B.G. Kingsman].

Table 1. A comparison of make-to-order and make-to-stock companies.

Characteristics	Make-to-stock companies	Make-to-order companies
Product mix	Many standard products	Few standard products
Resources	Specialist machinery and workforce	Multi-task machinery and flexible workforce
Product demand	Demand for standard products can be forecast	Demand is volatile and can rarely be predicted
Capacity planning	Based on forecast demand. Planned well in advance. Adjusted later if necessary	Based on receipt of customer orders. Cannot be planned far in advance
Product lead times	Unimportant to customer. Can be set internally.	Vital for customer satisfaction. Agreed with customer.
Prices	Fixed by the producer	Agreed with customer before production commences

The early approaches to due date setting are basically heuristic methods sometimes coupled with simulation [Eilon and Chowdry (1976), Weeks and Fryer (1977), Weeks (1979), Bertrand (1983), Cheng (1986), Hedge et al. (1991)]. Once the due dates are fixed by using certain job- and workload-related parameters, orders are sequenced according to dispatching rules using a finite scheduling algorithm. Such an approach assumes a given fixed production capacity. As Hendry and Kingsman

(1989) point out, the method of fixing the due dates first and then assigning priorities to orders is not a correct method to treat the problem, because:

- i. capacity adjustment should be made at the customer enquiry stage and should not be assumed as fixed;
- ii. tasks do not arrive in order of importance and it is necessary to reschedule all orders when a new order arrives.

Consequently, many researchers concentrate on lead time management which in due course leads to setting attainable due dates. Since lead time is a function of backlog, and backlog is a function of the input/output relationship, Tatsiopoulos and Kingsman (1983) conclude that lead times are determined by both order backlogs (input) and capacity (output). Kingsman et al. (1989) define backlog length as the difference between accumulated input and output and state that for successful lead time management backlog length must be controlled. Control must be gained through the following hierarchical sequence:

- i. the performance norms setting phase,
- ii. due date assignment phase,
- iii. job release phase and scheduling phase.

More recently, Hendry and Kingsman (1993), propose a customer enquiry management system based on the backlog length concept.

Bechte (1988), has proposed a heuristic algorithm called BORA which identifies the orders to be released in the next planning period. The aim is to prevent work-in-process from exceeding the planned level. Work-in-process can be defined as the queue length (in work loads) in front of each resource. BORA is controlled by the time limit and the load limit. The load limit is calculated from planned work-in-process level. The time limit is the number of time periods that an order is allowed to be released before its planned start date. Since BORA covers only one planning period ahead, the effects of current order releases on future work-in-process cannot be taken into account. Consequently, capacity utilisation cannot be smoothed over time [Zapfel and Missbauer (1993)].

Philipoom and Fry (1992) also concentrate on the order acceptance phase. The authors compare two order acceptance methodologies, the first of which resembles BORA. The second method is similar to the Drum-Buffer-Rope concept by Goldratt

and Fox (1986) where the current load of the bottleneck resource affects the acceptance or rejection of arriving orders.

Some researchers attack the production planning problem via aggregate planning models. For example, Markland et al. (1990), propose a zero-one goal programming model which aims at achieving Just-In-Time plans assuming that due dates are already assigned to orders. This approach also suffers from the weakness of the scheduling approaches described above and furthermore is not tractable for practical size problems.

Fumero and Vercellis (1994) model the assemble-to-order environment. However, constraints and variables are defined at the end item level and zero-one variables exist. Hence, the authors propose Lagrangean relaxation techniques for solving the sub-problems instead of dealing with the monolithic model. The authors note that inconsistencies may exist among solutions found for the sub-problems and that the model outputs may represent only target plans rather than implementable plans.

Hierarchical planning systems where end items with similar set-up requirements are grouped into the same product family (Hax and Candea (1984)) have also been proposed for make-to-order environments [Gelders and Van Steelandt (1980), Bowers and Jarvis (1993)]. Although originally designed for make-to-stock systems [Mackulak et al. (1980), Axsater and Jönsson (1984), Tsubone and Sugawara (1987), Chung et al. (1988), Lin and Moodie (1989), Özdamar et al. (1995)], the concept of planning hierarchies is applicable in make-to-order systems as well. Gelders and Van Steelandt (1980) simulate machine loads in the aggregate level in order to specify order due dates. Then, detailed scheduling phase is applied. Bowers and Jarvis (1993) propose a three level planning hierarchy for a hybrid make-to-stock / make-to-order system. The first level involves a mathematical aggregate model and the second level considers the line assignment problem. The last level treats the minimisation of sequence dependent set-up times on each line.

III. THE PROPOSED PLANNING SYSTEM

The literature review demonstrates that lead time management and due date assignment are not easy tasks for the production planner in make-to-order-companies. Lead time management at the order release level should be supported by a higher level Master Production Schedule (MPS), the reasons being the following :

- i. If the capacity load is not balanced over time by the MPS, then even the best order release strategy will not work.
- ii. The MPS should assume the role of aggregate lead time manager with features which explicitly penalise the extension of lead times.
- iii. Additionally, the MPS should consider capacity constraints while preparing a production schedule. Otherwise, the major weakness of MRP II, i.e., the tiring repetition of the cycle consisting of planning, simulation and replanning, might become a major issue.

Figure 1 demonstrates the position of the capacity driven MPS in make-to-order environments.

The capacity driven MPS provides a feasible production schedule in terms of the capacity overloads and maximum allowed delay of order deliveries. It covers a time period to the extent of known customer orders. The planning time bucket might be a week or longer according to the firm's existing planning software. The output of MPS includes, for example, weekly production quantities of product families. Order indexed family production quantities can be easily disaggregated into order indexed end item production quantities by database manipulations, since all end items of the same order have equal priority.

Notice that if a mathematical model is to be solved for obtaining a MPS, the model constraints and variables must be of aggregate form so that the model remains to be tractable for problems of practical size. In other words, the MPS model should be based on product families and the capacity constraints should belong to the bottleneck resource.

The MPS provides weekly order due dates. An order is delivered when all its end items are ready for shipment. Hence, the due date of an order becomes the week that its last end item is produced.

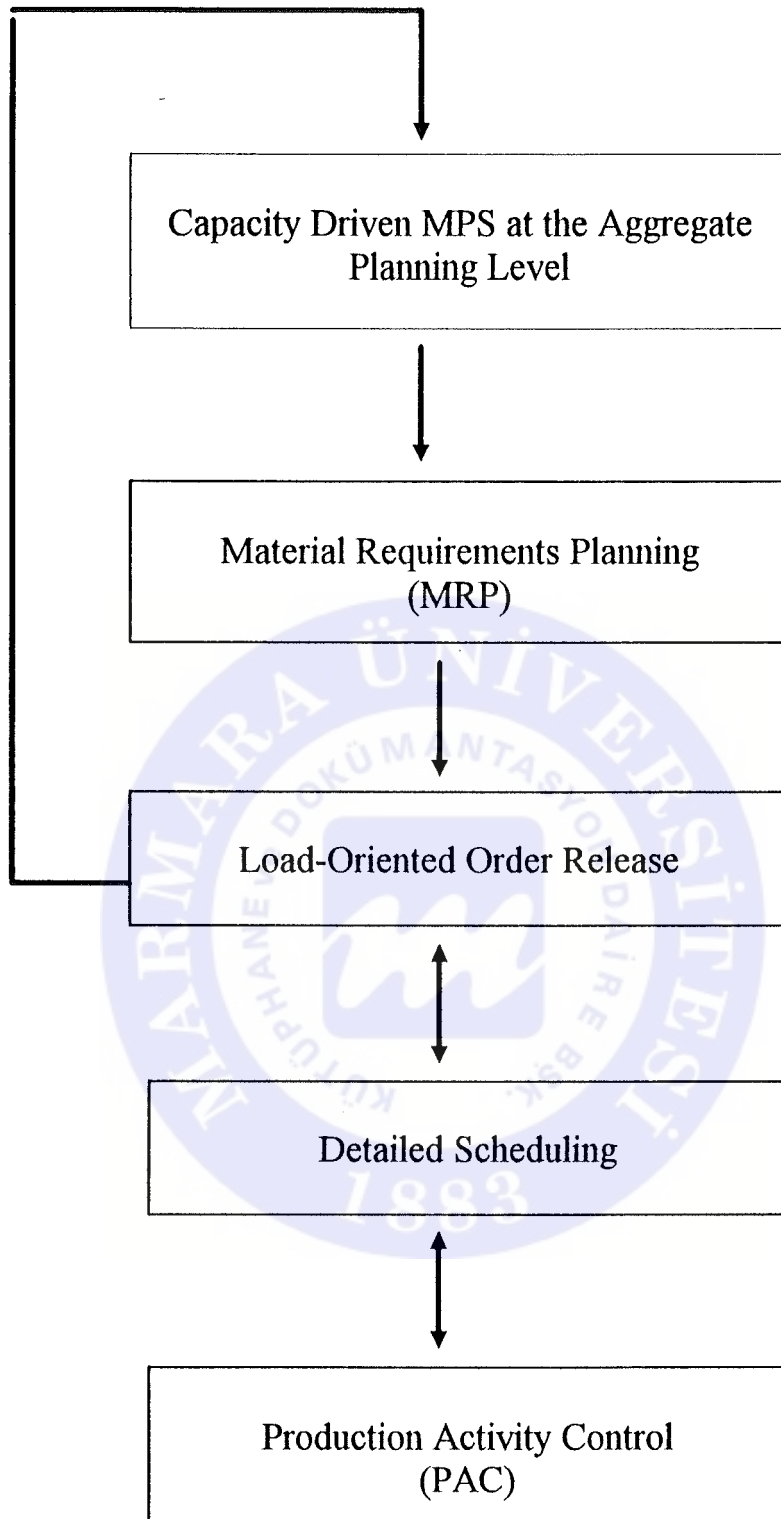


Figure 1. Proposed planning system for make-to-order environment.

Given the above perspective, the MPS module should be used at the customer enquiry stage where order due dates need to be specified.

The MPS should be flexible enough to include maximum allowed production lead times entered by the user. The user can extend production lead times to let the MPS module freely optimise capacity utilisation levels, or, at his/her own discretion, the user can reflect customer priorities through the allowed production lead time parameter of each order. Naturally, the MPS module may provide due dates earlier than the specified lead time while acting as a cost minimiser. To summarise, in this framework, order due dates are assigned jointly by the user and the MPS module.

The MPS output is frozen for a week and the schedule is revised once a week on a rolling horizon basis. At each revision, the user may enforce order due dates specified in the previous solution for existing orders or may allow some changes in production lead times according to newly arrived urgent orders.

Material Requirements Planning (MRP) is the next stage in the planning system. The disaggregated MPS output is fed into the MRP system in terms of end items. Now that replanning is made obsolete by the capacity driven MPS, material acquisition times provided by MRP become true in the first run.

At the order release level of the planning hierarchy, the output of the MRP package, namely, a list of items to be produced in the current week, is converted into released orders by the order release mechanisms so that actual production does not deviate from planned production schedules. Lead time management is necessary to prevent shop congestion and hence, late deliveries. In case large deviations between MPS outputs and actual production occur, feedback from the order-release phase is sent back to the MPS phase so that corrective actions are taken.

In the detailed finite scheduling phase, dispatching takes place among the released orders. Here, detailed production plans are made to specify the processing sequence of orders. Notice that there should be no consistency problems between the aggregate and detailed planning levels if the MPS model is fed with the correct current backlog data of product families and the order release parameters are well tuned to MPS parameters. The final phase which consists of Production Activity Control (PAC) is a continuous process with daily feedback to the detailed scheduling phase.

IV. SCOPE OF THE STUDY

4.1. Implementation Area

A make-to-order company manufacturing wooden furniture units for kitchen is the implementation area. Although the company has been established 3 years ago, it has an expanding market share due to the fact that its manufactured products are of unique high quality and classify as luxury goods. The market segment is not wide, but it is expanding parallel to the construction sector and customer awareness which is need for a well-designed kitchen room is becoming essential nowadays and customers begin to prefer kitchen rooms as a living area to others.

About 100 workers constitute the labour force of the company. There is 25 staff, that 4 of them are engineers. 25% of the workers are temporary, who are employed according to the customer order increases. Customer orders show a seasonal trend, means increases in the summertime. 30% of the rest of the workers are well educated in the wooden sector. This is important, because in this sector, hand-working still worthies.

Product quality, differentiation, and the functionality are the main issues of the market. There exist 2 main groups of furniture units which is mainly different brand-names, 16 groups of different furniture unit models where each group is distinguished by a front-door edge-cutting model and the price policy, in each different brand names. Models within each group are differentiated according to colour complement, dimensions and the cover materials. There exists approximately 5 different colour complements in each group of the furniture models. There are also 250 different furniture units, which are differentiated according to sizes, regals, front-doors and the drawers. The combination of these three factors causes 41250 different products.

Three fabrication/assembly lines are the major cost centres in the factory. Each of these lines is dedicated to a certain group of models. For the purpose of this study, the line which addresses the most capacity consuming orders is selected.

Furniture units are made of two main parts body and front-doors as shown in **Figure 2** . **Figure 3** describes the overall process flow of all fabrication lines, which is approximately same in all cost centers.

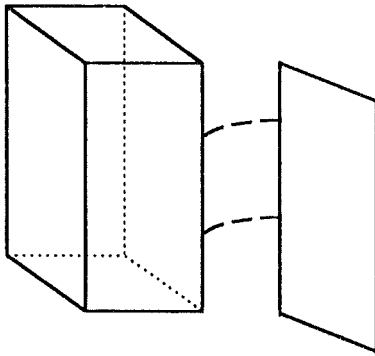


Figure 2. Body parts and front-door of a furniture unit.

The alternatives of the dimensions of the furniture units, the colour complement sets, and the front-door edge-cutting model are defined systematically. On the other side, one of the combinations among the 41250 alternatives are specified in the customer orders. Production of the front-doors is done according to the customer orders because the colour complements, the materials to be used and sizes are chosen in the customer orders. However, productions of body parts are done to stock, and assembled according to the customer orders, because there are so many common parts between the different furniture units and they are made of laminate, which means not painted. So the main problem occurs in production planning of the front-doors. On the other hand, if 41250 alternatives does not satisfy customer needs, special products to satisfy customer needs are also produced. They are mainly specified in sizes special to the customer order. Colour choice and the front-door edge-cutting models can not be different from the specified ones in the system itself.

Production processes of front-doors are as follows:

There are three main departments in the manufacturing ; i.Special Works; ii.Painting; iii.Assembly and Packaging. The average production lead time is assumed to be three weeks. An order is processed in the Special Works department in the first week, in the Painting department in the second week, and in the Assembly and packaging department in the last week.

Net sizing of front-doors, cutting the edges of front-doors -are in the first department- , painting and body-front-door assembly are the four major phases of production.

- i. Front-doors are cutted within known tolerances in the Rough Sizing phase, in order to decrease the percentage of scrap materials to the materials are used.
- ii. Then front-doors are cut into certain dimensions in the Net Sizing phase in the order of widths first, lengths second . Till the end of this process, production lead time differs according to the dimensions of the pieces.
- iii. Then processed according to an Edge-Cutting program specific to the order, here the production lead time differs from edge program of front-doors. For example, according to one edge-cutting program an edge of the piece passes through the machine once, which is equal to four when you multiply one by four edges, according to another twice which is equal to eight when you multiply two by four edges.
- iv. After surface cleaning, the front-doors are then ready for painting. One important thing to be considered here is four models of front-doors are not painted. So after surface cleaning they are ready to assemble.
- v. The painting includes some series of works such as preparing pieces for painting, rough polishing, surface cleaning, colour painting, again surface cleaning, and at last polish finishing. Then painted pieces wait for drying for some couple of days differs according to colour complements in the WIP inventory.
- vi. During above process body parts are taken from WIP inventory and drilled according to which the furniture unit they belong to. For example, a base unit, or a tall unit or a unit for appliances. A CNC machine is used for drilling the body parts according to the above classification. This machine is controlled and supported by a PC program.
- vii. The above grouping is also used for assembling the bodies.
- viii. Front-doors hinge and knob drills are opened in parallel phases in the order of kitchen groups..
- ix. Furniture units are built by assembling front-doors to body. This is done by the order of body assembling.
- x. Packaging is the last phase before shipment
- xi. Shipment is done weekly.

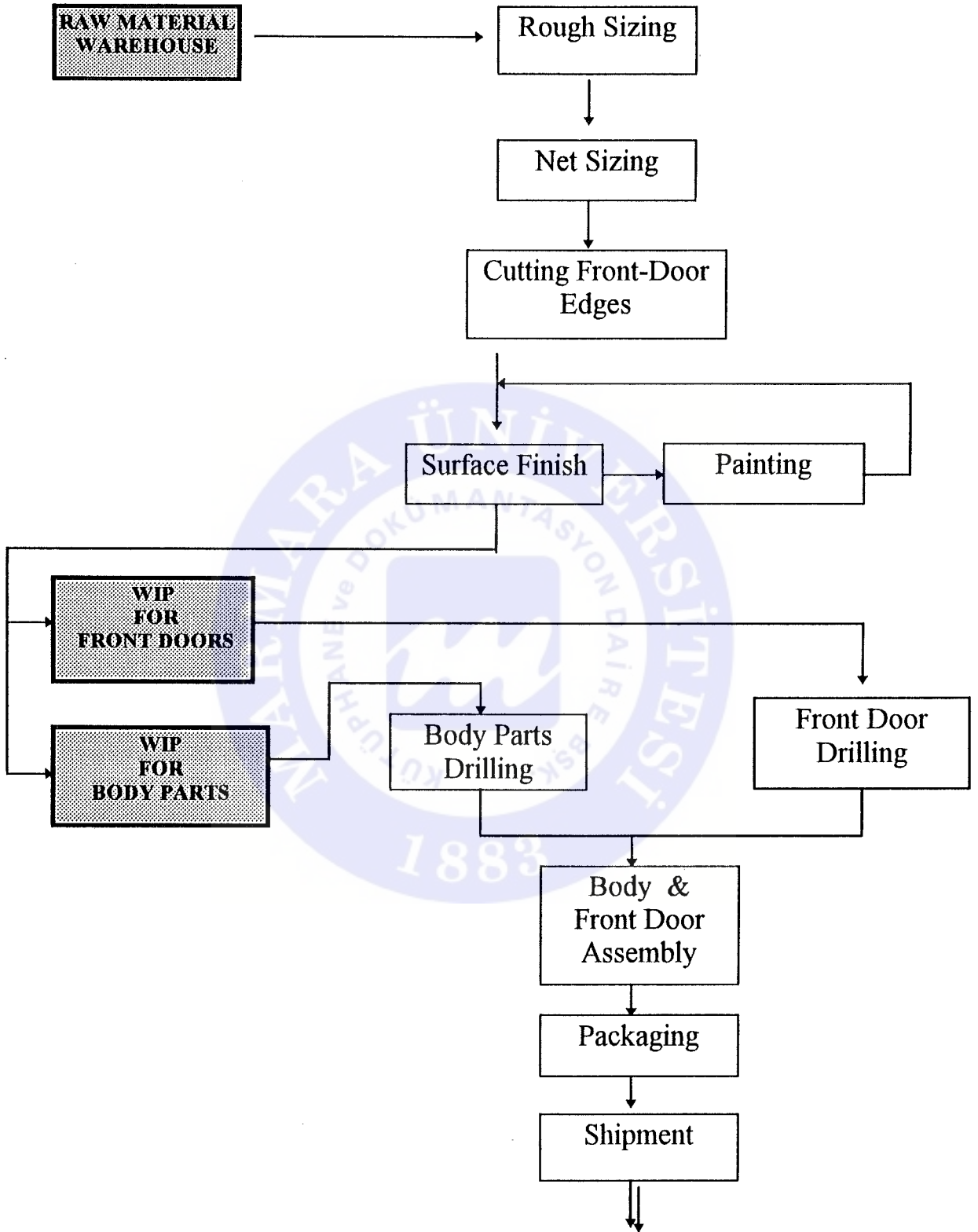


Figure 3. Process flow.

In each phase, product families are classified according to a different criterion. In the net sizing department, families are classified according to their dimensions; in edge-cutting, they are classified according to the cutting program, in painting, according to different colour complements, and finally in assembling according to drilling program. Changeover time in the edge-cutting department is due to the change in the cutting tools, in the painting department a set-up is required for cleaning the paint guns at each colour change, and preparing the new colour formula and in the assembly department a set-up is required for choosing the drilling program, but this is negligible.

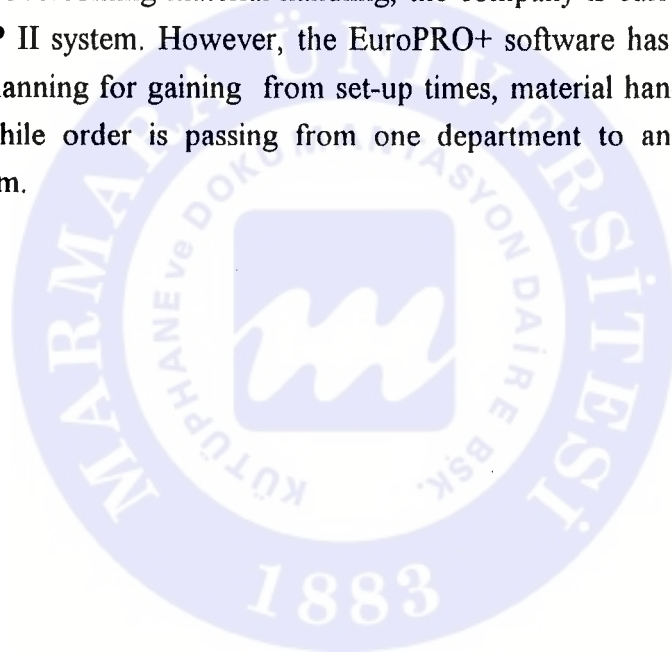
Body-door assembly phase causes no capacity problems on the line since inventoried bodies are assembled with doors which are ready for the final phase. The painting department is the bottleneck one in terms of capacity utilisation. Each department's workload is planned weekly, because of the unsatisfactory capacity loads. Due to the fact that every department's product family classification is different, a production plan which is prepared for the painting department (which is assumed to be the last operation for planning purposes) has to be rearranged according to the classification of the edge-cutting department. A similar regrouping should be made for preparing the weekly plan for net sizing. The tendency here is to accept the painting department as the triggering department and work the triggering plan backwards as a pull system.

The current planning policy in the company is as follows. The customer order flow of the company is given in **Figure 4**. The Sales department takes the customer orders and passes them to the Customer Order Control department. The Customer Order Control department controls the customer order according to the productibility, correctiveness of the dimensioning, and materials are chosen. The customer order is taken into process after they approved it.

The Sales department has a rough estimate of capacity, which is always revised with the feedback come from the Planning department, and it sequences arriving orders filling each week's capacity until customer orders are established for the next three weeks. Then, planning is carried out just by listing three weeks' customer orders to the manufacturing department according to the order of one week at the Special Works, one week at the Painting, and one week at the Assembly and Packaging department and letting the manufacturing people do what they can in order to assign detailed valid due dates. The visible problem related to this ad hoc planning is working too many overtime hours in order to squeeze production lead time and achieve a high customer service level. As there is no detailed planning program percentage of scrap materials

increases in the chaos of working hours. So, the absence of a formal due date setting procedure which may lead to workload smoothing is really the cause of the current excessive overtime working hours.

Furthermore, rushing the jobs in this manner leads to quality problems and any feedback from the shop floor to the planning department serves no more than reporting violated due dates to the sales department. On the other hand, due to the customers' approach to luxury goods, it is important to provide valid due dates for orders and stick to these due dates in order to secure the customer. This situation can be handled by a capacity driven MPS which is a lead time manager as well. To formalise the planning process, and the overcoming material handling, the company is currently installing the EuroPRO+ MRP II system. However, the EuroPRO+ software has no MPS module. The aggregate planning for gaining from set-up times, material handling process, and waiting times while order is passing from one department to another will not be supported by them.



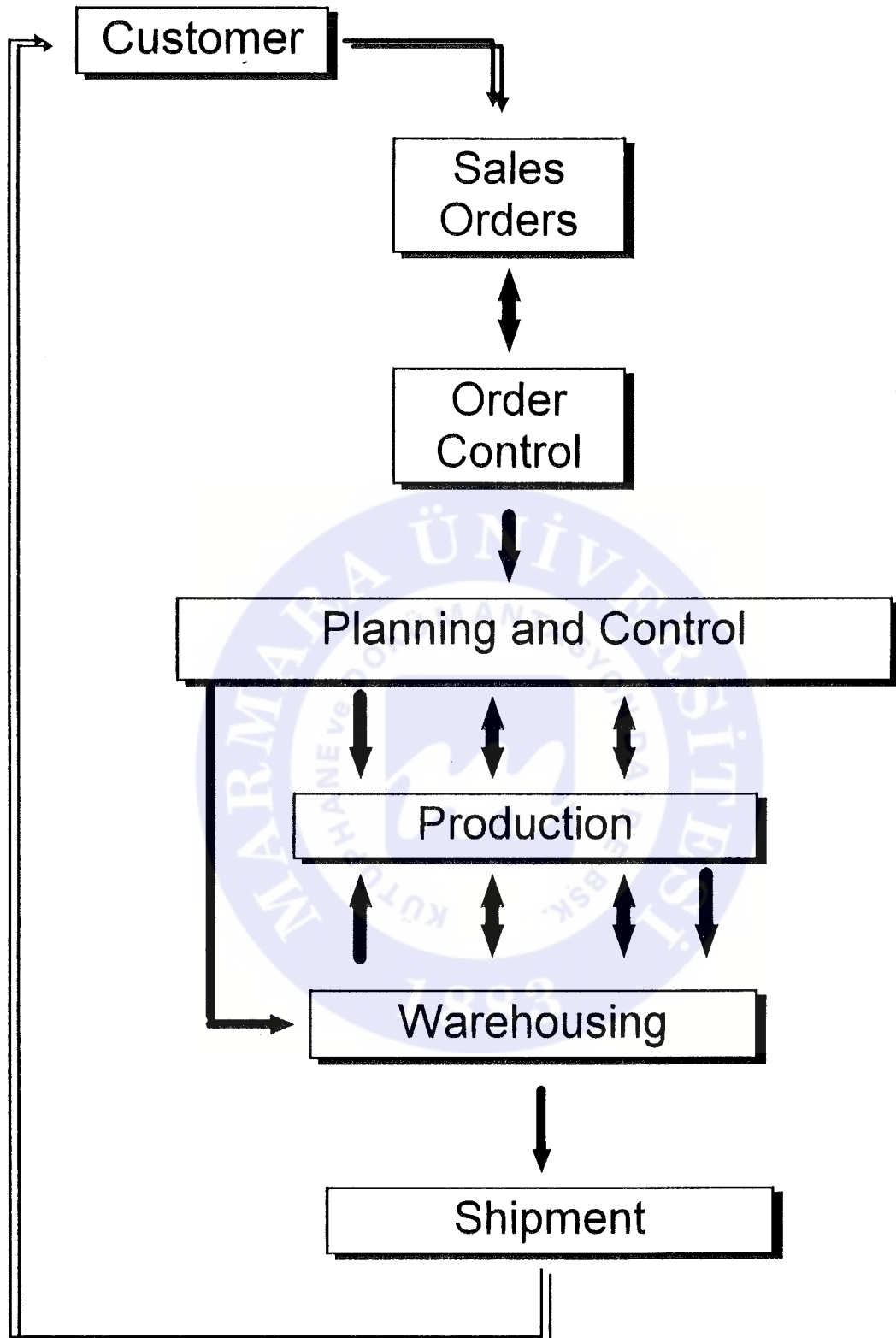


Figure 4. Order Flow

4.2. Capacity Driven MPS: The Core of the Planning System

As described in the previous section, the make-to-order company under consideration has a flow type of production. Consequently, the load-oriented order release and detailed scheduling phases found in **Figure 1** do not pose serious problems [Zapfel and Missbauer (1993)]. Simple rules which keep the daily loads at reasonable levels should be sufficient to achieve control. The major requirement of the current system is a MPS module which considers capacity restrictions while keeping aggregate lead time under control.



V. THE MPS MODULE

5. 1. An Aggregate Model for MPS

A MPS is required for planning the production in the painting department. The plan will trigger production in upstream departments. A mathematical model is proposed for obtaining a weekly MPS.

Order data are incorporated into the model after being aggregated into product families in order to reduce the model size when the number of orders is high. Thus, the hierarchy of the planning system described in **Figure 1** is supported by the MPS model.

Families in the painting department are classified according to colour complements, and set-up times during colour changes consume capacity such as changing painting guns, cleaning the gun which also cause waste material, preparing new colour complement . Hence, zero-one variables exist in the capacity constraints.

The model also includes backorder - demand - production balance constraints. An order is assumed to be backordered if it is delivered later than its arrival date. Notice that the standard definition of backorder (delivery past the due date) is not used here, since due dates are to be determined by the MPS. Thus, the time during which an order is backordered actually represents the production lead time.

The objective is the minimisation of backorder and overtime costs. Penalising backorders enforces shorter production lead times. However, overtime is also a cost factor and in the optimal solution the trade-off between short lead times and overtime is optimized. The mathematical model P designed for generating the MPS is given in **Table 2**.

Table 2. Mathematical model P for MPS.

$$\mathbf{P:} \quad \min \quad z \quad = \quad \sum_k \sum_t cb_k B_{kt} + \sum_t co O_t$$

subject to:

$$\sum_{n=t}^{t+\Delta_k} PR_{kjn} \geq d_{kjt} \quad \forall k, j, t \quad (1)$$

$$\sum_{i=1}^{t+\Delta_k} PR_{kji} \geq \sum_{i=1}^t d_{kji} \quad \forall k, j, t \quad (2)$$

$$\sum_j PR_{kjt} - B_{k,t-1} + B_{kt} = \sum_j d_{kjt} \quad \forall k, t \quad (3)$$

$$\sum_j \sum_k c_j PR_{kjt} + \delta_{jt} S_j \leq cr_t + O_t \quad \forall t \quad (4)$$

$$O_t \leq or_t \quad \forall t \quad (5)$$

$$\sum_k PR_{kjt} \leq M\delta_{jt} \quad \forall j, t \quad (6)$$

$$O_t, PR_{kjt}, B_{kt} \geq 0 \quad \forall k, j, t \quad (7)$$

$$\delta_{jt} = 0,1 \quad \forall j, t \quad (8)$$

Table 3. Variables and Parameters of Mathematical model for MPS.

VARIABLES AND PARAMETERS:	
j	: product family index (j = 1..J)
t	: week index (t = 1..T)
k	: order index (k = 1..K)
PR_{kjt}	: production quantity of family j in order k during week t
B_{kt}	: backordered quantity of order k at the end of week t
O_t	: overtime in week t (hours)
M	: a large number
δ_{jt}	= $\begin{cases} 1 & \text{if family j is produced in week t} \\ 0 & \text{otherwise} \end{cases}$
Δ_k	: the maximum production lead time allowable for order k (weeks)
c_j	: process time of family j (hours/ unit)
cr_t	: regular time capacity in week t (hours)
or_t	: overtime capacity in week t (hours)
d_{kjt}	: demand for family j in order k during week t
co	: overtime cost (TL/ hour)
cb_k	: backorder cost for order k (TL/ unit-week)
S_j	: set-up time for family j (hours)

As mentioned before, the objective is the minimisation of backorder and overtime costs.

$$\min z = \sum_k \sum_t c b_k B_{kt} + \sum_t c_o O_t$$

Constraints (1) and (2) guarantee that demand is satisfied over the planning horizon. Notice that Δ_k , which is the maximum production lead time allowable for order k , is decided upon by the sales department and may reflect customer priority.

$$\sum_{n=t}^{t+\Delta_k} PR_{kjn} \geq d_{kjt} \quad \forall k, j, t \quad (1)$$

$$\sum_{i=1}^{t+\Delta_k} PR_{kji} \geq \sum_{I=1}^t d_{kji} \quad \forall k, j, t \quad (2)$$

The next set of constraints ensure backorder, demand and production balance.

$$\sum_j PR_{kjt} - B_{k,t-1} + B_{kt} = \sum_j d_{kjt} \quad \forall k, t \quad (3)$$

The fourth and fifth sets of constraints preserve the feasibility of total capacity including overtime. Total capacity is the set-up times for families produced in week t added to total process time in week t is less than or equal to regular capacity plus

overtime in week t . Of course, overtime in week t cannot be higher than a certain overtime capacity.

$$\sum_j \sum_k c_j PR_{kjt} + \delta_{jt} S_j \leq cr_t + O_t \quad \forall t \quad (4)$$

$$O_t \leq or_t \quad \forall t \quad (5)$$

The sixth set of constraints ensure that a set-up occurs if and only if a particular product family is produced in that period.

$$\sum_k PR_{kjt} \leq M\delta_{jt} \quad \forall j, t \quad (6)$$

The outputs of this model are :

- i. PR_{kjt} , production quantities identified by order and family indexes, and
- ii. B_{kt} , backorder quantities identified by order indexes.

The date of the last production quantity belonging to an order represents the due date of that order. The due date which is determined by the optimised MPS model can be anywhere between its arrival week and its arrival week plus Δ_k .

The use of this model on a rolling horizon basis implies that the current week's plan is frozen. The next week, the current backlog, namely, the portions of orders which have not been produced, is fed into the model as well as additional demand data for another week. Note that Δ_k for existing orders either become $\Delta_k - 1$ in the revised model or they are fixed according to quoted due dates in the previous week.

The existence of zero-one variables in model P may lead to undesirable high computation times. To handle this situation, the fourth set of constraints are linearized by excluding the zero-one variables δ_{jt} and the sixth and eighth sets of constraints are eliminated.

$$\sum_j \sum_k c_j PR_{kjt} + \delta_{jt} S_j \leq cr_t + O_t \quad \forall t \quad (4)$$

$$\sum_k PR_{kjt} \leq M\delta_{jt} \quad \forall j, t \quad (6)$$

$$\delta_{jt} = 0,1 \quad \forall j, t \quad (8)$$

Hence, the resulting linear formulation is called problem P1 in **Table 4**.

Table 4. Mathematical model P1 for MPS.

$$\mathbf{P1:} \min z = \sum_k \sum_t cb_k B_{kt} + \sum_t co O_t$$

subject to:

$$\sum_{n=t}^{t+\Delta_k} PR_{kjn} \geq d_{kjt} \quad \forall k, j, t \quad (1)$$

$$\sum_{i=1}^{t+\Delta_k} PR_{kji} \geq \sum_{i=1}^t d_{kji} \quad \forall k, j, t \quad (2)$$

$$\sum_j PR_{kjt} - B_{k,t-1} + B_{kt} = \sum_j d_{kjt} \quad \forall k, t \quad (3)$$

$$\sum_j \sum_k c_j PR_{kjt} \leq cr_{t+} O_t \quad \forall t \quad (4)$$

$$O_t \leq or_t \quad \forall t \quad (5)$$

$$O_t, PR_{kjt}, B_{kt} \geq 0 \quad \forall k, j, t \quad (7)$$

5. 2. An Iterative Algorithm to Accommodate Set-Up Times

Formulation P1 can be solved efficiently by any linear programming package. Nevertheless, set-up times which consume capacity in reality cannot be ignored. In order to leave some capacity space for accommodating set-up times, an iterative algorithm which reassigns a reduced level of regular time capacity at each iteration is proposed.

In the first iteration of the algorithm, regular time capacity (RC) is equal to its original value cr_t . Without any loss of generality, it is assumed that cr_t is constant during the planning horizon. Thus, we call the original regular time capacity cr . We differentiate between cr and RC, because at each iteration RC is further decreased to reserve some space for set-up times. (MIC) is minimum incumbent cost which is set to infinite, is further decreased by calculated total cost at each iteration .

Problem P1 is then solved with a linear programming package. Given its outputs, which consist of the production quantities of order indexed product families, we calculate the production hours (PH_t) and set-up times (SH_t) required to realise the optimised production schedule during each week of the planning horizon. Thus, taking the sum of PH_t and SH_t , we obtain the total required production hours of each week including set-up times. The solution to problem P1 is evaluated according to the sum of backorder and overtime costs. The overtime costs are calculated by considering the difference between the total required production hours and actual regular time capacity, cr .

In the optimised production schedule, the required production hours PH_t might imply positive overtime for certain weeks. In this case, the additional overtime (AO_t) implied by the set-up times is equal to SH_t . On the other hand, if there is no overtime caused by PH_t , then AO_t is equal to total production hours minus regular time capacity ($\max\{0, PH_t + Sh_t - cr\}$), which is zero. Hence, AO_t is equal to the minimum of set-up times and the overtime caused by total production hours. The amount of weekly capacity (CD) to be deducted from RC in the next iteration, is the average of AO_t over the whole planning horizon. Hence, we consider only the additional overtime caused by set-up times in reducing the regular time capacity for the next iteration. This completes the calculations of one iteration.

In the next iteration, problem P1 is re-solved with cr substituted by RC. Total costs pertaining to the solution are calculated as in formulation 3.4 in Table 5, and if

they are lower than the previous iteration's total costs, then CD is calculated again to continue with the iterations. Otherwise, the algorithm stops with the best incumbent solution which represents the MPS.

Thus, the algorithm deducts some capacity from regular time capacity at each iteration, so that total required production hours are decreased both by saving on the production amount of families and probably, on the number of different families produced. Consequently, the algorithm tends to balance overloads among different weeks by squeezing the regular time capacity which dominates problem P's solution.



Table 5. The iterative algorithm**1. INITIALISE**

Regular time capacity (RC) = cr

Minimum Incumbent Cost (MIC) = ∞

2. SOLVE PROBLEM P1 (Substitute RC for cr)**3. ANALYSE THE SOLUTION GIVEN BY P1**

3.1. Prepare the MPS according to the PR_{kjt} values in the solution.

3.2. Calculate required production hours (PH_t) and set-up time (SH_t) for each week.

3.3. Additional Overtime (AO_t) = $\min\{SH_t, \max\{0, PH_t + SH_t - cr\}\}$.

3.4. Total Costs (TC) = $\sum_t \max\{0, PH_t + SH_t - cr\} c_o + \sum_k \sum_t c b_k B_{kt}$

4. If $TC < MIC$, go to **Step 5**. Else, **STOP**.

5. Prepare for the next iteration:

5.1. Weekly Capacity Deduction (CD) = $\sum AO_t / T$.

5.2. $RC \leftarrow RC - CD, \forall t$.

5.3. $MIC \leftarrow TC$.

5.4. Go to **Step 2**

Table 6. The Variables and Parameters of the iterative algorithm

VARIABLES AND PARAMETERS	
RC	: Regular time capacity
MC	: Minimum Incumbent cost
CD	: The amount of weekly capacity
TC	: Total cost
T	: Whole planning horizon
co	: Overtime cost TL/hour
cr	: Original regular time capacity
PH_t	: Production hours for week t
SH_t	: Set-up times for week t
AO_t	: Additional overtime for week t
cb_k	: Backorder cost for order k (TL/unit-week)

VI. IMPLEMENTATION

6.1. Planning for the Bottleneck Operation

As already indicated, the bottleneck operation is the painting department and the MPS is prepared for this specific operation. The process time is also very long in the painting department and as it is a chemical reaction the process time cannot be shortened effectively. The model P1 and the iterative algorithm are applied using the data pertaining to the painting department. Then, weekly plans for the edge-cutting and net sizing departments are prepared according to a pull system.

In the painting department there exist 14 different product families which differentiate according to colour complements. Front-doors and filling materials are painted in this department. Weekly orders are grouped according to different colour complements and integrated into the model P1 in terms of product families.

Table 7. The colour complements according to front-doors and filling materials

Colour Complements	Front-doors	Filling materials
1A	A1	MC
2A	A2	ME, KA
3A, 3B, 3C, 3D, 3E	A3	MS
4A, 4B, 4C, 4D	A4, T1	ML, MM, FM
5A, 5B, 5C, 5D, 5E, 5F	A5, T3	RL, MR, FR
6A, 6B, 6C, 6D, 6E	T2	PL
7A	R1, R2	SL
8A, 8B, 8C	G1	LM
9B	D1	-

* The colour complements in the coloured rows are colour of laminates means they are not painted in the painting department .

The Sales department provides the next three weeks' orders to the Planning department through the Customer Order Control department. The proposed planning system is applied on a rolling horizon basis and revised every week to take into account another week's order data. The current week's production plan is frozen. At every revision, the current order backlogs are incorporated into the model and the maximum delay time, Δ_k , for each order is updated by decreasing it by one time unit. For the purpose of this study, we assume that Δ_k is the same for each order.

The parameter values to be used in the formulation P1 are given in **Table 8**. Notice that Δ_k , S_j , and c_j are constant over all orders and families, respectively. The regular and overtime capacities are also constant over the planning horizon.

Table 8. Parameter values.

co	Δ	S	c	cr	or
66000 TL/ hour	2 weeks	0.25 hours	0.1 hours	45 hours/ week	39 hours/ week

In **Table 10.a,b,c**, three weeks' customer orders specified by front-door characteristics (data belongs to the current year) are listed indicating customer/order code, colour complement code, quantity (units) and edge-cutting program.

Weekly loads in hours are also given in **Table 10.a,b,c** excluding set-up times. In this particular set of data, we observe that the same customers do not give different orders in consecutive weeks. Hence, each customer is identified with the week that the order is given. Consequently, the second set of constraints found in P1, which consider accumulated orders, are eliminated from the formulation.

Among the edge-cutting programs indicated in **Table 10.a,b,c**, R1, R2, A1..A5, T1..T3, D1 and G1 are actual edge-cutting programs whereas the other codes represent filling materials.

The orders in **Table 10.a,b,c** are grouped according to colour complement code not considering if it is a front-door or a filling material, so that the demand data are properly integrated in the MPS model. For instance, the order quantity of colour 4A in order 12 in the 16th week is the sum $24+11=35$. Hence, aggregate data are obtained by grouping the order end items according to product families. The backorder variables, on the other hand, aggregate the data according to order codes. For instance, the backorder

quantity for order 12 in the 16th week represents total backordered quantities for both families 4A and 5D.

The backorder costs represent the weekly amount of interest (2%) lost due to delayed sales income. The prices of goods depend on production costs. The backorder cost of an order is calculated by multiplying the weekly interest rate by the weighted average of the prices of end items within the order.

As mentioned before, the price policy is determined by the differences of the materials used for the front-doors and the filling materials. It also depends on the edge-cutting programs. The price correlation between the models is given in **Table 9**. As easily can be seen from tableau, the correlation factor increases when the materials used are expensive.

Table 9. The price correlation between the models.

R2	R1	A1 - A2 - T1 -T2	T3	A3 - A4 - A5	D1-G1
1.00	1.59	3.53	3.82	4.28	5.16

The data in **Tables 8 and 10.a,b,c** have been imbedded in the formulation of problem P1 which is made up of 312 constraints and 515 variables. If model P were used instead, 60 constraints and 60 integer variables would have been added.

The iterative algorithm is then applied to obtain the least costly MPS. The algorithm iterates four times and these iterations are displayed in **Table 11** with their corresponding costs and the capacity utilisation profile over the weeks. The detailed MPS tableau consisting of production quantities of order indexed product families is omitted here. Note that the planning horizon is pushed three weeks ahead due to the fact that this lead time is required for the upstream operations of rough sizing, net sizing and edge-cutting. Namely, an order arrival of the 16th week is treated as an arrival of the 19th week. Thus, the MRP package provides the order releases for the rough sizing department by offsetting the MPS with the appropriate lead time. Had the bottleneck operation been other than the painting operation, the MPS would have been prepared for that bottleneck operation and the production lead time would be arranged accordingly.

Table 10.a. Orders of the 16th week :

16th week			
Working hours		69.7	
Customer Code	Colour Code	Quantity	Edge-Cutting Program
11	4C	61	A4
12	4A	24	T1
13	4A	26	T1
14	3E	73	A3
15	4B	13	T1
16	4B	20	T1
17	4B	30	T1
18	4A	21	T1
19	4B	32	T1
110	2A	27	A2
111	4A	21	ML
11	2A	26	ME
12	4A	11	ML
12	5D	17	RL
13	4A	5	ML
13	4B	9	ML
13	4B	4	MM
112	2A	39	ME
11	4C	18	FM
112	4A	3	ML
14	2A	32	ME
14	3E	26	MS
15	4B	12	ML
15	4B	1	MM
15	5E	18	RL
16	4A	1	MM
16	5E	16	RL
17	4B	1	MM
17	4B	1	ML
17	5D	16	RL
18	4A	5	ML
18	4A	3	MM
18	5A	11	RL
113	4B	2	MM
113	5A	21	RL
114	4A	1	MM
19	4B	13	ML
19	5D	22	RL
110	2A	13	ME
110	5C	1	MR
110	5C	1	FR

Table 10.b. Orders of the 17th week :

17th week			
Working hours		58.3	
Customer Code	Colour Code	Quantity	Edge-Cutting Program
21	4B	25	T1
22	4A	8	T1
23	4B	38	T1
24	4C	30	T1
25	3D	18	A3
26	4C	54	T1
27	4C	11	A4
28	4D	44	T1
28	5E	2	T3
28	4D	21	ML
28	5E	11	RL
28	2A	1	KA
27	4C	3	FM
21	5D	18	RL
29	4B	7	ML
210	4A	1	MM
210	5D	11	RL
211	4A	1	MM
211	5D	11	RL
212	4A	2	MM
212	5D	13	RL
213	2A	1	KA
213	5B	10	RL
214	6E	13	PL
215	5E	14	RL
216	5D	7	RL
217	4B	1	MM
217	5B	7	RL
217	5C	16	RL
218	4B	2	MM
218	5E	25	RL
219	5E	21	RL
22	4A	14	ML
23	4B	12	RL
23	5B	21	RL
24	4A	1	MM
24	4C	21	RL
24	5E	2	MS
25	3D	2	MS
25	5E	8	RL
26	4C	55	ML

Table 10.c. Orders of the 18th week :

18th week			
Working hours		88.8	
Customer Code	Colour Code	Quantity	Edge-Cutting Program
31	4C	26	A4
31	5A	2	A5
32	3D	22	A3
33	4A	28	T1
34	4B	23	T1
35	5C	27	T3
36	4C	29	A4
37	5E	26	T3
38	3E	30	A3
39	4C	44	T1
310	4C	35	T1
311	4B	31	T1
312	4C	23	A4
313	4C	41	T1
314	4C	55	T3
31	4A	1	MM
31	4C	3	FM
31	5A	4	FR
31	5E	14	RL
32	2A	12	ME
32	3D	13	MS
33	4A	1	ML
33	4A	5	RL
33	5D	19	RL
34	4B	10	ML
34	5C	6	RL
35	2A	6	KA
35	5F	22	RL
35	5C	20	RL
36	5E	21	RL
37	4D	10	ML
37	5E	21	RL
38	2A	16	ME
38	3E	13	MS
39	2A	4	KA
39	4C	9	ML
39	5A	23	RL
310	4A	4	MM
310	4C	8	ML
310	5B	27	RL
315	2A	20	ME
311	4B	14	ML
311	5D	15	RL
312	2A	1	KA
312	4C	11	FM
312	4C	10	MM
313	4C	11	ML

18th week (continued)			
Working hours		88.8	
Customer Code	Colour Code	Quantity	Edge-Cutting Program
313	5E	28	RL
316	5A	1	RL
317	4A	1	MM
317	5D	13	RL
314	4B	3	MM
314	4B	31	ML
314	5D	17	RL



Notice the difference between the initial capacity utilisation profile and the one belonging to the best (third) iteration in Table 11. The latter profile is much more smooth than the former resulting in reduced overtime costs.

Unfortunately, it is not possible to compare the best MPS (obtained at the third iteration) with the optimal solution of model P, since model P has been attempted to be solved by the package HyperLindo on an IBM 486 PC and the optimal solution could not be obtained within a computation time of 24 hours. However, we believe that the iterative algorithm provides a near-optimal solution.

Table 11. The MPS module's iterations resulting in the production plan for the weeks 19 to 23.

Weeks	19	20	21	22	23	Backord. Costs	Overtime Costs	Total Costs	RC	CD
FIRST ITERATION	Capacity Utilisation (hours)									
PH_t	45.00	44.88	45.00	35.45	43.69	59925	450120	510045	45.00	1.37
PH_t + SH_t	46.75	47.13	47.25	37.80	45.69					
Overtime	1.75	2.13	2.25	0	0.69					
AO_t	1.75	2.13	2.25	0	0.69					
SECOND ITERATION	Capacity Utilisation (hours)									
PH_t	43.33	43.33	43.63	41.68	43.33	63186	156420	219606	43.63	0.47
PH_t + SH_t	45.08	45.83	45.88	44.68	45.58					
Overtime	0.08	0.83	0.88	0	0.58					
AO_t	0.08	0.83	0.88	0	0.58					
THIRD ITERATION	Capacity Utilisation (hours)									
PH_t	44.25	42.68	43.16	42.60	42.68	62639	132660	195299	43.16	0.40
PH_t + SH_t	45.75	44.93	45.41	45.85	44.93					
Overtime	0.75	0	0.41	0.85	0					
AO_t	0.75	0	0.41	0.85	0					
FOURTH ITERATION	Capacity Utilisation (hours)									
PH_t	45.84	42.28	42.76	42.30	42.29	61070	207900	268970	42.76	-
PH_t + SH_t	47.59	44.53	45.01	45.55	44.54					
Overtime	2.59	0	0.01	0.55	0					
AO_t	1.75	0	0.01	0.55	0					

However, only 3 weeks' data are not sufficient for reaching a valid conclusion about the performance of the MPS module. The capacity utilisation levels shown in Table 11 may seem lower than they actually are and hence, the situation favours the proposed MPS module. Therefore, the planning horizon is rolled twice, taking into account the 22nd and 23rd weeks' orders (actually, 19th and 20th weeks' orders). The

effects of an ongoing planning horizon are thus reflected. **Table 12.a,b** list the orders of the 19th and 20th weeks along with their workloads.

Table 12.a. Weekly orders, 19th week :

19th week			
Workload hours 63.6			
Customer Code	Colour Code	Quantity	Edge-Cutting Program
41	4C	35	T1
41	5C	22	ME
41	3D	30	MS
42	3E	45	A3
42	4C	24	MM
43	4A	16	MM
43	4C	12	FM
43	4B	45	T1
44	4B	37	T1
45	5D	21	RL
45	5A	28	A5
46	4C	37	T1
47	2A	30	A2
47	3E	28	RL
47	4B	15	ML
48	5E	34	FM
48	4C	44	T1
49	4B	44	MM
49	2A	29	KA
49	4A	35	T1
410	4C	25	T1

Table 12.b. Weekly orders, 20th week :

20th week Workload hours 35.4			
Customer Code	Colour Code	Quantity	Edge-Cutting Program
51	4B	30	T1
51	4A	10	MM
51	5D	8	RL
52	4A	25	T1
52	4C	20	T1
53	5C	30	T3
53	3D	20	ML
54	4C	11	FM
54	4C	11	A4
55	2A	13	ME
55	3E	5	MS
55	4B	14	T1
56	2A	13	KA
56	5E	26	T3
57	4A	17	T1
58	4C	15	T3
58	3D	14	ML
58	5D	7	RL
59	4C	4	FM
59	4D	12	T1
510	4A	11	T1
510	4B	15	T1
510	5C	12	T3
510	4C	11	A4

Table 13 demonstrates the iterations accomplished when the orders of the 22nd week (actually 19th week) are added to the model. In this case, the amount produced in the 19th week (specified by the third iteration's MPS in **Table 11**) is deducted from the demand of orders arrived on the 19th week (16th week). The production lead times are also updated accordingly. Only two iterations have occurred in **Table 13** due to the fact that the average production hours required per week during the weeks 20 to 24 exceeds the regular time capacity. Consequently, it is not possible to smooth the capacity utilisation profile by reducing RC. **Table 14** tabulates the iterations made to generate the production plan for the weeks 21 to 25 where the orders of the 23rd week (20th week) are added.

Table 13. The MPS module's iterations resulting in the production plan for the weeks 20 to 24.

Weeks	20	21	22	23	24	Backord. Costs	Overtime Costs	Total Costs	RC	CD
FIRST ITERATION	Capacity Utilisation (hours)									
PH_t	53.60	46.20	45.00	44.70	45.00	76151	1419000	1495151	45.00	2.34
PH_t + SH_t	56.10	48.70	48.00	46.70	47.00					
Overtime	11.10	3.70	3.00	1.70	2.00					
AO_t	2.50	2.50	3.00	1.70	2.00					
SECOND ITERATION	Capacity Utilisation (hours)									
PH_t	63.00	43.90	42.60	43.60	42.60	68791	1541100	1609891	42.66	-
PH_t + SH_t	65.75	46.15	45.60	45.85	44.35					
Overtime	20.75	1.15	0.60	0.85	0					
AO_t	2.75	1.15	0.60	0.85	0					

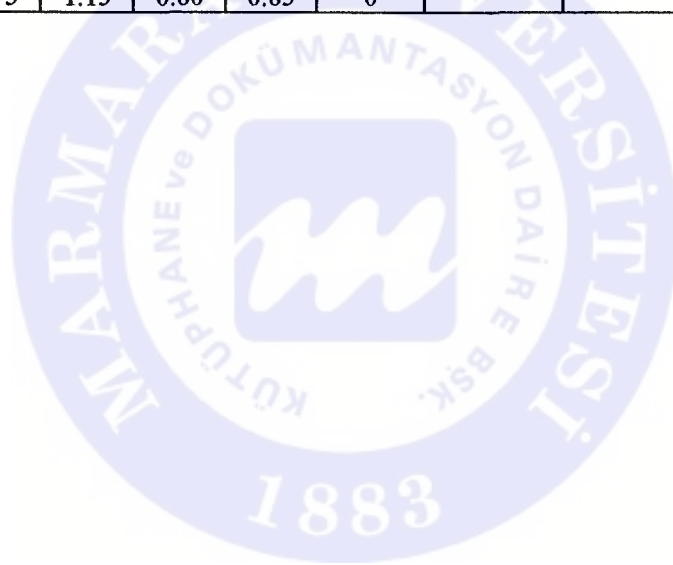


Table 14. The MPS module's iterations resulting in the production plan for the weeks 21 to 25.

Weeks	21	22	23	24	25	Backord. Costs	Overtime Costs	Total Costs	RC	CD
FIRST ITERATION	Capacity Utilisation (hours)									
PH_t	45.50	36.60	45.00	45.00	40.40	104608	379500	484108	45.00	1.05
PH_t + SH_t	47.25	39.60	46.75	46.75	42.80					
Overtime	2.25	0	1.75	1.75	0					
AO_t	1.75	0	1.75	1.75	0					
SECOND ITERATION	Capacity Utilisation (hours)									
PH_t	44.50	38.10	44.00	43.90	40.40	102936	191400	294336	43.95	0.58
PH_t + SH_t	46.50	40.60	45.75	45.65	42.40					
Overtime	1.50	0	0.75	0.65	0					
AO_t	1.50	0	0.75	0.65	0					
THIRD ITERATION	Capacity Utilisation (hours)									
PH_t	44.00	39.80	43.30	43.40	40.40	102388	62700	165088	43.37	0.19
PH_t + SH_t	45.75	42.80	45.05	45.15	42.40					
Overtime	0.75	0	0.05	0.15	0					
AO_t	0.75	0	0.05	0.15	0					
FOURTH ITERATION	Capacity Utilisation (hours)									
PH_t	43.80	40.40	42.80	43.20	40.40	102321	3300	105621	43.18	0.01
PH_t + SH_t	45.05	43.15	44.55	44.95	42.40					
Overtime	0.05	0	0	0	0					
AO_t	0.05	0	0	0	0					
FIFTH ITERATION	Capacity Utilisation (hours)									
PH_t	43.70	40.50	43.10	43.20	40.40	102243	19800	122043	43.17	-
PH_t + SH_t	45.20	43.50	45.10	44.95	42.40					
Overtime	0.20	0	0.10	0	0					
AO_t	0.20	0	0.10	0	0					

The actual weekly workloads realised in the factory during the same planning period is given in **Table 15**. The least costly MPSs given in **Tables 11, 13 and 14** can be compared with the actual production plan found in **Table 15**. The actual planning policy is to complete each order in the week of its arrival as long as there exists sufficient production capacity. The detailed plan implied by **Table 15** is omitted here, but we remark that only a single order belonging the 21st week (18th week) is backordered to the next week due to capacity restrictions. In the actual planning policy, there is no effort to balance the overtime costs with the backorder costs. This is due to the fact that there is no formal due date setting procedure which takes capacity restrictions into account. There is one more negative effect of this policy apart from excessive overtime costs. When urgent orders arrive, valid due dates cannot be given because capacity is already used at its maximum level. This issue is a constant bother to the planning department. Another point to remark is that analysing the plan provided by the MPS, we discovered that the average production lead time calculated over all five weeks' orders is 1.13 weeks excluding the week of order arrival. This value is quite acceptable since the company policy is to set Δ_k to two weeks after the arrival date.

Table 15. The actual production plan over the weeks 19 to 23.

Week	19	20	21	22	23	Backord. Costs	Overtime Costs	Total Costs	cr
PH_t	69.70	59.00	80.30	70.80	35.40	30240	7345800	7376040	45.00
PH_t + SH_t	72.45	62.00	83.55	73.30	37.90				
Overtime	27.45	17.00	38.55	28.30	0				

In order to make a valid comparison between the actual and the proposed plans, we isolate the costs belonging to the weekly MPS fixed for the weeks 19 to 21. Note that the plan for the 22nd week will change when the plan will be rolled once more. **Table 16** demonstrates the latter comparison. The backorder costs in both plans include the backorder costs of the orders incomplete by the 21st week.

Table 16. Comparison between the proposed and actual production plans.

Week	19	20	21	Backorder Costs	Overtime Costs	Total Costs
Proposed Plan						
PH_t	44.25	53.60	43.80	42347	785400	827747
$PH_t + SH_t$	45.75	56.10	45.05			
Overtime	0.75	11.10	0.05			
Actual Plan						
PH_t	69.70	59.00	80.30	30240	5478000	5481024
$PH_t + SH_t$	72.45	62.00	83.55			
Overtime	27.45	17.00	38.55			



6.2. Planning of Upstream Operations

All upstream operations are planned according to the MPS of the painting department. Since the edge-cutting department is the next capacity bottleneck in the process flow, we analyse the capacity utilisation profiles of this department imposed by the MPS and by the actual production plan. **Table 17** displays this information. The processing time of the family group T1..T3 is 4 min./unit and the one for the group A1..A5 is 10 min./unit. Furthermore, the changeover time between the groups A1-A2, A3..A5 and T1..T3 takes 30 minutes each. The weekly regular time capacity of the edge-cutting department is 40 hours. In **Table 17**, the italic figures demonstrate the capacity utilisation levels fixed at each week that the plan is rolled. Notice that as the plan is updated on a weekly basis, the capacity utilisation figures in the weeks 18 to 20 reach their normal levels. Furthermore, the erratic workload implied by the actual plan in the painting department also affects the loads in the edge-cutting department.

Table 17. Capacity utilisation profiles in the edge-cutting department imposed by the MPS and the actual production plan.

Week	Capacity Utilisation (hours)						
	18	19	20	21	22	23	24
Imposed by the least costly MPS in Table 4	<i>31.66</i>	19.86	24.86	13.00	14.00		
Imposed by the least costly MPS in Table 6	<i>31.66</i>	<i>27.30</i>	17.16	30.66	17.23	12.30	
Imposed by the least costly MPS in Table 7	<i>31.66</i>	<i>27.30</i>	<i>27.53</i>	25.16	9.60	17.70	21.76
Imposed by the actual plan in Table 8	<i>39.40</i>	<i>19.10</i>	<i>39.10</i>	<i>44.53</i>	<i>19.93</i>		

6.3. Software Requirements

In order to achieve the least costly MPS, it is necessary to solve problem P1. The linear programming package HyperLindo is used on an IBM compatible 486 PC for this purpose. The outputs are then transferred to the Microsoft spreadsheet software EXCEL 5.0. Capacity utilisation profiles, costs and the capacity reduction for the next iteration, CD, are obtained by using EXCEL. All these steps take place in a few seconds. However, the modifications (adding new orders, updating existing demand and order lead times) which have to be incorporated in the formulation each week of the rolling horizon are made manually. Regrouping production quantities of end items for the upstream operations is also carried out manually. The interaction of the MPS with EuroPRO+ poses no problem, since the MRP package reads EXCEL sheets.

The proposed planning system can be fully automated by using a fourth generation programming tool, such as SQLWindows, operating under WINDOWS and having strong database features. Furthermore, using this tool, the problem P1 can be reformulated automatically by database manipulations which incorporate new data into the formulation. Input/output transfer between the linear programming package and WINDOWS can be managed through DOS-WINDOWS transition. The end item disaggregation of the MPS and the preparation of plans for upstream operations represent simple database operations. All similar database manipulations can be easily handled by this tool. Using WINDOWS applications is also important from the user-friendliness point of view. The user may modify the MPS provided by the iterative algorithm according to his/her preferences and observe the consequences on capacity utilisation and total costs. This type of support is easily given to the users on the spreadsheet - like interface of the SQLWindows application. Automating the system in this manner results in its fast-and-easy use and enables the user to simulate scenarios involving the assignment of different production lead times to orders so that hot orders can be squeezed in or smoother capacity utilisation profiles are obtained.

VII. CONCLUSION

The subject of concern in this thesis is the development of a Master Production Schedule (MPS) for a make-to-order manufacturing company. The MPS acts as a capacity and lead time manager and provides order due dates as well. The validity of due dates is achieved via the resource-feasible production plan that the MPS provides for the bottleneck operation. Other operations are planned by offsetting the MPS appropriately.

The MPS is prepared by using a linear mathematical model which is flexible in terms of reflecting implicit order priorities. The size of the model is reduced by aggregating end item data into product families. Set-up times which consume considerable capacity are included in the plan through an iterative heuristic algorithm which reserves some more capacity for set-up times at each iteration. The system provides smoother capacity utilisation profiles and a formal due date assignment procedure to be used at the customer enquiry stage.

The proposed planning system is compared with the actual one which involves an informal capacity and due date management system. The proposed system reinforces current efforts to establish formal planning procedures in the production planning department and enables cost reduction while providing reasonable due dates.

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