Manufacturing strategy incorporated in aggregate production planning through a multi-objective linear programming model

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Abstract
Aggregate Planning activity is a relevant stage of the production planning process and has been regularly discussed in the literature for almost 50 years. It seeks to suggest a production strategy in order to meet demand, given capacity constraints. This paper presents a model based on multi criteria decision analysis to overcome the problem of aggregate planning. This decision model takes into account performance objectives obtained in the manufacturing strategy planning process. To do so, the decision maker chooses the most appropriate combination of resources to meet foreseen demand, in accordance with trade-offs amongst the performance objectives. Therefore the resulting aggregate plan reflects the competitive factors of the business. That is, the proposed decision model allows the implementation of the manufacturing strategy by the production function.

Keywords: Aggregate Planning, Manufacturing Strategy, Multi Criteria Decision Analysis, Multiple Objective Linear Programming, Step Method.

INTRODUCTION

Aggregate Planning is an important topic that has been regularly discussed in the literature for almost 50 years. Despite several works having been published in this area, most of the models developed that consider multiple objectives only consider different kinds of production costs. Recently, some papers have used new objectives in their models of aggregate planning, by considering new criteria such as variations in manpower, the tangible and intangible costs associated with the planning alternatives, and so forth.

Recently published models for aggregate planning problem use concepts of fuzzy sets (WANG & FANG, 2001; WANG & LIANG, 2005), stochastic programming (KIRA et al., 1997), multi-objective tabu search (BAYKASOGLU, 2001), genetic algorithms and multi-objective genetic algorithms (STOCKTON et al., 2004th; STOCKTON et al. 2004b; LI & MAN, 1998) and accounting consequences of the losses in aggregated planning (PIPER & VACHON, 2001).

In spite of some authors having used a multiple criteria approach for the aggregate planning problem, no-one has sought to integrate the objectives or goals defined in manufacturing strategy to the objectives and strategies (aspects of manpower, stock costs, regular production regime, outsourcing regime and other intangible costs) of aggregate planning. In this paper, a multi-objective model for aggregate planning that includes the context of manufacturing strategy in the aggregate planning of production will be presented.

In order for aggregate planning to be aligned with the manufacturing strategy adopted by the company, the winning aspects of orders (performance objectives) will be optimized to increase the company´s competitive advantage. So the production alternative chosen will help the production function to implement the manufacturing strategy.

In this paper, an expression (Equation 3) is proposed to quantify those winning aspects of orders. This expression will be maximized to achieve the best performance in these winning aspects, so that, in the end, it will be possible to choose a compromise solution, considering all the winning aspects, which implies best sales.

AGGREGATE PLANNING

Aggregate Planning represents one of the most important decisions in the medium term, by forming a connection between Capacity Planning and Production Programming and Control (PPC) (SLACK et al., 2003; MONKS, 1982; HEIZER & RENDER, 1993; GAITHER & FRAZIER, 1999; DAVIS et al., 2004).

Aggregate Planning consists of drawing up a strategy to meet demand. To make it feasible, several changes in production level will be necessary to follow demand

forecast in the horizon planning. This horizon planning takes place in intervals between six and twelve months in most of cases. This balancing can be undertaken by acting on the productive resources capable of influencing and changing production capacity in the short and very short term. It seeks to combine these productive resources in a way to meet the demand and simultaneously reach the minimum cost possible.

To keep production in balance with demand, several options are used such as hiring and firing employees, making use of overtime, subcontracting a part of production, accumulating stocks in the months of low demand and using them to cover excess demand in months of high demand, and so on.

However, Aggregate Planning can be used as an inverse guide, when the problem to be tackled is not a deficit in production, but rather a deficit in demand. In this sense, the search will be to eliminate loss-making resources, by seeking to reduce production costs so that these might be adapted to periods of insufficient demand.

Each one of these alternatives can be related directly and / or indirectly to a cost. In considering these costs, the models of Aggregate Planning seek a solution that minimizes the total production cost for the horizon of time over which the planning is made. To do so, an analysis is made of the costs involved in compiling a set of production alternatives to change the production levels in each period t, where these costs are represented by *PCt* (*Production Cost* in the period *t*). In this way, the total production cost for the n periods is:

$$PC = \sum_{t=1}^{n} PC_t$$

(1)

The Production Cost in each period t includes costs that vary according to the number of employees hired/ fired (*At, Dt*), the number of units stored in the stock (*STt*) and the number of units produced in each of the respective production regimes (*Rt, Ot, St*). This cost can be expressed as in Equation 2:

$$CP_t = C_r r_t + C_o o_t + C_s s_t + C_D D_t + C_A A_t + C_{ST} ST_t$$

(2)

An Aggregate Planning solution determines the combination of each combination of production alternatives in each period such that, at the same time that production meets demand, the total production cost (*PC*) is minimized to the smallest possible amount.

Among the models that assume that the variation of costs is linear, the literature presents the Model of Trial and Error and the Linear Programming Model as the most well-known. Eilon (1975) presents three other models. However, the two models previously mentioned appear in the literature as the best known.

MANUFACTURING STRATEGY

Manufacturing strategy is defined in the literature as a collection of decision models to determine structure, resources and infra-structure of a production system. However, Miller & Hayslip (1989) define manufacturing strategy as a projected pattern to production alternatives made to improve results on the performance objectives and support the business strategy.

For Wheelwright (1984), the main objective of manufacturing strategy is to develop and support durable competitive advantages. Thus, an efficacious strategy may not imply production with maximum efficiency, but production which fits in with business needs. For this reason, it can be concluded that decisions made in this field might consider a multi-criteria approach, because it does not make sense to consider only one single objective optimal solution (for example, Cost), but a compromise solution where all objectives which represent the business needs have been considered (which may not lead to maximum efficiency), and all objectives have obtained the best results considering the proportional importance to business needs so that, in the end, durable competitive advantage can be achieved.

There are many concepts and classifications about the aspects that bring competitive advantage in manufacturing. Miller & Roth (1994) summarized and developed one taxonomy for manufacturing strategy. Miller & Roth (1994) used cluster analysis to identify eleven aspects to competitive advantage in manufacturing strategy. These aspects are Low Price, Design Flexibility, Volume Flexibility, Conformance, Product Performance, Delivery Speed, Dependability, After-Sales Service, Publicity, Broad Distribution and Broad Product Line.

Performance Objectives

In the literature, lists of these competitive aspects (capabilities) can generally be summarized into five performance objectives to achieve competitive advantage based on manufacturing. These objectives are Cost, Quality, Dependability, Flexibility and Speed (HILL, 1993; SLACK et al., 2003; SLACK, 1992).

As to Quality, manufacturing strategy basically seeks to improve product quality through the reduction of the non-conformance item index. Making "better products" can mean several things, from "deluxe products" and "built-in quality" discussed lately for all dimensions proposed by Garvin (1987).

The objective Speed seeks to make minimize the lead time to produce and deliver an order. To achieve good results for Speed, it is necessary to improve acquisition processes and all logistics operations. In manufacturing strategy, the speed and dynamics of releasing a new product is also related to this performance objective. This approach is considered very often in technology industry.

Dependability means the capability of the production system to estimate and accomplish order / delivery deadlines, keeping the product's integrity until it is under the client's responsibility.

The objective Flexibility can have many meanings like Quality, because there is a wide field where flexible capabilities are needed in a production system, so Flexibility can take into account the number of models on offer, its capability for adapting to different production levels, being able to adapt orders to special client requests and being able to handle special clients, for example. In the end, what should be expected from a good performance in Flexibility is the capability to satisfy different needs in production.

For Cost, there is only one meaning: to minimize production costs and consequently to minimize product price for customers or to maximize profits for the company. Maybe that is the oldest objective, or in other words, the "natural objective" of any industry. That is why, in most cases, it is one of the most important objectives in production systems.

Performance Objectives Classification

To support the decisions made in a manufacturing strategy context, it is necessary to establish the priority between the performance objectives. Hill (1993) proposed a performance objectives classification which gives one easy way to prioritize these objectives, taking into account the competitive value or utility, given an improvement in each objective.

These objectives are classified into Order Winners Criteria and Order Qualifiers Criteria. Figure 1 shows the behavior of managerial effort to improve the level of performance objective results in terms of competitive advantage or competitive value to manufacturing.
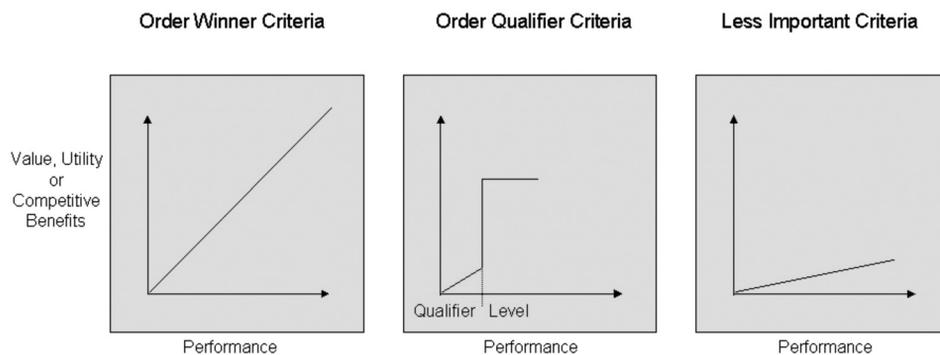

Figure 1 - Competitive Benefits from Performance Objectives, Adapted from Slack et al. (2003)

An object is an Order Qualifier Criterion if it has a critical level to be achieved. After satisfying this level, no improvement on this objective will be considered a competitive advantage. In other words, the customers will be satisfied when the manufacturing system achieves this critical level and any extra effort to give improvements in this objective will be a waste of managerial effort.

Some objectives do not have this property that makes customers satisfied. Each improvement in the objective will be perceived by customers and will represent competitive advantage. It can be used for resolving an evenly split outcome, making the decision favorable to the company which provides best levels for this kind of objective. So if a relevant objective follows this property, it is considered an Order Winner Criterion.

STEM – STEP METHOD

STEM (Step Method) is a method of progressive reduction of the feasible region. It was developed by Benayoun et al. (1971). This method is part of the set of interactive methods of multiple objective linear programming that is an extension of the classical model of linear programming for the case in which more than one objective function is considered.

The procedures for this method consist of ensuring that for each interaction, the decision maker specifies an amount which he is willing to sacrifice in a given objective function, the one for which the decision maker is satisfied with the result obtained. Therefore, what is sought is to improve the result of those other functions, the values of which do not satisfy him.

The search for satisfactory solutions in STEM is made through minimizing Tchebycheff´s weighted distance to the "ideal" solution. This "ideal" solution is a fictitious alternative represented by a solution that assumes in each objective function the optimum value of these functions when optimized. It is hard to imagine such an alternative might exist, since this combination of values becomes infeasible due to the conflicts that almost always exist when multiple objectives are considered. This is a characteristic found in multi-criteria problems.

At each iteration of the method, an optimization problem is solved, into which are incorporated the decision maker´s preferences. Each one of these calculation stages reflects the choices that the decision maker made previously, and in which the decision maker´s preferences can be noticed since the feasible region has been reduced.

At the end of iteration, the decision maker finds a compromise solution obtained through the minimization of Tchebycheff´s weighted distance to the "ideal" solution. The decision to maintain this compromise solution or to discard it is made by the decision maker, and this decision determines if another iteration should begin or if the process should finish.

PROPOSED MODEL

The proposed model seeks to ensure that a typical problem from the context of production planning allows the production function to implement the manufacturing strategy adopted.

A cost will associated with each alternative for meeting demand. Therefore, the proposed model seeks to find a strategy for meeting demand (obtained through Aggregate Planning) that is aligned with the defined manufacturing strategies, with regard to the priority and the established relationships among the performance objectives.

Thus, the manager (decision maker) can undertake the planning of the resources to be used in order to meet demand by prioritizing the performance objectives that best reflect the competitive factors of the business, and which represent consumers´ needs.

After defining the business strategy, the production managers define a manufacturing strategy so that the production function can develop the objectives and policies appropriate to their resources, by supplying the conditions necessary for allowing the company to reach its strategic objectives. Therefore, the performance objectives (HILL, 1993; SLACK, 1992) will be defined which will act as constraints (Order Qualifier Criteria, the production function should always satisfy a given minimum level of performance) and the others that should be maximized or minimized through an objective function (Order Winner Criteria).

The performance objective Cost appears traditionally in Aggregate Planning models through minimizing the total cost of production.

The other performance objectives (Quality, Dependability, Speed and Flexibility) should be maximized. In this paper, a standard form is defined which may represent them without loss of generality. However, the parameters of this function will have a different meaning for each performance objective. This standard form represents the average level of a performance objective. Equation 3 represents this function:

$$\max \quad Obj_k = \frac{1}{n} \sum_{t=1}^{n} \left(\frac{\alpha_{rk} r_t + \alpha_{ok} o_t + \alpha_{sk} s_t}{r_t + o_t + s_t} \right) \tag{3}$$

This equation presents a generic expression to represent the average level of a given performance objective, where α_r, α_o, α_s are parameters that have a specific meaning for each performance objective (Quality, Dependability, Speed and Flexibility), representing in a generic way a performance index for each production regime in the context of a given performance objective. The result of this objective function is the average value obtained for a given performance objective over the whole planning horizon (n periods).

However, the expression of Equation 3 is not a linear expression, which violates the linearity hypothesis considered for the model, which leads us to a simplification that guarantees linearity. Instead of using the expression suggested above, a similar expression should be used that maximizes the expression suggested previously.

$$\max \quad Obj_k = \sum_{t=1}^{n} (\alpha_{rk} r_t + \alpha_{ok} o_t + \alpha_{sk} s_t) \qquad \textbf{(4)}$$

This expression gives a measure of the global performance regarding the accumulated performance in the whole planning period. Through Equation 4, it is possible to use linear programming, so allowing the choice of one among the several methods of multiple objective linear programming, optimizing the global measures of the performance objectives considered, and keeping the specific meaning (for each performance objective) defined for the parameters.

The parameters α_r, α_o, α_s are established through the company´s knowledge regarding relative performance among different production regimes in the performance objective analyzed.

The equations below represent the proposed aggregate planning model, where the first constraint represents the smallest level admitted for the Order Qualifier Criteria.

$$\min \quad C = \sum_{t=1}^{n} (C_r r_t + C_o o_t + C_s s_t + C_D D_t + C_A A_t + C_{ST} ST_t)$$

$$\max \quad Obj_k = \sum_{t=1}^{n} (\alpha_{rk} r_t + \alpha_{ok} o_t + \alpha_{sk} s_t)$$

$$s/a$$

$$Obj_k \geq NObj_k$$
$$ST_t \leq N$$
$$r_t \leq u_r (E_{t-1} + A_t - D_t) \qquad \textbf{(5)}$$
$$o_t \leq u_h (E_{t-1} + A_t - D_t)$$
$$s_t \leq C_s$$
$$r_t + o_t + s_t + ST_{t-1} \geq d_t$$
$$ST_t = ST_{t-1} + r_t + o_t + s_t - d_t$$
$$E_t = E_{t-1} + A_t - D_t$$

The other constraints represent the relationships between the production alternatives and the productive system:

- capacity constraints on stocking products ($STt < N$);
- capacity in regular production regime by period ($r_t \leq u_r E_t$, where $E_t = E_{t-1} + A_t - D_t$);
- capacity of production under a regime of overtime by period ($o_t \leq u_o E_t$, where $E_t = E_{t-1} + A_t - D_t$);
- capacity in subcontracting production regime by period ($s_t \leq C_s$);
- demand to be satisfied in each one of the n periods ($d_t \leq r_t + o_t + s_t + ST_{t-1}$);
- volume of stocked products in period t ($ST_t = ST_{t-1} + r_t + o_t + s_t - d_t$)
- number of employees in period t ($E_t = E_{t-1} + A_t - D_t$)

NUMERICAL APPLICATION

In this section, a numerical application will be made to illustrate how the Multi-objective Aggregate Planning Model proposed can be used. For this, the numerical application was drawn up using data and characteristics found in the literature. The model presented will be applied on this application.

A fictitious company was considered where Cost and Dependability are considered Order Winner Criteria, so they should be optimized.

The other performance objectives (Quality, Flexibility and Speed) behave as Order Qualifier Criteria. These three classes of restrictions will not be incorporated into this application, because the hypothesis will be assumed that all production regimes and whatsoever combination of these do not have a performance level less than the minimum levels demanded by the customers. Therefore, there is no need to consider the Order Qualifier Criteria restrictions in this application.

The quantification of the Dependability parameters is given by the probability that an order is fulfilled on time. To find this value, company knowledge could be used about the relative frequency of delays in deliveries by each production regime. These probabilities are the parameters of the second objective function of the multiple objective linear programming model given below:

$$\min \quad F_1 : C = \sum_{i=1}^{n} (250r_i + 350o_i + 425s_i + 12500A_i + 36500D_i + 30ST_i)$$

$$\max \quad F_2 : Dep = \sum_{i=1}^{n} 0{,}95r_i + 0{,}80o_i + 0{,}70s_i$$

s/a

$$ST_t \le 1500$$
$$r_t \le 90(E_{t-1} + A_t - D_t)$$
$$o_t \le 30(E_{t-1} + A_t - D_t)$$
$$s_t \le 600 \tag{6}$$
$$r_t + o_t + s_t + ST_{t-1} \ge d_t$$
$$ST_t = ST_{t-1} + r_t + o_t + s_t - d_t$$
$$E_t - (E_{t-1} + A_t - D_t) \le 10$$
$$ST_0 = 0$$
$$E_0 = 8$$

where *t=1,2,...,12.*

The data on the problem can be visualized in the equations that comprise the model above, except for the demand foreseen which is described in table 1 below:

Table 1 – Foreseen Demand

Month (t)	1	2	3	4	5	6	7	8	9	10	11	12
Demand (d)	1200	1500	1250	1800	1350	2200	2100	2300	1580	1470	1350	1100

Several methods of multiple objective linear programming can be used to find a compromise solution to this problem. However, choosing STEM is justified because it is an interactive method that can be implemented easily (which adds greatly to the viability of using it) in order to minimize Tchebyneff´s weighted distance to the "ideal" solution independently of the decision maker, thus leaving subjectivity only to the stage of exploring the frontier of efficient or non-dominated solutions. During this stage, the decision maker looks for a solution to the problem by making trade-offs among the values obtained for each objective. By being about a numerical application of a fictitious example, only a few points will be considered in order to demonstrate how an efficient compromise solution can be chosen for this problem through this method of multiple objective linear programming.

In order to examine the problem thoroughly, the first stage of STEM consists of optimizing each one of the objective functions. The optimum value of each objective

function represents a "goal" which one desires to reach. This "goal" should be an "ideal" alternative, which has the greatest performance in all its objective functions.

The optimum found for the Cost objective function was a total annual cost of R$ 6,158,500.00. If this solution were chosen, the Dependability level would be 85.8%, i.e. an expected value of 16,490 units delivered within schedule.

When Dependability was optimized, the maximum result was 91.4% i.e. an expected value of 17.550 units delivered within schedule. To reach this performance level of Dependability, a total annual cost of R$ 6,913,600.00 is necessary. This increase of the index of Dependability is achieved due to the increase of stock levels, which provide a safety margin for the company.

In this stage, the decision problem consists of finding an intermediate alternative that is more balanced between the two criteria defined for this problem. The following stage of applying the STEM method consists of finding a feasible solution that minimizes Tchebycheff´s weighted distance to the "ideal" alternative. The weightings used were obtained through the STEM procedure for calculating weightings. However, the alternative that minimizes Tchebycheff´s weighted distance is the alternative that minimizes the total annual cost, not taking the Dependability objective into account. This is due to the fact that the variations occurring in the total annual cost are much greater than those occurring in Dependability.

Moving on to the following stage of STEM where there is interaction with the decision maker, the objective function of total annual cost was relaxed to improve the values of the objective function of Dependability that were not considered satisfactory

A decision maker could evaluate the trade-off between the losses arising from the increase of costs and the strategic earnings obtained by increasing the number of products delivered within schedule. In looking for an intermediate solution and evaluating the cost possibilities, it was arbitrated that a maximum cost of R$ 6,550,000.00 would be considered satisfactory since this promoted a performance increase in Dependability that justified this cost increase.

The solution obtained by relaxing the total annual cost function was that, at a total cost of R$ 6,550,000.00, it is possible to obtain a Dependability level of 89.1%, making it viable to expect a value of 17,106 items delivered on schedule. The solution obtained for the recommendation is described in table 2 below:

Table 2 – Final solution after the relaxation of the Total Cost

	Alternatives to Assist Demand	Regular Production Regime	Overtime Production Regime	Outsourcing Regime	New Employees' Admission	Employees' Dismissal	Units in Stock	Number of Employees	Demand
Month 0	0	-	-	-	-	-	0	8	-
1	1	900	300	0	2	0	0	10	1200
2	2	900	300	500	0	0	200	10	1500
3	3	900	300	600	0	0	750	10	1250
4	4	900	300	600	0	0	750	10	1800
5	5	900	300	600	0	0	1200	10	1350
6	6	900	300	600	0	0	800	10	2200
7	7	900	300	600	0	0	500	10	2100
8	8	900	300	600	0	0	0	10	2300
9	9	900	300	380	0	0	0	10	1580
10	10	900	300	270	0	0	0	10	1470
11	11	900	300	316	0	0	166	10	1350
12	12	900	300	600	0	0	866	10	1100
13	13	-	-	-	-	0	866	10	-

This solution was considered satisfactory for illustrating the approach proposed in this paper in order to obtain a solution for Aggregate Planning Problem that is aligned with the manufacturing strategy adopted.

CONCLUDING REMARKS

This paper has presented a multicriteria decision model to tackle the problem of Aggregate Production Planning that seeks to extend the priorities of manufacturing strategy for decision making in the context of Aggregate Production Planning. The proposed model quantifies the performance of the production alternative chosen in the aspects considered priority ones for a manufacturing strategy.

The application of this model allows the decisions taken in Aggregate Planning context (the amount of items to be produced in each production alternative for each period of the planning horizon, the stock levels along the planning horizon and the variations in manpower so that the demand foreseen is met) to be aligned with the manufacturing strategy adopted by the company, generating results that allow the production function to offer competitive advantage to the organization.

In the numerical application, use was made of an interactive method of multiple objective linear programming that could be implemented easily, thus making it viable to solve the problem contained in Microsoft Excel. Furthermore, this problem can be solved using LINDO, GAMS or any other optimization tool.

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Biography

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