Production Planning under Dynamic Product Environment: A Multi-objective Goal Programming Approach

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SOM theme A: Primary Processes within firms

Abstract

Production planning is a complicated task that requires cooperation among multiple functional units in any organization. In order to design an efficient production planning system, a good understanding of the environment in terms of customers, products and manufacturing processes is a must. Although such planning exists in the company, it is often incorrectly structured due to the presence of multiple conflicting objectives. The primary difficulty in modern decision analysis is the treatment of multiple conflicting objectives. A formal decision analysis that is capable of handling multiple conflicting goals through the use of priorities may be a new frontier of management science. The objective of this study is to develop a multi objective goal programming (MOGP) model to a
real-life manufacturing situation to show the trade-off between different some times conflicting goals concerning customer, product and manufacturing of production planning environment. For illustration, two independent goal priority structures have been considered. The insights gained from the experimentation with the two goal priority structures will guide and assist the decision maker for achieving the organizational goals for optimum utilization of resources in improving companies’ competitiveness. The MOGP results of the study are of very useful to various functional areas of the selected case organization for routine planning and scheduling. Some of the specific decision making situations in this context are: (i). the expected quality costs and production costs under identified product scenarios, (ii).under and over utilization of crucial machine at different combinations of production volumes, and (iii). the achievement of sales revenue goal at different production volume combinations. The ease of use and interpretation make the proposed MOGP model a powerful communication tool between top and bottom level managers while converting the strategic level objectives into concrete tactical and operational level plans.

1. Introduction

Production planning is a complicated task that requires cooperation among multiple functional units in any organization. Planning is the consequence of a hierarchy of decisions dealing with different issues in the manufacturing environment (Ozdamar et al., 1998). In order to design an efficient production planning system, a good understanding of the environment in terms of customers, products and manufacturing processes is a must (Olhager and Wikner, 2000). A proper production planning within these entities is a key condition to a manufacturing system success to deal with the limitations of efficiency and flexibility, and to consider the real world resource limitations (i.e., budget, time, labour,
etc.). Although such planning exists in the company, it is often incorrectly structured due to the presence of multiple conflicting objectives. Therefore, new tools for production planning are required that consider these issues. To choose between alternative courses of action and guide managerial decision making, a production manager has to have appropriate performance criteria (Tabucanon and Majumder, 1989). At the strategic level, these criteria are usually based on rather broad organizational objectives. For tactical and operations decisions, however, these general goals have to be converted into more concrete performance criteria that are amenable to measurement and tracking over time. The primary difficulty in modern decision analysis is the treatment of multiple conflicting objectives. A formal decision analysis that is capable of handling multiple conflicting goals through the use of priorities may be a new frontier of management science. Companies and research are therefore called upon to develop their own innovative ideas and to expand them to new tools and procedures. A classical approach to handle this multi-level decision making process is multi-objective goal programming (MOGP) approach.

Traditionally production plans in any manufacturing organization are developed through stages, aggregate production plan (APP); master production schedule (MPS); and short-term production schedule. The APP plays a key role in translating the strategies of the business plan into an operational plan for the manufacturing process. For example, it allows managers to determine that whether they can satisfy budgetary goals without having to schedule the company’s several product models and scarce resources. Even if a planner could prepare such a detailed plan, the time and effort required to update it would make it uneconomical. Here the information flows in two directions: from the top down and from the bottom up. If an aggregate plan cannot be developed to satisfy the objectives of the business or annual plan, the business or annual plan might have to be adjusted. Similarly, if a feasible MPS or work force schedule cannot be developed, the aggregate plan might have
to be adjusted. Thus, the planning process is dynamic, with periodic plan revisions or adjustments based on two-way information flows.

The economic significance of APP within firms has been well recognized. But, the most difficult problem encountered in APP is the fluctuations in product demands. By allowing overtime or idle time operations of the shop while maintaining a constant workforce can absorb demand fluctuations. So design of an appropriate production planning strategy is indeed a dynamic process that relates demand of goods. This decision problem has been the target of extensive research, and several linear mathematical models for finding the optimal strategy have since been introduced. In this regard, the reader is referred to Lee (1972) for a comprehensive review of various mathematical models. However, none of these suggested methods has found any widespread use in industry. One reason seems to be that industry is not yet ready to accept the use of formal mathematical models for production planning. But the primary reason seems to be that the proposed models are gross oversimplifications of reality, and moreover, they do not provide room to reflect management’s preferences or policies in the solution.

In reality, however, production planners take a number of objectives into account during the planning process. The reality can here be expressed as a ‘customer’ demanding a ‘product’ that is processed through a ‘manufacturing process’, and we have a production planning system for the planning and control of the dynamics of these elements as they interact. All the three entities customer, product, and manufacturing process create a very complex problem to be solved (Olhager and Wikner, 2000). The qualifiers in the perspective of production planning system design associated with the three entities are summarized in Table 1. For instance, under the customer entity, many of the typical order/market and the order winner qualifiers (e.g. quality, price and different aspects of flexibility), have large implications for the PPC system. According to Slack et al. (2000),
capacity utilization directly affects the speed of response to customers’ demand. Hence, by targeting operations, gains in flexibility, lead time and deliverability will be achieved. Delivery performance standards (e.g. product volume) relate an operation’s performance directly to its competitive ability in the market place.

Quite often, most of these goals are competitive in terms of need for scarce resources. In presence of incompatible goals the manager needs to exercise his judgement about the importance of the individual goals. Stated more simply, the most important goal must be achieved to the extent the management desires before the next goal is considered.

In order to achieve the ordinal solution i.e. to achieve the goals according to their importance, negative and/or positive deviations about the goal must be ranked according to the “preemptive” priority factors. In this way the low-order goals are considered only after higher-order goals are achieved as desired (Lee, 1972). Conventional linear programming is unable to encapsulate this kind of problem directly, as it can only handle a single goal in the objective function. Of course, by a combination of extensive modifications of right-hand side values in the constraints and sensitivity analysis, linear programming could be used, but would be extremely time consuming and unwieldy. The complexity of the problem can only be addressed explicitly through multi-objective decision models. Therefore, an effective application of such methods may be possible only at the expense of changing organizational goals.

In order to solve such multi dimensional planning problems, a flexible and practical methodology, known as goal programming (GP), was developed by Charnes and Cooper (1961). Since then many researchers have done a lot of work about extensions of goal programming methodology (such as preemptive/lexicographic linear goal programming, integer goal programming (Schniederjans and Hoffman, 1992), extended lexicographic goal programming (Romero, 2001), etc.) and extensive surveys on fields of
its applications (Lee, 1972; Schniederjans, 1995; Tamiz, M., Jones, D., and Romero, 1998) (such as production planning, financial planning, capital budgeting planning, agricultural running planning, etc.).

Table 1: The three entities for understanding the conditions for production planning environment

<table>
<thead>
<tr>
<th>Entity</th>
<th>Qualifiers in the perspective of production planning system design</th>
<th>Description</th>
<th>Sample performance measure(s) selected for the study presented in this paper</th>
</tr>
</thead>
</table>
| Customer                | ♦ The order qualifiers -- what is required by the customers  
♦ The order winner qualifier – what makes a product offer to a customer a winner (e.g. quality, price, flexibility) | Analyzing these properties of the customers, we obtain a picture of the customer values and can use this as a point of departure when designing the PPC system                                                                 | • Product quality                                                               |
| Product                 | Bill of materials (BOM) in order to support aggregate planning and multi-level master scheduling  
(e.g. product groups, representing the average product in the group, or modules that are assembled to order) | The BOM can be viewed as a hierarchy of deliverables in successive customer-supplier relations                                                                                                                      | • Production volume                                                            |
| Manufacturing process   | ♦ Material interface  
♦ Transformation process interface  
• Depending on the type of planning and control method used, the planning point must be modeled using certain properties, e.g. capacity, capability and process times to sufficiently describe the resources  
♦ Resource Interface | The three interfaces are models of reality capturing properties necessary to the PPC system. Also, specifically, the release of discrete orders works as a direct planning mechanism for the manufacturer.  

The system bottleneck is a key issue for the design of the PPC system. A bottleneck or constraining resource limits the output of the whole manufacturing system, and must therefore be monitored closely with respect to both capacity and material                                                                                       | • Sales Revenue  
• Production costs  
• Machine Utilization  
• WIP Inventory                                                             |
The objective of this study is to develop a multi objective goal programming model to a real-life manufacturing situation to show the trade-off between different some times conflicting goals concerning customer, product and manufacturing of production planning environment. For illustration, two independent goal priority structures have been considered. The insights gained from the experimentation with the two goal priority structures will guide and assist the decision maker for achieving the organizational goals for optimum utilization of resources in improving companies’ competitiveness. The ease of use and interpretation make the proposed MOGP model a powerful communication tool between top and bottom level managers while converting the strategic level objectives into concrete tactical and operational level plans.

1.1. The problem context

The organization selected for the present study is one of the leading precision machine tool manufacturing firms in India producing standard as well as sophisticated and advanced machine tools. To maintain the secrecy of data, we hide the company’s name as well as the exact financial figures while explaining the history of the case organization.

The company is organized in three divisions, namely machine tool, forging & foundry, and CNC machines. The company at its machine tool division manufactures various standard machine tools viz., cutter & tool grinder, surface grinder, milling machine and thread-rolling machine of various models including other CNC versions. The company has eight market regional offices located all over the country. Sales forecasts were made for planning production. The sales have exceeded the forecast in a few items and fallen short in certain other items. A market intelligence cell has been functioning to gather timely information and developments.
For the last several years, the company is running at a loss, though its performance till then was satisfactory. The loss is due to drop in sales in most of the products and increase in production overheads. Severe competition was the major reason for drop in sales in most of the products. The company has a total manpower of 2000, out of which around 60% of the employees' fall under the operator cadre that includes skilled, semi skilled and unskilled workers.

To promote the clarity of the MOGP approach, the manufacturing case under study will be limited in scope to the CNC division of the company, which manufactures CNC lathe and CNC machining centers of various models. According to the management, the Indian engineering industry is still in the infant stage for introduction of CNC machines in a large way. These machines are extensively used in automobile industries i.e. in both local as well as global markets. Whenever there is a boom in this sector, as is the situation in the country, the demand for the CNC machine tools could be very high. This puts a pressure on the corresponding production units to step up their production by making their facilities more efficient and even by increasing their capacities.

In the CNC division there are two NC machines (one each of horizontal miller and slideway grinder), two CNC machines (vertical miller and horizontal boring) and one conventional radial drilling machine. Out of the five machines, the major bottleneck had been the slideway grinding (SWG) operation, which required special skills and was needed for all parts of the products. The management stated that SWG capacity was not available with sub-contractors locally, to meet the requirements of the company. Also, the production manager of the CNC division stated that its capacity was the critical and the deciding factor while working out the capacity of the whole CNC division. Also, it was observed that there were more overheads incurred especially with the production of CNC machining centres.
However, the quality of products and vigorous drive to capture the market had given the company an edge over its competitors. The company is holding more inventories than the norm because of new models fall in demand and to prevent stock-out of imported items. From the last couple of years, the numbers of CNC lathes sold by company have declined. The fall in demand was attributed to the adverse economic and market conditions though products of the company were stated to be popular. The description of the production environment of the CNC division shows the complexity of their production planning and multi functions with several product models.

To meet the company’s main objectives, the CNC division has set some objectives at its divisional level as i) to produce sophisticated, flexible precision machine tools for the local as well as global markets; ii) flexibility to adapt the product design changes in the market; iii) to improve productivity and reduce product costs to maintain the market share; and (iv) to enhance customer satisfaction by offering quality products. For translating these specific objectives into concrete tactical and operational plans, a GP model under multi-objective environment has been proposed in this paper to evaluate the trade-offs among the three entities of the production planning process (refer Table 1).

Section 2 gives brief description of the related literature. In Section 3, multi-objective model has been developed. Goal programming formulation, its testing with various goal priority structures and discussion of results is given in Section 4. Finally, Section 5 summarizes the main conclusions and gives directions for further research.

2. Review of related research

The scope of this literature review is limited to applications of goal programming (GP) approach to real life manufacturing situations in the multi-objective environment. However,
for a rigorous mathematical analysis of multi objective programming approach, the reader is referred to Steuer (1985). A summary of the selective literature highlighting the specific problem type with the identified multiple objectives and the solution methodology followed is presented in Table 2. The multi-objective models in the context of manufacturing were formulated and solved in the recent past (a few sample studies include Demmel and Askin 1992; Stam and Kuula, 1992; Kim and Schniederjans 1993; Kalpic, Mornar and Baranovic, 1995; Nagarur, Vrat, and Duongsuwan, 1997) to provide information on the trade-off among multi-objectives. However, although it represents a viable approach to production planning, MOGP is not as widespread among manufacturing companies as desired.

The GP appears to be an appropriate, powerful, and flexible technique for decision analysis of the troubled modern decision maker who is burdened with achieving multiple conflicting objectives under complex environmental constraints. The extensive surveys of the GP by Schniederjans (1995), Tamiz, Jones, and Romero (1998), and Aouni and Kettani (2001) have reflected this. The modeling approach of GP does not attempt to maximize or minimize the objective function directly as in the case of conventional linear programming. Instead of that the GP model seeks to minimize the deviations between the desired goals and the actual results to be obtained according to the assigned priorities.
<table>
<thead>
<tr>
<th>Study</th>
<th>Type of Problem Environment</th>
<th>Multiple Objectives Identified</th>
<th>Method Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee and Clayton (1978)</td>
<td>Resource allocation in an institution of higher learning</td>
<td>Total cost, salary increase, faculty/student ratio, faculty/graduate assistant ratio</td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Sundaram (1978)</td>
<td>Selecting levels of machine parameters in a fine turning operation</td>
<td>Finish turning depth in one pass, finish turning with in a stipulated time.</td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Singh and Agarwal (1983)</td>
<td>Determination of the optimum size of extended octagonal ring</td>
<td>Sensitivity, rigidity</td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Stam and Kuula (1991)</td>
<td>Selection of a flexible manufacturing system</td>
<td>Production volume, cost, flexibility</td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Shafer and Rogers (1991)</td>
<td>Formation of manufacturing cells</td>
<td>Min. setup time, Min. intercellular movements, Min. the investment in new equipment, Maintain acceptable utilization levels</td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Premchandra (1993)</td>
<td>Activity crashing in project networks</td>
<td>Crashing time of an activity, Project cost, Project time</td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Kim and Schniederjams (1993)</td>
<td>Just-in-time manufacturing</td>
<td>Production smoothing, balancing of production line, number of kanbans, setup time, idle and overtime, production cost</td>
<td>Multi Objective Programming</td>
</tr>
<tr>
<td>Lyu, Gunasekaran, Chen and Kao (1995)</td>
<td>Coal blending</td>
<td>Demand of each boiler, environmental requirement of the sulphur oxide emission, heating value requirements, volatile matter content requirement, ash content requirement, inventory.</td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Nagarur, Vrat, Duongsuwan (1997)</td>
<td>Production planning and scheduling for injection moulding of pipe fittings</td>
<td></td>
<td>Goal Programming</td>
</tr>
<tr>
<td>Shang and Tadikamalla (1998)</td>
<td>Design and control of a cellular manufacturing system</td>
<td>Flow time, waiting time, work-in-process inventory</td>
<td>Simulation with optimization techniques such as Taguchi method and response surface methodology</td>
</tr>
<tr>
<td>Su and Hsu (1998)</td>
<td>Machine-part cell formation</td>
<td>Total cost, intracell machine loading unbalance, intercell machine loading unbalance</td>
<td>Simulated annealing</td>
</tr>
<tr>
<td>Zhao and Wu (2000)</td>
<td>Manufacturing cell formation problem</td>
<td>Minimizing costs due to intercell and intracell part movements, Minimizing the total within cell load variation, Minimizing the exceptional elements</td>
<td>Genetic algorithm approach</td>
</tr>
<tr>
<td>Linares and Romero (2000)</td>
<td>Electricity planning</td>
<td>Min. total cost, CO₂, SO₂, NOₓ emissions, amount of radioactive waste produced</td>
<td>AHP</td>
</tr>
<tr>
<td>Wang, Shaw, Chen (2000)</td>
<td>Machine selection in flexible manufacturing cell (FMC)</td>
<td>Purchasing cost, machine floor space, machine number, productivity of the FMC</td>
<td>Fuzzy MADM approach</td>
</tr>
</tbody>
</table>
Therefore, the GP model handles multiple goals in multiple dimensions (Sundaram, 1978). Further, the distinguishing characteristic of GP is that it allows for an ordinal solution (Lee, 1972). Stated differently, management may be unable to specify the cost or utility of a goal, but often upper or lower limits may be stated for each goal. A commonly used generalized model for goal programming is as follows (Kwak et al. 1991):

$$\text{minimize } Z = \sum w_i P_i (d_i^+ + d_i^-)$$

subject to

$$\sum a_{ij} x_{ij} + d_i^- - d_i^+ = b_i \quad (i = 1, 2, \ldots, m)$$

$$x_{ij}, d_i^-, d_i^+ \geq 0 \quad (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$$

where $P_i$ is the preemptive factor/priority level assigned to each relevant goal in rank order (i.e. $P_1 > P_2 > \ldots P_n$), and $w_i$ are non-negative constants representing the relative weights assigned within a priority level to the deviational variables, $d_i^+$ and $d_i^-$, for each j-th corresponding goal, $b_i$. The $x_{ij}$ represents the decision variables, $a_{ij}$ represents the decision variable coefficients.

From the literature it is clear that the GP approach has been applied for a variety of applications. Examples of problems solved by GP technique are resource allocation in an institution of higher learning (Lee and Clayton 1978), selecting levels of machining parameters (Sundaram 1978), determining optimum size of a machined component (Singh and Agarwal 1983), production planning in a ship repair company (Tabucanon and Majumdar 1989), cell formation problem (Shafer and Rogers 1991), activity crashing in project networks (Premchandra 1993) and production smoothing under just-in-time manufacturing environment (Kim and Schnierderjams 1993). The applicability of MOGP to the planning decisions have been established (Kwak et al. 1991, Giokas and Vassiloglou, 1991). Linear MOGP approach has successfully been applied for the
planning objectives include calculating the optimum production mix and achieving the capacity and material balance, while maximizing the contribution and minimizing the duration of the longest resource management (Kalpic, Mornar, and Baranovic, 1995). Another application illustrated the use of zero-one GP for the development of a production planning and scheduling model in a injection moulding factory with an objective to minimize the total costs of production, inventory, and shortages (Nagarur, Vrat and Duongsuwan, 1997).

It appears that production planning is an area where GP can be applied very efficiently. The primary reason is, of course, that there are only limited human factors involved in decision analysis. Therefore, the future outcome can be forecast with a greater accuracy. Also, it is apparent from the literature that, the GP technique has potential to solve the conflicting aspects of the three entities, namely, customer, product and manufacturing process of the manufacturing firm under consideration. As far as the authors know, MOGP is not used for this purpose so far. Furthermore, quantification of the performance criteria of these three entities is a challenging task. In this regard, we propose a linear multi objective goal programming model to a machine tool manufacturing industry to illustrate the impact of variations in product demand on the firm performance by evaluating the trade-off among the three entities.

3. The multi-objective model

Good products with improved quality and styles can promote customer demand to a certain degree, thereby increasing revenues. A revenue increase, however, is not always possible because customers usually determine the selling price and the demand is highly uncertain and fluctuating. Unless a company manufactures superior products just in time,
the products may not be sold, piling up inventories. Even the products already sold could be recalled or returned, eventually making the company out of business (Son, 1994, pp.443). Short lead times and a high schedule performance determine the companies logistical quality, where as high and steady utilization of the production facilities and low WIP inventory influence the profitability of the production process. Problems occur due to the fact that these objectives are partly conflicting.

As world class companies have proved that the product quality is one of the major strategic factors in managing manufacturing systems. Studies of Son (1993) state that increased product quality can be measured by reduced quality cost and increased customer satisfaction can be measured by reduced external failure costs (p.419). Improving product quality is now at the top of a manufacturer’s priority list. Quality control professionals (Juran 1951 and Feigenbaum, 1961) first developed the concepts of ‘quality cost’ and have been recognized by the practitioners widely. For better quality management, quality should be convertible to monetary terms since dollars are the easiest and most effective communication language (Son and Hsu, 1991). Quality cost is usually broken down into four categories of appraisal, prevention, internal failure and external failure costs and most of them are costable. While building MOGP model, we reduce these four categories to two: prevention (that includes appraisal cost) and failure (that include external and internal costs) in the similar lines as that of Son and Hsu (1991). Here prevention cost is redefined as the cost of preventing product defects by checking and correcting in-process quality problems before final inspection. And failure cost is redefined as the loss due to failure of finished products to meet quality standards set by both a company and its customers.

As a result of market dynamics and fierce global competition, it is felt that crucial performance criteria regarding to customer satisfaction should be considered in the planning process. Also, the manufacturing firm under consideration is forced to provide a
better quality product on a more cost-effective basis while significantly reducing processing waste such as rework and scrap. To focus on these issues, and after discussing with the quality control department professional of the case study, we separated the quality cost component from the production cost and categorized under customer’s goal. In practice, however, it will not be the case with many of the practitioners. Also, due to the capital-intensive nature of the products (machine tools) of the firm under consideration, it is assumed that the planning horizon as one year. Because, the top management sets the company’s strategic objectives for at least the next year in the business plan, which facilitates the overall framework of demand projections, functional area inputs, and capital budget from which the aggregate plan can be developed.

In a machine constrained production system, a key issue is how to evaluate the crucial resource use for varying demand opportunities. There is, therefore, a certain machine over or idle capacity will exists. If there is any idle capacity, it can be used for to meet the excess product demands. But on the other hand if there is any over capacity, then the management must be plan to meet this situation through someway or other. For instance, operate the crucial resources either on overtime basis or create an additional capacity by adding new machines to the existing system. Important then is how to evaluate the crucial resource use in the dynamic product mix and volume scenarios. As mentioned in the introduction, this situation occurs frequently in the selected case study especially with the operation of SWG. In this bottleneck scenario, the capacity evaluation of SWG is suggested as one of the multi-objectives of the study.

Performance measures are selected to achieve goals and are provided with the intent to monitor, guide and to communicate to all the business functions in an effective way between the top and the bottom level managers of the manufacturing firm under consideration. In the past, many researchers have attempted the manufacturing
performance evaluation problem in terms of various performance measures. In consultation with the shop floor and marketing managers of the selected machine tool industry, various performance measures (that representing the conditions of customer, product, manufacturing process) such as sales revenue, quality costs, capacity utilization, production cost, WIP inventory and production volume were identified as crucial measures of the study for building a linear MOGP model (refer, Table 1). But the selected performance criteria of the three entities of the production planning system are interrelated and often conflicting in nature. For instance, more precision and flexible products of the manufacturer obviously provide more satisfaction to the customer, but it can take time to incorporate any major design changes in the existing product design especially in the present case situation. The true value of MOGP approach is, therefore, the solution of problems involving multiple conflicting objectives according to the management’s preferences towards their attainment. The details of variables, and the objective functions representing the various performance criteria are presented as follows.

**Notation**

Indices

i = Product type (i = 1, 2,.., n)

j = Machine (non-crucial) type (j = 1,2,..,m)

Parameters

a_i = SWG machine capacity required for processing of product i

c_i = Production cost of i th product

o_ij = Capacity required for the i product from j th non-crucial machine

q_i = Quality costs incurred on i th product
\( s_i = \) Sales revenue from \( i \)th product

\( w_i = \) Cost of work-in-process inventory associated with \( i \)th product

\( \text{CAP}_j = \) Total available capacity of the \( j \)th non-crucial resource.

**Decision variable**

\( x_i = \) Production volume (number of machines) of \( i \) type to be produce per period

### 3.1 Development of the multi objectives

The problem considered here involves the production planning of two different product types, CNC machining centre and CNC lathe using the existing manufacturing facilities include one SWG, which is of crucial type and four non-crucial machines. As mentioned earlier, the firm is experiencing severe competition from the local as well as global markets. There is an urgent need to increase the product quality as well as customer satisfaction. Also, the management wants to avoid under utilization of SWG. At the same time it wants to operate SWG on overtime to maintain good employer-employee relations, minimize production overheads, quality costs, WIP inventory costs and to maximize the gross sales margin of the plant as much as possible. In this regard, the top management is to make a decision that will achieve these objectives of the three entities as closely as possible with the minimum sacrifice. The following performance criteria are incorporated in the model: (i) quality cost; (ii) production volume of each product (iii) production cost; (iv) SWG utilization, (v) cost of work-in-process inventory; and (vi) sales revenue. These important criteria are formulated as:

Minimize quality costs, \[ QC = \sum_i q_i x_i \] \( \ldots (1) \)

Maximize production volume, \[ V = x_i \] , for all \( i \) \( \ldots (2) \)
Minimize production costs, \[ C = \sum c_i x_i \] ... (3)
SWG utilization, \[ U = \sum a_i x_i \] ...(4)
Minimize work-in-process inventory cost, \[ W = \sum w_i x_i \] ...(5)
Maximize sales revenue, \[ SR = \sum s_i x_i \] ...(6)
\[ \sum o_{ij} x_i \leq CAP_j \quad \text{for all } j \] ... (7)

Equations (1) to (6) represent functional relationship between the production volumes of product i (decision variable), and the various performance measures of the three entities. Where as equation (7) denotes the system constraints.

The equation (1) ensures the condition of the customer satisfaction in terms of final product quality. The parameter \( q_i \) can be represented in terms of different product quality costs. The total production volume per period of all products is represented through the objective (2). This equation closely resembles to that production volume criteria given by Stam and Kuula (1991). Equations (3-6) represent the conditions of the manufacturing process. The total cost of production per product is represented as \( c_i \cdot x_i \) in equation (3). Here \( c_i \) is nothing but the unit cost of production excluding product quality costs, which is the sum of machine costs, tool costs, parts pallets costs, software costs, transportation costs and other costs and this is represented through the parameter. The SWG machine capacity utilization can be obtained through the equation (4), which will directly affects the speed of response to customers’ demand (Slack et al. 2000). Work-in-process inventory is one of the crucial performance measures of the case study. This can be computed through equation (5). Finally, the objective of sales revenue is formulated through equation (6), which is represented as \( s_i \cdot x_i \) for the i th product. It is clear that many of the above performance criteria are conflicting, and that the decision problem of evaluating their trade-off is a
complicated one. In such a conflicting multi objective environment the conditions of the three entities should be appropriately treated to reflect the decision makers’ targets on various performance criteria into the planning process through an ordinal hierarchy. Due to these reasons only a goal programming solution approach for the above model has been sought. The details of the formulation of the problem in goal programming format are presented below.

4 Formulation of the problem in goal programming format

4.1 Estimation of parameters of the GP model

To formulate the model, the parameters used for input to the GP model in each priority structure should be given or else estimated by the company. Therefore, the company personnel are get involved and also encouraged to take a major role in formulation. All model parameters are assumed to be deterministic and constant during planning horizon. As mentioned earlier, the planning horizon is taken as one year. The management is mainly focused on the SWG operation while formulation of the capacity utilization goal. Because it is only the bottleneck machine within the CNC division of the company. The parameters and estimation of their values are described below.

4.1.1. SWG capacity required ($a_i$) and available ($A$)

This is estimated based on the time needed for machining of one unit of product $i$ on slideway grinder (SWG). Average setup times of the products are also taken into consideration in the fixation of $a_i$. The average manufacturing time for each product $i$ on SWG is obtained from the process plan. The production manager of the company provides
the capacity available in the planning horizon for each non-crucial machines (m = 4, in the present case study). Factors such as allowances for planned maintenance and average breakdown times are calculated from past data. Special holidays are also taken into consideration in the computation of net available times of the machines. In the existing operational environment, the shop floor managers calculate the available capacity of the SWG as well as other non-crucial machines as 4500 hours per year.

4.1.2. Production cost (c_i)

The total cost of production per product is estimated as the sum of machine costs, tool costs, parts pallet costs, software costs, internal transportation costs and other costs. Only direct investment costs are included in the machine costs. The tool costs are estimated based on the complexity of the products and the number of tools needed. The management in consultation with the operations management department decides the production cost parameter.

4.1.3. Quality cost (q_i)

If the customer quality is increased, the costs of providing the effort – through extra quality controllers, inspection procedures, and so on – increases proportionally (Slack et al. 2000; p.823). These costs of quality are taken as the sum of prevention and failure costs. The company quality norms are followed while estimation of this parameter.

4.1.4. Sales revenue (s_i)

This parameter depends on the company’s sales target in the planning horizon. The demand is forecasted by the marketing department of the company, and is assumed to be deterministic. The marketing department estimates unit sales contribution from each product by using the previous year’s sales data.
4.1.5. Work-in-process inventory (wi)

This is taken as the opportunity cost of the capital blocked in inventory as work-in-process. Due to frequent introduction of new product models and to prevent stock-out of imported items, this value is taken as 30% annual rate on the production cost. This cost is assumed to be constant over the planning horizon.

4.2 Model formulation

1. Customer’s goal: product quality

Final product quality is expected to be 100 percent to satisfy the customer fully. As mentioned earlier, this can be represented in terms of different quality cost components. At the same time the sum of these components should be maintained at minimum level. Satisfaction of the customer goal of product quality can be represented as

\[
\text{minimize} \quad (d_1^+)
\]

subject to

\[
\sum q_i x_i + d_1^- - d_1^+ = 0 \quad \ldots (8)
\]

where

- \(x_i\) = product volume of i to be produced to fulfill the customer’s quality requirements, 
- \(i = 1, 2\) (selected CNC division is producing only two product types)
- \(d_1^+, d_1^-\) = over and under achievements of quality goal.

Here, the underachievement of the quality goal is allowed and hence negative deviation is not included in the objective function. The solution will consists all x’s which satisfy \(\sum q_i x_i \leq 0\), provided such a solution set is possible. If the model cannot minimize \(d_1^+\) to zero, the solution consists of all x’s which minimize \(\sum q_i x_i\) to the possible extent.
2. Market goal: meet aggregate product volumes

Market requirements with respect to aggregate product volumes of product 1 and product 2 (i.e. sum of all customer orders in the planning period) are to be met. Here, exact achievement of the product volumes is desired and hence both negative and positive goal deviations must be considered in the objective function. This goal can be represented as

\[
\text{minimize } (d^+_2 + d^-_2 + d^+_3 + d^-_3)
\]

subject to

\[
x_1 + d^-_2 - d^+_2 = V_1 \quad \ldots (9), \text{ and } \]
\[
x_2 + d^-_3 - d^+_3 = V_2 \quad \ldots (10)
\]

where

\[
d^+_2 = \text{over achievement of product 1 volume goal}
\]
\[
d^-_2 = \text{under achievement of product 1 volume goal}
\]
\[
d^+_3 = \text{over achievement of product 2 volume goal}
\]
\[
d^-_3 = \text{under achievement of product 2 volume goal}
\]
\[
V_1 = \text{market goal on product 1 volume (aggregate) as per prediction (goal)}
\]
\[
V_2 = \text{market goal on product 2 volume (aggregate) as per prediction (goal)}
\]

Here, minimization of \(d^-_2 + d^+_2\) will minimize the absolute value of \(x_1 - V_1\). In other words, minimization of both negative and positive deviations of product volume will tend to search for the \(x_1\) and \(x_2\) which achieves the goal \(x_1 = V_1\) exactly.

3. Sales revenue: manufacturer’s goal

In view of past sales records and increased customers’ awareness towards factory automation, the management feels that the sales goal for the next year should be \(S\) million rupees. And, achievement of the sales revenue goal, which will be set at \(S\), is a function of
total gross margin of the product1 and product 2 respectively. This goal can be represented as
minimize \( (d_4^-) \)
subject to
\[
\Sigma s_i x_i + d_4^- - d_4^+ = S
\] ... (11)
where
\( d_4^- \) = under achievement of the sales revenue goal
\( d_4^+ \) = over achievement of the sales revenue goal
\( S \) = sales revenue goal fixed by the management.
Here, the over achievement of sales goal is acceptable, and hence positive deviation from the goal is eliminated from the objective function. The solution set will consist of all \( x \)'s such that \( \Sigma s_i x_i \geq S \) by minimizing \( d_4^- \) to zero, if such solutions are possible in the model. If it is not possible to minimize \( d_4^- \) to zero, the solution set will consist of all \( x \)'s that minimize \( (S - \Sigma s_i x_i) \) to the extent possible.

4. Production cost: manufacturer’s goal
The manufacturer’s goal of minimizing the production cost for the product volumes of product 1 and product 2 can be represented as
minimize \( (d_5^-) \)
subject to
\[
\Sigma c_i x_i + d_5^- - d_5^+ = 0
\] ... (12)
where
\( d_5^- \) = under achievement in production cost goal
\( d_5^+ \) = over achievement in production cost goal
Here, the solution will identify all x’s which satisfy $\Sigma c_i x_i \leq 0$, provided such a solution is possible. If the model cannot minimize $(d_5^+)$ to zero, the solution consists of all x’s which minimize $\Sigma c_i x_i$ to the fullest possible extent.

5. Utilization of SWG: manufacturer’s goal

The management of the case study believes that a good employer-employee relationship is an essential factor of business success. Therefore, they feel that a stable employment level with occasional overtime requirement is a better practice than an unstable employment with no overtime. Hence the positive deviation from the goal can be eliminated from the objective function. The manufacturer’s goal of minimize the under utilization of SWG machine can be represented as

minimize $(d_6^-)$

subject to

$$\Sigma a_i x_i + d_6^- - d_6^+ = A \quad \text{... (13)}$$

where

$A$ = available capacity of the SWG machine (goal)

$d_6^+$ = over time required for operation of SWG machine

$d_6^-$ = idle capacity of SWG machine

Here, the solution will identify all x’s such that $\Sigma a_i x_i \geq A$, by minimizing negative deviation to zero, if such a solution is possible in the model.
6. Work-in-process inventory: manufacturer’s goal

At present the company is holding more work-in-process (WIP) inventory than the norms. Due to this, the manufacturer’s goal of minimizing WIP inventory for the production volumes of product1 and product2 can be represented as

minimize \( (d_7^-) \)

subject to

\[ \sum w_i x_i + d_7^- - d_7^+ = 0 \] ... (14)

where

- \( d_7^+ \) = over achievement in WIP inventory goal
- \( d_7^- \) = under achievement in WIP inventory goal

Here, the under achievement of the WIP inventory goal is encouraged and hence negative deviation is not included in the objective function. Also, the solution set will consist all \( x \)’s which satisfy \( \sum w_i x_i \leq 0 \), provided such a solution space is possible. If the model cannot minimize \( (d^-) \) to zero, the solution consists of all \( x \)’s which minimize \( \sum w_i x_i \) to the possible level.

4.3 Sensitivity to changes in the goal priority structures

In order to test the GP model, two independent goal priority structures have been formulated based on the preferences that the company’s top management expressed especially to suit specific market conditions. A goal priority structure is nothing but a hierarchical representation of the goal priorities, which reflect the decision makers’ preferences. Production and marketing personnel were actively involved in the selection and prioritizing of the various goals. In addition to variables and constraints (from 9-15) stated above the
following “preemptive” priority factors for the two finalized goal priority structures (for summary, refer Table 3) are defined.

**Goal Priority Structure #1**

P₁ = the highest priority is assigned by the management to the satisfaction of product demand. Both the negative and positive deviations (i.e. \(d^+_{2} + d^-_{2} + d^+_{3} + d^-_{3}\)) from product 1 and product 2 demands should be minimized.

P₂ = the second highest priority factor is assigned to the minimization of over achievement of quality cost goal (i.e. \(d^+_{1}\)) to meet customer’s quality requirements.

P₃ = the last priority factor is assigned to the manufacturing process goals i.e. minimization of under achievement of sales revenue (\(d^-_{4}\)); minimization of over achievement of production cost (\(d^+_{5}\)); minimization of underutilization of SWG machine (\(d^-_{6}\)); and minimization of over achievement of WIP inventory (\(d^+_{7}\)).

Now the model for this priority structure #1 can be formulated. The objective is the minimization of deviations from various goals imposed by the production planning environment. The deviant variable(s) associated with the highest preemptive priority (P₁) must be minimized to the fullest possible extent. When no further improvement is possible in the highest goal, then the deviations associated with the next highest priority factors (in the order of P₂, P₃) will be minimized. The model can be expressed as:

\[
\text{minimize } Z_1: P_1 (w_2 d_{2}^+ + w_2 d_{2}^- + w_3 d_{3}^+ + w_3 d_{3}^-) + P_2 (w_1 d_{1}^+) + P_3 (w_4 d_{4}^- + w_5 d_{5}^+ + w_6 d_{6}^+ + w_7 d_{7}^+) \quad \ldots \quad (15)
\]

subject to goal constraint (9) - (14) and
\[ x_1, x_2, d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+, d_4^-, d_4^+, d_5^-, d_5^+, d_6^-, d_6^+, d_7^-, \text{ and } d_7^+ \geq 0. \]

Where \( w(.) \) are non-negative constants representing the relative weights assigned within a priority level to the deviational variables.

**Goal Priority Structure #2**

Under the priority structure #1, the product demand goal for product1 and product2 was fixed as the top most priority by the management. But as per the problem context the company has experienced decline in demand for the product2 and also it is holding more inventories than the norm. To reflect these issues especially to see the trade-off among various performance measures, within the priority structure #2, suppose the production volume goal of product2 is now of utmost important and is, therefore, given top priority. That is, to stay in the business, selling of product2 has become company’s first and foremost important priority. However, it is worth to note that this is only possible through customer’s satisfaction i.e. through enhancing the quality of the product. The MOGP approach provides the decision makers with the flexibility they desire and is able to offer them an optimal solution. This is an important advantage of goal programming, allowing the decision makers to evaluate
Table 3: Company’s ranking of goals under various priority structures

<table>
<thead>
<tr>
<th>Entity</th>
<th>Goal</th>
<th>Priority Structure #1</th>
<th>Priority Structure #2</th>
<th>Goal Deviation(s) Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer</td>
<td>Quality Cost</td>
<td>P₂</td>
<td>P₃</td>
<td>d₁⁺</td>
</tr>
<tr>
<td>Product</td>
<td>Product1 Volume (v1)</td>
<td>P₁</td>
<td>P₂</td>
<td>d₂⁺, d₂⁻</td>
</tr>
<tr>
<td></td>
<td>Product2 Volume (v2)</td>
<td>P₁</td>
<td>P₁</td>
<td>d₃⁺, d₃⁻</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Sales Revenue</td>
<td>P₃</td>
<td>P₂</td>
<td>d₄⁺</td>
</tr>
<tr>
<td>Process</td>
<td>Production Cost</td>
<td>P₃</td>
<td>P₂</td>
<td>d₅⁺</td>
</tr>
<tr>
<td></td>
<td>SWG Utilization</td>
<td>P₃</td>
<td>P₂</td>
<td>d₆⁺</td>
</tr>
<tr>
<td></td>
<td>WIP Inventory</td>
<td>P₃</td>
<td>P₂</td>
<td>d₇⁺</td>
</tr>
</tbody>
</table>

Note:
**Priority Structure #1**
Priority 1: Meet product1 and product2 demand goal
Priority 2: Meet customer’s quality goal
Priority 3: Meet manufacturing process goals

**Priority Structure #2**
Priority 1: Meet product2 demand goal
Priority 2: Meet the product1 demand as well as manufacturing process goals
Priority 3: Meet customer’s quality goal

P₁ = Priority 1, P₂ = Priority 2, P₃ = Priority 3, and P₁ > P₂ > P₃

various solutions and choose the one that they believe the best given the current circumstances. The following goal structure represents the management’s preemptive priority factors associated with the goals under priority structure #2.

P₁ = the preemptive priority factor assigned by the management to meet product2 demand. Here, the negative and positive deviations from product2 demand (i.e. d₁³ + d₃⁻) should be minimized.
P₂ = the second priority factor is assigned to the manufacturing process and product demand goals i.e. minimization of under achievement of sales revenue (£d₄); minimization of over achievement of production cost (£d₅); minimization of underutilization of SWG (£d₆); minimization of excess WIP inventory (£d₇); and minimization of the negative and positive deviations from product demand (i.e. £d₊₂ + £d₋₂).  

P₃ = the lowest priority factor is assigned to the minimization of over achievement (i.e. £d₊₁) of quality cost goal. 

Now the overall model for the priority structure #2 can be represented as:

\[
\text{minimize } Z₂: P₁(w₃₋d₃₋ + w₃₊d₃₊) + P₂(w₂₋d₂₋ + w₂₊d₂₊ + w₄₋d₄₋ + w₅₊d₅₊ + w₆₋d₆₋ + w₇₊d₇₊) + P₃(w₁₊d₁₊) \quad \ldots (16)
\]

subject to goal constraint (9) - (14) and

\[x₁, x₂, d₁₋, d₁₊, d₂₋, d₂₊, d₃₋, d₃₊, d₄₋, d₄₊, d₅₋, d₅₊, d₆₋, d₆₊, d₇₋, d₇₊ ≥ 0.\]

In the above model, \(Z₂\) in the objective function can be interpreted as the total of the unattained portions of production planning goals. And \(wᵢ \) are non-negative constants representing the relative weights assigned within a priority level to the deviational variables.

4.4 Model results and discussion

The proposed MOGP model is tested using as the inputs, the firm’s data for a specific one year period. A sample of the input data is given Table 4, for both of the preemptive goal priority structures. Each priority structure was executed using LINGO software package (LINDO Systems Inc. 1999) with \(P₁ = 100, P₂ = 10, \) and \(P₃ = 1\), which are finalized based on the policies of the management of the case study.
Also, the non-negative constants representing the relative weights assigned within a priority level to the deviational variables are set at a value of one. The sensitivity analysis for the two goal priority structures was carried out for different combinations of tentative product demands specified by the company’s marketing division. The solution obtained under the priority structure #1 is considered appropriate by the management under the current situation. But marketing conditions may change from time to time that require a restructuring of the goals to suit the circumstances. To illustrate the power of GP, a different solution representing a different prioritization of the same goals was investigated. The solution (under priority structure #2) that was generated will be discussed immediately, following a discussion of priority structure #1 solution. The output for the two different goal priority structures is shown in Table 5-6. The trade-offs among the various performance measures and the optimized production volumes were tabulated (Table 7-8). Inferences drawn from the results are presented below:

**Priority structure #1**

To operationalize the MOGP solution obtained under the priority structure#1, marketing department should supply their products, namely, CNC machining centre and CNC lathe to the prescribed customers according to the optimal production volumes defined by the model’s resulting $x_i$’s. The optimal and maximum possible measures such as sales revenue, quality cost, production cost and WIP inventory cost are summarized in Table 7.
Table 4. The sample input data

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Parameter Used</th>
<th>Parameter value</th>
<th>Product 1</th>
<th>Product 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality Cost</td>
<td>( q_i )</td>
<td>1.410</td>
<td>0.406</td>
<td></td>
</tr>
<tr>
<td>Sales Revenue</td>
<td>( s_i )</td>
<td>7.142</td>
<td>2.150</td>
<td></td>
</tr>
<tr>
<td>Production Cost</td>
<td>( c_i )</td>
<td>5.188</td>
<td>1.505</td>
<td></td>
</tr>
<tr>
<td>SWG Capacity</td>
<td>( a_i )</td>
<td>361.42</td>
<td>049.10</td>
<td></td>
</tr>
<tr>
<td>WIP Inventory</td>
<td>( w_i )</td>
<td>0.311</td>
<td>0.090</td>
<td></td>
</tr>
<tr>
<td>Non-crucial Machine Capacities (j = 4)</td>
<td>( o_{ij} )</td>
<td>53.00</td>
<td>35.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>72.75</td>
<td>16.00</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>18.00</td>
<td>24.00</td>
<td></td>
</tr>
</tbody>
</table>

Note:
All cost/revenue figures are in million rupees
SWG and non-crucial machine capacities are in hours

If the company decides to utilize the capacity of SWG fully and to allow its operation on overtime basis for some occasions, it has to reach \( x_i \)'s as prescribed. Then in that case the achievable sales revenue and associated costs will be more than the targets. For instance, the optimal production volumes (11,15), (14,4), and (14,18) are equivalent to the marketing department’s targets that represent the total achievement of the product demand goal, which has specified as the top priority. Then in that case the associated
revenue and cost figures are nothing but the optimal values. Whereas in the other product scenarios (7,7), (2,8), and (8,4) (refer Table 7), the optimal $x_1$ and $x_2$ are higher than the targets (due to positive deviation in product1 volume, refer Table 5). The suggested production volumes are justifiable due to the idle capacity of SWG at the target volumes and also the company is trying to regain its market share through its product quality campaigns. At the suggested production volumes of the model, the associated costs and sales revenue will be on higher side. For example, the optimal sales revenue figures at the targeted product scenarios (7,7), (2,8), and (8,4) are 65.04, 31.48, and 65.74 million rupees i.e. if the company is able to supply only the targeted product volumes. But if the marketing department is able to sell all the produced machines i.e. (11,7), (11,8), and (11,4) then the company’s tentative sales revenue at these volumes will be 96.59, 98.73, and 90.13 million rupees respectively.
Table 5: MOGP model Output for priority structure #1

<table>
<thead>
<tr>
<th>Market Demand/Product Scenario</th>
<th>Optimum Production Volume</th>
<th>Quality Cost</th>
<th>Deviations in Product1</th>
<th>Deviations in Product2</th>
<th>Sales Revenue</th>
<th>Production Cost</th>
<th>SWG Utilization</th>
<th>WIP inventory</th>
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<tbody>
<tr>
<td>V₁</td>
<td>V₂</td>
<td>x₁</td>
<td>X₂</td>
<td>d₁⁺</td>
<td>d₁⁻</td>
<td>d₂⁺</td>
<td>d₂⁻</td>
<td>d₃⁺</td>
</tr>
<tr>
<td>11</td>
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<td>27.04</td>
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<tr>
<td>Market Demand/Product Scenario</td>
<td>Optimum Production Volume</td>
<td>Optimum Production Volume</td>
<td>Quality Cost</td>
<td>Deviations in Product 1</td>
<td>Deviations in Product 2</td>
<td>Sales Revenue</td>
<td>Production Cost</td>
<td>WIP</td>
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</table>
### Table 7: MOGP model results for priority structure #1

<table>
<thead>
<tr>
<th>Market Demand</th>
<th>Optimum Production Volume as per Model</th>
<th>Sales Revenue</th>
<th>Production Cost</th>
<th>Quality Cost</th>
<th>WIP Inventory Cost</th>
<th>SWG (*)</th>
<th>Suggested Operational Strategy for SWG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Product 1 (V₁)</td>
<td>Product 2 (V₂)</td>
<td>Product 1 (x₁)</td>
<td>Product 2 (x₂)</td>
<td>Optimum (V₁)</td>
<td>Maximum Possible (*)</td>
<td>Optimum (V₂)</td>
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<tr>
<td>11</td>
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<td>142.46</td>
<td>142.46</td>
<td>99.72</td>
</tr>
</tbody>
</table>

**Note:**
All costs/sales revenue figures are in million rupees and over/under utilization of SWG is in hours.
SWG (*): Capacity Deviations in SWG capacity if it runs at the optimum production volume levels
(*)&: if all produced goods are supplied to customers.
### Table 8: MOGP model results under priority structure #2

<table>
<thead>
<tr>
<th>Market Demand</th>
<th>Optimum Production Volume as per Model</th>
<th>Sales Revenue</th>
<th>Production Cost</th>
<th>Quality Cost</th>
<th>WIP inventory Cost</th>
<th>SWG (*)</th>
<th>Over-Capacity</th>
<th>Idle Capacity</th>
<th>Suggested Operational Strategy for SWG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Product1 (V1)</td>
<td>Product2 (V2)</td>
<td>Optimum</td>
<td>Maximum Possible (*)</td>
<td>Optimum</td>
<td>Maximum Possible (*)</td>
<td>Optimum</td>
<td>Maximum Possible (*)</td>
<td>Over-Capacity</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>15</td>
<td>11</td>
<td>15</td>
<td>113.78</td>
<td>113.78</td>
<td>79.64</td>
<td>79.64</td>
<td>21.60</td>
</tr>
<tr>
<td></td>
<td>07</td>
<td>07</td>
<td>13</td>
<td>07</td>
<td>065.04</td>
<td>111.41</td>
<td>46.85</td>
<td>77.97</td>
<td>12.71</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>08</td>
<td>13</td>
<td>08</td>
<td>031.48</td>
<td>113.56</td>
<td>22.42</td>
<td>79.48</td>
<td>06.07</td>
</tr>
<tr>
<td></td>
<td>08</td>
<td>04</td>
<td>14</td>
<td>04</td>
<td>065.74</td>
<td>113.37</td>
<td>47.52</td>
<td>78.65</td>
<td>12.90</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>04</td>
<td>14</td>
<td>04</td>
<td>112.37</td>
<td>112.37</td>
<td>78.65</td>
<td>78.65</td>
<td>21.36</td>
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<tr>
<td></td>
<td>14</td>
<td>18</td>
<td>11</td>
<td>18</td>
<td>120.22</td>
<td>120.22</td>
<td>84.15</td>
<td>84.15</td>
<td>22.81</td>
</tr>
</tbody>
</table>

**Note:**
All costs/sales revenue figures are in million rupees and over/under utilization of SWG is in hours.

SWG (*): Capacity Deviations in SWG capacity if it runs at the optimum production volume levels

(*): if all produced goods are delivered to customers.
Also for both the cases, the associated costs such as production, quality and WIP inventory are summarized in Table 7. To gain more insights from the proposed MOGP approach, select the following optimal solution from Table 5 for the product scenario (14,18):

\[ x_1 = 14, \ x_2 = 18, \]

\[ d_2^\ominus = d_3^\oplus = d_4^\ominus = d_5^\oplus = 0, \ d_1^\oplus = 27.04, \ d_4^\ominus = 78.65, \ d_7^\ominus = 5.98. \]

The goals such as product volumes under priority 1 and sales revenue under priority 3 are achieved, but the other goals such as quality cost, production cost, and WIP inventory are not completely minimized. This kind of result reflects a typical day to day production situation where there are several minimum costs while producing some tangible goods. The associated quality, production, and WIP inventory costs incurred for production of 14 CNC machining centres and 18 CNC lathes in the year are 99.72, 27.04, and 5.98 million rupees respectively. To get further clarity of the proposed MOGP model, the result under product volume scenario (11,15) is also now analyzed. The solution of the problem yields the following results at this scenario.

(a). Variables: \[ x_1 = 11, \ x_2 = 15, \ d_2^\ominus = d_3^\ominus = d_4^\oplus = d_6^\ominus = 0; \]

\[ d_1^\oplus = 21.60, \ d_4^\oplus = 79.64, \ d_6^\oplus = 212.12, \ d_7^\oplus = 4.78. \]

The solution indicates that the firm produces 11 CNC machining centres and 15 CNC lathes with 212.12 hours of overtime operation in SWG machine. The total sales revenue was 113.79 million rupees (refer Table 5), 1.21 million rupees (i.e. \( d_4 \), refer Table 7) short of the 115 million rupees limit as set be the management. The associated costs of quality, production, and WIP inventory in the particular year are 21.60, 79.64, 4.78 million rupees respectively. The revenue and cost
figures will facilitate the management for allocation of budget to the concern
departments to meet the various activities of production.

(b) Goal attainment

Product1 volume goal: Achieved
Product2 volume goal: Achieved
Avoid underutilization utilization of SWG goal: Achieved
Sale revenue goal: Not achieved

The above-stated goal attainments indicate that the firm is able to achieve the
goals of market and the most important manufacturing process related goal (i.e.
avoid underutilization of SWG) during the year. The optimal solution is to avoid
product shortages and underutilization of the normal production capacity of the
SWG by scheduling overtime operation whenever this is possible. In this way our
MOGP model results will act as an effective communication tool between the top
and lower level managers of the case study to enhance the productivity of the
system as well as for improvement of the business However, under this goal
priority structure #1 some of our critical observations are as follows:

• The organization may closely meet the sales revenue target of 115
  million rupees if it decide to produce product volume combinations
  either (11, 15) or (14, 4). However, this can be achieved at the expense
  of additional operational cost especially due to overtime operational
  strategy of SWG (refer Table 7).

• As explained in the problem context, SWG is only the bottleneck
  machine. Goal deviations with respect to this machine are also presented
  in Table 5. Results indicate that SWG machine will be under-utilized if
  the product demands are (7, 7), (2,8) and (8,4) for instance. Whereas for
other scenarios of product demands the machine capacity of SWG is insufficient under normal working conditions. To operationalize the solution, the company should run the SWG on overtime basis (according to over utilized hours prescribed by the model) to meet the on time delivery of products to the market. The suggested operational strategy for SWG under each of the product scenario is also summarized in Table 7. This information facilitates the planner specifically to tackle the issue of workforce balancing i.e. to maintain good employer-employee relations on long term basis, indeed it was one of the main objective of the management of the firm under consideration.

**Priority structure #2**

Under the priority structure #2, the first priority i.e. meet product2 demand goal was fully satisfied in all product scenarios. The product1 demand goal, which was assigned as the second priority was satisfied only in the two occasions i.e. at (11,15) and (14,4) product scenarios. Further, at the product scenario of (14,18), it is not only to meet the sales revenue goal, which was kept as a second priority but also to cross the sales revenue target of 113 million rupees. The goal in that case was to maintain product1 demand level of 14 and was included under priority 2 i.e. P2. However, there is a shortage of 3 units in the product1 demand that represents a curtailment of product1 production, resulting underachievement of this goal (d2 = 3, refer Table 6). In this case the company does not prefer this production strategy. In priority structure #2 also, the best operational solution to the selected firm is that of product scenario (11,15), at which it can meet the sales
revenue limit with a slight higher margin of 0.78 million rupees (Table 8) as well as product1 and product2 demand goals.

The optimal production volumes at production scenarios (11,15) and (14,4) are the only production volume levels that coincide with the priority structure #1 solution. Therefore, the maximum possible measures such as sales revenue, production cost, quality cost, and WIP inventory are realized in product scenarios (11,15) and (14,4) are the same under both the priority structure #1 and the priority structure #2 solution. The only difference between the two solutions occurs in the suggested operational strategy of SWG due to deviations (cf. last column of Table 7 and 8) in its capacity at various product scenarios as stipulated by the marketing managers.

The results of the priority structure #1 are compared with the priority structure #2 for the same planning period. The trade-offs between the two solutions is evident: in the priority structure #2, variations such as costs were high if the company wants to sell/supply all the produced goods. To operationalize a solution where the \( x_i \)'s do not equal to ‘goal product demand’ marketing department seeks, it may be advisable to look for the ways to increase the product sales perhaps through sales promotion schemes. Otherwise costs such as production, quality and WIP inventory will be increased enormously when compared with priority structure #1 values. For example for the product scenario (7,7), the cost changes are: production cost from 67.61 to 77.97 million rupees, quality costs 18.35 to 21.17 million rupees, and WIP inventory 4.05 to 4.68 million rupees. Although various costs are increasing, the customer satisfaction in terms of offering better quality products outweighs the
disadvantage of increasing various costs. Even more important than savings in costs is the achievement of marketing goal, i.e. nothing but timely supply of products to the customers, which is the key policy of the company in running its business in a competitive manner. Except in one product scenario, i.e. under priority structure #2, this can be seen from Table 5 and Table 6, where the underachievement in product demand goals tends to zero. Also, It can be seen from the results that the WIP inventory cost decreases substantially for the priority structure #1 in all the product scenarios, thus satisfying the main objective of the company and hence the results obtained under this priority structure are recommended to the case organization for further consideration.

From the results of MOGP model, it can be seen that the model performs well in communicating the trade-offs among the various performance measures to various functional levels of the organization such as marketing, sales, finance and operations. These cost figures are useful for these departments for routine planning and scheduling. In both of the priority structures, there are some instances when the product demand goals have crossed the targets, resulting in the higher costs. But these instances are found to be rare, and at the most seen in three occasions of product scenarios. However, the overachievements are not serious as, in any way, the information can be used as a basis to arrive to an appropriate production plan.
5 Summary, Conclusions, and Further Research

Summary
Development of goal programming models and their applications to the real life manufacturing problems have received an increasing attention during the past several years as a powerful decision making tool for the problems that involve multiple conflicting objectives. Modern manufacturing is complex owing to increased uncertainty in the customer demands, competitive markets, and rapid technological developments. Production management under this scenario is challenging and the problem complexity is due to some of the following features:

- The product structures looks similar but are not identical.
- The operational capacities are the only constraints from the system view.
- Product demand is highly uncertain.

In such a scenario, it is necessary to determine the optimum production plan to assist the decision maker to achieve the organization goals for optimum utilization of resources. The MOGP model presented in this paper would be useful to discrete item manufacturers especially to find out an optimum level of production activities in terms of utilization of the critical machine i.e. SWG.

The MOGP results of the study are of significance to the production manager in decision making for long run production planning and scheduling of SWG operation. Also it can be useful to other functional areas such as marketing and finance for routine planning. Some of the specific decision making situations in this context are-

(i). the expected quality costs and production costs under identified product scenarios
(ii). under and over utilization of SWG at different combinations of production volumes

(iii). the achievement of sales revenue goal at different production volume combinations

These results are expected to guide the production manager to estimate the effects of product mix changes on load conditions at SWG. In this way, the MOGP output may act as a link between the firm’s broad strategies and tactical plans that enable the firm to achieve its goals. However, the three entities customer, manufacturer, and competitor must weigh the consequences of accomplishing goals at the expense of others and must attain acceptable balance in the achievement of their various goals.

Conclusions

The paper investigates the MOGP approach when applied to a real life case situation with an intention to evaluate the trade-offs of the three entities of the production planning environment under multiple conflicting objectives. To simplify this illustration, the problem was limited in a scope to an application of only one division of the case study. However, an application such as this could be easily be expanded to deal with the more complex real world problems confronting planners and managers. We notice that results show that the model can be an effective planning tool to aid decision makers faced with multiple conflicting goals where the three entities of production planning are significant determiners of any firm’s success. In addition, the model is computationally feasible, it requires approximately a three seconds to obtain the results for the selected data.
Further research

In the proposed MOGP approach, all of the parameters are assumed as constants and deterministic. In other words, the problem requires a solution in a static decision environment. However, in reality the decision environment is usually dynamic rather than static. Therefore, the model coefficients are neither known nor constant. Hence, some research efforts concerning stochastic approach are needed in this regard. Also, We recommend the use of regression analysis for estimation of various parameters and to more accurately weight the importance of various performance measures such as quality, production overheads, and WIP inventory. Lastly but not least, we also encourage researchers to explore the use of AHP for determining relative weights or priorities based on numerous qualitative factors, where AHP may bring a recognized and uniformly fair framework for the assessment of those weights.

References:


