Ross School of Business at the University of Michigan

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A Capacity Planning Strategy Based on Optimal Flexibility

- A Scenario Based Approach -

by

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A research paper submitted in fulfillment of the requirements for three credits, GRADUATE INDEPENDENT RESEARCH PROJECT Fall Term 1997, Professor Kannan Sethuraman, Faculty Supervisor

Faculty Comments

Companies can no longer follow the trail blazed by Henry Ford, capturing market share and high profits by producing large volumes of a standardized product. Today, consumer's needs and wants change rapidly. Companies that understand these changing preferences and respond to them quickly, with appropriate products, have a substantial advantage over their competitors. In the auto industry, there has been a steady increase in the number of car models that are being offered worldwide. Levels of uncertainty confronting managers in auto industry today are so high that they need a different approach to think about long-term strategy. Production capacity has always been one of the most important strategic variables for the major automobile firm. This research report presents a scenario-based approach for capacity planning to achieve optimal levels of flexibility in plant configurations. Although the model is applied to a particular application in the auto industry, it is applicable to a wide variety of decisions under risk.

Signature of Faculty Advisor

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Executive Summary

Given the large capital investments and a high degree of market uncertainty associated with the automotive industry, manufacturing flexibility can be an important competitive advantage for automotive companies. Flexibility allows a company to be able to respond quickly to changing demand scenarios, competitor movements or economic changes. However, achieving flexibility can be expensive. In addition to uncertainty, owing to long lead times, decisions relating to capacity have to be made several years ahead of actual production. The benefits and features of manufacturing flexibility and scenario based planning are described in this report.

A capacity planning model to determine the optimal level of flexibility in automotive assembly has been developed and implemented in this work. The optimization model described in this report aims at maximizing total expected profits (over the life of each product), given several different demand scenarios, capacity constraints and required investments. A general framework has been developed to account for the various factors that are to be considered in a long range capacity plan. A simple example involving two plants and three products has been presented and solved to illustrate the benefits of this approach. The model, which uses a mixed integer linear programming formulation, has been implemented in GAMS.Several sensitivity analyses ("what-if" studies) have also been illustrated to test the robustness of the optimal solution.

Modeling long range planning usually requires extensive input data which can be a limiting factor for such models. However, with support from various organizations involved, it can be seen that analytical models can be quite powerful in formulating long term business strategies

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1. Introduction – Strategic Planning

Long range planning presents unique challenges to the automotive industry. This industry is very capital intensive, characterized by a huge up-front investment (in facilities, tooling and development) that generates sales over subsequent years (typically 5 years for each product in recent times). Cyclicality, increased market segmentation and intense competition are three important features of the U.S. auto industry. The cyclicality of the U.S. auto industry is shown in Figure 1 [1]. The figure shows an increasing trend in the size of the total U.S. market but with a remarkable periodicity. However, the magnitude of the fluctuations appear quite random. Table 1 shows the increased fragmentation in the U.S. auto market over a 30 year period. The number of different products (defined as requiring different sheet metal) has increased more than four-fold (30 in 1955 vs. 142 in 1989 [1]). Also, the number of units sold per product and the market shares of the largest selling segments have fallen significantly. These reduced market shares are partly due to entry of more vehicle types in the market. The greater the number of types of vehicles a company has to manufacture, the greater the need for manufacturing & investment flexibility.

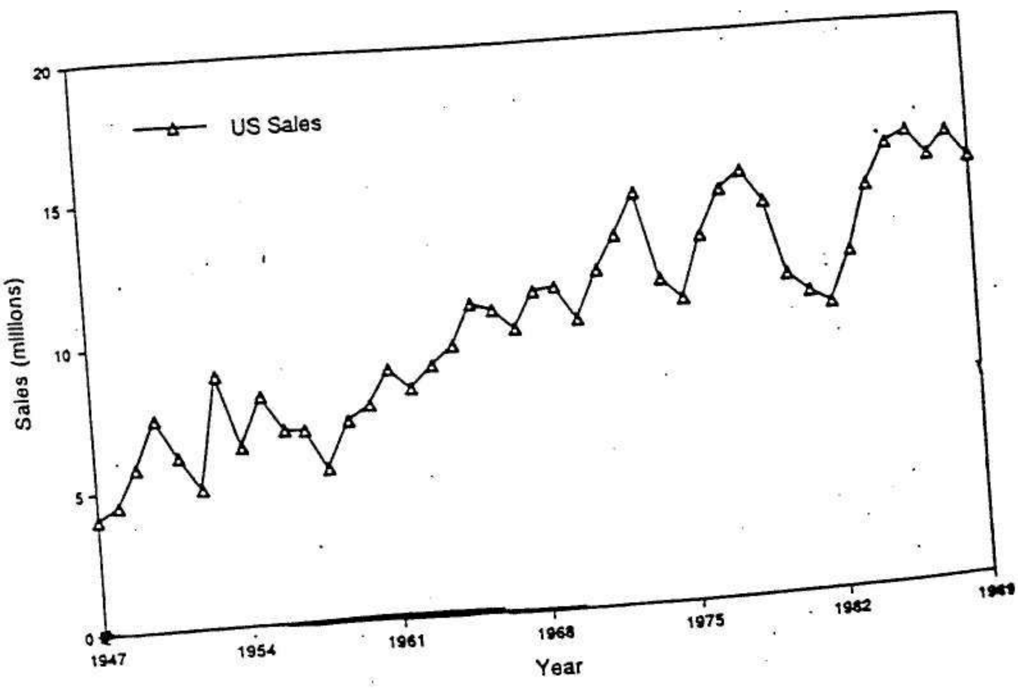

Figure 1: Cyclicality in the U.S. auto market [1]

	1955	1989
Products on sale	30	142
Sales/product (000s)	259	112
Mkt Share of 6 largest selling products	73	24

Table 1: Fragmentation in the U.S. auto market [1]

Table 2 shows increased competition in the U.S. marketplace over the same period. An auto company which had to position a new product against a background of 29 others in 1955 has to do the same against a background of more than 130 products today. The increased competition has contributed significantly to difficulties in new product definitions and market research.

	1955	1989
American products	25	50
European products	5	30
Japanese products	0	58
Total	30	138

Table 2: Increased competition in the auto market place [1]

Cyclicality, segmentation and competition have all led to a highly uncertain business environment for the auto industry. Traditional approaches of mass production, which were well-suited to large market segments and high volumes, have to be modified to reflect a more dynamic and demanding market place. Globalization of the auto industry has further complicated the picture. New and emerging markets are extremely volatile and competitive, accompanied by large excess capacity in the industry [2]. All these factors are forcing automotive corporations to pay much closer attention to huge capital investments and expected returns. Risks associated with these investments are high due to various uncertainties and unpredictable returns. In light of long lead times for product launches and associated market uncertainty, long range strategic planning assumes a new level of significance in an automotive company.

A recent *Harvard Business Review* article[3] highlights various approaches to long term strategic analysis under uncertain business environments, especially when large capital investments are involved. A traditional approach to long range strategy consists of adopting one of three possibilities: bet big, hedge, or wait and see. A company bets big when it invests in the most probable scenario it perceives. If there is a high degree of uncertainty in that particular industry, this approach can be very risky. When a company makes strategic investments which allow it to respond quickly to changing conditions, it is considered to "hedge" its position. Hedging solely due to uncertainties can also be risky. The risks associated with a wait and see approach are typically lost sales or lost time to market. These three approaches mentioned above depend on the ability to lay out future events with enough precision to allow a discounted cash flow analysis. The article concludes that traditional strategic planning approaches work well in relatively stable business environments where future events can be described with a high degree of certainty. Depending on the extent and type of uncertainty, appropriate approaches have to be developed by individual companies.

1.1 Levels of Uncertainty

Courtney *et al.*[3] categorize uncertainty into four levels and define approaches that they believe are appropriate to address these uncertainties. They also emphasize the analytic nature of these approaches. The four levels of uncertainty are:

1. Clear-enough future: In situations where accurate forecasts can be developed to define future events precisely, traditional strategic planning methods are the most appropriate. These methods, basically, would identify precise cash flows and estimate the net present value of a proposed strategic plan. The authors give the example of a major airline trying to decide on what strategy it should take against a low-cost entrant. The market, capacities and competition are quite clearly defined in such situations.
2. Alternate futures: This kind of uncertainty occurs when future events can be described as one of a few alternate outcomes. For example, companies formulating strategies based on estimating regulatory changes face these kinds of uncertainties. Depending on the regulatory outcomes (given a range of possibilities), subsequent events could change dramatically. An example of this kind of uncertainty is exemplified by recent events in Kyoto, Japan at the United Nations conference on global warming. It is uncertain what impact the greenhouse reduction treaty signed at Kyoto will have on the automotive industry. If a long range strategic plan is to be developed for an automotive company, this kind of uncertainty has to be dealt with. Also, depending on how binding the treaty is, automotive companies will be subject to distinctly different future events.
3. A Range of Futures: At this level of uncertainty, companies are faced

with a range of future outcomes depending on a few key variables. A consumer goods manufacturer entering an emerging market would face this kind of uncertainty. In such a situation, market penetration could probably take on a whole range of values and the company would have to take into account this uncertainty in deciding whether to invest in production capability in that market.

4. <u>True Ambiguity:</u> True ambiguity occurs when there is no basis to forecast the future. Entering post-Communist Russia immediately after the fall of communism would lead to this kind of a situation. In such cases there is neither precedence nor basis to forecast the future.

The appropriate approaches for each level of uncertainty (as presented by Courtney *et al.)* are shown in Table 3. The table also attempts to justify why these approaches are appropriate. Section 2 of this report analyses some of these approaches further.

Uncertainty	Clear-enough Future	Alternate Futures	Range of Futures	True Ambig
Analytic Tools	- "Traditional" strategy tool kit	- Decision analysis - Option valuation models - Game theory	- Scenario planning - Technology forecasting	- Analogies pattern recognition - Nonlinear dynamic m
Why ?	- Well known market, accurate forecasts of cash flows	- Discrete possible outcomes requiring different valuation models - No baseline scenario - Future events and industry structure path dependent (like a decision tree)	- Given baseline variables, a range of possible future outcomes - Industry structure not necessarily different for each scenario	- A primari qualitative analysis - Informati changing constantly, requiring dynamic approach

Table 3: Levels of uncertainty and analytic approaches to address them [3]

1.2 Long Range Strategic Planning in the Automotive Industry

Strategic planning in the auto industry is carried out typically for a 5-10 year horizon. For example, investment decisions and product plans for the 2002 model year are made in 1997. Several aspects of the auto industry cause such long lead times, including:

- Engineering product designs
- Facilitizing plants
- Establishing a supply and distribution base
- Launching a new product in a plant
- Meeting future regulatory requirements

In addition to having long lead times, the planning process is compounded further when key pieces of information, primarily related to the market, are known with very little certainty. Aspects which play a key role in ultimate company performance include:

- Customer demand for a particular (type of) future product
- Customer tastes 3-5 years into the future
- Economic outlook over a 5 year horizon
- Competitor strategies, products and pricing over a 5 year horizon

While the goal of all automakers is to minimize the planning horizon, current trends indicate at least a 3-5 year horizon. Let us consider the various organizations in an automotive corporation that feed information into a strategic plan. Figure 2 schematically shows the organizations and the information exchange that occurs between the various organizations that ultimately lead to a strategic plan.

The organizations and their role in strategic planning are briefly described below:

- **Business Strategy Organization (BSO):** This business strategy organization is ultimately responsible for formulating and communicating the strategic plan. It could be considered as the "engine" of the company. It initially suggests what products are suitable for which markets etc.

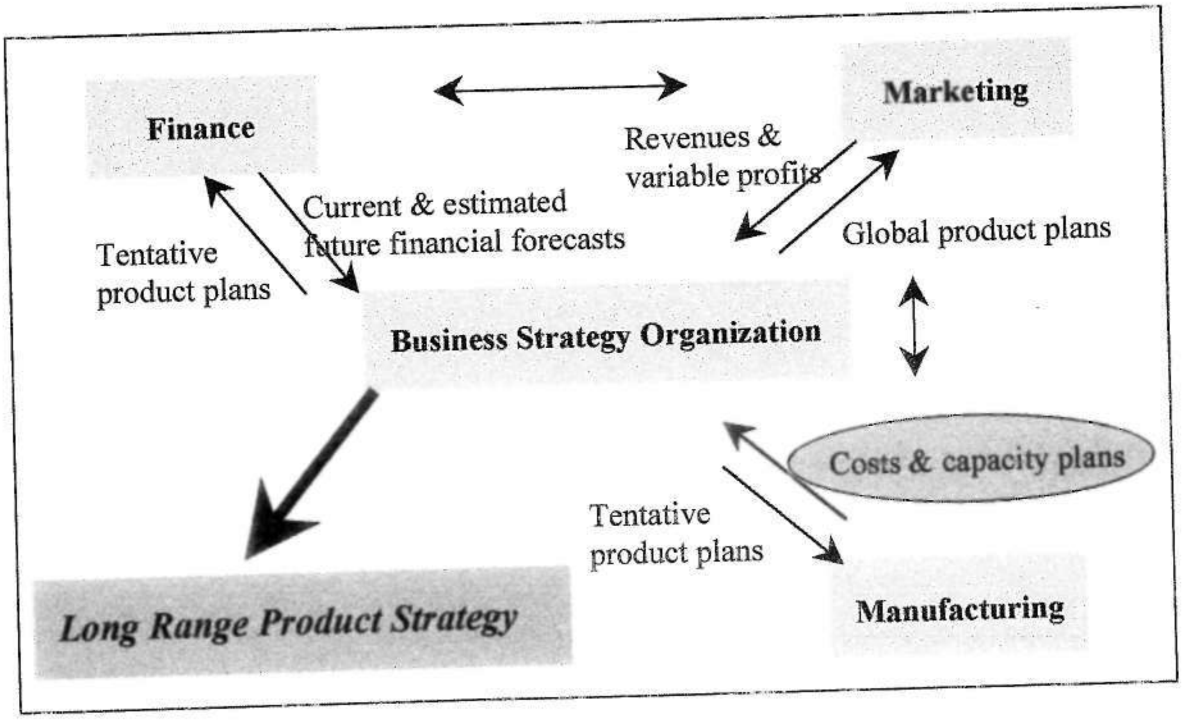

Figure 2: Organizations & information exchange in formulating long term company strategy

Marketing: Given a tentative product plan by BSO, marketing determines (forecasts) market demand volumes, revenues and variable profits by product and market. It then provides this information to other organizations involved in the planning process. Market demand volumes (sales) are one of the most important inputs into a strategic plan and also one of the most difficult to determine. Often, marketing will develop several different **scenarios** for demand volumes depending on other company products as well as the competition in similar segments. The forecasted volumes are largely dependent on estimates of future economic conditions and competitor information.

Finance: Finance is responsible for reporting current and estimating future company financial performance based on product plans. It tries to forecast cash flows and ultimate shareholder value (earnings per share, profitability, investment efficiency, etc.). Finance also assists the Business Strategy Organization in developing and helping achieve corporate goals.

. **Manufacturing Operations:** The manufacturing operations have ultimate responsibility for implementing the product strategy. They are also responsible for developing and recommending appropriate sourcing strategies for production, as well as developing costs of facilitizing plants for production. They are engaged in **overall**

capacity planning to meet the various goals set forth by the company. **Capacity planning is a critical step in deciding where, when and how much capital investment has to be made** to meet market demand and financial targets. The capacity planning process is also responsible for developing strategies that allows the company to be nimble and responsive to a dynamic marketplace by having the ability to launch and deliver products on demand. The focus of this report is on capacity planning and the development of analytical tools to assist manufacturing operations with its role in the overall strategic planning process.

.3 Why Scenario Planning ?

From the discussions in the previous sections, it is clear that every auto company is faced with a high degree of uncertainty. The uncertainty primarily stems from the need to develop and initiate plans several years prior to actual product launch. The market demand volumes are very uncertain because the customer preferences and competitor product portfolios are not known precisely. While historical data provide some guidelines, they do not eliminate uncertainty. In order to ensure timely production, capital investment decisions have to be made many years ahead of actual production. Capacity planning establishes these investments given product, market research and basic financial information. Market research provides critical input for the capacity planning process. Depending on where the products are to be sold and how many units of each product are expected to be sold, the capacity planning process allocates facilities for production. Since the future is uncertain, market research often provides demand information in the form of **scenarios**. Scenarios are determined based on forecasted sales of a product and the impact on sales of other products in similar and related segments. Scenarios are also dependent on economic forecasts which determine overall industry sales. Given the range of possible outcomes in the form of demand scenarios and adopting a framework (such as Courtney *et al.*'s [3]) for handling uncertainty, scenario planning can be one of the methods suitable for strategic planning in the auto industry. Scenario-based capacity planning aims to maximize expected profits (or returns) by choosing investments and facilities in a near optimal fashion. This approach differs from a more traditional approach where investments might be allocated based on a most probable demand scenario.

1.4 Flexibility: Its Definition & Role in Strategic Planning

Flexible strategies share multiple products within each plant and between different plants. Such strategies allow a company to tailor production as markets evolve. For example, if two different vehicle models can be manufactured in a single plant, management can respond to market demand of each product (as it evolves) purely by scaling production of each product. If the plant is capable of producing only one product and if the demand for that product falls, then it would be unable to respond to the market quickly due to long lead times involved in launching a new product.

Vehicle assembly flexibility is becoming an important element in automotive companies' strategies [4]. Traditionally, the majority of the North American automotive market has been sharply divided between cars and light trucks. However, in recent years the line differentiating cars and trucks is becoming increasingly blurred with the emergence of very popular minivans and sport-utility vehicles (SUVs). Two important factors are expected to significantly influence the automotive industry over the next several years.

First, several new "platforms" or vehicle types are expected to emerge, including[4]:

- "high" cars: vehicles with truck like (high) seating in cars
- "cross-dressing" cars: cars with increased ground clearance and truck cosmetic cues
- "macho" minivans: minivans with truck-like or SUV-like features
- Hybrids: SUV's with car like features

These new entrants are believed to have a sizable market but are also considered financially risky, due to uncertainties in the estimates of their market size. These products, therefore have serious implications for capacity planning. However, in principle, since most of these products are car or truck derivatives, they could be built in existing facilities if a flexible manufacturing strategy is adopted. This, flexibility, is assuming an increasingly important role in automotive planning strategies.

A second factor which has a big influence on the North American automotive market is the growing size of the truck market (up from 25% in 1985 to more than 45% in 1997) and the huge incremental capacity in North American truck production (estimated to increase by nearly 50% or approx. 4 million units between 1990 and 2002). But with such big increases in capacity, if the market were to turn around and favour more cars and their new derivatives, these manufacturers with the most flexible capacities are going to be the winners because converting capacities from trucks to cars or vice versa is very expensive and time consuming. Flexibility in manufacturing capacity reduces the risks of entering new markets or launching new products.

While flexibility can be a competitive advantage, it is also expensive to introduce into the production system. Adding a new product to an assembly plant, however similar to an existing product, costs several hundreds of millions of dollars. The decision to invest in flexibility has to be made carefully by trading off costs vs. expected profits. The focus of this project is to develop tools to analyse these tradeoffs using a scenario approach and recommend a capacity planning strategy with optimal flexibility.

2. Recent Work

2.1 Strategic Planning

Strategic planning has been the focus of several researchers in recent years. Rumelt, Schendel and Teece [5] have compiled an excellent set of articles on fundamental issues in strategy. They address several aspects of strategic planning relative to the firm and its management and highlight many open issues in strategic planning. Geus[6] describes planning as a learning process by citing examples of multinational companies who have had to absorb several shocks to themselves and their industry, survive them and eventually grow. Strategic planning has emerged as a discipline in its own right over the last three decades. It has evolved from studies of economics of organizations prior to the 1960s. Analytical approaches to strategic planning are more recent, evolving rapidly with computer technology and computational methods. Three classes of analytical approaches for strategic planning are briefly described here:

Game Theory: Brandenburger and Nalebuff [7] have elegantly described the relationship between game theory and business strategy. They describe business managers as playing the game of business in which their fortunes are interdependent. A game theory approach helps managers understand the relevance of every competitor and themselves in the game. Game theory allows business managers to understand the consequences of their possible actions. New business insights on the business can surface when the competition and industry are analysed using this approach. In addition to understanding the "game" this approach also helps to identify new strategies to change the "rules of the game". They cite the example of General Motors launching a credit card wherein card holders earned rebates towards the purchase of a new car. This new strategy helped GM to eliminate year-end rebates to a large extent and to develop a loyal customer base. Game theory helps business managers deal with uncertainty with respect to competitors' actions. For a more comprehensive understanding of game theory the reader is referred to "Thinking Strategically: The Competitive Edge in Business, Politics and Everyday Life" by Dixit and Nalebuff [8].

Option Pricing Models: Dixit and Pindyck [9] present an analogy between stock options and opportunities for capital investment. They present an argument against conventional NPV analysis by suggesting that capital investments are often irreversible and can be delayed, which a conventional NPV analysis ignores. They then draw an analogy between holding a call option and an opportunity to make a capital investment *(i.e.* with a right to future cash flows when the option or investment is exercised). When a company decides to invest, it in effect kills the option. Therefore, it gives up the possibility of waiting for new information that might affect the desirability or timing of the investment. Option pricing models are particularly useful where there are uncertainties regarding a few alternate future outcomes. The analysis is similar to decision (or binary) trees that are used to evaluate options. For example, if a regulation is forthcoming, option pricing models can be used to evaluate the benefits of investing (and its timing) depending on, say, a probability of the regulation being approved (such as the environmental regulations being debated by the United Nations in Kyoto, Japan). Option valuation models have successfully been used in valuing capital investments for flexibility in manufacturing processes. Kulatilaka [10] presents a framework for using option valuation models to evaluate the value of flexibility in the context a company analysing the **option** of installing an expensive industrial steam boiler.

Scenario Planning: Schoemaker [11] argues that scenario planning stands out as a tool to help managers with strategic planning for its ability to capture a whole range of possible futures in great detail. Scenario planning is a method of evaluating strategic options by imagining a range of possible future outcomes. It helps a manager avoid overconfidence on one hand and a restricted vision on the other. Schoemaker presents an excellent description of scenario planning as a planning tool. He details the process of constructing scenarios and using them for strategic decisions in the context of an advertising agency. Scenario planning has seen applications in the auto industry as well [12]. The focus of that work is application of scenario planning to achieve optimal flexibility with respect to capacity planning. The scenarios used in the auto industry are based primarily on market demand volumes. A detailed discussion of the approach, based on Eppen *et. al.'s* [12] work is presented later.

2.2 Manufacturing Flexibility

Flexibility, as defined by Upton [13] is the ***"ability to adapt or change".*** Manufacturing flexibility has been the focus of much attention in recent years. Significant efforts by researchers are being directed at approaches to implementing flexibility at all levels - from the shop floor [14] to strategic planning [15, 16, 17]. Several new developments in flexible manufacturing systems are summarized in [18]. Flexibility in manufacturing systems is becoming an integral part of modern manufacturing systems, as is JIT [19]. Manufacturing flexibility development and implementation requires close interaction between strategic planners (management) and manufacturing operations (engineers). There is no doubt that flexibility is becoming a major component of automotive strategic plans. Even though flexibility is an important strategic element in manufacturing, measuring the impact of flexibility on manufacturing performance is an important issue [20, 21].

The focus of this work is to address flexibility requirements at a vehicle assembly level. Jordan and Graves have written well recognized articles [22, 23] on this topic. Their analyses of flexibility in vehicle assembly sourcing is an important basis for the work outlined in this report. Jordan and Graves developed the principles of benefits of flexible manufacturing processes.

They suggest that flexibility is a key strategy for improving response time to a changing marketplace. They look at assignment of products to plants and show the benefits of having flexibility in vehicle assembly capacity. **They showed that ignoring the costs of flexibility, assuming a constant total capacity in the plants, and given an uncertain product demand, a flexible configuration would always lead to a higher level of overall expected capacity utilization and expected sales.** The intuition is best expressed in the context of an example.

Consider two products A,B and two plants 1,2. Figure 3 shows

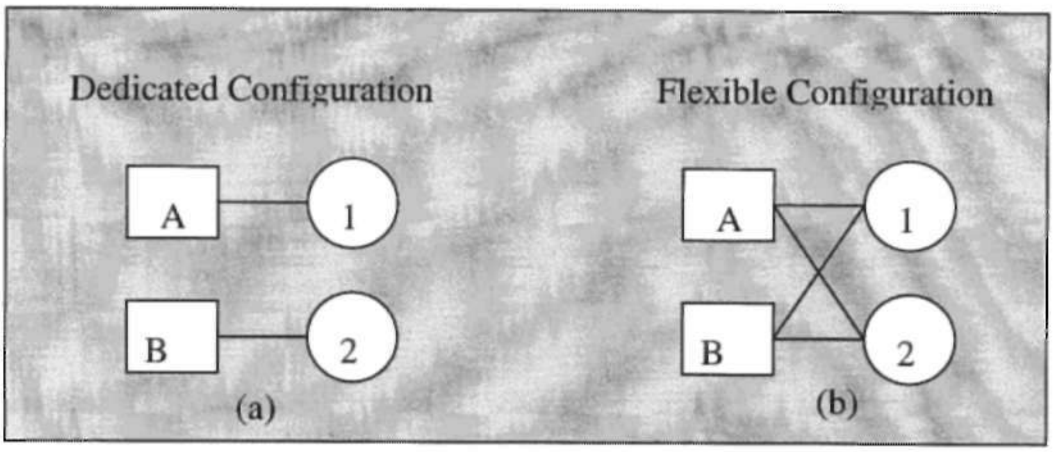

Figure 3: Schematic of two product-plant configurations: (a) dedicated configuration and (b) flexible configuration

dedicated and flexible configurations for the two plants. In the dedicated configuration, Plant 1 can manufacture only Product A and Plant 2 can manufacture only Product B. In the flexible configuration, both Plants 1 and 2 can produce Products A and B. Let us assume that the demand for products A and B are independent of each other and have demand scenarios as follows:

Demand (Units) Scenario	Probability of Scenario
50	1/3
100	1/3
150	1/3

Let us assume that the two plant capacities are equal and the total capacity between the two plants can have one of the following values: 100, 130, 150, 170, 200, 230, 250, 270 and 300. Since the demand scenarios for the two products are assumed to be independent, there can be a total of nine product demand combinations for A-B (50-50, 50-100, 50-150, 100-50, ...150-150). Let us consider the following situation, which depicts one of the several demand-plant capacity combinations:

Demand for Product A = 150 units

Demand for Product B = 50 units

Probability of Demand Scenario occurring = 1/3 * 1/3 = 1/9

Total Plant Capacity = 200 units (100 each in Plant 1 & 2)

The total sales and capacity utilization for the two configurations (dedicated & flexible) occur as follows:

Sales of Product A:

Dedicated Configuration: 100 units (since A can be produced only in Plant 1 whose capacity = 100)

Flexible Configuration: 150 units (since A can be produced in Plants 1 & 2)

Sales of Product B:

Dedicated Configuration: 50 units (= demand)

Flexible Configuration: 50 units (=demand)

Total Sales:

Dedicated Configuration: **150 units**

Flexible Configuration: **200 units**

Capacity Utilization (total sales/total capacity)

Dedicated: (100+50)/(200) = 75%

Flexible: (200)/200) = **100%**

Therefore, in this case, both the total sales and capacity utilization are higher for the flexible configuration than for the dedicated configuration.

This analysis sequence can be repeated for all demand scenarios with varying total capacity levels, and a total expected sales and capacity utilization can be computed (the probability of each demand scenario occurring is 1/9). The complete results of the calculations are shown in Figure 4. The Excel spreadsheet calculations are shown in Appendix 1.

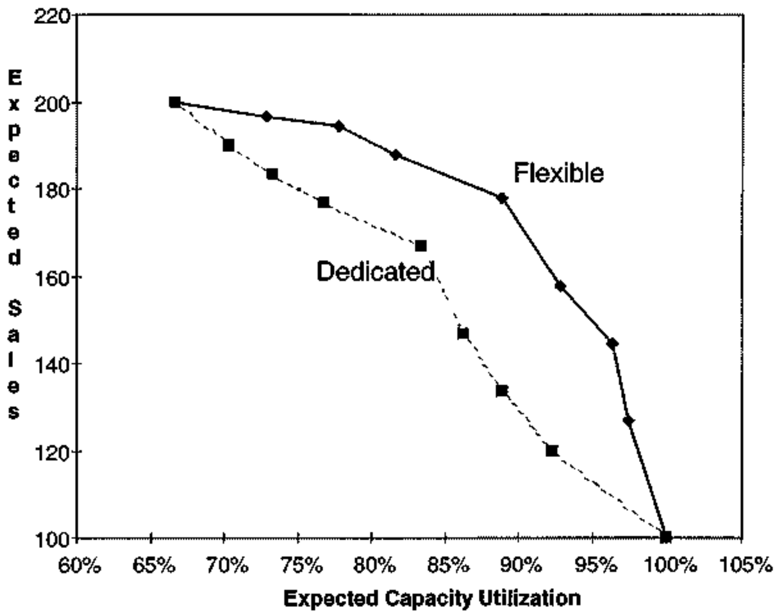

Figure 4: Total expected sales and capacity utilization for dedicated and flexible configurations as shown by Jordan & Graves

It can be seen from the figure that the Expected Sales/Capacity Utilization envelope for dedicated facilities is below that of flexible configurations. At an extreme, when the capacity for each plant is set to the minimum possible demand, flexibility has no value since both plants will be fully utilized. Similarly, at the other extreme, if the plant capacity is set to the maximum demand, all the demand for both products will always be met and flexibility will have no additional value. However, if the capacity is set to something in between, expected sales and utilization for the flexible configuration will always be higher. Also, at the same total capacity level, a flexible configuration will exhibit a higher expected sales and utilization.

In addition to the benefits of flexibility in these simplistic terms, Jordan and Graves [22, 23] also showed that "chaining" (or linking) production facilities in a long linked chain is almost as good as having total flexibility. Consider 10 products and 10 plants as shown in Figure 5. Figure 5(b) shows a configuration with total flexibility, *i.e.* all products can be manufactured at all sites. Figure 5(a) shows the plants and products linked in one long chain. As an example, the authors show that if the standard deviation for expected demand for each product was 40, the maximum and minimum demands were 180 and 20 units, respectively and each plant capacity was a constant of 100 units, then the expected sales and capacity utilization for a plant configuration with 1 chain (or 10 links) is almost equal to that of a totally flexible configuration with 90 links (see 22,23 for further details). In their article, Jordan and Graves developed the following heuristics for capacity planning in the context of flexibility:

- try to equalize the number of plants that each product in a chain is directly connected to
- try to equalize the number of products that each plant in the chain is directly connected to
- try to create a circuit that encompasses as many plants and products as possible

- a little flexibility in the "right" fashion can yield most of the benefits of total flexibility
- flexibility is most effective at increasing expected sales and capacity utilization when it is added to create longer chains of plants and products

While Jordan and Graves presented a very elegant description of the intuition behind the principles of the benefits of flexibility, some open issues remain which makes their model inconvenient to use directly for practical applications:

- Interdependence or cannibalization of product demands: The launching of new products in the automotive industry can have two effects in the marketplace: take market share away from competition and/or cannibalize one's own product in a similar or another segment. Including product demand interdependence in a model is normally difficult since it can lead to nonlinearities in the formulation. In our work, we do not include product demand interdependence directly (functional form) but do allow it to be included in the construction of demand scenarios.
- How to arrive at an appropriate chain: The question of how many and which plants should be grouped together must be addressed. This is an important issue because flexibility investments are significant and these costs were ignored in their analysis. Their analysis focused on maximizing expected capacity utilization and sales, but not profits. Our work is aimed

at including the costs of flexibility explicitly and optimizing the tradeoffs between the benefits of flexibility and costs of achieving it.

- Their approach to arrive at an appropriate level of flexibility used a simulation model (to look at nearly all possible plant-product combinations) based on heuristics. Our model uses a mixed integer linear programming approach to achieve optimality with respect to flexibility. Our model does not use heuristics.

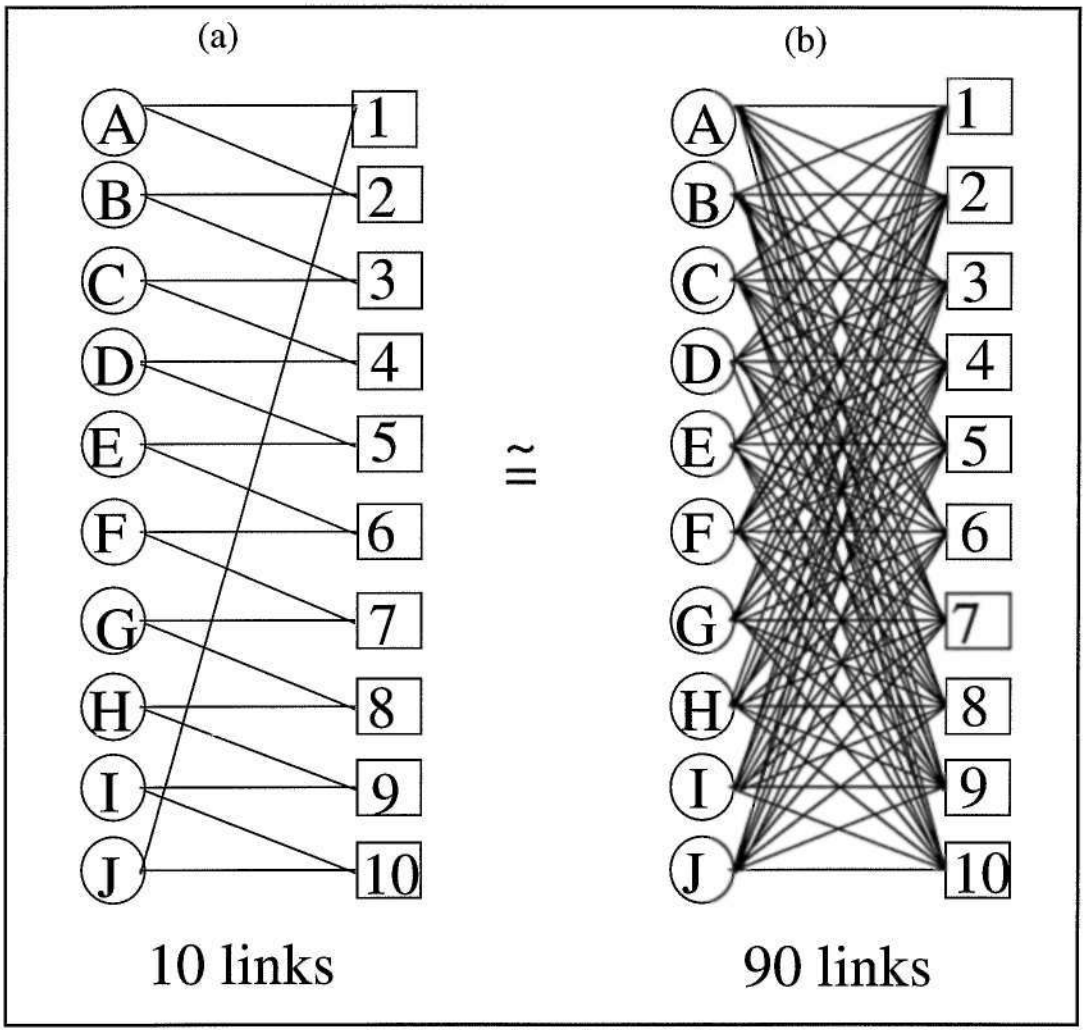

Figure 5: Chained and total configurations between ten products and ten plants. Jordan & Graves showed that if costs of flexibility are ignored and given a total capacity, 10 links (as shown in (a)) are almost as effective as 90 links (as shown in (b)) [22,23].

2.3 Scenario Based Capacity Planning (Eppen et. al. [12])

Eppen *et. al.* have presented a practical approach to scenario based capacity planning for an auto manufacturer. They present a mixed integer linear program formulation to approach the capacity planning problem in general. Their model includes several aspects of automotive capacity planning that need to be considered. The optimization approach maximizes total profits obtained over multiple time periods. Their model included facilities and their flexible configurations for multiple products in the same facility. Given total plant capacity constraints and product demand constraints, the program chooses near optimal values for facilities and their flexible configurations in each time period. It estimates changeover of each plant configuration in each time period and also estimates production levels of each product in each given demand scenario. It also automatically allows for a near optimal level of unmet demand. If facilitizing a plant for a particular product is not profitable, it allows the demand for that product to be unmet. Unmet demand for each product, therefore, is also a result of the optimization. Further details of the model will be clear when the formulation used in the current work is discussed in Section 4. In addition to maximizing profits, a unique feature of the Eppen model was a "downside" risk constraint. This constraint could be tuned so that the optimal capacity plan would meet a target profit level (while minimizing the risk of losing money). This idea, borrowed from financial literature [24], was a clever aspect of their work.

While Eppen *et at.* described a general and practical approach to capacity planning, their model did not have the ability to pick an optimal level of flexibility - *i.e.* the ability to determine optimal configuration with changeovers. **Their model assumed that all changeovers in configurations were identical and that the changeovers required identical investments.** In reality, flexibility costs vary with facilities and configurations. Costs associated with changeovers are an important aspect of production decisions. Due to this limitation of their model, they allowed only one changeover per facility over the planning horizon considered in the model (five years). Eppen *et at.* were also limited by the computational power available at that time (their study was conducted in 1989). They had to resort to using mainframe computers to solve problems that can be solved today on a desktop personal computer. However, Eppen *et at.* clearly demonstrated the viability of optimization techniques for capacity planning.

The model developed in our work builds upon the ideas presented by Eppen *et. at.* by relaxing some of the assumptions. Focus in this work is primarily on the notion of optimal flexibility and maximizing expected total profits over a multiple period time frame. The next few sections describe the model in detail and present results of sample analyses.

3. Introduction to Modeling & Using Linear Programming

Analytical business models are often used for executive planning [25]. These models can be used to forecast future events, explore alternatives, to develop contingency plans, etc. Models help management describe real world situations in an analytical framework. A variety of techniques can be used to analyse models, depending on the type of modeling being carried out. The steps typically involved in a modeling process in strategic planning can be listed generally, as follows:

- Real world situation: problem identification
- Formulation and construction of model, including data acquisition
- Model analysis and solution
- Model output - decisions and predictions
- Output comparison with management experience, judgment and intuition
- Model implementation or model revision with a repeat of the process

A large number of models fall under the class of "Constrained Optimization Models". Often, in real world applications, a set of allowable decisions are restricted in some way. These restrictions are called constraints. Constrained optimization models provide near optimal decisions to the mathematical description of the real world problem. The optimal solution provided by these optimization methods are not necessarily the best (since the problem description usually does not include every possible issue at hand), but should be interpreted as leading to "good" decisions.

The general form of a constrained optimization is as follows:

Maximize(or minimize) $f(x_1, x_{2,\dots,} x_n)$ subject to

$g_1(x_1, x_{2,\dots,} x_n) \leq$ or $= b_1$

$g_2(x_1, x_{2,\dots,} x_n) \leq$ or $= b_2$

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.

$g_m(x_1, x_{2,\dots,} x_n) \leq$ or $= b_m$ $\quad (m \neq n)$

When all the functions (listed above) in this model are linear, the model is a special case of a "linear programming model". The function f is called the objective function, the functions g_1 through g_m are called the constraints and $x_1, x_{2,\dots,} x_n$ are called the decision variables. Additionally, when some of the decision variables are restricted to integers (such as number of units of a product to be produced), then the model is referred to as a mixed integer linear programming model. A solution represents optimal values of x so that the constraints are satisfied and the objective is maximized (or minimized). Several commercial tools are available to solve linear programming models. Some popular tools are Microsoft Excel [26], LINGO Systems [27] and GAMS [28]. An introduction to model development, optimization and linear programming in the context of capacity planning is presented in the next section.

3.1 Capacity Planning Using Excel Spreadsheets

The example used in this section is meant to illustrate the issues related to capacity planning and will also point out some limitations related to solving such problems using spreadsheets. However, it also illustrates the ease of use of spreadsheets for linear programs.

Let us consider three products, A, B and C, and two plants, I and II where the products can be produced. There are three annual demand scenario forecasts available (Table 4). For purposes of illustration, let us consider demand scenario II. Total annual capacities of the two plants are given as 350,000 and 166,000 units, respectively. Investments required to build each product in both plants are given as well as variable profits for each product (Table 4). Using the "SOLVER" capability in Excel, a mixed-integer program can be set up using the following model:

Objective: Maximize total profits over 5 years (Cell in green - Objective).

Decision Variables: Levels of production of each product in each plant (cells in blue) are decision variables. Investment is incurred when the first unit is produced in a certain facility.

Constraints: The following constraints are specified:

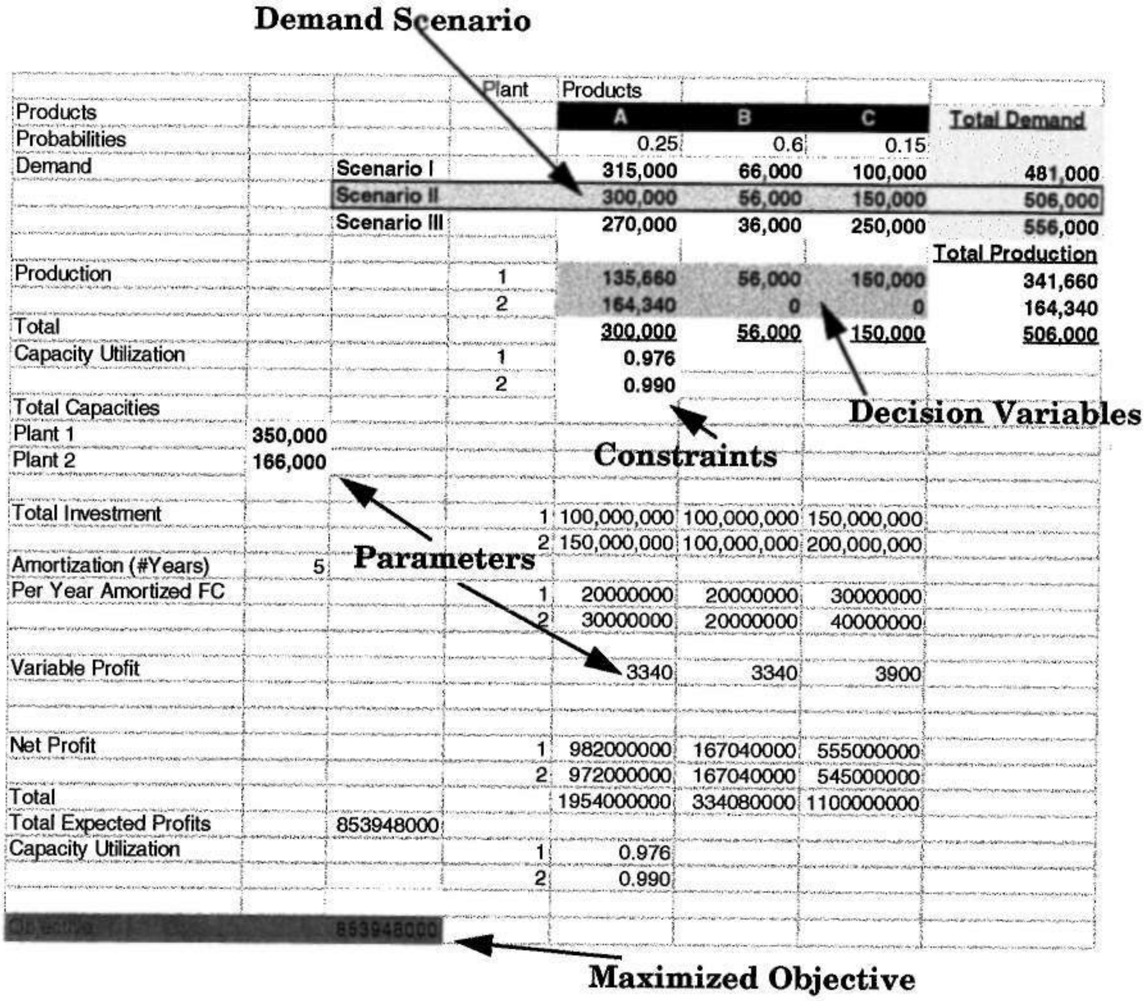
- Production (decision variables) should be integer values and positive
- Total production of each product should be equal to its demand
- Total capacity utilization of each plant should be between 85% and 99%

- Total production of products in each plant should be less than total plant capacity

The results show that analysis recommends that Plant I produce products A, B and C and that Plant 2 produce only A, *i.e.,* it adds one "link" for Product A. This observation stems from the fact that the solution indicates 0 units of Products B and C are to be produced in Plant II. Also, note that capacity utilizations of the two plants, based on the above configurations, are 97.6% and 99%, thereby satisfying the specified constraints. Objective function evaluation predicts a total profit of $8.54 billion.

This simple analysis illustrates the concepts behind capacity planning and use of spreadsheets for linear programs. However, it makes two important assumptions which render it impractical. They are:

- Each demand scenario occurs with a probability of 100%. In reality there may be several different scenarios for which profits should be maximized in an expected sense.
- Investments in facilities are unique to a product, *i.e.* the costs of launching a product in a certain plant are independent of what other products might be produced there. In reality, investments are highly dependent on plant configurations. To introduce costs in an appropriate fashion, the model should be able to accommodate several possible configurations as decision variables.



			Plant	Products			
Products				A	B	C	Total Demand
Probabilities				0.25	0.6	0.15	
Demand		Scenario I		315,000	66,000	100,000	481,000
		Scenario II		300,000	56,000	150,000	506,000
		Scenario III		270,000	36,000	250,000	556,000
							Total Production
Production			1	135,660	56,000	150,000	341,660
			2	164,340	0	0	164,340
Total				300,000	56,000	150,000	506,000
Capacity Utilization			1	0.976			
			2	0.990			
Total Capacities							
Plant 1	350,000						
Plant 2	166,000						
Total Investment			1	100,000,000	100,000,000	150,000,000	
			2	150,000,000	100,000,000	200,000,000	
Amortization (#Years)	5						
Per Year Amortized FC			1	20000000	20000000	30000000	
			2	30000000	20000000	40000000	
Variable Profit				3340	3340	3900	
Net Profit			1	982000000	167040000	555000000	
			2	972000000	167040000	545000000	
Total				1954000000	334080000	1100000000	
Total Expected Profits		853948000					
Capacity Utilization			1	0.976			
			2	0.990			
Objective		853948000					

Table 4: Capacity planning using spreadsheets

Some other limitations to using spreadsheets for modeling such problems are:

- input can be cumbersome when complex models are involved
- input description is completely explicit (does not allow compact notation)
- spread sheets are limited by the numerical algorithms available within the software.

The next section develops a more general formulation to the capacity planning problem.

4. General Formulation of the Capacity Planning Problem

The formulation described here is a general framework taking into account several aspects of a capital investment plan. It must be noted that the model in its entirety (as presented in the following discussion) would probably be inconvenient to use due to the extensive amount of data required or due to the characteristics of the particular problem being addressed.

Let us assume:

- there are K facilities (assembly plants): **k = 1, ….., K**
- each facility can take **H** configurations: **h = 0, 1, ….., H**. A configuration of 0 implies the initial configuration of the facility. Each configuration, h, implies a certain level of flexibility. Decisions regarding allowable configurations of the facilities can thus be made *a priori*
- there are N products: **i = 1, ….., N**
- there are M product demand scenarios: **m = 1, ….., M**. Individual product demand scenarios will be specified for each demand scenario.
- there are T time periods: **t = 1, ….., T**

A **mixed integer linear program formulation** has been developed for the capacity planning problem. The various constituents of the model are:

Parameters (Inputs):

Market Parameters

$\mathbf{D}_{imt}$ = demand of each product i (in 000s of units), in scenario m, in period t

$\mathbf{Scenario}_m$ = probability of scenario m occurring in any period

$\mathbf{prof}_{it}$ = variable contribution per unit of product i in period t

Capacity Parameters

$\mathbf{Maxcap}_{kh}$ = maximum capacity (in 000s of units) of facility k in configuration h

$\mathbf{Mincap}_{kh}$ = minimum capacity (in 000s of units) of facility k in configuration h

The two capacity parameters listed above allow the model to make adjustments to the required capacity at a facility and to allow the model to reflect input of any union-negotiated agreements (changes in available capacity usually expressed as number of jobs/hour)

$\mathbf{u}_{ikh}$ = units of capacity used up by product i in facility k in configuration h. This parameter allows the capacity to be scaled by product. Often, the entire capacity of a facility may not be available to one product. For example, if the total plant capacity at facility k in configuration h is 350,000 units but a maximum of only 275,000 units of a product i can be produced in that plant, the parameter u(i,k,h) = 350,000/275,000 = 1.27. If the entire plant is available to the product then, u(i,k,h) = 1.0

$\mathbf{lostcap}_{kh1h2}$ = lost capacity at facility k (in thousands of units) when retooled from configuration h1 to h2 (h, h1 and h2 represent the same set of configurations)

Cost Parameters

$\mathbf{Newfac}_{kht}$ = cost of obtaining a new facility k in configuration h in period t (in millions of dollars)

$\mathbf{Chg}_{kh1h2}$ = cost of retooling facility k from configuration h1 to configuration h2 (in millions of dollars)

$\mathbf{Fcost}_{kh}$= fixed cost of operating facility k in configuration h

$\mathbf{IC}_{kht}$ = cost of increasing capacity at facility k in configuration h in period t by 1000 units (in millions of dollars)

$\mathbf{DC}_{kht}$ = cost of decreasing capacity at facility k in configuration h in period t by 1000 units (in millions of dollars)

Decision Variables (Values determined by optimization):

The decision variables that are computed as part of the optimization solution are:

$\mathbf{x}_{ikhmt}$ = level of production of product i in facility k in configuration h under scenario m in period t (in 000s)

$\mathbf{y}_{kht}$ = 1, if a facility k in configuration h in period t is chosen, otherwise = 0

$\mathbf{iy_{kht}}$ = 1, if a new facility k in configuration h in period t is chosen, otherwise=0

$\mathbf{Cap_{kht}}$ = actual installed capacity at site k in configuration h in period t (in 000s)

$\mathbf{Icap_{kht}}$ = increase in capacity at facility k in configuration h in period t (in 000s)

$\mathbf{Dcap_{kht}}$ = decrease in capacity at facility k in configuration h in period t (in 000s)

$\mathbf{z_{imt}}$ = unsatisfied demand for product i in scenario m in period t (in 000s)

$\mathbf{w_{kh1h2t}}$ = 1, if facility k is retooled from configuration h1 to configuration h2 in period t, otherwise = 0

Objective Function

$$Max(\sum_{ikhmt} 1000 * x_{ikhmt} * prof_{it} * scenarios_m - 1000000 * (\sum_{kh1h2t} chg_{kh1h2} * w_{kh1h2t} + \sum_{kht} Newfac_{kht} * iy_{kht} + \sum_{kht} FCost_{kh} * y_{kht} + \sum_{kht} IC_{kht} * icap_{kht} + \sum_{kht} DC_{kht} * dcap_{kht})) \quad \ldots(2)$$

Constraints

Capacity Constraint

$$\sum_{i} u_{ikh2} * x_{ikh2mt} \le cap_{kh2t} * y_{kh2t} - lostcap_{kh1h2} * w_{kh1h2t} \quad \textit{for all } k,h1,h2,m,t \qquad \ldots(3)$$

Note: $h1,\ h2 \in \{0, \ldots, H\}$

Market Demand Constraint

$$\sum_{k}\sum_{h} x_{ikhmt} + z_{imt} = D_{imt} \quad \textit{for all } i,\ m,\ t \qquad \ldots(4)$$

Capacity Balance Constraint

$$cap_{kht-1} + icap_{kht} - dcap_{kht} = cap_{kht} \textit{ for all k, h, t>0} \qquad \text{...(5)}$$

Facility Balance Constraint

$$y_{kht-1} + iy_{kht} = y_{kht} \qquad \text{...(6)}$$

Retooling (Changing) Configuration Constraint

$$y_{kh2t} + y_{kh1t-1} - 1 \leq w_{kh1h2t} \textit{ for all k, h1, h2, t>0} \qquad \text{... (7)}$$

Ensure Only One Configuration for Each Facility

$$\sum_{h} y_{kht} = 1 \textit{ for all k, t} \qquad \text{...(8)}$$

Ensure Exactly One Changeover Per Time Period

$$\sum_{h1} \sum_{h2} w_{kh1h2t} = 1 \textit{ for all k, t} \qquad \text{...(9)}$$

Bound Capacity Between Maximum & Minimum

$$cap_{kht} \leq y_{kht} * \max cap_{kh} \textit{ for all k, h, t} \qquad \text{...(10)}$$

$$cap_{kht} \geq y_{kht} * \min cap_{kh} \textit{ for all k, h, t}$$

Initial Conditions

$$y_{kh2t} \leq w_{kh1h2t} \textit{ for t=0 and all k, h, h1 and h2} \qquad \text{...(11)}$$

Equation (2) is the objective function for the constrained optimization. Simply, it represents (total expected profits - total costs). The total expected profits are computed by multiplying the total production of each product in each scenario, its contribution margin and the probability of that scenario occurring. A scaling factor of 1000 is used because all numbers pertaining to the product (demand, capacity and production) are in thousands of units. Total costs are computed by including changeover, fixed and capacity change costs. A scaling factor of 1000000 is used because all costs are in millions of dollars. Equation (3) is a capacity constraint which ensures that the total production in each facility does not exceed the net capacity in that facility in that time period. The total available capacity (right hand side of Equation (3)) is calculated as the difference between the net capacity (which is computed in Equation (5)) and the lost capacity incurred during a changeover (input parameter), if any, in that time period. The net capacity is the capacity in the previous period plus the net change due to any increase or decrease in capacity. A related constraint is shown in Equation (10) which ensures that the total capacity used at a particular facility is within the bounds of allowable capacity at that facility. These bounds are specified *a priori* and can either be determined by the facility size or be negotiated with a union. The left hand side of Equation (3) ensures that the total production is adjusted based on the unit capacity consumption of each product. Equation (6) ensures that any new facility used (if $iy_{kht} = 1$), y_{kht} will reflect that. For example, if a new facility with $k = 3$, $h = 2$ and $t = 2$ is used, then $iy_{322} = 1$. Therefore, using Equation (6) would yield $y_{322} = 1$ (since the facility did not exist in t=1 and y_{321} = 0) thus ensuring facility balance. Equation (6), therefore links iy_{kht} to y_{kht}. Equation (4) is used to ensure that the total production of each product plus any unmet demand of that product in each time period and scenario is equal to the total demand of that product in that particular scenario and period. Equation (7) helps track the changeover from period to period. If the plant configuration changes in two consecutive periods (as expressed by the left hand side), the binary flag, then w = 1. For example if the configuration of facility 1 changed from a to ab in period 2, then $w_{1\,a\,ab\,2}$ = 1. Equation (9) is a constraint that works in tandem with this constraint. It makes sure there is exactly one configuration change for every plant in every period. Therefore, if there is no change in configuration at a particular plant, then h1=h2 for the decision variable w. This feature is illustrated in the example described later. Equation (8) ensures that each facility is used only in one configuration. Equation (11) provides initial conditions for the initial time period and ensures consistency between y_{kht} and w_{kh1h2t}.

5. Application

The capacity planning model described in Section 4 has been implemented in GAMS [28], a commercially available optimization environment. GAMS provides an application programming interface to describe the equations such as those in Section 4. It provides several tools to carry out linear and nonlinear mixed integer program analysis. The MINOS module in GAMS has been used in this work. The implementation is best described in the context of an example.

5.1 Example Problem

The model described in Section 4 has been used to analyse a real capacity planning problem for an automotive company. Due to the confidential nature of the information, the data has been modified in this discussion. The nature of analysis and results however remain unchanged.

Consider three products A, B and C, and two plants, I and II. The goal of the analysis is to decide which products to produce at each plant. The planning horizon is five years (t=1..6), with time period 1 being defined as the initial period. Figure 6 is a schematic representation of the problem. The two extreme options are either a "base configuration" defined as sourcing products A and B in Plant I and product C in Plant II (see Figure 9(b)) or completely flexible, *i.e.*, all three products, A, B and C, in both Plants I and II. However, certain configurations are not allowed due to manufacturing and

and facility constraints. Let us present the given data systematically.

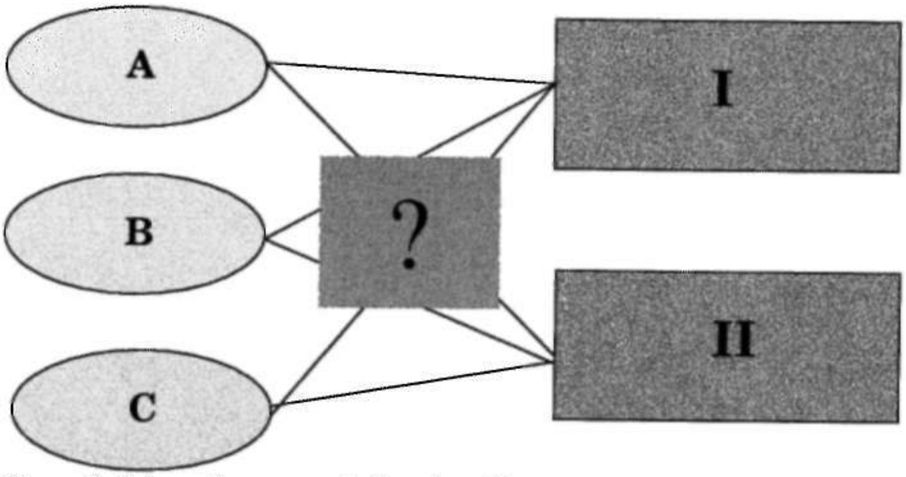


Figure 6: Schematic representation of problem statement; How to source three products in two plants

Demand Scenarios

Five annual demand scenarios with varying probabilities of occurring are possible. These scenarios and probabilities are shown in Figure 7.

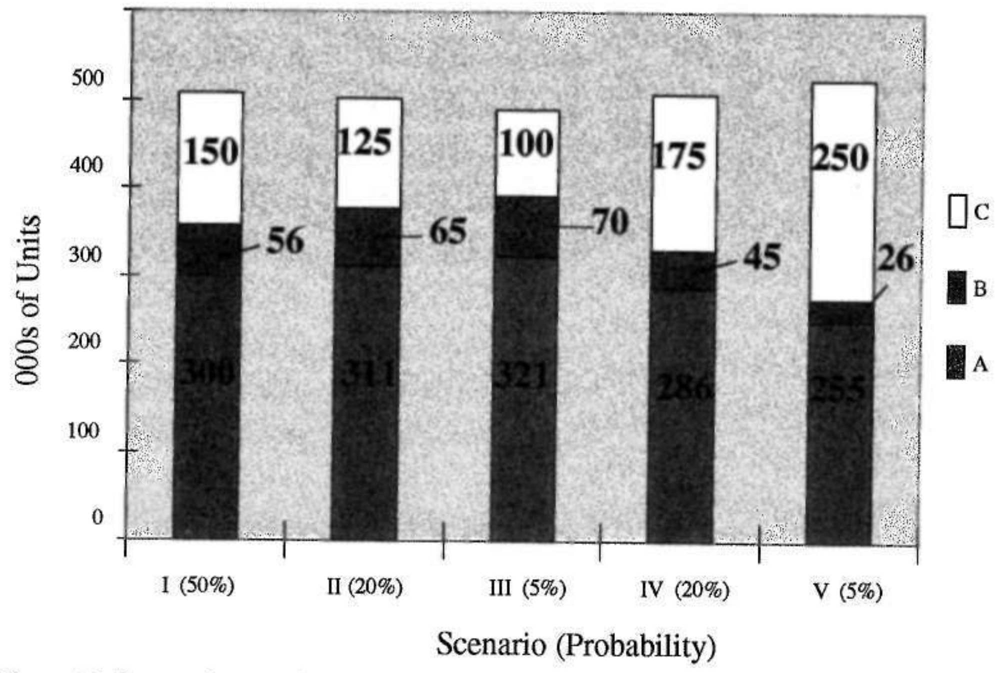


Figure 7: Demand scenarios for products A, B and C. Five scenarios with probabilities are along the abscissa

The figure shows that the demand for Product C (being a new product) has a great deal of uncertainty, ranging anywhere from 150,000 to 250,000 units. C is in a vehicle segment similar to A and B. The demands for each product shown in the figure takes into account the cannibalization that is expected to occur when C is launched. Therefore, independent product demands are assumed for modeling purposes. Also, note that while the total demand for all three products remains approximately the same (500,000 units), the expected demand distribution between the products varies significantly. This phenomenon is quite common during demand forecasting.

Per Unit Contribution Margin (Variable Profit)

The per unit contribution margin (variable profit) is shown in Figure 8. Products A and B have the same estimated variable profit of $3340 and Product C has a variable profit of $3900. Demand scenarios and profitability estimates are provided by the marketing organizations.

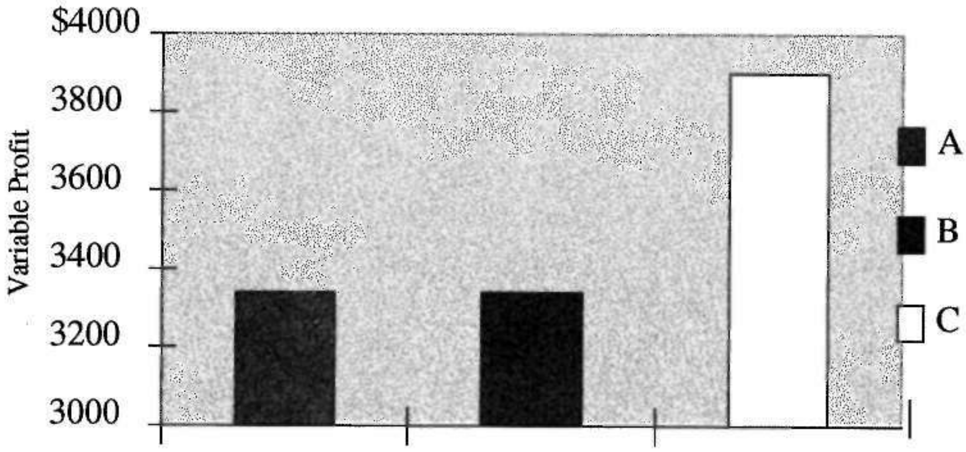


Figure 8: Variable profits of A, B and C. A and B have the same variable profit ($3340) and C has a variable profit of $3900

Capacities, Investments (Changeover Costs) and Fixed Costs

Plants I and II **have total capacities** of **350,000 and 166,000 units** respectively. Also, let us assume that the facilities are indifferent to which products they make, *i.e.* $u(i,k,h) = 1$ **for all** i, k **and allowable** h.

Currently, the plants are assumed to be in Configuration 0 (see initial conditions in Appendix 2) with no production, *i.e.* the facilities exist but are not committed. Table 5 shows the allowable configurations and required investments for the two plants. The decision to either allow or disallow certain configurations is made by manufacturing organizations based on existing facilities, their capabilities and the product complexities. For example, having all three products in Plant II is considered infeasible because the plant cannot support three production lines. In addition to manufacturing considerations, demand considerations can also help identify certain infeasibilities. For example, given the relatively low demand for product B and the relatively large plant capacities, it can be concluded that neither plant will be configured to produce B only. The investment and configuration information is usually provided by manufacturing operations organizations.

Configuration	Plant I	Plant II
	(Mils)	(Mils)
A	$422	$215
C	Not Allowed	260
A,B	467	285
A,C	632	Not Allowed
A,B,C	677	Not Allowed

Table 5: Allowable plant configurations and the required investments

The annual **fixed costs** of running plants I and II are given to **be $158.7 and $53.5 Million** respectively. Fixed costs usually include real estate, energy and some labor costs.

Other Assumptions

- Several other assumptions have been made for this model either due to unavailable data or lack of relevance:
- there is no lost capacity during changeover; lost capacity is important, but accurate data was not available
- no new facilities are being considered for this particular case, *i.e.* no new plants will be built for this product line
- the total capacity is fixed and cannot be changed; capacity variations require input from several different organizations and the information

was not available

5.2 Model Implementation

The data presented in Section 5.1 needs to be incorporated in a format that is complete and amenable to GAMS solution. The data and model equations have to be included in a GAMS input file which is provided in Appendix 2. Let us look at a few important aspects of data representation and model assumptions.

<u>Product Demands</u>

Figure 7 provides the total annual demand for each product in each scenario. Since we are have five time periods, the data can be represented by the following table:

	1	2	3	4	5	6	
a.scene1	0	300	300	300	300	300	(a in scenario 1)
a.scene2	0	311	311	311	311	311	
a.scene3	0	321	321	321	321	321	
a.scene4	0	286	286	286	286	286	
a.scene5	0	255	255	255	255	255	
b.scene1	0	56	56	56	56	56	
b.scene2	0	65	65	65	65	65	
b.scene3	0	70	70	70	70	70	
b.scene4	0	45	45	45	45	45	
b.scene5	0	26	26	26	26	26	
c.scene1	0	150	150	150	150	150	
c.scene2	0	125	125	125	125	125	
c.scene3	0	100	100	100	100	100	
c.scene4	0	175	175	175	175	175	
c.scene5	0	250	250	250	250	250	

Table 8: GAMS representation of demand scenarios; For example, the first row represent s the demand for product a in scenario 1 in time periods 1-6

Each row of the table provides the demand for a product in a certain scenario in each time period. The probabilities of each scenario occurring are given in a list as shown in Appendix 2.

Changeover Costs

The investment numbers are the changeover costs in this particular problem. (Table 5) This is because no new facilities are allowed and the facilities that are required already exist and have only to be reconfigured. These numbers are represented by the following table:

	a	c	ab	ac	abc
1.0	422	5000	467	632	677
1.a	0	5000	5000	5000	5000
1.c	5000	0	5000	5000	5000
1.ab	5000	5000	0	5000	5000
1.ac	5000	5000	5000	0	5000
1.abc	5000	5000	5000	5000	0
2.0	215	260	285	5000	5000
2.a	0	5000	5000	5000	5000
2.c	5000	0	5000	5000	5000
2.ab	5000	5000	0	5000	5000
2.ac	5000	5000	5000	0	5000
2.abc	5000	5000	5000	5000	0

Table 9: Changeover costs for the two plants; For example, the first row implies the changeover costs of Plant 1 going from configuration 0 to configuration a are $422 million

The above table provides the cost of changing a particular facility (I or II) from one configuration (a...abc) to another (a...abc) or (h1 to h2 in the context of variables **chg** and **w**). For example, to change the configuration of facility 1 from 0 (initial condition) to Configuration ab requires an investment of

$467 million. However, to change from Configuration a to Configuration a costs 0. The configurations or changes not allowed are basically represented by using the penalty of a huge investment ($5 billion). Notice, in this table, that once a configuration has been changed from 0 to something else, it cannot be changed again. However, the model itself allows for other changes; but since no new facilities are being considered, the **Newfac** term in the objective function is not included.

Capacity Data and Constraints

The assumptions related to capacities in the two plants listed in Section 5.1 manifest themselves in changes in the constraint equations and input parameters. The **total capacity** of each plant is fixed. They are **350,000 units for Plant I and 166,000 units for Plant II**. Therefore, since these are known *a priori*, they become input parameters and are included using the following table:

	a	c	ab	ac	abc	0
1	350	350	350	350	350	0
2	166	166	166	166	166	0

Table 10: Input parameters to indicate total fixed capacities for the two plants in all configurations

Equations (5) and (9) are no longer needed in the model, since the total capacities are parameters, not variables. Equation (3) suffices because $\boldsymbol{cap}_{kh2t}$ is provided directly by the above table. Since the capacities are fixed, the two terms in the objective function relating to increase and decrease in capacity are eliminated.

The objective function (maximizing total profits), therefore becomes,

$$Max(\sum_{ikhmt} 1000 * x_{ikhmt} * prof_{it} * scenarios_m - 1000000 * (\sum_{khth2t} chg_{kh1h2} * w_{kh1h2t} + \sum_{kht} FCost_{kh} * y_{kht})) \quad \text{... (11)}$$

The other data and equations listed in Section 4.0 are used as they are and are represented in the input file (Appendix 2).

5.3 Results

The results of the optimization are presented in two parts. The first part contains results of the baseline analysis of the problem presented in Section 5.2. The second part contains results of a sensitivity study carried out on the same problem to evaluate robustness of the solution.

Baseline Analysis

The results of the optimization has two components - the value of the **objective** (maximized expected profits) in dollar terms and the values of the decision variables. The value of the objective for the baseline analysis = **$6.903325 billion**. Note that this number is an expected value for total profits over five years for all products. The other decision variables from the solution are:

Configurations (variable: $\mathbf{y_{kht}}$) & Investments

The optimization recommends that all three Products A, B and C be sourced in Plant I and Product A only in Plant II. The configurations are schematically shown in Figure 9(a).

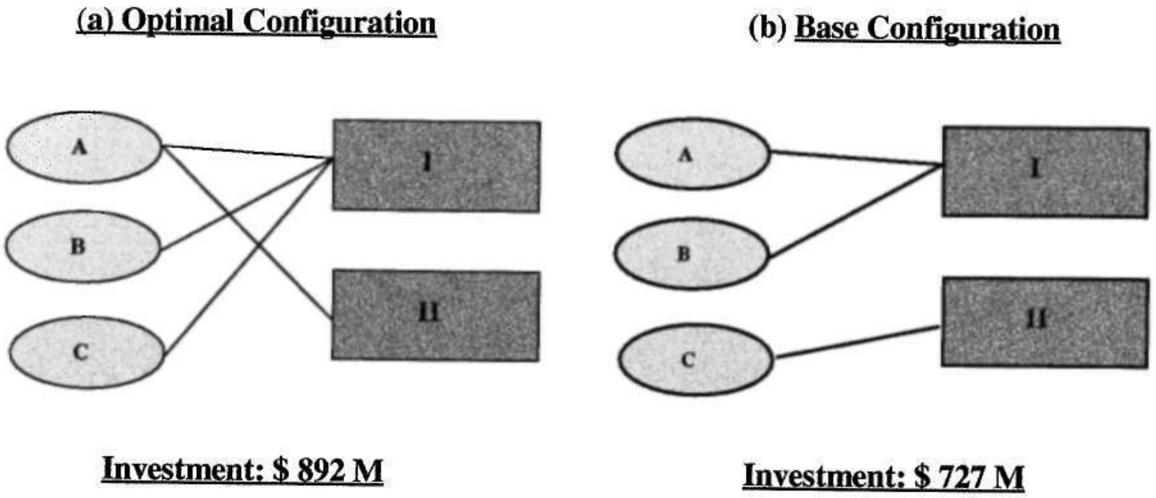


Figure 9: (a) Optimal configuration - flexibility with respect to A; (b) Base configuration - no flexibility between plants I and II.

The solution, in fact, computes the configuration for every time period. The output from the optimization is represented in the following table.

	1	2	3	4	5	6
Plant I, Configuration 0	x					
Plant I, Configuration ABC		x	x	x	x	x
Plant II, Configuration 0	x					
Plant II, Configuration A		x	x	x	x	x

Table 10: Plants & configurations used for the optimal solution

The table basically says that both Plants I and II are in Configuration 0 (specified by the initial conditions in the model) in time period 1 and are in configurations ABC & A respectively in periods 2 through 5. Going along with this data, the changeover decision variable ($\mathbf{w}_{kh1h2t}$) looks as follows:

Plant I (k=1)

h1 to h2	1	2	3	4	5	6
0 to 0	x					
0 to ABC		x				
ABC to ABC			x	x	x	x

Plant II (k=2)

h1 to h2	1	2	3	4	5	6
0 to 0	x					
0 to A		x				
A to A			x	x	x	x

Table 11: Configuration changeovers based on the optimal solution

The total investment for the optimal configurations, therefore, based on Table 5 is:

\$677 Mils + \$215 Mils = \$892 Mils

Production (variable: $\mathbf{x}_{ikhmt}$)

The production of each product in each scenario in each plant in each time period as obtained from the solution is summarized in the following tables (in thousands of units):

Plant I

Product A

	2	3	4	5	6
Scenario 1	144	144	144	144	144
Scenario 2	160	160	160	145	160
Scenario 3	155	180	155	155	155
Scenario 4	130	130	130	130	130
Scenario 5	74	89	89	74	74

Product B

	2	3	4	5	6
Scenario 1	56	56	56	56	56
Scenario 2	65	65	65	65	65
Scenario 3	70	70	70	70	70
Scenario 4	45	45	45	45	45
Scenario 5	26	11	11	26	26

Product C

	2	3	4	5	6
Scenario 1	150	150	150	150	150
Scenario 2	125	125	125	125	125
Scenario 3	100	100	100	100	100
Scenario 4	175	175	175	175	175
Scenario 5	250	250	250	250	250

Plant II

Product A

	2	3	4	5	6
Scenario 1	156	156	156	156	156
Scenario 2	151	151	151	166	151
Scenario 3	166	141	166	166	166
Scenario 4	156	156	156	156	156
Scenario 5	166	166	166	166	166

Table 12: Level of production of each product in each plant in each scenario in each time period - obtained from the optimized solution

Unmet Demand (z_{imt})

The final decision variable in this model is the unmet demand (z_{imt}). This value corresponds to the product demand that was considered not worth meeting based on the optimization. The unmet demand (in 000s of units) for the baseline analysis is summarized in the following table:

Product, Scenario	2	3	4	5	6
A, Scenario 5	15			15	15
B, Scenario 5		15	15		

Table 13: Unmet demand obtained from optimal solution

It should be noted that because the profitability of products A and B in this case are the same ($3340/unit), the model is indifferent between producing either product in either plant (since there are no variable cost differences between plants either). This aspect manifests itself both in the production fluctuations as shown in the production tables and the unmet demand result. The only unmet demand based on the optimal capacity plan is 15,000 units of either A or B annually. The expected lost profits due to the unmet demand are

expected lost profits = variable profit * volume of unmet demand * probability

$$= 3340 * 15{,}000 * 0.05 \qquad \text{.... (12)}$$
$$= \underline{\$\ 3\ \text{Million}}$$

As we shall see later, lost profits are a good metric to compare various capacity plans.

The base plan, as mentioned earlier, corresponds to Products A and B sourced at Plant I and Product C sourced at Plant II (no flexibility between plants - see Figure 9(b)). Given the total capacity of each plant and the demand in each scenario, the annual lost sales for this configuration can be computed. For example consider Scenario 1:

Demand for Product A = 300,000 units

Demand for Product B = 56,000 units

Demand for Product C = 150,000 units

Capacity for A+B in Plant I = 350,000 units

Total demand for Products A+B = 356,000 units

Therefore, unmet demand = 6,000 units of A or B or some mix of both

There is no unmet demand for Product C because the demand = 150,000 units and the capacity at Plant II = 166,000 units. Extending these calculations for other scenarios, one obtains the results shown in Table 14.

Scenario	A	B	C	Probability of Scenario	Expected Lost Profits (Rounded off to Mils)
1	6			0.5	10
2	26			0.2	17
3	41			0.05	7
4			9	0.2	7
5			84	0.05	16
				Total	**$58 Mils**

Table 14: Expected lost profits for the base capacity plan - if Products A & B were made in Plant I and Product C alone in Plant II

The expected gains from a flexible configuration amount to \$58 - \$3 = \$55 million per year. The cost of the added flexibility is

= Cost of flexible configuration - Cost of base configuration

= \$892 Mils - \$727 Mils = <u>**\$165 Mils**</u>

The **payback period,** for the added flexibility =

= (Extra Investment for flexibility)/(Gains fro flexibility)=165/55= <u>**3 years**</u>

Before a decision is made to invest in flexibility based on gains in profits due to flexibility, management should decide if a payback period of 3 years is sufficient. The decision is based on the corporate financial policies of the company and on the required rate of return for investments

<u>Sensitivity Analysis</u>

One of the advantages of using scenario planning in conjunction with an optimization model is that additional scenarios can be created (if feasible) and evaluated. The additional scenarios can be built by varying any of the input parameters in the model. These scenarios are particularly useful when there is a high demand uncertainty. The analysis of these variations provides management with a feel for the robustness of the plan or the sensitivity of the plan to various input parameters. An example of a sensitivity analysis is provided here.

For the baseline analysis, a set of scenario probabilities are given (Figure 7). These probabilities are only an estimate and no one is really sure of what they will be. A sensitivity analysis with respect to the probabilities is carried out to see if changes in the probabilities leads to a drastic difference in solution.

Several scenarios were created by changing the probabilities. The scenarios and results of the individual optimization runs are tabulated as follows:

	Scenario Probabilities (%)					Optimal Configuration		
Case	1	2	3	4	5	Plant 1	Plant 2	Annualized Profit ($ bils)
1	50	20	5	20	5	ABC	A	1.38
2	30	5	5	10	50	ABC	A	1.42
3	10	5	5	30	50	ABC	A	1.43
4	30	10	50	5	5	ABC	A	1.35
5	10	30	50	5	5	ABC	A	1.34
6	5	5	5	20	65	ABC	A	1.44

Table 15: Results of sensitivity analysis based on changing scenario probabilities

Table 15 shows 6 cases with various distributions in probabilities between Scenario 1 through 5. Case 1 is the base case that was given. Cases 2 through 6 represent various situations in which a high probability is assigned from Scenario 1 through Scenario 5, in turn. It can be seen that in spite of drastic changes in the probabilities the optimal configuration remains the same as that of the baseline analysis. Additional sensitivity studies are shown in Table 16 where extreme cases with respect to scenario probabilities are used.

In this study in each case, one scenario assumes a probability of a 100% and all other scenarios 0%. Only in the case of Scenario 1 occurring with a probability of 100%, the model recommends a base configuration (Figure 9(b)) with no flexibility between plants. In all other cases, the analysis recommends a flexible configuration.

Case	Scenario Probabilities (%)					Optimal Configuration		Annualized Profit ($ bils)
	1	2	3	4	5	Plant 1	Plant 2	
[redacted]								
2	0	100	0	0	0	ABC	A	1.35
3	0	0	100	0	0	ABC	A	1.31
4	0	0	0	100	0	ABC	A	1.40
5	0	0	0	0	100	ABC	A	1.47

Table 16: Sensitivity analysis based on each scenario assuming a 100% probability in turn

5.4 Discussion

Analyses shown in the previous two sections demonstrate how optimization methods can be used by management to study capital investment options using a scenario based approach. The model presented in this report is meant to provide a framework and a representation of the modeling process.

The optimal configurations based on the analysis requires all three products A, B and C to be produced in Plant I and Product A alone in Plant II (Figure 9(a)). Earlier in the report, it was mentioned that one of the advantages of having flexibility is that it leads to a higher capacity utilization. Let us look at the capacity utilization for both the optimal configuration and the base configuration (Figure 9(b)). Figure 10 shows that the capacity utilization in every scenario

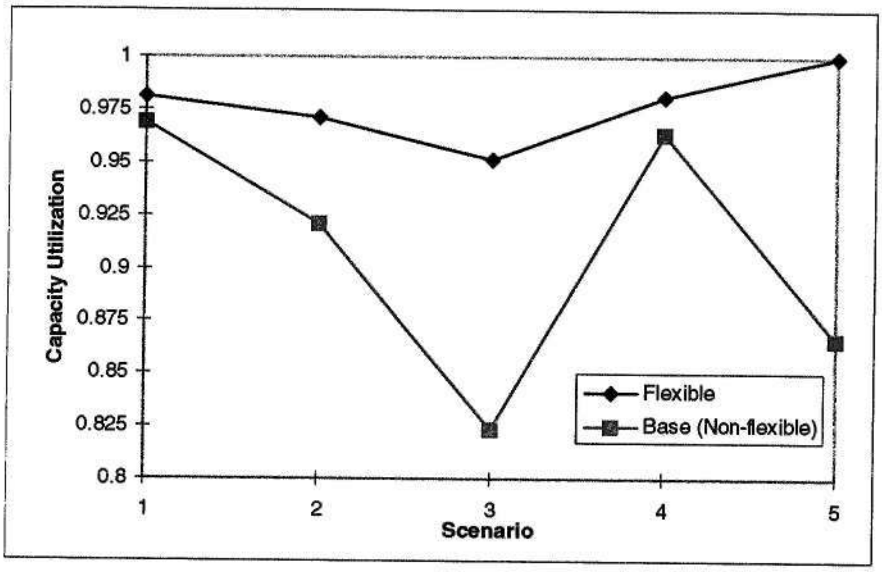


Figure 10: Capacity utilization for the flexible and base configurations for each scenario

for the flexible configuration is always higher than the base configuration which does not have any flexibility between plants (even though it has flexibility in Plant I between Products A & B). The calculations for Figure 10 are shown in Appendix 3.

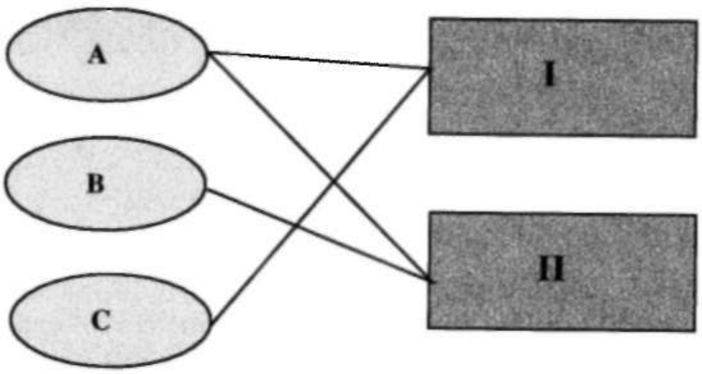


Figure 11: Alternate flexible configurations (non-optimal)

It is also worthwhile to compare the optimal flexible configuration with other optimal configurations which are allowed. Based on Table 5, the configurations shown in Figure 11 are also allowable. However, let us compare the investment required to achieve this configuration with the gains in profits.

The investment required to achieve the configurations shown in Figure 11 (using data in Table 5) is:

$ 632 Million + $ 285 Million = $ 917 Million

The investment required to achieve the optimal configuration is

$ 892 Million. Therefore the increase in investment = $ **25 Million.**

If the new configuration were to be used, it is evident that all possible demand for all products will be met. Therefore, all unmet demand in the optimal case will be met. The expected gains from this configuration is:

Expected gains = Expected gains from covering the lost sales in the optimal configuration

= $3 Million * 5 = **$ 15 Million** (From Equation (12))

However, **$15 Million < $ 25 Million**, which implies that

Implying, the alternate flexible configuration will be non-optimal.

While the optimization approaches presented here have several strengths, they also have certain weaknesses. A summary of their strengths and weaknesses are presented in Table 17. Certainly, the advantages of optimization comes from the capability of analytical methods to consider decision options exhaustively that would be difficult to analyze otherwise. The analytical methods, however, are limited by the detail in the model. Including great detail usually requires a corresponding increase in input data and model complexity. Gathering data pertaining to marketing, investments and product plans can be a challenge in a large corporation. Modeling techniques require support and buy-in from several different organization in a corporation, and it takes time to develop this support. In the auto industry, it requires a major cultural change, where historically, each of the planning organizations has operated on its own.

Strengths	Weaknesses
Allow the study of several options together and includes input from several organizations	Can be deceiving: Analysis limited by input accuracy
A versatile analytical tool - allow several "what-if" scenario analyses	Buy-in required from several different organizations: Require significant input data
Allow consistency in analysis for several investment decisions	Limited by particular model: qualitative strategic drivers are difficult to include
Maximize returns/profits in an expected sense	Linear program approaches to optimization (such as this one) in are limited by nature: cannot include implicit dependencies of variables. Require non-linear programs. Non-linear programs are however limited by difficulties in numerics and robustness
Better than most conventional "ad-hoc" approaches	Problem size can be an issue. For example, problem described in Section 5.1 has approx 1700 integer decision variables - considered fairly large. Large models can be difficult to solve using packaged techniques.

Table 17: Strengths & weaknesses of scenario based optimization approaches

6. Conclusions

A scenario approach for capacity planning to achieve optimal manufacturing process has been developed and implemented. The target application for this work has been assembly sourcing for new products in the automotive industry. The advantages of achieving optimal flexibility in plant configurations have been demonstrated. A novel method of achieving optimal flexibility in assembly plant has been developed and implemented in a model using mixed integer linear programming. The approach has been illustrated using an example based on a real situation.

A natural extension would be to modify the model implementation to optimize capacity plans based on cash flows. This would require including taxes and other important financial aspects of a long term strategic plan. The model can then be used to optimize investments based on a typical cost of capital for the corporation. Another extension could be to modify the model to recommend changes to product plans. The model can be modified to include alternative products and these products can be rated based on how the overall profitability of a capacity plan changes.

Lastly, the model can be significantly improved from usability standpoint if a graphical user interface (based on an Excel front end) can be implemented. This will allow better transfer of data between the "real" world and the model input.

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Appendix 1

		Demand																			
		A		50				100					150		50				100		
		B		50				50					50		100				100		
		Total		100				150					200		150				200		
Total Capacity	Capacity			Flexible		Dedicated			Flexible		Dedicated		Flexible		Dedicated		Flexible		Dedicated		Flexible	
	I	II	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales	Cap. Utilization	Sales
100	50	50	100	1	100	1	100	1	100	1	100	1	100	1	100	1	100	1	100	1	100
130	65	65	100	0.77	100	0.77	130	1	115	0.884615385	130	1	115	0.884615385	130	1	115	0.884615385	130	1	130
150	75	75	100	0.67	100	0.67	150	1	125	0.833333333	150	1	125	0.833333333	150	1	125	0.833333333	150	1	150
170	85	85	100	0.59	100	0.59	150	0.882352941	135	0.794117647	170	1	135	0.794117647	150	0.882352941	136	0.794117647	170	1	170
200	100	100	100	0.5	100	0.5	150	0.75	150	0.75	200	1	150	0.75	150	0.75	150	0.75	200	1	200
230	115	115	100	0.43	100	0.43	150	0.652173913	150	0.652173913	200	0.869565217	165	0.717391304	150	0.652173913	150	0.652173913	200	0.869565217	200
250	125	125	100	0.4	100	0.4	150	0.6	150	0.6	200	0.8	175	0.7	150	0.6	150	0.6	200	0.8	200
270	135	135	100	0.37	100	0.37	150	0.555555556	150	0.555555556	200	0.740740741	185	0.685185185	150	0.555555556	150	0.555555556	200	0.740740741	200
300	150	150	100	0.33	100	0.33	150	0.5	150	0.5	200	0.666666667	200	0.666666667	150	0.5	150	0.5	200	0.666666667	200

		150				50				100				150							
		100				150				150				150							
		250				200				250				300							
Dedicated	Flexible		Dedicated		Flexible		Dedicated		Flexible		Dedicated		Flexible		Dedicated		Flexible			Dedicated	
Sales	Cap. Util	Sales	Cap. U	Sales	Cap. U	Sales	Cap. Utiliz	Sales	Cap. U	Sales	Cap. U	Sales	Cap. U	Sales	Cap. U	Sales	Cap. U	Exp. Cap. Util.	Expec	Exp. Cap. Util.	Exp. S
100	1	100	1	100	1	100	1	100	1	100	1	100	1	100	1	100	1	1	100	1	100
130	1	130	1	130	1	130	1	115	0.88	130	1	130	1	130	1	130	1	0.974358974	127	0.923076923	120
150	1	150	1	150	1	150	1	125	0.83	150	1	150	1	150	1	150	1	0.962962963	144	0.888888889	133
170	1	170	1	170	1	170	1	136	0.79	170	1	170	1	170	1	170	1	0.928104575	158	0.862745098	147
200	1	200	1	200	1	200	1	150	0.75	200	1	200	1	200	1	200	1	0.888888889	178	0.833333333	167
200	0.86957	230	1	215	0.93	200	0.869565	165	0.72	230	1	215	0.93	230	1	230	1	0.816425121	188	0.768115942	177
200	0.8	250	1	225	0.9	200	0.8	175	0.7	250	1	225	0.9	250	1	250	1	0.777777778	194	0.733333333	183
200	0.74074	250	0.93	236	0.87	200	0.740741	185	0.69	250	0.93	236	0.87	270	1	270	1	0.728395062	197	0.703703704	190
200	0.66667	250	0.83	250	0.83	200	0.666667	200	0.67	250	0.83	250	0.83	300	1	300	1	0.666666667	200	0.666666667	200

Total Cap	Capacity		Flexible		Dedicated	
	I	II	Exp. Cap. Util.	Expec	Exp. Cap. Util.	Exp. Sales
100	50	50	1	100	1	100
130	65	65	0.974358974	127	0.923076923	120
150	75	75	0.962962963	144	0.888888889	133.3333
170	85	85	0.928104575	158	0.862745098	146.6667
200	100	100	0.888888889	178	0.833333333	166.6667
230	115	115	0.816425121	188	0.768115942	176.6667
250	125	125	0.777777778	194	0.733333333	183.3333
270	135	135	0.728395062	197	0.703703704	190
300	150	150	0.666666667	200	0.666666667	200

Data for figure 2

Appendix 2

GAMS 2.25.092 DOS Extended/C 12/23/97 10:03:20 PAGE 1
General Algebraic Modeling System
Compilation

```
sets
      i     products           /a, b, c/
      k     facilities         /1*2/
      h     configurations     /0,a, c, ab, ac, abc/
      m     scenarios          /scene1, scene2, scene3, scene4,
                                scene5/
      t     Time periods       / 1*6 /
      alias (h, h1, h2);

Parameters


      scenarios(m)     probability of scenario m occuring
          / scene1      0.5
            scene2      0.2
            scene3      0.05
            scene4      0.2
            scene5      0.05/;


Table prof(i,t)   cont per unit for each product across periods
                  1    2     3     4     5     6
              a   0  3340  3340  3340  3340  3340
              b   0  3340  3340  3340  3340  3340
              c   0  3900  3900  3900  3900  3900 ;


Table Chg(k,h1,h2)  Cost of retooling facility k from h1 to h2 in mils
                   a     c     ab    ac    abc
          1.0     422  5000   467   632   677
          1.a      0   5000  5000  5000  5000
          1.c    5000    0   5000  5000  5000
          1.ab   5000  5000    0   5000  5000
          1.ac   5000  5000  5000    0   5000
          1.abc  5000  5000  5000  5000    0
          2.0     215   260   285  5000  5000
          2.a      0   5000  5000  5000  5000
          2.c    5000    0   5000  5000  5000
          2.ab   5000  5000    0   5000  5000
          2.ac   5000  5000  5000    0   5000
          2.abc  5000  5000  5000  5000    0;



Table FCost(k,h) Fixed Cost per period of having plant k in h (in mills)

          a        c      ab     ac     abc   0
     1  158.7    158.7  158.7  158.7  158.7  0
     2   53.5     53.5   53.5   53.5   53.5  0;


**************************************************************************

```

```
*****          Capacity Parameters          ************

*****************************************************************
Table u(i,k,h) Units of capacity needed to produce one unit of product

          a      c      ab     ac     abc  0
    a.1   1      10000  1      1      1    10000
    b.1   10000  10000  1      10000  1    10000
    c.1   10000  1      10000  1      1    10000
    a.2   1      10000  1      1      1    10000
    b.2   10000  10000  1      10000  1    10000
    c.2   10000  1      10000  1      1    10000;

Table lostcap(k,h1,h2) at site k if it is retooled from h1 into h2 (000s)
             a    c    ab   ac   abc
     1.0     0    0    0    0    0
     1.a     0    0    0    0    0
     1.c     0    0    0    0    0
     1.ab    0    0    0    0    0
     1.ac    0    0    0    0    0
     1.abc   0    0    0    0    0
     2.0     0    0    0    0    0
     2.a     0    0    0    0    0
     2.c     0    0    0    0    0
     2.ab    0    0    0    0    0
     2.ac    0    0    0    0    0
     2.abc   0    0    0    0    0;

Table cap(k,h)   Capacity in each facility (in 000s)

          a     c     ab    ac    abc   0
    1     350   350   350   350   350   0
    2     166   166   166   166   166   0;

*****************************************************************

*****          Demand Parameters          ************

*****************************************************************

Table demand(i,m,t) Demand in '000s of units in scenario m in time t
                 1    2     3     4     5     6
     a.scene1    0    300   300   300   300   300
     a.scene2    0    311   311   311   311   311
     a.scene3    0    321   321   321   321   321
     a.scene4    0    286   286   286   286   286
     a.scene5    0    255   255   255   255   255
     b.scene1    0    56    56    56    56    56
     b.scene2    0    65    65    65    65    65
     b.scene3    0    70    70    70    70    70
     b.scene4    0    45    45    45    45    45
     b.scene5    0    26    26    26    26    26
     c.scene1    0    150   150   150   150   150
```

```
               c.scene2  0  125   125  125   125   125
               c.scene3  0  100   100  100   100   100
               c.scene4  0  175   175  175   175   175
               c.scene5  0  250   250  250   250   250
                                   ;


*****************************************************************

*****          Decision Variables          ***********

*****************************************************************

variables

 x(i,k,h,m,t)   amt of prodn of product i at fac k in h in period t
 y(k,h,t)       1 if a fac exists at site k in h in period t
 z(i,m,t)       Amnt of unsatisfied demand for i, scen m and period t
 w(k,h1,h2,t)   1 if site k is retooled into conf h2 from  h1 in t

 Profit         total profits;


integer variable x,z;
binary variable y,w;
x.up(i,k,h,m,t)= 1000;
z.up(i,m,t)    =1000;

**********

equations

      total                   define objective function
      capacity(k,h1,h2,m,t)   total capacity for facility k
      market(i,m,t)           total market demand for product i
      retool(k,h1,h2,t)       retool forcing
      s_config(k,t)           each facility k should be in some conf
      w_config(k,t)           force only one change in config
      yinit(k,t)              y initialisation
      winit(k,t)              w initialisation;

*************** Objective Function *******************

total ..    Profit    =e=

 1000* sum((i,k,h,m,t),x(i,k,h,m,t)*prof(i,t)*scenarios(m))
  - 1000000*(sum((k,h1,h2,t),chg(k,h1,h2)*w(k,h1,h2,t)) +
        sum((k,h,t),FCost(k,h)*y(k,h,t)));


*************** Constraints ****************************

capacity(k,h1,h2,m,t) ..  sum(i, u(i,k,h2)*x(i,k,h2,m,t)) =l=
```

```
                    cap(k,h2)*y(k,h2,t) - lostcap(k,h1,h2)*w(k,h1,
                                        h2,t);

market(i,m,t) .. sum((k,h),x(i,k,h,m,t))+ z(i,m,t) =e= demand(i,m,t)  ;

retool(k,h1,h2,t)$(ord(t) gt 1) ..   y(k,h2,t) + y(k, h1, t-1)-1 =l=
                                     w(k,h1,h2,t);

s_config(k,t) .. sum(h1,y(k,h1,t)) =e= 1;

w_config(k,t) .. sum((h1,h2), w(k,h1,h2,t)) =e= 1;

yinit(k,t)$(ord(t) eq 1)..  y(k,'0',t) =e= 1;

winit(k,t)$(ord(t) eq 1) .. w(k,'0','0',t) =e= 1;

model plan /all/;
option limrow = 0;
option limcol = 0;
option solprint=off;
option optcr=0.0;
solve plan using mip maximizing profit;
display x.l, y.l, w.l, z.l;
```

```
**** LIST OF STRAY NAMES - CHECK DECLARATIONS FOR SPURIOUS COMMAS
**** STRAY NAME SCEN      OF TYPE VAR
```

Appendix 3

Optimal Configuration

Scenario	Production		Total Production	Total Capacity	Capacity Utilization
	I	II			
1	350	156	506	516	98%
2	350	151	501	516	97%
3	325	166	491	516	95%
4	350	156	506	516	98%
5	350	166	516	516	100%

Base Configuration

Scenario	Production		Total Production	Total Capacity	Capacity Utilization
	I	II			
1	350	150	500	516	97%
2	350	125	475	516	92%
3	325	100	425	516	82%
4	331	166	497	516	96%
5	281	166	447	516	87%

Scenario	Flexible	Base (Non-flexible)
1	98%	97%
2	97%	92%
3	95%	82%
4	98%	96%
5	100%	87%

Data for Figure 10