Capacity Acquisition for Continuous Production Systems

by

V. Thillainathan
System Dynamics Research Group
University of Bradford

Abstract

Problems concerned with capacity acquisition are discussed. A simple production model is considered to explain how System Dynamics Methodology could be used in planning capacity acquisition. The consequences of a discrete type of capacity ordering policy which reacts only to capacity requirements above a specified minimum value is presented; capacity requirements are computed by linear extrapolative forecast. Effects of proportional, integral and derivative control on capacity are compared.

Introduction

The brief description given here of the problems connected with capacity planning and the consequences of certain acquisition policies is a simplified version of a research project for Ph.D. As it is not possible in a paper of this length to give all the salient features and possibilities of a project of this nature only a general discussion on capacity acquisition is presented here. Capacity in this discussion is assumed to represent the aggregate of capital equipment and manpower used for productive purposes. This assumption is not in anyway a limitation of the model as it can quite easily be relaxed to take account of capital equipment and manpower to any degree of disaggregation desired. Even with this limitation the model will have applicability in industries such as chemical processing where production is limited by physical capacity.

Planning can be done either on a continuous basis or on a discrete basis; for certain conditions, model behaviour would be the same under both discrete and continuous capacity orders.

Problems in Capacity Acquisition

Capacity acquisition can have significant effects on the growth and stability of a firm and it is possible that some of the fluctuations or even collapse of the activities of a firm are nothing but the manifestations of ill-designed capacity acquisition policies. Policies which are designed on intuitive basis alone without proper understanding of the interactions in the system can be counterproductive (Forrester, 1961). It is no exaggeration to say that capacity planning has an overriding effect on all the other functions related to production and, in a hierarchy of sub-systems, capacity planning would be on top feeding into such sub-systems as Sales, Production Planning and Distribution. Despite this importance of capacity planning, it has not received even the same amount of attention as production planning, inventory control, quality control or distribution. There has been, and still is, a proliferation of books, journals and research papers dealing with these topics whereas only a scanty literature is available in capacity planning. This lack of enthusiasm can only be attributed to the overwhelming pressure within many manufacturing organisations for short-term results. By limiting the attention to such narrow and short-term views, organisations can miss the potential benefits which could be derived from planning on a long-term basis for an integrated system (total systems approach). However, planning on a long-term basis presents practical problems; problems such as the difficulty of estimating consumer demand, environmental shocks due to stop-go cycles of budgetary measures, parameter drifts, and quite often, changing order of time delays due to technological changes, etc. Since long-term planning can only be done on forecasts about the future, and capacity planning typically involves a long-term projection of the forecasts, there is always a risk in implementing capacity acquisition policies. Over-estimation of capacity requirements and subsequent commitment of funds on large orders of capital equipment brings in contractual liabilities which could lead to loss of finance or unnecessary idle capacity if there is a downturn in demand for products. On the other hand, under-estimation of capacity requirements would mean not having enough capacity to meet customer demand and hence loss of market share - this could be very damaging in that it can affect the future growth of the firm. No doubt it is difficult, if not impossible, to devise an ideal capacity acquisition policy which perfectly satisfies varying demand situations. What one can do is to devise some 'robust control policies' which would neither lead to unacceptably high capacity nor to large unfilled demand under varying shocks and parameter drifts.

Another problem which complicates capacity acquisition is that capital equipment can only be purchased in large chunks and as such continuous analysis which assumes divisibility of capital equipment may not be realistic.

Model

Modelling systems using System Dynamics Methodology is fairly well documented (Forrester, 1961; Coyle, 1974; Sharp, 1974; and a large number of publications and dissertations from M.I.T.).

A simple model of a production system is considered to explain the approach. It is assumed that the system is driven by an exogenous input, i.e. there is a demand for products and the objective of the system is to satisfy this demand as best as it can. Constraints on the system are that production and inventory levels are not allowed to fluctuate rapidly and/or above a certain specified limit - in other words the system is expected to attenuate any oscillations in order rate. Capacity cannot be depleted and idle capacity is undesirable. One measure of system performance is the percentage of capacity utilized. An 'influence diagram' of the model is shown in fig. (1). In the influence diagram 'smoothed order rate' refers to exponentially smoothed order rate. This is done to remove random components in order rate. 'D' indicates time delays in action, for example there is time delay between the placing of orders for capacity and them arriving to be assimilated into productive capacity. Similarly, but on a much smaller time scale, there is time delay between scheduled production and current production. As can readily be seen from the influence diagram it is a simplified version of a production sector. Variables and time delays shown in the diagram are aggregated to various degrees and time delays of small magnitudes are completely ignored. An influence diagram only indicates the causal links in the system and it is the first phase in building any system dynamics model. It represents the signal flows - the flow of material, men, money, information and capital equipment in the system. These causal links create feedback loops and a large amount of information on the qualitative characteristics of the model can be gleaned from feedback loop analysis. There are four feedback loops in the model, numbered, 1,2,3 and 4 in the influence diagram. Each loop is controlling a key variable - loop 1 controls backlog and loop 2 controls production capacity. Physical constraints, such as the sales rate being limited by inventory of finished products and scheduled production rate being limited by available capacity, are shown in the influence diagram by linked arrows crossed by small double-lines.

Some of the observations from the influence diagram are:-

1) There is no feedback loop connecting variables in the production capacity sector with production or inventory sectors except by way of constraints. Each of these sectors are in fact being driven independently by the common exogenous input - order rate. Inventory information is not used in controlling capacity. Neither is capacity information used in controlling orders coming into the system.

2) Both production planning and capacity acquisition use a forecast of order rate.

    Capacity orders are placed at periodic intervals of time if the desired fractional increase in capacity is larger than a specified minimum fraction. About 90 equations, including equations for constants, plot and print variables were required to simulate the model. The model is programmed
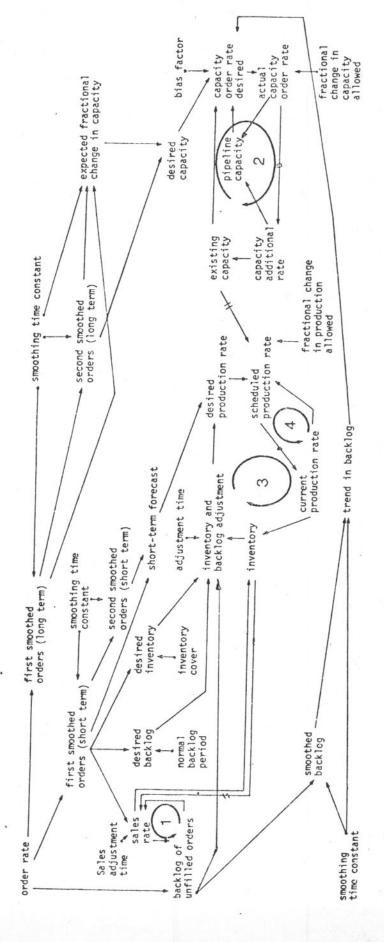
Fig. 1 INFLUENCE DIAGRAM

in DYSMAP, a slightly modified and extended version of DYNAMO II
and simulated on ICL 1904A. There are about 10 state variables
(level equations) and most of the equations are linear. Capacity,
backlog, inventory, order rate and production are all expressed
in terms of a common, nondimensional 'capacity unit'. Also the
numerical values used are the normalised values which are unity
in the equilibrium state. Nondimensional variables and
normalised values are used in order to make the model flexible.
It also facilitates easier linear snalysis of the model as it
would be a straight forward procedure to make the approximation
around the equilibrium state. Time is measured in terms of a
general 'time unit' rather than the conventional days, weeks or
months. One time unit is the minimum significant time in
the system and it could represent days, weeks or months
depending on the product as well as management's attitude towards
planning interval.

Results

A large number of runs for different types of exogenous inputs and
parameters were obtained but only a few of the results are mentioned
here. A 20% step increase in order rate and a sinusoidal cyclical
demand of amplitude 20% of equilibrium value and periods 10,20 and
50 time units were used to excite the system. Cyclic demand of 10 time
unit period represents seasonality in order rate, 20 and 50 period
cycles were used to test the response of the model to various business
cycles. Performance of the model is judged from the qualitative
characteristics of the transient response. Initial condition of the
model is its equilibrium state in which there is 100% utilization of
capacity.

1) Capacity acquisition based on extrapolative forecast of order
    rate with correction for backlog

    This policy is expressed by the following equations:-

    Desired Capacity = Expected capacity requirement after DLT time units

    _____(i)

    Fractional increase) = Desired   Pipeline   Existing
    in capacity desired)   Capacity - Capacity   - Capacity   _____(ii)
    _____
                              Existing Capacity

    Capacity order)
         rate   ) = (Existing capacity x Fractional increase in
                           capacity) + (bias factor x correction for
                           backlog of unfilled orders)   _____.(iii)

where DLT is the time delay is acquiring capacity, expected capacity is obtained by double exponential smoothing of order rate and capacity orders are placed at intervals of 10 time units if the desired fractional increase in capacity is larger than 0.1. This policy of ordering capacity only if it is larger than a 10% increase is taken to reflect management's reluctance to react to small requirements in capacity increase as the model has no facility to deplete capacity. It represents reality in most cases as it would not be possible to acquire capital equipment in such small amounts and often these requirements are met by overtime or additional shifts. Backlog correction and bias factor are used to supplement order rate and reflects the degree of optimism.

A step increase in order rate led to quick response in capacity addition but the increase was more than required (due to bias factor) and there was only 77% capacity utilization. Disturbances created in the system due to this sudden step took about 80 time units to settle.

Seasonality of 10 time units period did not cause any capacity orders and production level remained constant except for a slight disturbance in the beginning lasting for about 10 time units. Variations in order rate were accommodated entirely by inventory.

Cyclical demands of 20 and 50 time unit periods gave rise to idle capacity in the system. The amount of idle capacity can be reduced by making the bias factor zero, i.e., taking no notice of trend in backlog of unfilled orders or by increasing the smoothing time constant used.

The policy adopted works very well for high frequency disturbance (periods less than 10 time units) in order rate but for step changes and low frequency variations the system is sensitive to smoothing constants and bias factor.

2. Capacity Acquisition based on smoothed order rate with correction for backlog

The following equations represent the modifications made in capacity order rate:-

Desired capacity = 1.2 x smoothed order rate(long-term) _____(i)

$$\text{Fractional increase in capacity desired} = \frac{(\text{Desired Capacity} - \text{Pipeline Capacity} - \text{Existing Capacity} - \text{Trend in Backlog error})}{\text{Existing Capacity}}$$

_____(ii)

The system responded quickly to a sudden step increase in order rate and this type of response is to be expected with trend correction terms included in decision policy. There was a large amount of idle capacity in the system.

Response of the system to seasonality of 10 time unit periods was not good as it was with the previous policy. There were fluctuations in both production rate and inventory.

Cyclical demands of 20 and 50 time unit periods led to excess capacity in the system and superimposed sudden steps on these made things worse by creating unacceptably high idle capacity. By proper choice of parameters the amount of idle capacity can be reduced but the basic problem is that this policy structure makes the system sensitive to certain parameters, and this is not desirable.

3. Capacity Acquisition based on smoothed order rate and Cumulative error in Capacity

Desired capacity = 1.2 x smoothed order rate (long-term)_____(i)

Capacity error = Desired capacity - Pipeline capacity - Existing Capacity _____(ii)

$$\left.\begin{array}{l}\text{Cumulative} \\ \text{capacity error}\end{array}\right) = \sum_{o}^{t} \text{capacity error} \qquad \underline{\qquad\qquad}(iii)$$

$$\left.\begin{array}{l}\text{Fractional change in} \\ \text{capacity desired}\end{array}\right) = \left(\frac{\text{Capacity error+cumulative error}}{\text{Existing capacity}}\right) \underline{\quad}(iv)$$

where t is the time elapsed.

This policy led to a sluggish response to sudden step increase in order rate; it took the system about 100 time units to settle to a steady state. Response to seasonality was about the same as 2) but the performance for a superimposed step increase was much better.

There was no idle capacity for cyclical demands of 20 and 50 time unit periods whereas superimposed step changes caused large increases in capacity.

Here again the system is sensitive to some parameters and therefore fails to meet requirement for robustness.

4. Capacity acquisition based on linear extrapolative forecast of order rate with cumulative error in capacity

Equations are already given in 1(i), 3 (iii), 3 (iv). The system was very sensitive to parameters in ordering policy and produced unacceptably high idle capacity to all exogenous inputs tried - this is definitely a disastrous policy.

Conclusion

The model used was a simple one and only some of the results obtained from it are shown here. Even with this limitation one can see how System Dynamics helps in policy formulation. It appears that, with the present structure of the model, policy 1) is by far the best to cope with shocks from environment.

Since the model behaviour is fairly sensitive to parameters in capacity acquisition policy further improvement can be expected only from structural changes in the model. The system could be re-designed to include consumer promotion which would link inventory and capacity with order rate. Large inventories and idle capacity would trigger promotional activities to boost sales. The model could also be extended to include customer reaction to delivery delays. If these modifications are made then the whole structure would be enclosed in a feedback loop which controls idle capacity, inventory and backlog.

References

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