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System Dynamics Archetypes in Capacity Planning

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Abstract

This paper describes how system dynamics play a major role in capacity planning and what problems occur when neglected to account for. While the first sections focus on defining the terms, the core of the article lies in the third and fourth section where examples are provided showing the effects of system dynamics on capacity planning. Casual loop diagrams and stock and flow diagrams are constructed for the examples and the systems are simulated using the Vensim PLE software. The simulations show the importance of managing the systems as a whole and devoting attention to feedback loops and time delays in the systems.

1. Introduction

The goal of this paper is to discuss potential effects of system dynamics on capacity planning. This is done by introducing an appropriate example model and simulating its behavior depending on changing variables. All results are presented in graphical form and discussed; conclusions are subsequently drawn from them. All models and simulations are done using the Vensim PLE software. [1]

2. System archetypes

[2] defines a system as a combination of various components, which together form an entity that can be studied in its entirety. [3] offers a similar definition, that describes a system as a set of interacting or interdependent components forming an integrated whole.

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System dynamics is a powerfulmethodology and computersimulationtechniqueforframing, understanding, and discussingcomplexproblems. Originally developed in the 1950s to help corporate managers improve their understanding of industrial processes, system dynamics is currently being used throughout the public and private sector for policy analysis and design [4]. It allows for taking interactions between components into account and for studying them in relation to time [10] which can then be viewed using standard graphs or using phasegrams [11].

System archetypes are general patterns of systems found throughout the world and in various fields that describe the system using causality circles, positive and negative feedback loops and reinforcing and balancing cycles. Since these cycles can only be put together in a limited number of ways, it makes sense to distinguish archetypes base on the positions and relations between each feedback loop. Understanding system archetypes helps making the correct decisions because it allows the users to see beyond the apparent behavior and leads them to understand the system in its entirety. This allows for predicting reactions of the system depending on what archetype best describes it. [5, 6]

3. Limits to growth

Limits to growth is one of the simpler archetypes characterized by one reinforcing and one balancing loop where the first one drives the growth while the second acts as the limiting factor. [7]

In general the reinforcing loop operates for some time before the limits become known and manifest themselves openly. At that point the limit starts to counteract the growing action thus slowing the growth until it completely stops. In some cases, the system may then begin to decline since the growing action overreached the limit and has to return to appropriate values. [8]

Let us first consider the following example, where capacity acts as the limiting factor: A firm generates demand for its products using various marketing techniques. It produces products to cover the demand using one machine with a set capacity. This machine can be overloaded and its capacity thus increased, however this leads to a higher failure rate and subsequently to increased costs. The casual loop diagram of this system is presented in Fig. 1.
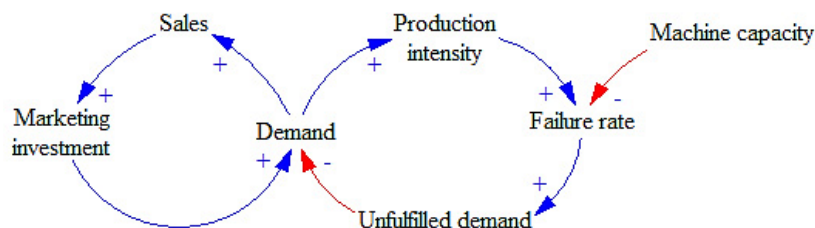

Fig. 1. Casual loop diagram – Limits to growth.

Demand, sales and marketing form a reinforcing loop – the higher the demand, the higher the sales, the higher the marketing investment. These in turn generate higher demand. On the other hand, overloading the machine creates a limiting factor manifested through a balancing loop – the higher the demand, the higher the production intensity. Since the machine capacity remains constant, the failure rate increases as the production intensity increases. Higher failure rate leads to higher unfulfilled demand which subtracts from the total demand.

In other words, marketing investment can only increase the effective fulfilled demand to a point, depending on the machine capacity. Stock and flow diagram used for simulating the behavior of this model is presented in Fig. 2.

Let us use the following values and equations as a starting point in simulations.Failure rate is considered zero when the machine capacity is sufficient to cover the total demand.

- Investment factor = 0.01; Marketing efficiency = 0.001; Price = 15000, Initial demand = 1000
- Machine capacity = 5000; Machine overload factor = 0.01
- Sales = Demand * Price; Marketing investment = Investment factor * Sales
- Demand increase = Marketing investment * efficiency; Unfulfilled demand = Demand * Failure rate
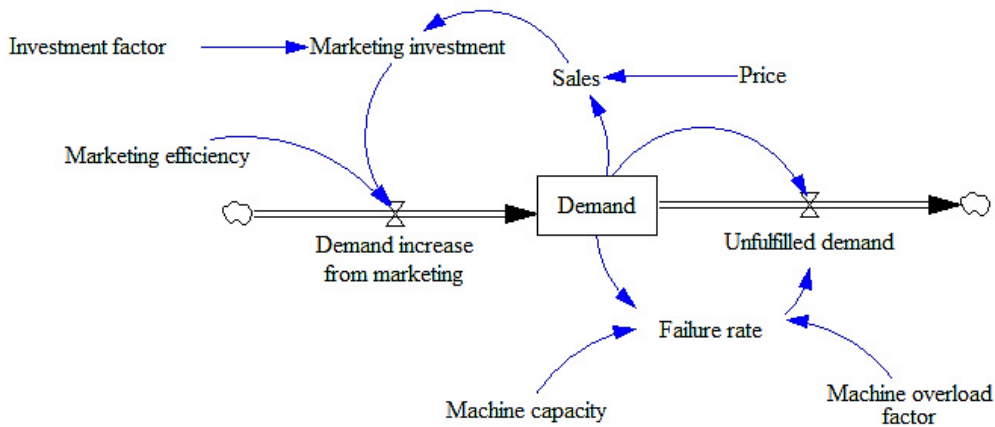- Failure rate = Machine overload factor * (Demand – Machine capacity)

Fig. 2. Stock and flow diagram – Limits to growth.

Fig. 3 shows the simulation results for 200 time steps using various different values for the Machine overload factor while holding all other input parameters constant.
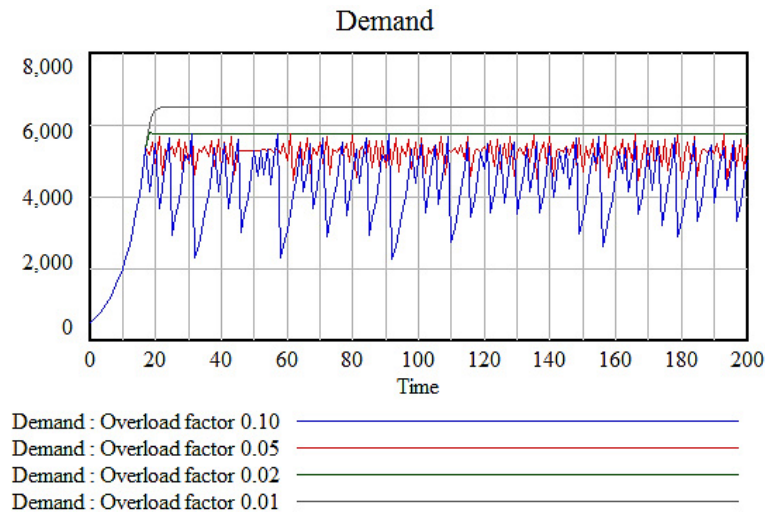

Fig. 3. Simulation results of limits to growth for varying Machine overload factor.

Base case results show that the system will level off at a demand value higher than the machine capacity due to it being profitable to overload the machine despite increasing the failure rate. However, once the failure rate becomes too high, the marketing investment can no longer cover the lost demand and the system stabilizes.

This is no longer the case for Machine overload factor values 0.05 and 0.10. For these values the system doesn't stabilize and continues to behave chaotically without periodicity. This can be explained by higher jumps in demand between each time step. A high overload factor means a failure rate so high it can push the total demand back under the critical level dependent on the machine capacity.

This simulation shows that insufficient capacity may under certain circumstances causes the fulfilled demand to fluctuate wildly despite no input variables changing.

4. Growth and underinvestment

When the Limits to growth archetype is extended by another balancing loop that acts upon the limiting condition, a Growth and underinvestment archetype is created.This archetype allows for alleviating the limiting condition; however it does so with a time delay. Since there is a delay between the first impulse to act and the actual action, there is enough time for the balancing loop to decrease the pressure, which leads to underinvestment. [9]
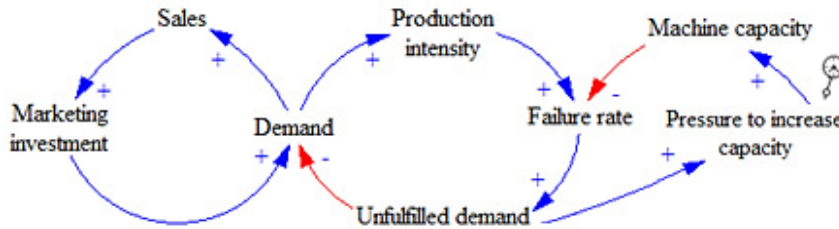
Fig. 4.Casual loop diagram – Growth and underinvestment.

Let us revise the example shown in the previous section and increase its scope. Let us assume that the company's management does indeed see that the problem is insufficient capacity and wants to invest in increasing the capacity. However, let us also assume that details of the order may be changed after the initial order had been placed. In other words, once the management decides to upgrade the capacity, it still has some time left to determine the precise new level of required capacity. For the purposes of simulation, let us use 4 time steps as the time between the first order and the delivery of increased capacity with and 3 time steps as the time frame after the initial order in which the new capacity level needs to be finalized.Fig. 4 shows the updated casual loop diagram for this system.
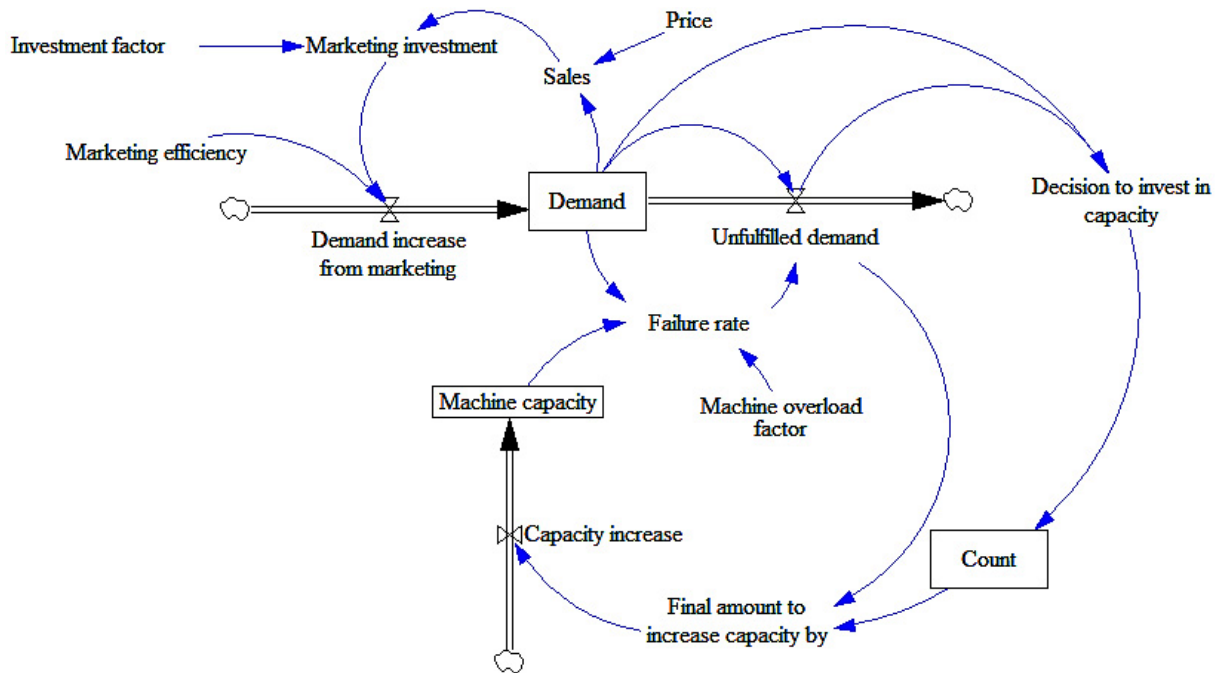
Fig. 5. Stock and flow diagram – Growth and underinvestment.

As the unfulfilled demand increases and management starts to see losses due to insufficient capacity, pressure begins to build to increase the machine capacity. This pressure will in time transfer into actual capacity increase and the failure rate will drop. However, it is very important to note the time delay between the pressure to increase the capacity and the actual increase. During this time delay, the balancing loop has time to affect the system in such a way that the failure rate will drop anyway due to the dropping demand caused by the insufficient capacity.

This leads to slowly changing the decision about the new level of capacity, since it seems as though the higher level is no longer needed. After the initial decision to upgrade, the rising failure rate causes the demand to decrease which in turn causes the unfulfilled demand to decrease which in turn lowers the pressure to increase the capacity. When the time comes to finalize the order and decide on the new level of capacity, the pressure is no longer as high as it was before, which leads to underinvestment.

The stock and flow diagram used to simulate this system is shown in Fig. 5.

Let us use the same values and equations as in the previous stock and flow diagram with the following logic added. Once the unfulfilled demand reaches a certain percentage of the total demand (10% by default), the decision to invest in increasing the machine capacity is made and a countdown is started before the increase can be delivered and implemented. 3 time steps after the initial decision to invest is made, another decision is made on the new level of capacity. This new level of capacity is dependent upon the level of unfulfilled demand at the time, which is bound to be lower than the level based on which the initial decision was made. This leads to underinvesting.

Fig. 6 shows the simulation results for 200 time steps using various different values for the Machine overload factor (value 0.10 omitted for the sake of clarity) while holding all other input parameters constant.
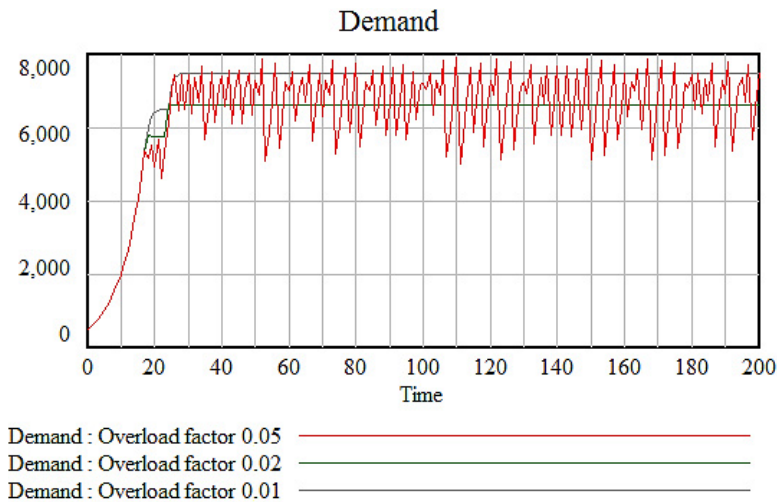

Fig. 6. Simulation results of growth and underinvestment for varying Machine overload factor.

The results vary slightly from the first example in this paper but the general behavior remains the same. The system again stabilizes for Machine overload factor values of 0.01 and 0.02 while continuing to behave chaotically for value 0.05. It is important to note the jump in demand due to increasing capacity but also to note the new level of capacity. For the Machine overload factor of 0.02, the initial decision to upgrade the capacity was made at the level of unfulfilled demand equal to 899 units. This should theoretically mean that the capacity will be upgraded at least by this amount after the required time delay. However, the actual increase in capacity was only by 862 units leading to underinvestment.

5. Conclusion

This paper analyzed examples from the field of capacity planning by using system dynamics. The results confirm that insufficient capacity may cause the entire production system to wildly and unpredictably fluctuate even though all input parameters are held constant. If the machine capacity is a limiting factor causing marketing efforts to be partially wasted and if this problem is not addressed, the fulfilled demand may fluctuate around the machine capacity chaotically. In the case where machine failure rate increases dramatically when overloaded, then once the demand increases above the capacity, increased failure rate causes the fulfilled demand to drop below the capacity for the next time step. Thus, the fulfilled demand is never above the failure-rate-free machine capacity for more than one time step. This discourages the company from increasing the machine capacity, since it seems as though it is not needed. For this reason, the company may never realize that the problem lies in the machine capacity and may interpret the chaotic behavior as simply a fluctuating demand.

If the company realizes that the problem lies in the machine capacity, time delays may lead to poor decisions and underinvesting. This occurs when the decision of whether or not to order the increased capacity is separated from the decisionof how much to increase the capacity by. Once the decision to invest is made, the overloaded machine causes the failure rate to increase, which causes the fulfilled demand to decrease. This in turn lowers the pressure on the management to increase the capacity, which may lead to withdrawing the order entirely or ordering a lower increase of capacity than previously planned. This in the end means that the company will fulfill a smaller volume of orders than it would be capable of if the time delay didn't exist.

Therefore it is extremely important to view the company as a dynamic system when considering capacity increases and to make note of any feedback loops and time delays that may be incorporated in the system.

Acknowledgements

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