A Generic Pattern for Modeling Manufacturing Companies

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Abstract

The work presented in this paper originates from the early stage of a master's thesis, analyzing a manufacturing industry supply chain. Prior to the investigation of the supply chain at large, separate models needed to be created to gain insights into the structure of decision processes at the different supply chain stages. Due to the lack of empirical data, a generic approach was employed for the modeling process. The models were intended to represent single manufacturing companies as well as consolidated supply chain links. The paper deals with this approach by introducing the sectors that compose the business of manufacturing companies and by pointing out the interdependencies among those areas. Subsequently, a model case demonstrates one possibility of transforming the generic pattern of causalities into a simulation model. An appropriate set of model equations is included. The analysis of the resulting simulation and its implications concludes the discussion.

Keywords: *corporate metamodel, manufacturing industry, system dynamics simulation*

Introduction

Numerous models focusing on particular types of companies and tackling specific problems have been discussed in the literature: Lyneis (1981) examines an exemplary manufacturing company and, amongst other things, deals with the optimization of material and informational flows in order to alleviate the bullwhip effect. Schöneborn (2003) examines a manufacturing company from the capital goods industry, considering the sectors marketing, production, finance, research and development, and administration. The resulting model is used for corporate planning and strategic controlling. Senge (1990) addresses the process of corporate learning, and Zahn (1971) models the growth of industrial companies.

Those examples illustrate the efforts of building models for distinctive aspects of business analyses. However, guidelines for building company models on a lesser level of detail have received little attention, although they might be particularly useful when a number of smaller models needs to be created for the purpose of assembling a comprehensive model, e.g., if several companies with individual characteristics shall be aligned to construct a supply chain. What is needed is a metamodel for the rapid development of simplified corporate models. This paper establishes such a metamodel based on a generic pattern from the manufacturing industry. Here, the fact that companies in the manufacturing industry have a number of commonalities is exploited. In the following, those commonalities are subdivided into different sectors and it is shown, how those sectors are connected with one another. This approach is kept as general as possible in order to allow for individual adaptations with each deployment. The second section then demonstrates one possibility of using the concept for modeling a real company by setting up a simulation model. Finally, the third section provides an analysis of valuable findings gained from a simulation run.

I Common Interdependencies in the Manufacturing Industry

The pattern emerging from the causal effects introduced in the following is not tied to one particular company. Instead, it is generically applicable to corporate modeling in the manufacturing industry. It is therefore considered a metamodel that can serve as a starting point for system dynamics analyses of a broad range of manufacturing companies.

In general, the causal forces can be distinguished into five scopes: production and inventory, capacity, demand and sales, costs, and sales price. They are all closely interrelated to one another, resulting in diverse causal feedback loops that influence a manufacturing company's business. Table 1 shows a partly arbitrary way of grouping those interrelations and gives each group a name. Subsequently, each group is introduced separately. Exogenous influences affecting manufacturing companies are discussed thereafter.

Scope / ***Interrelation***	production and inventory	capacity	demand and sales	costs	sales price
1. impact of inventory	*				*
2. capacity and fixed costs	*	*	*	*	*
3. economies of scale	*		*	*	*
4. inventory and idle time costs	*	*		*	
5. pricing and demand	*		*		*

Table 1: Interrelations of scopes

I.1 Impact of Inventory

A company's production replenishes the inventory of finished goods, whereas increased amounts of finished goods kept in stock lead to reduced production volumes – a balancing feedback loop which controls the flow rate of production. On the other hand finished goods inventories filled up by production also increase product availability and thus lead to decreases in sales price. This makes production less attractive and forms another balancing feedback loop. Note that increases and decreases of the inventory goal, i.e., the targeted safety stock, influence production volumes in the same direction whereas they have an effect in the opposite direction on product availability. The latter is due to the definition of product availability as the ratio between the overall quantities supplied and demanded in one period, both for sales and the desired safety stock.

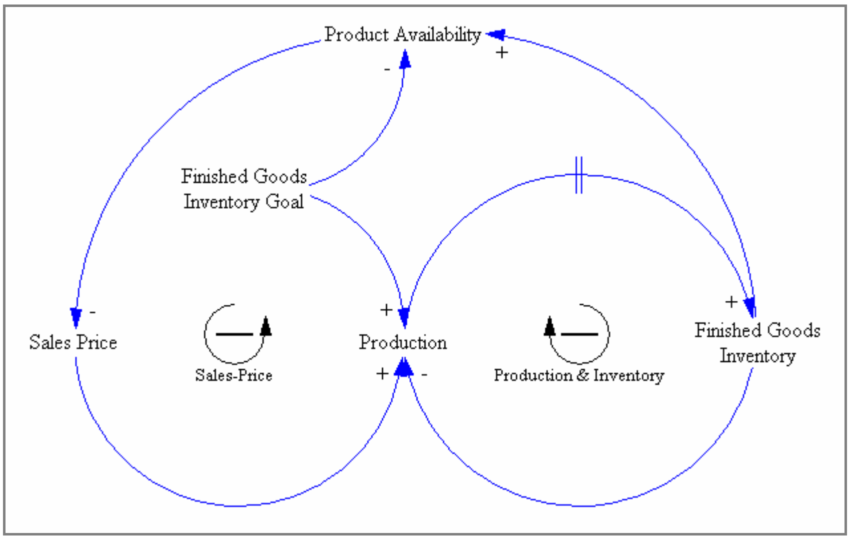

Figure 1: Impact of Inventory

I.2 Capacity and Fixed Costs

Depending on the available production capacity, a manufacturer adjusts his production throughput. A greater capacity does not only allow for higher production volumes, but it also urges a company to produce more in order to realize economies of scale. This heightens finished goods inventories, which, in turn, increase the product availability and thus decrease the sales price. Once the drop in sales price is perceived by the customers, the order volume increases. A reinforcing feedback loop emerges when, upon perception of the increased demand, production capacity is expanded. Contrariwise, the capacity puts a limit to the production output. A shortage of finished goods increases sales prices and restrains the number of orders, resulting in a reduction of capacity in the long run.

Installing additional capacity gives rise to fixed costs and thus adds to the total costs. Thereby, the costs per unit and the sales price increase, resulting in less orders and a decrease in the perceived demand. Hence, investments in production capacity are restricted by means of a balancing feedback loop.

The two loops described influence capacity investment decisions; they are depicted in figure 2.

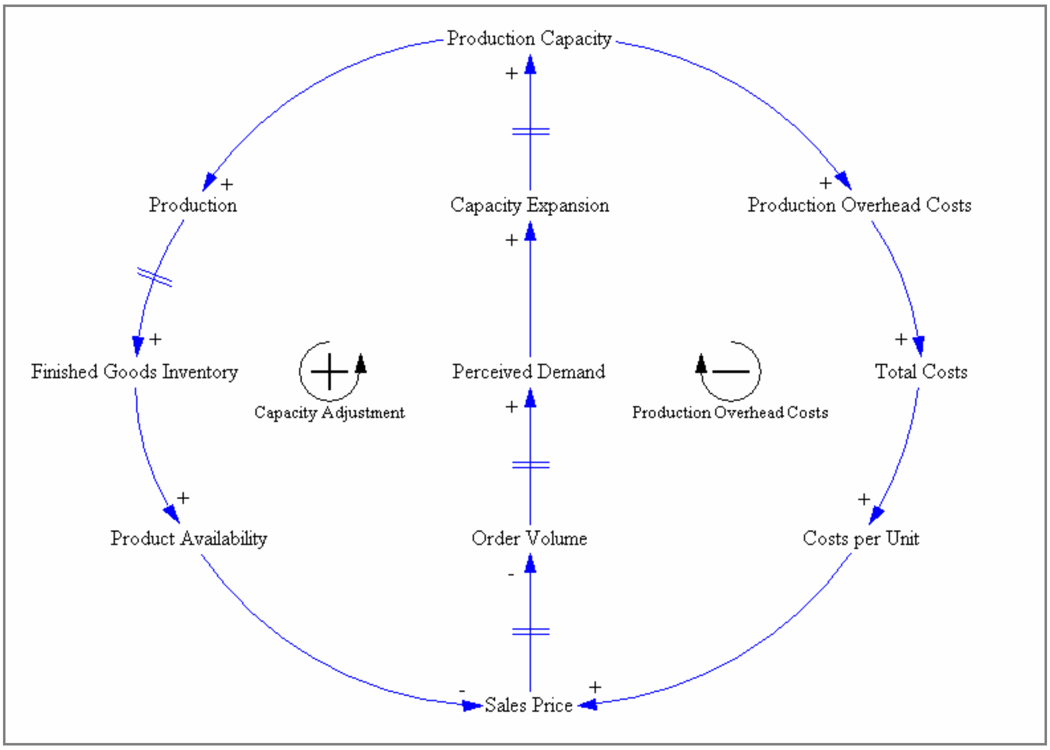

Figure 2: Effects pertaining to production capacity

I.3 Economies of Scale

Production decisions influence and are influenced by costs per unit. Firstly, increased production volumes raise raw material costs, which are variable - albeit not necessarily linear, but potentially subject to supplier discounts - and add to the total costs. Those, in turn, increase the unit costs and with it the sales price. A rise in sales price has a negative impact on the number of orders, so that the production volume is limited by the resulting balancing feedback loop. Secondly, considering the definition of unit costs as the ratio between the total costs and the total production output, increased production volumes also lower the costs per product and thus decrease the sales price. A drop in sales price makes the product more appealing to the customer so that order and production volume increase. This feedback loop is reinforcing itself and inducing economies of scale. Figure 3 depicts how the two loops discussed influence production.

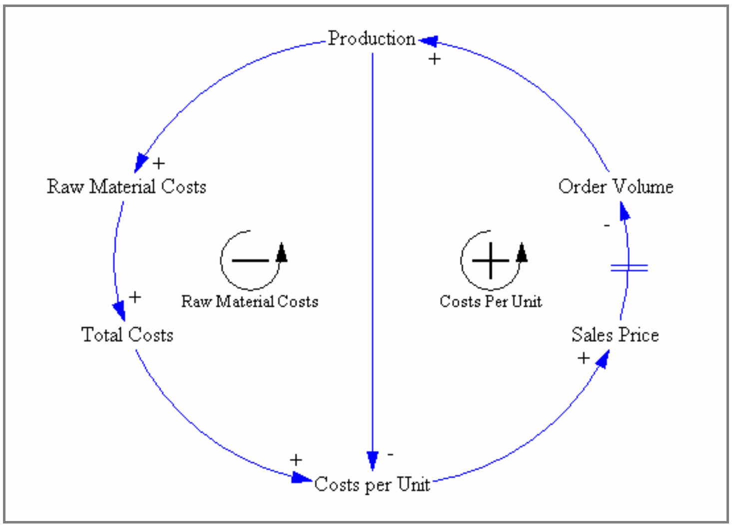

Figure 3: Economies of scale

I.4 Inventory Costs and Idle Time Costs

Figure 4 depicts how production decisions are affected by inventory costs and idle time costs. On the one hand, rising production volumes cause greater finished goods inventories and thus higher inventory costs. Since high inventory costs constrain production, a balancing feedback loop emerges. On the other hand, lower production volumes increase idle capacity, defined as the difference between total capacity installed and capacity used for production. Consequently, idle time costs rise, which are calculated as the ratio between idle capacity and total capacity, multiplied by production overhead costs. Since companies aim at avoiding high idle time costs and having a reasonable capacity utilization, production volumes are increased and another balancing feedback loop occurs. Besides, higher capacity utilization might be favored in order to realize economies of scale. The amounts of inventory costs and idle time costs determine the strength of their respective loop and hence trade off the impact of the two cost types on production decisions.

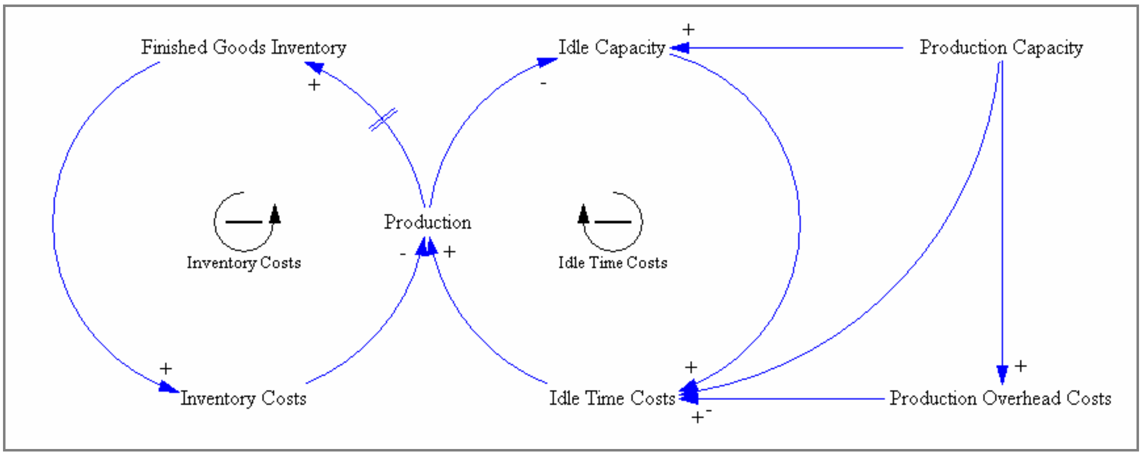

Figure 4: Inventory costs and idle time costs

I.5 Pricing and Demand

Four feedback loops influence the formation of sales price and the adjustment of production; they all involve market demand represented by order volume. A growth of order volume decreases the product availability, which is defined as the ratio between the quantity available and the quantity demanded. Lower product availability increases the sales price which constrains the order volume. This balancing feedback loop characterizes the influence of demand on sales price. Furthermore, a grown number of orders increases sales volume and thereby depletes finished goods inventory. This, in turn, reduces product availability and raises the sales price, so that once more the number of orders gets constrained. The resulting balancing feedback loop regulates pricing based on the available supply.

Higher order volumes increase production volumes so as to replenish finished goods inventory and ensure adequate product availability thereby. Lower sales prices and even higher order volumes result. This feedback loop reinforces order and production volumes and thus captures one facet of company growth. Considering the fact that production will usually not respond to every fluctuation in the number of orders, the corresponding figures are smoothed over time in order to perceive the true average order volume. This process entails a delay in the perception of true demand. Upon the observation of market needs production volumes are then adjusted accordingly, and by means of finished goods inventory, product availability, and sales price, the magnitude of the change in order volume is amplified again. A second feedback loop reinforcing order and production volumes arises. It has a longer delay time than the first one.

In individual cases, it depends on the impact of each of the four feedback loops and also on the delay times inherent to the system, how a company can influence and benefit from particular market developments.

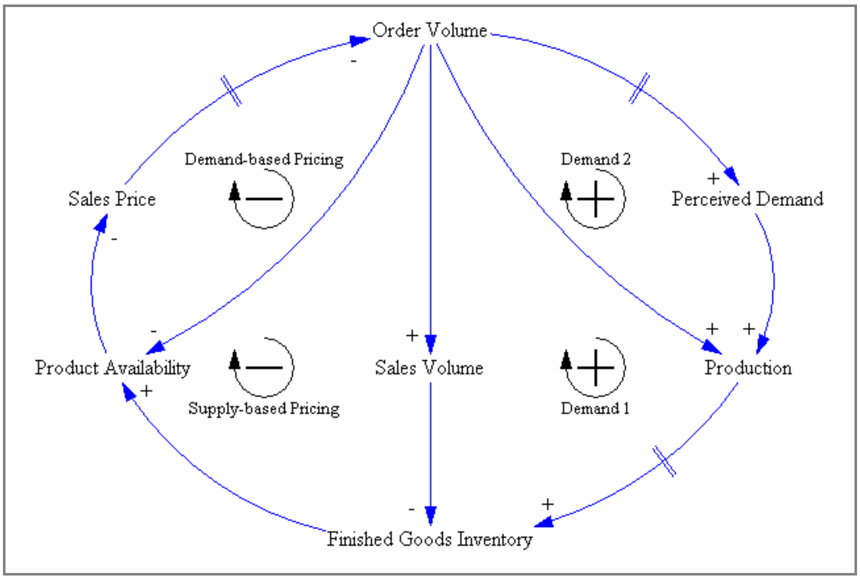

Figure 5: Pricing and demand

I.6 Exogenous Influences

In addition to the causal structures described so far, there are several effects on the system from outside of its boundary. Firstly, the market growth rate has a considerable impact on a company's business, but can hardly be influenced. Causally, market growth is connected to the order volume and to the perceived demand and therefore affects a company's decisions regarding production volumes and capacity expansions. Secondly, top management will intervene in the system in order to improve a company's competitive position and to gain market share. Those interventions can include pricing decisions such as low price policies to increase sales volume and attain market leadership or skimming strategies to increase sales revenues. Such decisions are based upon the current market situation, the current stage of the product life cycle, and further strategic considerations. Other managerial interventions pertain to the expansion of production capacity and to the variation of production volumes. Since a certain time span passes from the initiation of capacity expansions until their completion, management might decide to expand capacity beyond the current needs, e.g., to be ahead of competitors if market growth is anticipated to increase or to realize economies of scale and achieve overall cost leadership. Moreover, production volumes might be shifted so as to avoid major fluctuations in capacity utilization or in preparation for larger orders expected in the short-run.

Figure 6 outlines the entire generic pattern of causal interrelations as introduced afore (not including exogenous influences). Subsequently, the simulation model of an exemplary manufacturing company shall demonstrate one possibility of applying the pattern to the analysis of a specific company.

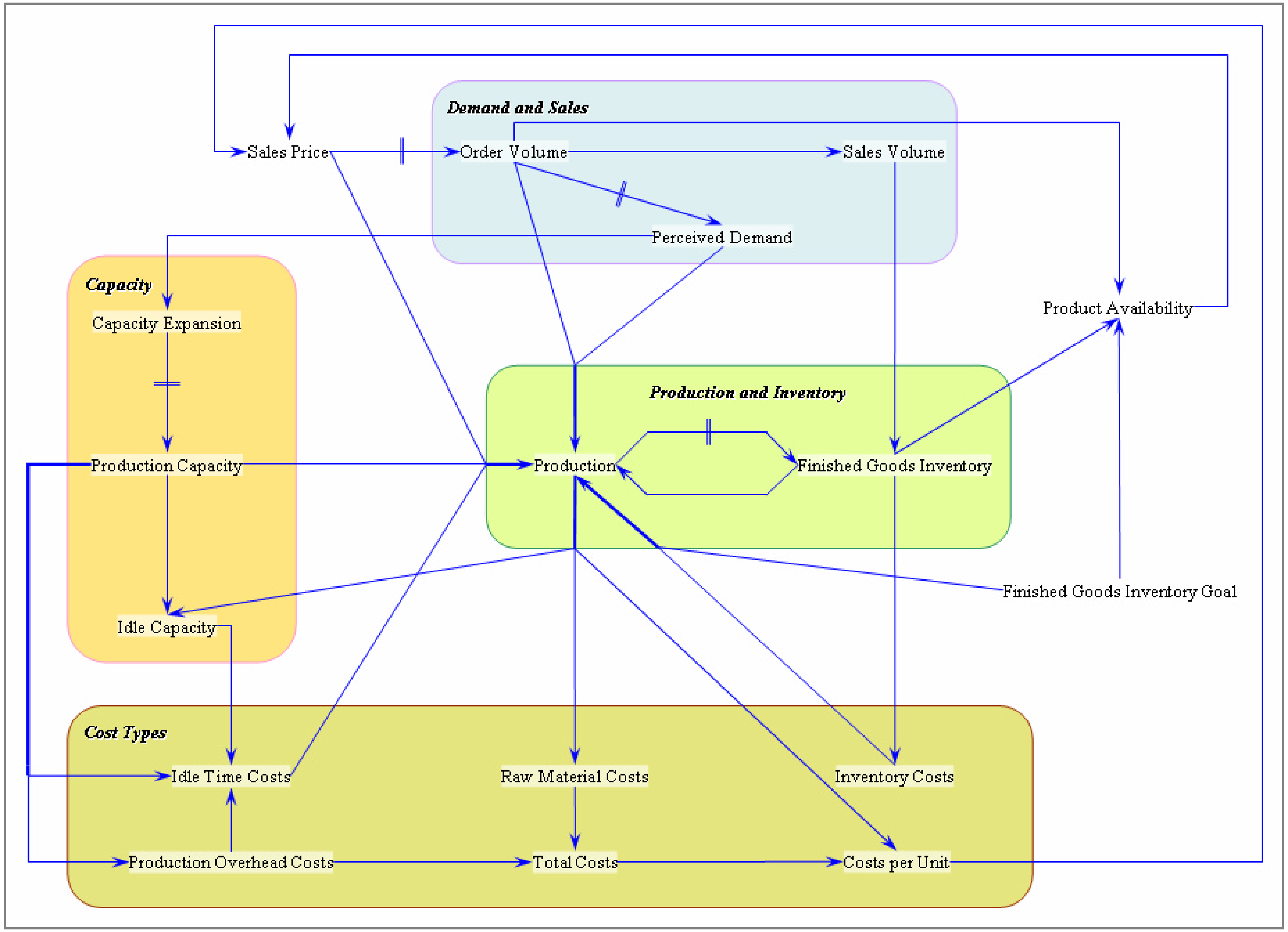

Figure 6: Generic pattern of causal interrelations in the manufacturing industry

II A Model Case of a Manufacturing Company

This section aims at the selective transition from the above model of causal structures to a simulation model, i.e., it shows one possible way of using the generic pattern introduced to analyze a manufacturing company. In doing so, it is demonstrated that even applying just parts of the pattern can result in a sufficiently detailed simulation model. In this case, the sector of costs is omitted. This section has two main focuses: The gradual introduction of a stock and flow model and the set up of model equations, so as to allow for simulation runs and analyses of the system. The four sectors of the stock and flow model are: flow of materials, production capacity, sales prices, and order volume. Along the way, their mutual influences are elaborated mathematically. At the end, figure 7 depicts the overall stock and flow diagram of the simulation model.

II.1 Flow of Materials

The central focus of the stock and flow diagram lies on the company's material flow. It starts with the production from raw materials, continues with the work in process and the work completed which replenishes the finished goods inventory. The inventory depletes by sales to the customer. In its simplest form, the production is a function of the order volume and the targeted safety stock for finished goods, both at the beginning of a period[1]:

production [Units/Week] =
(Order Backlog + FINISHED GOODS INVENTORY GOAL
- Finished Goods Inventory) / WEEK)[2]

with

FINISHED GOODS INVENTORY GOAL [Units] = 100

However, the production volume is also subject to capacity restrictions, and furthermore, a non-negativity check should be included:

production [Units/Week] =
MAX(MIN(
(Order Backlog + FINISHED GOODS INVENTORY GOAL
- Finished Goods Inventory) / WEEK ,
production capacity per week) , 0)

Additionally, the price elasticity of supply could be included as a stimulus to raise or reduce production according to the current sales price.

[1] In the following model equations and in the stock and flow diagram, variable names are written according to the conventions established by the System Dynamics Model Correctness Checklist (D-4851) (Lai, Wabha, 2001). The simulation environment used was VENSIM® PLE.
[2] Note that the constant WEEK is used in several equations to ensure consistency of units:
WEEK [week] = 1 .

Depending on the production lead time, all products get delayed while traversing the production line. They accumulate within the work in process level until they are finished and get transferred to the inventory:

Work in Process [Units] = INTEG(production - work completed , 0)
work completed [Units/Week] =
DELAY1I(production , PRODUCTION LEAD TIME , production)
PRODUCTION LEAD TIME [Weeks] = 2

All finished goods accumulate in the inventory until they are sold to the company's customers. The flow of sales depends on the current order backlog and is limited only by the amount of finished goods on stock:

Finished Goods Inventory [Units] =
INTEG(work completed - sales ,
FINISHED GOODS INVENTORY GOAL)
sales [Units/Week] =
MIN(Order Backlog/WEEK , Finished Goods Inventory/WEEK)

II.2 Production Capacity

Changes in production capacity follow the required production volume. However, capacity expansions should not directly be geared to the orders received each week and the production necessary to replenish safety stocks. Usually those numbers underlie certain fluctuations. Therefore, the perceived demand for production capacity is calculated by smoothing the weekly amounts requested over a longer period of time. The smoothing time is deliberately chosen to be longer than the time necessary to change capacity.

perceived demand [Units/Week] =
SMOOTH((Order Backlog + FINISHED GOODS INVENTORY GOAL
- Finished Goods Inventory) / WEEK ,
TIME TO PERCEIVE DEMAND)
TIME TO PERCEIVE DEMAND [Weeks] = 20

Using the perceived demand, the required amount of additional capacity can be determined. At this, not only the installed capacity but also the equipment that is currently being added but not productive yet, must be considered[3]:

capacity expansion [Units/Week] =
MAX(perceived demand - (production capacity per week +
Production Capacity being added/WEEK) , 0)
Production Capacity being added [Units] =
INTEG(capacity expansion-capacity added , 0)

[3] Due to restrictions imposed by the software, capacity is measured in units not in units per week, and thus, the flows of capacity changes are assessed with units per week.

capacity added [Units/Week] =
DELAY1I(capacity expansion , TIME TO ADD CAPACITY , capacity expansion)
TIME TO ADD CAPACITY [Week] = 10

After the addition procedure described, the new production capacity is added to what is already installed:

Production Capacity [Units] = INTEG(capacity added , 50)
production capacity per week [Units/Week] = Production Capacity/WEEK[4]

Note, that capacity reductions, which are not considered here, could easily be modeled with a delayed outflow from the production capacity level.

II.3 Sales Prices

In order to capture the circumstances of a free market, sales prices depend on the availability of goods. It is calculated as the ratio of all products available to all products needed:

product availability [Dmnl][5] =
(Finished Goods Inventory + work completed * WEEK) /
(Order Backlog + FINISHED GOODS INVENTORY GOAL)

The product's sales price is then adjusted accordingly: An availability ratio greater than 1 represents an oversupply so that the sales price must be decreased. If the ratio is less than 1, the price is increased due to a shortage situation. No price change emerges if the ratio is equal to 1; in this case demand and supply are in a perfect balance. The relation between product availability and sales price change is modeled using a table lookup function, the gradient of which is chosen arbitrarily as a straight line from +1 [Euro/Unit/Week] for the case where no goods are available to -1 [Euro/Unit/Week] for oversupply with an availability ratio of 2 or more. The sales price is represented as a level which gets refilled and depleted by a single flow, which is set up so as to avoid prices falling below 0.

Sales Price [Euro/Unit] = INTEG (change in sales price , 10)
change in sales price [Euro/Unit/Week] =
IF THEN ELSE(
LOOKUP PRICE CHANGE(product availability) < 0 ,
MAX(LOOKUP PRICE CHANGE(product availability) ,
-1 * Sales Price / WEEK) ,
LOOKUP PRICE CHANGE(product availability))
LOOKUP PRICE CHANGE((0,1),(1,0),(2,-1),(10,-1)) [Euro/Unit/Week]

[4] To assure correctness of units when using production capacity in other equations, an auxiliary variable has to be employed.
[5] "Dmnl" stands for "dimensionless" and is necessary to assure unit consistency in VENSIM®.

II.4 Order Volume

The following equations demonstrate how demand changes can be modeled to reflect changes in sales price, using a fixed value for the price elasticity of demand. A period's demand is represented as a level that is heightened and lowered by the flow of demand change. The flow's equation accounts for the influences of the compound annual growth rate (CAGR) and sales price changes. The CAGR is set to 10 % per year. The impact of sales price change is calculated using the definition of price elasticity of demand $\eta_{Q,P}$:

$$\eta_{Q,P} = \frac{\frac{(Q_2 - Q_1)}{Q_1}}{\frac{(P_2 - P_1)}{P_1}}$$

Q_1, Q_2, P_1, and P_2 represent the quantities demanded and the sales prices of the previous and the current period, respectively. Given the price elasticity of demand and the price change from one period to the next, the demand's change can be calculated as follows:

$$(Q_2 - Q_1) = \eta_{Q,P} \frac{(P_2 - P_1)}{P_1} \cdot Q_1$$

In the model described, unit elastic demand is assumed ($\eta_{Q,P}$ = -1); this implies that a given percentage change in sales price effects the same percentage change in demand:

Demand [Units] = INTEG(demand change , INITIAL DEMAND)
INITIAL DEMAND [Units] = 50
demand change [Units/Week] = PRICE ELASTICITY OF DEMAND
    * (Sales Price - last periods sales price)/last periods sales price
    * Demand/WEEK
    + CAGR * Demand
PRICE ELASTICITY OF DEMAND [Dmnl] = -1
CAGR [Dmnl/Week] = 0.1/52
last periods sales price [Euro/Unit] =
    DELAY FIXED(Sales Price , 1 , Sales Price)

The actual amount of orders that a company has to fulfill is represented by the order backlog level. It fills up through the flow of orders received, which equals the demand of the respective period, it's reduced by the flow of orders processed which is equal to the period's sales, and initially it's set to 0.

Order Backlog [Units] = INTEG(orders received - orders processed , 0)
orders received [Units/Week] = Demand/WEEK
orders processed [Units/Week] = sales

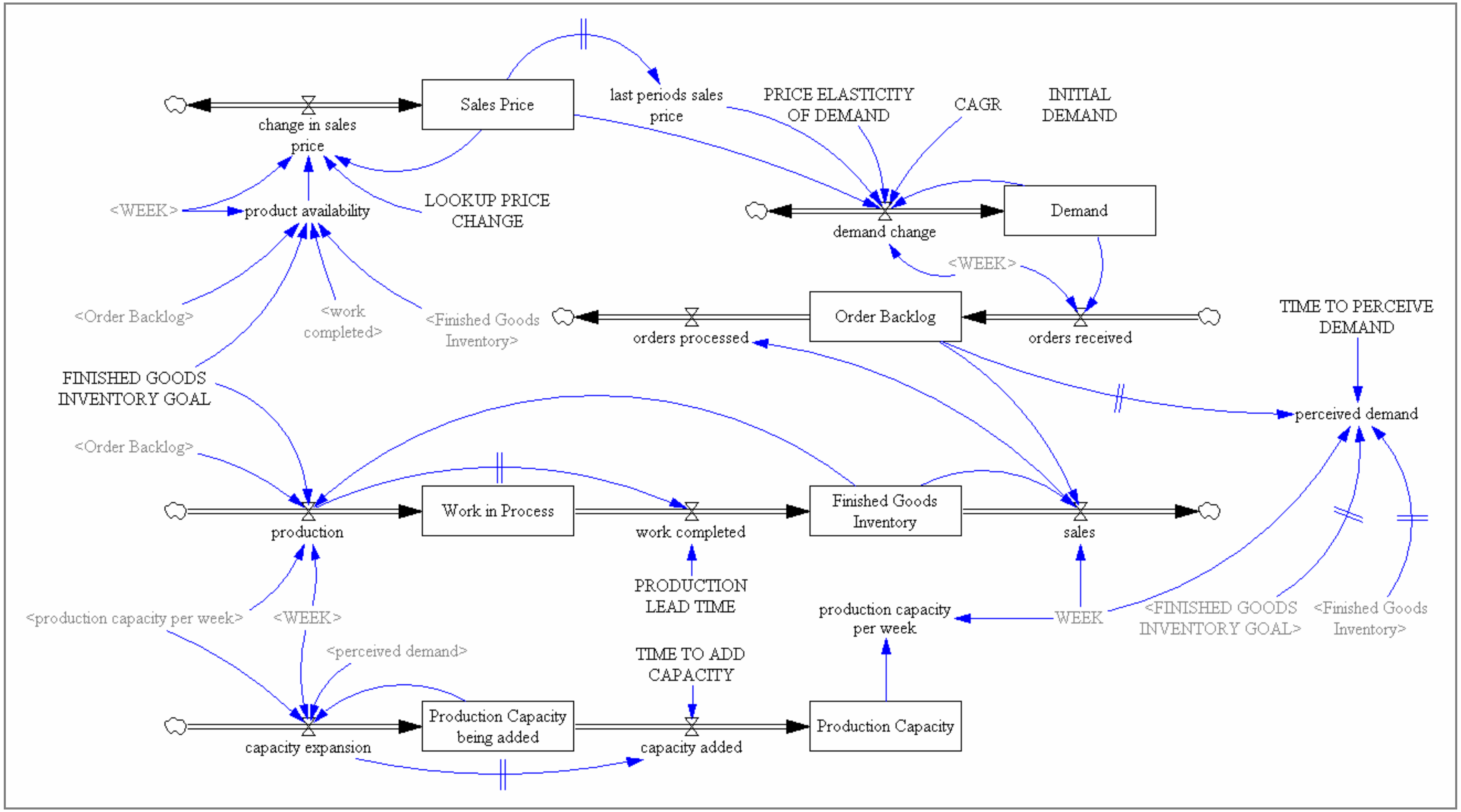

Figure 7: Stock and flow diagram of the simulation model

III Scenario Analysis

With the simulation model introduced in the previous section, a basic scenario shall now demonstrate how a market equilibrium can be determined under the assumption that the company considered does not alter its production volume if the price changes (no price elasticity of supply).[6] Furthermore it is assumed that no market growth or decline occurs (CAGR = 0). The results depend on the shape of the lookup function for the change of price, on the initial values of the levels, and on the values of the constants, all of which are chosen as specified in the equations above. The simulation is run over 156 weeks, i.e., three years with 52 weeks in each.

While the level of finished goods inventory was initialized with its desired value of 100 units, order backlog was initially set to 0 units. Thus, it now increases, driven by the demand which was initialized with 50 units per week. Due to production delays, at first, the demand has to be satisfied from safety stock, and the finished goods inventory depletes. After approx. four weeks, the finished goods coming from production start exceeding the number of orders received and while the safety stock gets replenished, order backlog begins to deplete. Due to the work in process and the decreasing order backlog, finished goods inventory overshoots its goal, but after some diminishing oscillations reaches the value of 100 units within 30 weeks. That is the same period that the rates of products completed and orders received need to be in line with each other. In the resulting equilibrium between demand, supply, and price, supply and demand amount approx. 37 units per week and the sales price is 13.33 [Euro/Unit].

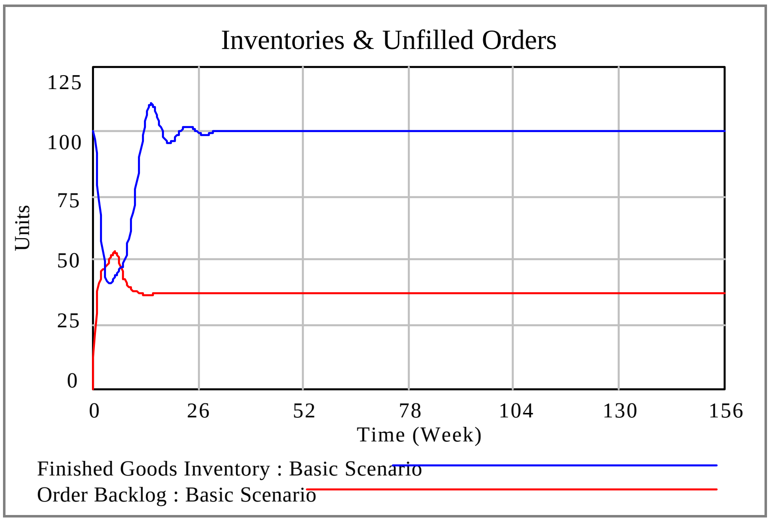

Figure 8: Finished good inventory and order backlog

[6] Further assumptions and restrictions as noted in the previous section should also be kept in mind.

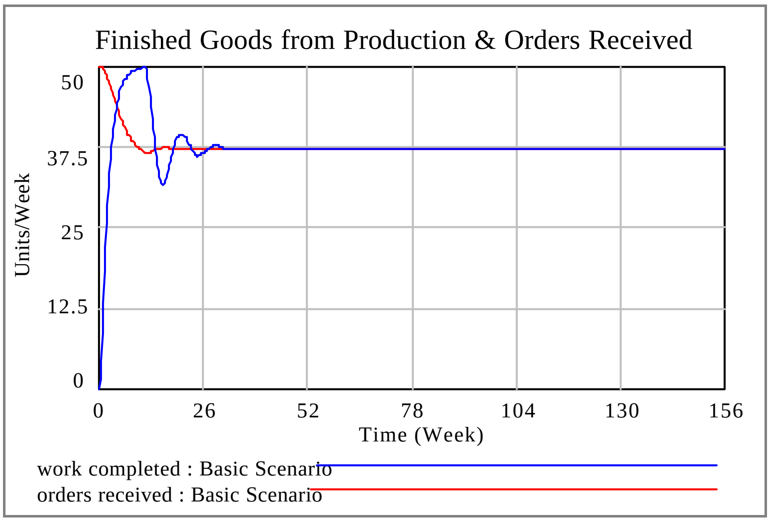

Figure 9: Work completed and orders received

The fact that stable demand is now below its initial value of 50 units per week is explained by the influence of price changes on demand. Price changes are induced by a product availability ratio unequal to 1. As long as this value is less than 1, sales price rises; for values greater than 1, sales price declines. The price change's magnitude depends on how much the availability ratio deviates from 1. As soon as the finished goods inventory and the order backlog even out, the product availability stabilizes at 1 and the sales price remains constant. The following figure reveals how demand depends on sales price. Demand is decreasing as long as sales price is rising, and vice versa. This relationship is primarily influenced by the price elasticity of demand.

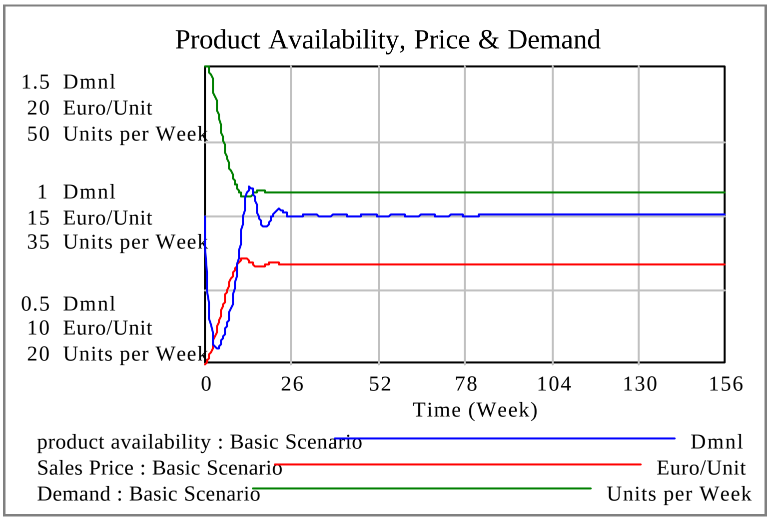

Figure 10: Product availability, sales price and demand

As mentioned in section 2, the smoothing time for perceived demand is chosen longer than the time needed to expand capacity, so as to disregard weekly fluctuations. The following figure shows the perceived demand, the weekly available production capacity, and the production volume. The latter is restricted by the capacity limit; this is expedient in order to avoid a greater overshooting of the finished goods inventory.

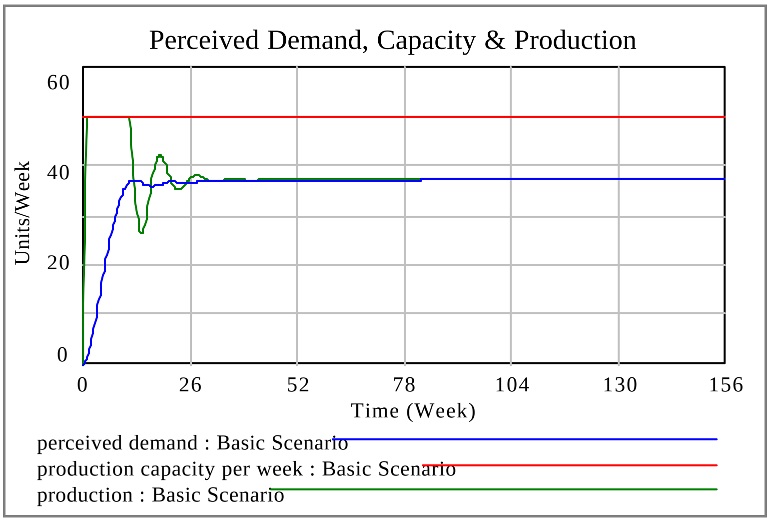

Figure 11: Perceived demand, weekly capacity and production

Summary and Further Research

The paper presented a pattern that marks an approach to the analysis of companies in the manufacturing industry. It was shown that the pattern represents a metamodel for building diverse company models in miscellaneous applications. The scheme is designed to deal with material, monetary, and informational flows, and it captures the restrictions given by limited production capacities as well as the requirements imposed by customer demand. Furthermore, an elementary approach for modeling the influence of sales price changes on customer demand has been included. By the use of a model case, it was shown how the pattern can serve as a blue print that facilitates rapid development of simulation models and it became apparent that even applying the metamodel just in extracts can be sufficient to meet the demands of a particular modeling task. Lastly, a basic simulation run gave an example of how insights can be gained from applying the model construction procedure. In this particular case the simulation was utilized to determine the equilibrium values of sales price and market demand.

To round out the pattern, future work might extend it with additional relations among the sectors or even with new sectors. Potential extensions include modeling the availability of raw materials, the utilization of capacity, the rate of yield, as well as sales revenues and profit.

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