A General Economic Model for Manufacturing Cost Simulation

Mathias Jönsson, Carin Andersson, Jan-Eric Ståhl
Division of Production and Materials Engineering, Lund University, Sweden

Abstract
The described technical-economic model clarifies the influence of different production technological factors on the processing cost of a part. Influential factors can be weighted against each other, which leads to different production development scenarios and their effects on the processing cost can be studied. This implies a way to generate a basis of decision by which a company can base their production related development goals. The model describes influence of technical factors on the manufacturing cost and thereby represents the important link between technical development and economy.

Keywords:
Manufacturing Economy; Cost Model; Deterministic Production Development

1 INTRODUCTION

A majority of all manufacturing companies are working with production development and improvements to meet the global competition of today. There are a number of methods and philosophies for working with continuous improvements, where the success of lean production [1], is the most widely spread. An important question is if considerations and decisions made regarding investments and development actions are based on correct and adequate knowledge in order to achieve the highest efficiency benefits.

The outsourcing debate has been going on for some time now [2], [3]. Decisions made about moving production-units to low-wage countries are often based on limited information, giving wages too big influence over the decisions. Existing economic models are inadequate in utilizing estimation of the development potential of a production system and possible development actions.

There are many questions to be asked when considering major improvement changes in a production facility. The most common questions the company management would like to have answered are:

- How much better do we have to be to compete with for example low-wage countries and what and where in the production facility do we have to improve?
- What are the bases of decision required to formulate goals for production development, and what are reasonable goals for the actual production system?

The economic model presented in this paper can help to give answers to these questions, if the required data about the production performance is known.

2 PURPOSE AND LIMITATIONS

The purpose of this economic model is to describe the costs added to the cost of a part at every processing step. The model is not intended to be used only to describe the present cost situation, but also to function as a simulation tool to simulate different development scenarios and their effect on the part cost. Thereby it can be used as a support tool in manufacturing development activities.

The economic model presented is defined to comprise the direct production cost. The overhead costs are excluded at this level, because they have little to do with developing the production system. Factors tied to the income side of the production are not considered in the model. The model primarily describes batch production and is summarised to describe one processing step or a so-called planning point (a planning point is a set of machines and robots where the cycle time is determined by the slowest machine in the line). This simplification enhances the principle of comparing the influence of different cost items on the total production cost. These factors influence on the production cost can therefore constitute the foundation for choosing research and development actions.

3 LIST OF SYMBOLS

The parameters in the list of symbols are partly tied to the factor groups described above. The economic parameters are described in the Swedish currency krona (kr).

Table 1: List of symbols

t_0	Nominal cycle time per part.	min
t_m	Machine time	min
t_h	Handling time	min
t_{vb}	Tool switch time	min
t_p	Production time per part	min
t_S	Average down time per part	min
q_S	Down time rate	-
N_0	Nominal batch size	unit

N	Total amount of required parts to be able to produce N_0 parts	unit
N_Q	Amount of scrap parts in a batch of N_0 parts	unit
q_Q	Scrap rate	-
t_{0v}	Cycle time including production rate losses	min
q_P	Production rate	-
T_{su}	Set up time of a batch	min
T_{pb}	Production time of a batch	min
t_{pb}	Production time per part of a batch with N_0 parts	min
k	Part cost	kr/unit
k_B	Material cost per part including material waste	kr/unit
k_{CP}	Hourly cost of machines during production	kr/h
k_{CS}	Hourly cost of machines during down time and set up	kr/h
k_D	Wage cost	kr/h
K_B	Material cost of a batch including scrapped parts and material waste	kr/batch
k_{B0}	Material cost of the manufactured part without material waste	kr/unit
q_B	Material waste factor	-
m_{tot}	Total consumption of material per part	weight
m_{part}	Remaining material in the machined part	weight
U_{RP}	Degree of occupation	-
n	Rational number > 0	-
∂z	Partial change in arbitrary variable.	-
Δz	Change in arbitrary variable	-
x_p	Process development factor for the cycle time	-
x_{su}	Process development factor for set up time	-

4 LITTERATURE REVIEW

Several different models have been developed for the purpose of calculating the manufacturing cost. According to Tipnis, *et al*. [5], the models can be divided in microeconomic and macroeconomic models. In the microeconomic models specific process parameters influence on the part cost is described. Microeconomic models dealing with machining has been described by Colding [6], [7] and Alberti, *et al*. [8] among others and Knight, *et al*. [9] has developed a corresponding model for forging. Within the field of machining a microeconomic model can describe how for example the cutting rate, feed or working margin influence the part cost. In a macroeconomic model several parameters are aggregated. An example of a macroeconomic model is when the cost calculations are based on the cycle time and not the factors influencing the cycle time. The fundamental principles for developing macroeconomic models are described by Kaplan and Anderson [10]. The authors have not developed any models that are directly applicable to calculate the part cost but leaving these activities to the reader.

Macroeconomic models have previously been illustrated by Groover [11]. In this model only one production loss parameter is taken into consideration; the scrap rate. Ravignani and Semeraro [12] have developed a model that combines the micro- and macroeconomic views by noticing both cutting technological conditions and the batch size. Non production loss parameters are regarded.

It can be stated that the microeconomic models are specific for different processing methods. Numerous models have been developed to describe the cutting cost of machining. The models are describing the connection between the cutting rate, the wear rate of a cutting tool and the tool switch time. In these models the tool cost is highly prioritized. Costs of down time and the scrap rate are not often taken into consideration.

A cost model for assembly is introduced by Teng and Garimella [13]. This model is based on inventory costs, assembly costs and costs associated with diagnostic and rework activities. The model has a high resolution concerning cost of different types of equipment in the assembly line. The model is based on average cycle times where also the scrap rate is considered. Boothroyd [14] is describing a specific cost model for robot assembly which is noticing the down time costs in the assembly line.

Production cost regarding design has been discussed by Locascio [15], Liebers and Kals [16] and Shehab and Abdalla [17]. Locascio is assuming that all cycle times of the processing steps is known in advanced. Any specific connection to production loss parameters is not considered. Shehab and Abdalla is describing an interesting model that estimate the manufacturing cost of machining for different choices of material where both the material cost and the processing cost is taken into consideration.

The model described below is general and can be regarded as a macroeconomic model but with the possibility to consider the microeconomic parameters. The model is intended to describe the part cost of various specific or aggregated processing methods without any major modifications.

5 MODELLING OF THE PART COST

The nominal processing time (cycle time) t_0 for a part is comprised of machine time, handling time and tool change time:

$$t_0 = t_m + t_h + t_{vb} \tag{1}$$

The equation assumes that the events are performed in a sequential order and can be considered as a planning point. The real processing time t_p will be longer than the nominal time due to disturbances and downtime. The rate of the disturbance and downtime can be expressed as the quotient between the downtime t_S and the observed production time t_p described in equation 2. The sum of the downtime and nominal processing time gives the real processing time t_p according to equation 3. Combining equation 2 and 3 the processing time can be determined based on the nominal cycle time and the downtime rate q_S:

$$q_S = \frac{t_S}{t_p} = \frac{t_p - t_0}{t_p} \quad (2)$$

$$t_p = \frac{t_0}{1-q_S} = t_0(1+\frac{q_S}{1-q_S}) \quad (3)$$

To obtain N_0 number of correct parts, N number of parts has to be manufactured due to scrapped parts. The rate of scrapped parts is expressed by q_Q:

$$q_Q = \frac{N_Q}{N} = \frac{N - N_0}{N} \quad (4)$$

$$N = \frac{N_0}{1-q_Q} = N_0\left(1+\frac{q_Q}{1-q_Q}\right) \quad (5)$$

Losses in production rate are a fact when the cycle time has to be increased from t_0 to t_{0v} to maintain the quality level or avoid unplanned downtime. The relative loss in production rate is described as:

$$q_P = \frac{t_{0v} - t_0}{t_{0v}} \quad (6)$$

$$t_{0v} = \frac{t_0}{1-q_P} \quad (7)$$

To changeover the production from manufacturing part A to part B a certain amount of setup time T_{su} is required. The production time for a batch including the setup time is:

$$T_{pb} = T_{su} + N \cdot t_p = T_{su} + \frac{N_0 \cdot t_0}{(1-q_Q)(1-q_S)(1-q_P)} \quad (8)$$

The average production time for a batch of N_0 number of correct parts is calculated as:

$$t_{pb} = \frac{T_p}{N_0} \quad (9)$$

In the presented model there are primarily three cost items specified; equipment costs k_C, wage costs k_D and material costs k_B. Equipment costs for a machine or a production line can be split up into a cost during production k_{CP} and a cost k_{CS} when the machine or production is not running. For the case in question both these cost items include all of the costs that can be related to the equipment as investment cost, local cost, cost of maintenance, tool costs etc. The cost of wages per hour k_D are presumed to be independent of if the machine is running or not and also presumed to be unchanged during setup.

To study the material cost including scrapped parts and material waste, a material waste factor q_B is introduced:

$$K_B = \frac{N_0 \cdot k_{B0}}{(1-q_B)(1-q_Q)} \quad (10)$$

$$q_B = \frac{m_{tot} - m_{part}}{m_{tot}} \quad (11)$$

where k_{B0} is the material cost of the manufactured part and K_B is the material cost of the batch including scrapped parts and material waste. The material waste factor q_B consider the total consumption of material m_{tot} per part and comprises also material that are machined or cut off as for example chips during turning or milling and retainer surfaces during sheet metal forming. The remaining material in the machined part is denoted m_{part}.

Reduced occupation in a manufacturing system leads to consequences for all manufactured parts. This situation can be considered in different ways, hence the free production resource can be considered both as an economic asset and a disadvantage depending on the situation. In a long term view the manufactured parts must carry the costs for the over capacity. The over capacity time can be distributed over all the batches in relation to their production time T_{pb} by introducing a degree of occupation U_{RP}, calculated as the quotient between real production time T_{prod} and planned production time T_{plan}:

$$U_{RP} = \frac{T_{prod}}{T_{plan}};\ T_{plan} = T_{prod} + T_{free} \quad (12)$$

The extra free capacity $T_{free,b}$ to be added to a specific batch is calculated according to equation 13. The free time can be considered as a setup time at the same time as the equipment is available for manufacturing:

$$T_{free,b} = \frac{1-U_{RP}}{U_{RP}} T_{pb} \quad (13)$$

The manufacturing costs per part k, including the previously described parameters and assumptions can be expressed as:

$$\begin{aligned} k = {} & \frac{K_{sum}}{N_0} + \left(\frac{k_B N_0}{N_0(1-q_Q)(1-q_B)}\right) + \\ & \left(\frac{k_{CP}}{60N_0} \cdot \frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right) + \\ & \frac{k_{CS}}{60N_0}\left(\frac{t_0 N_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right) + \\ & \frac{k_D}{60N_0}\left(\frac{t_0 N_0}{(1-q_Q)(1-q_S)(1-q_P)} + T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right) \end{aligned} \quad (14)$$

In some cases it can be necessary to introduce a disturbance factor q_{Ssu} to handle spreading in the nominal setup time.

The cost item K_{sum} in equation 14 comprises different types of costs that are not described separately in the model. A more complete economic model has a higher resolution and includes more of the separate terms that are now included in K_{sum}. A developed model can for example consider tool costs, cost of maintenance, remainder value of waste material, fixture costs, stock/buffer and transportation costs, surrounding equipment, costs arising due to environmental or recycling actions for example to eliminate cutting fluids or oils.

6 DETERMINISTIC PRODUCTION DEVELOPMENT

To be able to manage production development efficiently, clear goals has to be established for the development activities. Many companies today have implemented lean manufacturing to some degree, or they are by other methods developing and improving the manufacturing process. With this model those activities can be performed in a more deterministic, goal oriented way. The reasons for this is that an implementation of this model for every product in every processing step, enables the most critical factors from a cost perspective to be acquired. When you have this information it will be possible to establish concrete economic goals and to simulate the consequences these goals have on the parameters constituting the part cost. The consequences could for example be how much a given parameter must be changed to reach the established goal.

The development activities can be performed in relation to the present production conditions of the company or in relation to the competitors and other terms of the market. Example of production development goals are reduction of the manufacturing costs with 20% for a certain part type, a 50% reduction of setup time or an increase of production rate from 100 to 120 parts per week with unchanged cost parameters.

Considering that a lot of factors, isolated or in cooperation, influence the cost of a specific part, different changes in these factor can lead to same cost effects. To be able to separate the influence of these different factors on the part cost, different development factors are introduced to the parameters in equation 14.

$$\begin{aligned} k = {} & \frac{K_{sum}}{N_0} + \left(\frac{k_B \cdot N_0}{N_0(1-q_Q)(1-q_B)} \right) + \\ & \left(\frac{\kappa_C \cdot k_{CP}}{N_0 60} \cdot \frac{x_p \cdot t_0 \cdot N_0}{(1-q_Q)(1-q_P)} \right) + \\ & \frac{\kappa_C \cdot k_{CS}}{60 N_0} \left(\frac{x_p \cdot t_0 \cdot N_0}{(1-q_Q)} \cdot \frac{q_S}{1-q_S} + x_{su} \cdot T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right) + \\ & \frac{k_D}{60 N_0} \left(\frac{x_p \cdot t_0 N_0}{(1-q_Q)(1-q_S)} + x_{su} \cdot T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right) \end{aligned} \tag{15}$$

In equation 15 the development factor x_p operates on the cycle time and enables therefore analysis of changes in cycle time. The development factor x_{su} operates on the setup time and enables therefore studies of changes in setup time. The cycle time and setup time are the most important parameters describing the capacity and flexibility of a production system. A development factor given a value less than 1.0 result in a reduction in cycle time and setup time, if the factors are given for example the value 0.5, the production time and setup time has been reduced to half of the original size. The development factors can therefore be regarded as improvement variables in a goal function.

A cost development factor κ_C is introduced to describe an investment cost that can be connected to a change in cycle time. The cost factor operates on the equipment costs k_{CP} and k_{CS}. This factor is used to model changes in costs in primarily existing equipment, and can be used to determine the limit of investment justified by for example a decrease of the downtime rate to a certain value. For example does κ_C = 1.20 corresponds to an increase in equipment cost with 20%.

7 COST DERIVATIVES

Changes in part cost caused by a limited change in an arbitrary variable *z,* is calculated by partial derivative, and is described in linear form as:

$$\Delta k_i = \frac{\partial k_n}{\partial z} \cdot \Delta z \tag{16}$$

The changes in part costs can be calculated with respect to different parameters as for example changes in wage costs and share of downtime Δq_{Si}. Equation 17 is exemplifying changes in part costs due to changes in different governing parameters.

$$\Delta k_i = \frac{\partial k_i}{\partial k_{Di}} \cdot \Delta k_{Di} + \frac{\partial k_i}{\partial q_{Si}} \cdot \Delta q_{Si} \tag{17}$$

Cost neutral changes in each variable can be studied by putting the change in part costs $\Delta k_i = 0$. Equation 17 is written in a cost neutral form in equation 18, describing the size of the reduction in downtime share required to compensate for a change in wage costs.

$$\Delta q_{Si} = -\Delta k_{Di} \cdot \frac{\dfrac{\partial k_i}{\partial k_{Di}}}{\dfrac{\partial k_i}{\partial q_{Si}}} \tag{18}$$

The influence of a specific variable can be studied by calculating cost derivatives. A change in a variable giving a large influence on the part cost also gives large cost derivative values. It is hazardous to uncritically compare different cost derivatives with each other since the possibility of changing each variable is different. A weighting of the cost derivative can be made by multiplying the cost derivative with its functional value. A weighted cost derivative is a better indication of the impact each variable has on changes in the cost derivatives. All changes Δz in the variable *z* becomes relative with respect to the absolute value of the variable. By introducing a relative variable $\Delta z_0/z_0$, the changes expressed as a percentage for a specific variable can be compared with changes expressed as a percentage for another variable. This principal is expressed in equation 19.

$$\Delta k = \frac{\partial k(z_0)}{\partial z} \cdot z_0 \cdot \frac{\Delta z_0}{z_0} \tag{19}$$

8 MODEL EXAMPLE

In the present section the usefulness of the model will be shown by implementing the model using fictive input data. The example will illustrate what kind of analyses that could be performed and what decision-making bases you can get.

The costs for two different production cases can be studied by introducing an index *i* tied to the parameters and variables in equation 16 in order to separate them. In the following examples the part costs k_1 and k_2 are calculated for the presumption valid for each case. Below the developed model is exemplified by inserting technical and economic data according to Table 2.

Table 2: Applied data for the model.

t_0	10	min
T_{su}	100	min
k_{Cp}	1000	kr/h
k_{CS}	700	kr/h
k_{D1}	200	kr/h
k_{D2}	50	kr/h
k_B	20	kr/part
q_B	0	-
K_{sum}	0	kr/batch

Figure 1 illustrates the part cost k as a function of the nominal batch size N_0 with two separate values of the wage cost. In case 1 (dotted graph) is the wage cost unchanged, i.e. k_{D1} = 200 kr/h and in case 2 (continous graph) is the wage cost reduced; k_{D2} = 50 kr/h. The difference in wage cost can for example illustrate two manufacturing plants in different countries with different wage costs. All other parameters are unchanged. In the figure you can see that the value of k is clearly higher for case 1 because of the higher wage cost.

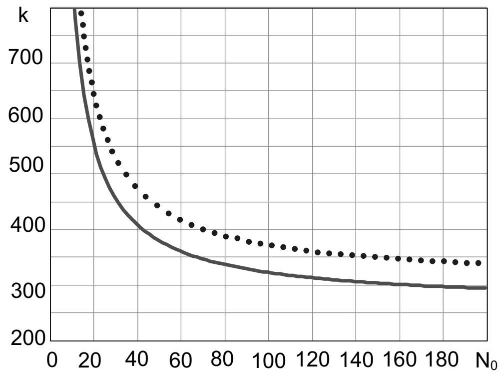

Figure 1: The part cost of the productio ıses 1 (dotted graph) and 2 (continuous graph) as a function of the nominal batch size N_0. In both case 1 and 2 is q_Q = 5 % and q_S = 40 %, x_p and x_{su} is 1.0.

For the plant in case 1 to be able to compete with the plant in case 2 it must take actions to alter one or more of the parameters building up the cost k. In Figure 2 has the plant in case 1 managed to decrease the down time losses from q_S = 40 % to q_S = 35 % and the process development factor x_{p1} has decreased from 1.0 to 0.95. By these changes the difference in part cost between the two cases has more than halved, even if it differ a factor 4 in wage cost.

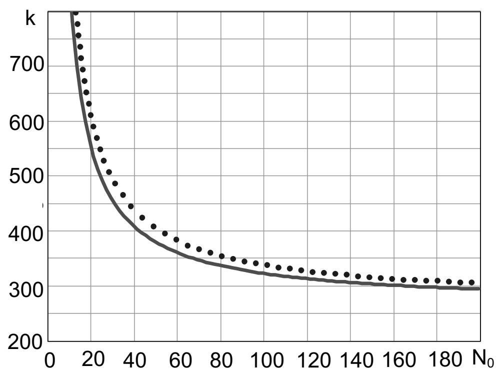

Figure 2: The part cost of the production cases 1 (dotted graph) and 2 (continuous graph) as a function of the nominal batch size N_0. In both case 1 and 2 is q_Q = 5 % and q_S = 40 % for case 2 and 35 % in case 1, x_p is 1.0 in case 2 and 0.95 in case 1.

In Figure 3 below, the down time factor q_{S1} has been further decreased with 5 % to 30 % and the process development factor x_{p1} is reduced to 0.80. In this situation the part cost for the plant in case 1 has been reduced and becoming 30 kr lower than the plant in case 2 for batches larger than 100 parts.

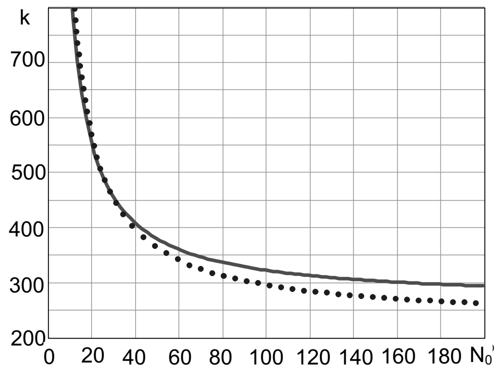

Figure 3: The part cost of production cas dotted graph) and 2 (continuous graph) as a function of the nominal batch size N_0. In both case 1 and 2 is q_Q = 5 %. q_S = 40 % for case 2 and 30 % in case 1, x_p is 1.0 in case 2 and 0.80 in case 1.

In Figure 4 the cost derivative is exemplified. The cost change Δk_1 is illustrated as a function of change in down time loss Δq_{S1} and change in relative wage cost $\Delta(k_{D1}/k_{D1})$. In the figure you can observe that a increase in part cost by 40 kr can either be received by increasing the down time loss 10 % or the wage cost by 70 %. In this linear model the corresponding decrease applies in the described variables.

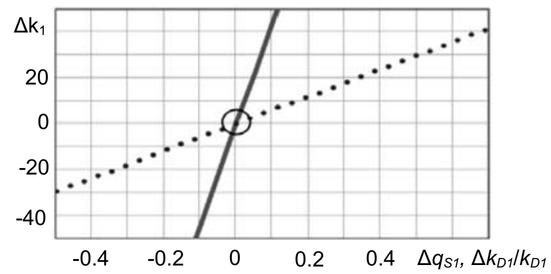

Figure 4: The relationships between the cost change Δk_1 and change in down time loss Δq_{S1} and change in relative wage cost $\Delta k_{D1}/k_{D1}$. In this case is q_Q = 5 % and q_S = 40 %, x_p and x_{su} is 1.0, the batch size 200 parts.

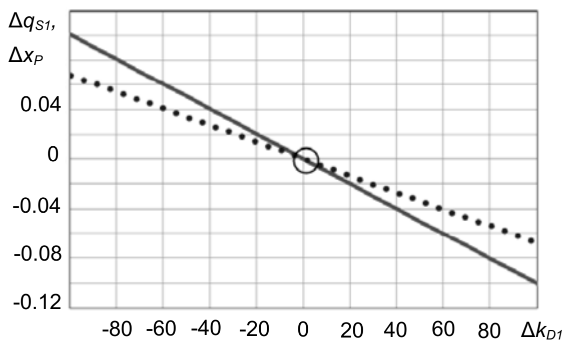

Figure 5: Cost neutral changes in wage cost and in down time losses (dotted graph) and also in wage cost and process development factor (continuous graph). In this case is q_Q = 5 % and q_S 40 %, x_p and x_{su} is 1.0 and batch size N_0 = 200 parts.

In Figure 5 the cost neutral changes are shown, which illustrate the balance for a change in wage cost and down time loss and also a change in wage cost and process development factor. In the figure it can be established that a wage increase by 40 kr per hour i.e. 20 %, corresponds a cost neutral improvement i the process development factor

Δx_p by about 4 % or a decrease in down time losses Δq_S by almost 3 %.

9 DISCUSSION AND CONCLUSIONS

The developed model enables analyses and economic estimations of various technical and organisational development alternatives. The model example shown in the section above illustrates for example how a higher wage cost can be compensated by technical and organizational improvements. Through studies of cost derivatives different alternatives related to production development can be judged. High cost derivatives shows the strength of a certain variable. The investment cost in research and development necessary to reduce x_{p1} from 1.0 to 0.80 and q_{S1} from 0.40 to 0.30 can for instance be weighted against alternative costs. The theoretical and practical possibilities to realize the necessary development for example in the case above must of course be estimated in each specific case. The conditions are highly governed by the present level of development and the belonged remaining development potential.

The difficulties of using the described model are that the model demands accurate input data. A systematic registration of the disturbances building up the parameters q_Q, q_S and q_P and parameters such as the set up time is of great importance. From experience the equipment costs represent though the greatest difficulties. These problems are dealt with by Ståhl (2007) among others.

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