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Manufacturing costs and Degree of Occupancy Based on the Principle of Characteristic Parts

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ABSTRACT

In making capacity estimates and cost calculations in the manufacturing industry, many products and production systems are often involved, making the data in their totality difficult to grasp. Introducing the concept of the characteristic part, which is a fabricated part seen as representative of all parts produced in terms of demand, setup time, cycle time, average batch size and total number of batches involved, makes the calculations required much more manageable and much less time-consuming. The article takes up how the characteristic part is defined and how it can be used in calculating production capacity, system unitization and manufacturing costs.

1. INTRODUCTION

In today´s manufacturing system, companies often produce a large variety of products, making visualization and planning difficult. This article address the possibility to plan the manufacture design and do cost calculation on one or a few parts representing the whole production system regarding setup time, cycle time, average batch size, total number of batches involved and losses in performance. The part used is called a characteristic part and is a fictive part composed by the production parameters from the products produced in the actual manufacturing system.

It is common in the industry, when making estimation for new equipment investments or production relocations, to select one or a few exciting products from the product portfolio for calculating production capacity, degree of occupancy and manufacturing costs. These products are often high volume products and are manufactured involving most of the processes within the system. Using information from just a few products there is a risk that valuable information is not taken into consideration. Some problems occurring when producing one type of product are not always present when producing another. One example is products produced in exactly the same processes but consisting of different materials, affecting the quality rate, cycle time and production rate. An alternative when investing in new equipment is to do estimations on all products produced but by use of the characteristic part it is possible to do calculations on one or a few products, making the amount of data easier to grasp and also take the production performance for all products into consideration.

The article propos a methodology for calculating the characteristic parameters for a fictive part representing a range of products manufactured in a defined set of equipment (cell or line). This together with models for calculating the degree of occupancy is used for analysing the possibility to use the characteristic part methodology to describe manufacturing costs. The term characteristic part is here defined as a product representing all of the parts belonging to a particular product family that can be manufactured in a given production line. The purpose of the proposed concept is to facilitate planning and preparation in connection to production system design and production relocation. The use of the characteristic part concept can also support the comprehensive planning needed when pronounced fluctuations in the market occur.

2. LITERATURE STUDY

To cope with the large variety of customer demands and with customization, companies could adopt a Group Technology (GT) approach for production [1, 2, 3]. When using the principles of GT the company group products with similar geometries, processes and functions together and connects these to specific machines and processes also called machine cells. There is no requirement that every product has to be handled in all machines within the cell. According to Asktin and Subramantan [4], GT make the production environment more economic and productive, with easier inventory control and reduction in material handling, work-in-process and throughput. The idea of the characteristic part is to use GT to group the correct products together and then do the comprehensive calculations. The concept of GT has been used before for calculating the economic lot size [5] and for scheduling the production to find the optimal set-up time [6].

A characteristic part can be compared in some respects with a complex part. A complex part is a detail composed of all the quality demand that occur in the group when GT is employed. In some cases the complex part is the most advanced product produced in the group and in some cases it is too complex to be genuine and only exists on a theoretical basis. The characteristic

part on the other hand can be seen as an average part of the product family regarding manufacturing performance. The reason for using a complex part is for planning a machine to be used when only small adjustments are needed in changing parts during production [7].

Asktin and Subramantan [4] describe a heuristic cost model for determining the manufacturing cost and maximizing the machine utilization when using product families and GT. The model takes the following costs into consideration; set-up costs, variable production costs, production-cycle inventory costs, work-in-process inventory costs, material handling costs and fixed machine costs. The major differences and similarities between the model presented by Asktin and Subramantan and the one employed in the present article are those shown in Table 1.

Table 1: Comparison of the two models

Askin and Subramantan	Presented model
Heuristic	Generic
Capacity the major consideration	Capacity the major consideration
Losses not included	Performance losses included at batch level
Time-based	Time-based
Yields the total manufacturing costs	Yields the total manufacturing costs and the part costs
	Take annual market demand and batch size in consideration

A lot of research work has been done regarding production planning were occupancy [9] alterative machine utilization [10,11] is a major factor affecting the final equipment setup. The degree of occupancy is an important but sometimes overlooked cost driver. Fluctuating market demand influences the ability to obtain a high degree of occupancy. The flexibility of introducing a new product increases the degree of occupancy, affecting the profit margins positively. It is of high importance to know the level of to what extent the machines are used in order to plan and calculate costs related to the manufacturing process. Therefor this article has a major focus on the degree of occupancy.

The basic concept of characteristic part is based on previous research in production performance and cost in discrete manufacturing system presented in [8] by J-E. Ståhl et al.

3. LIST OF SYMBOLS

Below are the different parameters used in the equations that are listed.

f_{N0}	Batch factor	-
h_{year}	Hours per year and shift	h/year
k	Costs per part	SEK/unit
k_A	Equipment costs	SEK/ unit
K_{AUH}	Maintenance of tools	SEK/batch
k_B	Material costs per part	SEK/ unit
$K_{b,ChP}$	Characteristic (Ch.) annual costs of producing a part	SEK
$K_{b,tot}$	Annual costs for producing a part	SEK
k_{ChP}	Ch. costs per part	SEK/unit
k_{Cp}	Hourly machine cost during production	SEK/h
k_{CS}	Hourly machine cost at downtimes and for adjustments	SEK/h
K_{CUH}	Costs of equipment maintenance	SEK/batch
k_D	Salary cost	SEK/h
K_{free}	Annual cost of free capacity	SEK
K_{GUH}	Costs of maintenance of material handling equipment	SEK/batch
K_{HL}	Handling and storage costs	SEK/batch
k_{mean}	Average costs per part	SEK/ unit
K_{RW}	Costs of reworking	SEK/batch
$K_{tot,ChP}$	Ch. total annual manufacturing costs	SEK
κ_c	Cost factor	-
MD	Market demand	unit
MD_{ChP}	Ch. market demand	unit
n	Number of complete shifts	-
N_0	Nominal batch size	unit
$N_{0,ChP}$	Ch. nominal batch size	unit
N_{0M}	Manufactured batch size	unit
$N_{0M,ChP}$	Ch. manufactured batch size	unit
$n_{b,ChP}$	Ch. number of batches per part	-
n_{line}	Number of equivalent machines	-
$n_{b,tot}$	Total batches manufactured	-
n_{op}	Number of operators during manufacturing	-
n_{pA}	Number of batches connected to a specific tool.	-
n_{part}	Number of different parts within a family	unit
p	Interest	-
PC_{ChP}	Ch. production capacity	unit/year
q_P	Relative rate reduction	-
$q_{P,ChP}$	Ch. rate of reduction	-
q_Q	Rejection rate	-
$q_{Q,ChP}$	Ch. rejection rate	-
q_S	Downtime proportion	-
$q_{S,ChP}$	Ch. downtime proportion	-
t_0	Nominal cycle time per part	min
t_p	Production time per part	min
$t_{p,ChP}$	Ch. production time per part	min
T_{free}	Free capacity time	h
$T_{free,b}$	time available for each batch	h
T_{pb}	Production time for a batch	h
$T_{pb,ChP}$	Ch. production time for one batch	h
$T_{pb,tot}$	Hours needed for production	h
T_p	Required production time	h
T_{plan}	Total paid and planned production time during a given period	h
$T_{ptot,ChP}$	Production time required for manufacturing the characteristic part	h
T_{su}	Time needed for adjustments	min
$T_{su,ChP}$	Ch. time needed for adjustments	min

U_{RP}	Utilization rate in the case of a reduced occupancy	-
x_p	Development factor: change in cycle time	-
$x_{p,su}$	Development factor: change in set-up time	-

4. METHOD

The aim of this article is to show that it is possible to use the characteristic part and still get accurate results compared to when calculating on all products produced. The comparison is done through use of mathematical simulations based on data from the Swedish industry. The calculation will take the following in consideration:

- Market demand MD for each of the different products produced in a production line.
- Batch size, N_0 and batch size compared to customer demand.
- Production capacity.
- Degree of occupancy in the production, U_{RB}.
- Differences in paid and planned production time, T_{plan}.

In selecting a paid and planned production time (T_{plan}) for a particular production line or production section in which some family of parts (j) is manufactured, it can sometimes be practical to compute the costs of a characteristic part. The concept of a characteristic part can be used in such contexts as the following:

- Computation of the production time per year needed T_{plan} for producing different parts or families of parts.
- Conducting comprehensive production analyses in connection with the planning of new production lines.
- Analysis of the degree of occupancy U_{RP} that takes place or is to be expected.
- Computation of the consequences of changes in demand.
- Computation of key performance indicators for different batches or different families of parts.

When setting up a new factory the analysis above is of high interest. It is important to know how much time that is needed in order to produce the number of part corresponding to the market demand. The aim is know the needed numbers of personnel and equipment based on the needed capacity in the new factory.

The article has the following structure; the first part provides a description of how the characterization is done and shows the equations and the parameters used for the characterization. After that comes a presentation of how to relate to batch size in comparison to market demand. Section 6 and 7 gives the degree of occupancy, capacity and cost calculation for determining the characteristic performance and cost for the manufacturing system and the parts it produce. Section 8 gives the results corresponding to the list above, based on the equations given in Section 5 to 7 and data collected from the Swedish manufacturing company. The article ends with conclusions and a shorter discussion.

5. CHARACTERISTIC PART

A characteristic part (index ChP) is a fictitious part seen as representative of all parts produced in terms of the demand MD_{ChP}, setup time $T_{su,ChP}$, cycle time $t_{0,ChP}$, average batch size $N_{0,ChP}$ and total number of batches $n_{b,tot}$ involved. Table 2 shows possible ranges for different characteristic data for different kind of parts used for creating the characteristic part. The characteristic data (see examples in Table 2) this requires is computed on the basis of average or weighted average values of by use of equation 1 – equation 13. The relationships involved that are taken up below apply under the assumption that the batch size N_0 for each part is constant. If the batch size for a given part varies, the computations are based on the average batch size. The characteristic annual demand MD_{ChP} for a given part is computed as the average of the demand for the part in question, one that belongs to a particular family of parts.

$$MD_{ChP} = \frac{\sum_{j=1}^{n_{part}} MD_j}{n_{part}} \quad (1)$$

where n_{part} is the number of different parts that the respective characteristic part includes.

The schematic configuration of the characteristic part is shown in Figure 1. A characteristic part can be used to present a product, a group of different parts, one product family or several product families, depending on the system. In this article the characteristic part represent a product family.
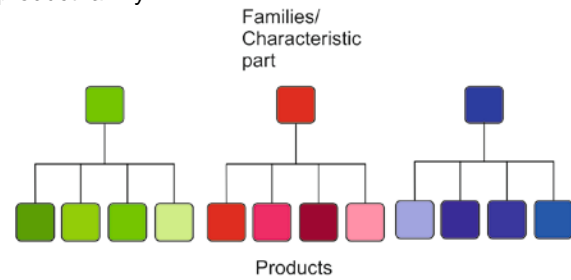
Figure 1: Structure of the characteristic part.

Table 2: Examples of data for various parts produced in a production line.

Part, $j = 1 - n_{part}$	Setup time, T_{su}	Cycle time, t_0	Batch size, N_0	Market demand, MD
1.	1.50	1.1	10	30
2.	2.50	2.2	15	60
3.	2.70	1.5	20	80
4.	3.10	2.1	23	70
5.	5.50	7.1	35	110
6.	1.00	0.5	25	125
7.	0.75	1.0	25	100
Calc. ChP	$T_{su,ChP}$	$t_{0,ChP}$	$\frac{1}{n_{part}} \cdot \sum_{j=1}^{n_{part}} N_{0j}$	$\frac{1}{n_{part}} \cdot \sum_{j=1}^{n_{part}} MD_j$

3.1. Characteristic production times

The characteristic setup time $T_{su,ChP}$ is weighted by the number of set-ups that occur for the part in question.

$$T_{su,ChP} = \frac{\sum_{j=1}^{n_{part}} T_{su,j} \cdot \frac{MD_j}{N_{0,j}}}{\sum_{j=1}^{n_{part}} \frac{MD_j}{N_{0,j}}} \quad (2)$$

The number of set-ups for a given part per year is computed as the product of and product specific annual demand MD_j and batches N_{0j}. The characteristic cycle time $t_{0,ChP}$ is weighted by the annual demand MD_j for the part in question using equation 3.

$$t_{0,ChP} = \frac{\sum_{j=1}^{n_{part}} MD_j \cdot t_{0,j}}{\sum_{j=1}^{n_{part}} MD_j} \quad (3)$$

3.2. Characteristic batch size

The characteristic batch size $N_{0,ChP}$ is computed as the average of the batch size N_{0j} for the respective part in the family to which it belongs.

$$N_{0,ChP} = \frac{\sum_{j=1}^{n_{part}} N_{0,j}}{n_{part}} \quad (4)$$

The total number of batches that are manufactured can be computed using equation 5.

$$n_{b,tot} = \frac{\sum_{j=1}^{n_{part}} MD_j}{\frac{\sum_{j=1}^{n_{part}} N_{0,j}}{n_{part}}} = \frac{\sum_{j=1}^{n_{part}} MD_j}{N_{0,ChP}} \quad (5)$$

3.3. Characteristic production capacity

The production time required $T_{ptot,ChP}$ for manufacturing a family of parts consisting of n_{part} different details can be computed using equation 6.

$$T_{plan} \geq T_{ptot,ChP} =$$

$$T_{su,ChP} \cdot n_{b,tot} + \frac{t_{0,ChP} \cdot MD_{ChP} \cdot n_{part}}{(1-q_{Q,ChP})(1-q_{S,ChP})(1-q_{P,ChP})} \approx$$

$$\sum_{j=1}^{n_{part}} \frac{MD_j \cdot T_{su,j}}{N_{0,j}} + \sum_{j=1}^{n_{part}} \frac{t_{0,j} \cdot MD_j}{(1-q_{Q,j})(1-q_{S,j})(1-q_{P,j})} \quad (6)$$

The production capacity for the characteristic part PC_{ChP} can be computed as:

$$PC_{ChP} = \frac{(T_{plan} - T_{su,ChP} \cdot n_{b,tot})(1-q_{Q,ChP})(1-q_{S,ChP})(1-q_{P,ChP})}{t_{0,ChP}} \quad (7)$$

The production capacity PC_{ChP} can also be obtained by computing the product of the total number of batches involved $n_{b,tot}$ and the characteristic batch size $N_{0,ChP}$.

$$PC_{ChP} = \frac{T_{Plan}}{T_{pb,ChP}} \cdot N_{0,ChP} = n_{b,tot} \cdot N_{0,ChP} \quad (8)$$

$$MD_{ChP} \cdot n_{part} = n_{b,tot} \cdot N_{0,ChP} \quad (9)$$

$$T_{pb,ChP} = \frac{T_{ptot,ChP}}{n_{b,tot}} \quad (10)$$

3.3. Batch size

An important decision to be made in series production of all types is that of batch size in light of the demand for the part or product in question. In some cases there is reason to distinguish between the batch size N_{0M} and the quantity of the product in question delivered to the customer N_0. The numerical relationship between N_{0M} and N_0 is expressed in terms of the batch factor f_{N0}, which can also be used in connection with describing the characteristic part.

$$f_{N0} = \frac{N_{0M}}{N_0} \qquad f_{N0} = \frac{N_{0M,ChP}}{N_{0,ChP}} \quad (11)$$

The number of parts per batch n_b and the total number of batches $n_{b,tot}$ can also be expressed as a function of the batch factor f_{N0} by use of equation 12.

$$n_b = \frac{MD}{f_{N0} \cdot N_0} = \frac{MD}{N_{0M}} \qquad n_b = \frac{MD_{ChP}}{f_{N0} \cdot N_{0,ChP}} \quad (12)$$

$$n_{b,tot} = \frac{MD_{ChP} \cdot n_{part}}{f_{N0} \cdot N_{0,ChP}} \quad (13)$$

6. DEGREE OF OCCUPANCY IN THE PRODUCTION SYSTEM

An increased degree of occupancy reduces equipment costs per part. For the needs that a given annual order volume represents to be met, a certain number of planned hours of production time are required. The cost model presented earlier [8,12,13] gives the part costs of a defined product and analysis how different parameters effect the final part costs. The previous cost model was designed for calculations considering a product or a small group of similar products, resulting in that the calculations having to be conducted for all the products in the production line. The cost model in its present version describes the economic consequences of failing to reach the level of planned production time needed in order to satisfy the demand that exist for a given part or family of parts.

Increasing the degree of occupancy of a particular production system in the manufacture of a given part reduces the part costs involved through the investment costs being distributed over a larger number of production hours (T_{plan}) than before.

The degree of occupancy indicates the extent to which a production time of given length, the costs of which are already determined in advance, is made use of. If one fails to utilize all of the capacity being paid for, this

results in an overcapacity also referred to as free capacity. From a production standpoint, this can be regarded as representing a downtime, even if the equipment is functioning just as it should. A certain amount of free capacity in the manufacturing system is often desirable nevertheless, through its enabling a smooth transition from one batch to another to take place. An degree of occupancy U_{RP} of about 96 – 97 % is thus often advantageous [13] based on interview with Swedish industry.

4.1. Degree of occupancy and capacity

The degree of degree of occupancy U_{RP} of the manufacturing facilities this represents can be computed using equation 14. The selection of paid and planned production time T_{plan} here usually takes place stepwise in the form of computing the number of complete shifts (n) times the number of hours per year and per shift that are involved (n·h$_{year}$) [8, 12, 13].

$$U_{RP} = \frac{T_{pb,tot}}{T_{plan}} = \frac{T_{plan} - T_{free}}{T_{plan}} = 1 - \frac{T_{free}}{T_{plan}} \qquad (14)$$

The free capacity of the manufacturing facilities can be expressed in terms of the degree of degree of occupancy of them, using equation 15 below [8, 12, 13].

$$T_{free} = \frac{1 - U_{RP}}{U_{RP}} \cdot T_{plan} \qquad (15)$$

If a company shows full degree of occupancy of its equipment four of five working days a week and no degree of occupancy of it on the 5th day, U_{RP} is computed as (5-1)/5 = 0.80, the degree of degree of occupancy of the equipment thus being 80 %. If the time available through overcapacity is distributed equally across all of the batches in relation to the production time T_{pb} involved, the additional time thus available for each batch $T_{free,b}$ can be computed as follows [8, 12, 13]:

$$T_{free,b} = \frac{1 - U_{RP}}{U_{RP}} \cdot T_{pb} \qquad (16)$$

The computational approach this represents results in the overcapacity, as computed by use of equation 17 being distributed evenly over the number of production hours involved. The fixed costs for overcapacity are primarily those of salary costs $n_{op} \cdot k_D$ and machine-time costs k_{CS} [8, 12, 13].

$$k_{free} = (n_{op} \cdot k_D + k_{CS}) \cdot \frac{1 - U_{RP}}{U_{RP}} \cdot T_{pb} \qquad (17)$$

By complementing the previously reported cost equation [8,12,13] with the costs of the overcapacity enables account to be taken in equation 18 of the effects of the degree of degree of occupancy on the part costs.

$$k_i = \frac{k_A}{N_0}\left[\frac{1}{n_{pA}}\right]_a + \frac{k_B}{N_0}\left[\frac{N_0}{1-q_{Qi}}\right]_b + \frac{\kappa_C \cdot k_{CP}}{60 N_0}\left[\frac{x_{pi}t_{0i}N_0}{1-q_{Qi}}\right]_{c1} +$$

$$\frac{\kappa_C \cdot k_{CS}}{60 N_0}\left[\frac{x_{pi}t_{0i}N_0}{1-q_{Qi}} \cdot \frac{q_{Si}}{1-q_{Si}} + x_{sui}T_{sui} + \frac{1-U_{RP}}{U_{RP}}T_{Pb}\right]_{c2} +$$

$$\frac{\kappa_D \cdot k_D}{60 N_0}\left[\frac{x_{pi}t_{0i}N_0}{1-q_{Qi}} \cdot \left(1+\frac{q_{Si}}{1-q_{Si}}\right) + x_{sui}T_{sui} + \frac{1-U_{RP}}{U_{RP}}T_{Pb}\right]_d +$$

$$\frac{1}{N_0}\left[K_{AUH} + K_{CUH} + K_{GUH}\right]_e + \frac{1}{N_0}\left[K_{HL}\right]_g + \frac{1}{N_0}\left[K_{RW}\right]_h \qquad (18)$$

4.2. Time planning

The time needed to manufacture a batch can be computed as follows by use of equation 19 [8, 12, 13].

$$T_{pb} = T_{su} + \frac{N_0 \cdot t_0}{(1-q_Q)(1-q_S)(1-q_P)} \qquad (19)$$

A particular level of annual market demand (MD) for a *given part* requires, for the manufacturing system involved, some specific number of production hours $T_{pb,tot}$, which can be computed by use of equation 20.

$$T_{pb,tot} = T_{su} \cdot \frac{MD}{N_0} + \frac{t_0 \cdot MD}{(1-q_Q)(1-q_S)(1-q_P)} \qquad (20)$$

The ratio of the demand for the part MD to the average batch size N_0 gives the number of set-ups and number of batches per part, n_b that would take place. Each of the parameters employed in the equation represents the average value of it during a one-year period.

The total time per year for use of a given production line or machine that would be needed for producing a particular part in the quantity foreseen can be computed using equation 21.

$$T_{plan} \geq T_{pb,tot} = \frac{T_{su} \cdot \dfrac{MD}{N_0} + \dfrac{t_0 \cdot MD}{(1-q_Q)(1-q_S)(1-q_P)}}{U_{RP} \cdot 60} \qquad (21)$$

4.3. Degree of occupancy

The degree of degree of occupancy U_{RP} can be expressed, in line with equation 14 presented earlier, on the basis characteristic data with use of equation 22. The parameter n_{line} indicates the number of machines or production lines similar to one another in their capabilities that can be used to manufacture the characteristic part in question.

$$U_{RP} = \frac{n_{part}}{n_{line}} \cdot \frac{T_{pb,tot}}{T_{plan}} \qquad (22)$$

$$T_{pb,tot} = T_{pb,tot}(N_{0,ChP}, f_{N0}, q_{Q,ChP}, q_{S,ChP}, q_{P,ChP}, T_{su,ChP}, t_{0,ChP}, MD_{ChP})$$

7. CHARACTERISTIC PART COST

If account is to be taken of the reduction in the degree of degree of occupancy involved, the costs of producing a part can be computed by use of equations presented

earlier according in articles equation 18. The relationships in question can be modified so as to be appropriate for describing the costs $K_{b,j}$ of manufacturing a particular annual volume MD_j of a given part j. The paid and planned production time T_{plan} this requires depends upon the annual volume, $\Sigma\ MD_j$, and the characteristic batch size $N_{0M,ChP}$ selected, the conditions in all other respects being constant. The number of set-ups needed for the manufacture of a particular number of batches n_b can be computed by use of equation 12, the production time required being given by the product of the annual demand MD_j and the cycle time $t_{0,j}$.

$$K_{b,j} = \frac{k_{B,j} \cdot MD_j}{1 - q_{Q,j}} + \frac{k_{CP}(p,n,T_{plan}) \cdot t_{0,j} \cdot MD_j}{(1 - q_{Q,j})(1 - q_{P,j})} +$$

$$\frac{k_{CS}(p,n,T_{plan}) \cdot t_{0,j} \cdot MD_j}{(1 - q_{Q,j})(1 - q_{P,j})} \cdot \frac{q_{S,j}}{1 - q_{S,j}} + \frac{k_{CS}(p,n,T_{plan}) \cdot T_{su,j} \cdot MD_j}{N_{0,j} \cdot f_{N0}} + \quad (23)$$

$$\frac{k_D \cdot n_{op} \cdot t_{0,j} \cdot MD_j}{(1 - q_{Q,j})(1 - q_{P,j})(1 - q_{S,j})} + \frac{k_D \cdot n_{op} \cdot T_{su,j} \cdot MD}{N_{0,j} \cdot f_{N0}}$$

The equipment costs k_{CP} and k_{CS} are a function in part of the interest rate p, the number of years of operation n planned and the paid and planned production time T_{plan} for the year in question. If $T_{plan} > T_{pb,tot}$, equation 23 needs to be complemented by inclusion of the degree of degree of occupancy U_{RP}, based on principles applying to equation 17 reported on earlier. The annual costs, based on the free capacity available for the manufacture of a given part j, can be computed as

$$K_{free,j} = (n_{op} \cdot k_D + k_{CS}) \cdot \frac{1 - U_{RP}}{U_{RP}} \cdot T_{pb,tot} \quad (24)$$

The costs for the manufacture of a particular part can be computed by dividing $K_{b,j}$ by the annual demand MD for the part in question.

$$k_j(N_0, f_{N0}, q_Q, q_S, q_P, T_{su}, t_0, p, n, T_{plan}, MD)_j =$$

$$\frac{K_{b,j}(N_0, f_{N0}, q_Q, q_S, q_P, T_{su}, t_0, p, n, T_{plan}, MD)_j}{MD_j} \quad (25)$$

The annual costs $K_{b,tot}$ of producing all of the parts involved, i.e. the entire family of parts in the production line in question, can be computed by use of equation 26.

$$K_{b,tot} = \sum_{j=1}^{n_{part}} K_{b,j} \quad (26)$$

The characteristic annual costs $K_{b,ChP}$ of a given part can be computed by insertion of the characteristic data that applies to it ($N_{0,ChP}$, $T_{su,ChP}$, $t_{0,ChP}$, $MD_{ChP, etc.}$) into equation 23.

$$k_{ChP} = k(N_{0,ChP}, f_{N_0}, q_{Q,ChP}, q_{S,ChP}, q_{P,ChP},$$
$$T_{su,ChP}, t_{0,Chp}, p, n, T_{plan}, MD_{ChP}) \quad (27)$$

The total annual costs of the parts in their entirety, $K_{tot,ChP}$, can be obtained by multiplication of this by n_{part}, the number of parts involved.

$$K_{tot,ChP} = K_{b,ChP} \cdot n_{part} =$$

$$k_{ChP} \cdot MD_{ChP} \cdot n_{part} \approx \sum_{j=0}^{j=n_{part}} \sum_{i=0}^{i=n_b} k_{j,i} \cdot N_{0M,i} \quad (28)$$

The costs of a characteristic part, k_{ChP}, can be derived from equation 28 by use of equation 29.

$$k_{ChP} = \frac{K_{b,ChP}}{MD_{ChP}} = \frac{K_{tot,ChP}}{MD_{ChP} \cdot n_{part}} \quad (29)$$

8. RESULT

Using the equation presented here and data collected from a Swedish manufacturing company regarding batch sizes, cycle times, performance parameters, set-up times and annual market demands for different products, different relationships between parameters have been investigated. The figures in this section show how it is possible to do analysis regarding production planning when doing investment in a new factory using the characteristic part. A comparison between the characteristic manufacturing cost and the manufacturing cost based on the different products are made.

8.1 Batch size

The use of equation 6 is exemplified in Figure 2, in which the total batch time T_{ptot} is described as a function of the batch factor f_{N0}, with use of the downtime rate q_S as the parameter. In the diagram, the batch factor $f_{N0} = 1.0$ is marked by a vertical line. For $f_{N0} < 1.0$ the production time required increases in relation to the nominal batch size ($N_0 = N_{0M}$), whereas for $f_{N0} > 1.0$ it decreases. In the examples the total production time is shown as a function of the batch factor f_{N0} for each of 3 different downtime rates q_S, as based on the characteristic part in question (solid lines), and the sum of the production times for the parts as a whole, reported by means of the discrete symbols that are shown, where $n_{part} \approx 45$.
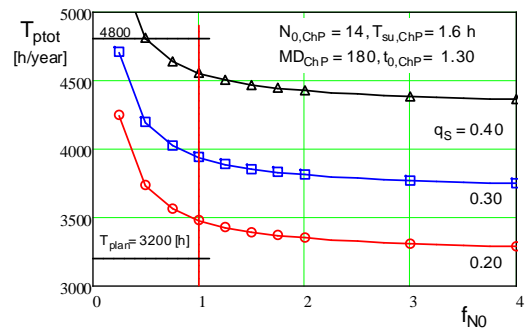

Figure 2: An example of the computed total production time, shown as a function of the batch f_{N0} for each of 3 different downtime rates q_S.

8.2 Degree of occupancy analysis

The relationship between the part costs k (equation 18) and the degree of degree of occupancy U_{RP} is shown in Figure 3 for three different levels of paid and planned production time per year T_{plan}. The part cost is highly depending on to what extend the machines are utilized.
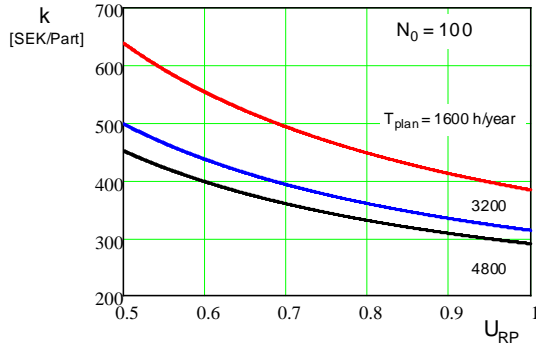
Figure 3: Examples of part costs k as a function of the degree of degree of occupancy U_{RP} for different paid production time levels per year T_{plan}.

Use of this equation 21 is exemplified in Figure 4, in which the paid and planned production time T_{plan} is presented as a function of the annual demand MD, both in the case of full degree of occupancy, $U_{RP} = 1.0$, and the degree of occupancy of 0.9 and 0.8.
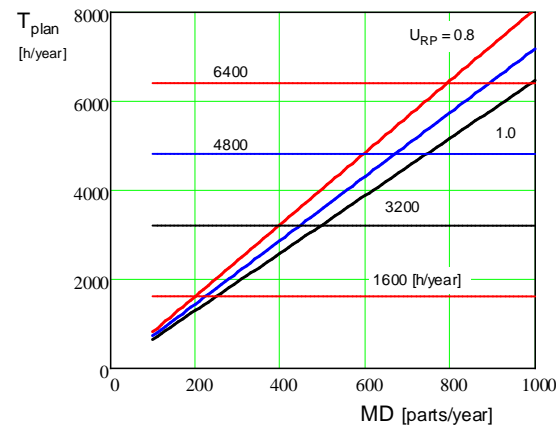

Figure 4: Examples of paid and planned production time T_{plan} shown as a function of demand MD.

Figure 3 and Figure 4 shows how important the knowledge of the degree of occupancy is. The level affects both the part cost and the needed hour to be able to deliver the correct numbers of parts responding to the market demand.

8.3 Time planning

Figure 5 and Figure 6 exemplify the relationships between different production parameters for a family of parts. For the case in question, one can note that the setup time T_{su} increases with the cycle time t_0 and that an increase in the annual demand MD tends to result in an increase in the nominal batch size N0 selected. In all four cases the location of the characteristic part is marked with a blue square. The figures give the relationship between the characteristic parts and the parts it represent, showing that the characteristic part is an average part regarding production parameters.
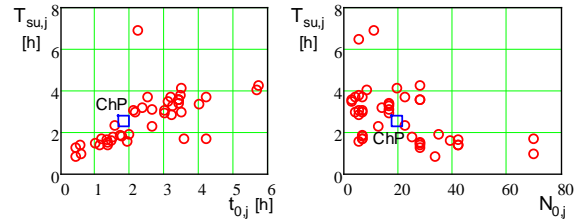

Figure 5: Examples of how the setup time $T_{su,j}$ can vary for a family of parts, with different values for the cycle time t_{0j} (left) and for the nominal batch size $N_{0,j}$ (right).
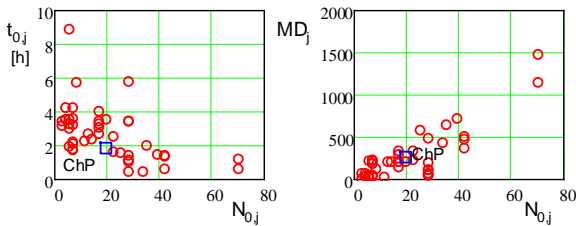
Figure 6: Examples of how the relationship between the cycle time $t_{0,j}$ and the nominal batch size $N_{0,j}$ (left) and between the annual demand MD_j and the nominal batch size $N_{0,j}$ (right) can vary within a family of parts.

The use of equation 22 is exemplified in Figure 7 for three different levels of the paid and planned production time, T_{plan} = 3200, 4800 and 6400 h/year, respectively. A degree of degree of occupancy of $U_{RP} > 1.0$ means that overtime is needed to achieve the production goals that have been set. This kind of analysis could be very useful when estimating the production capacity.
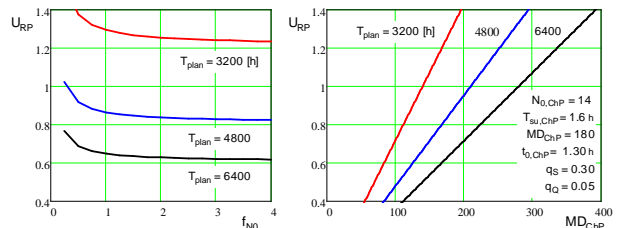
Figure 7: Examples of the degree of degree of occupancy U_{RP}, shown as a function of the batch factor f_{N0} (left) and of the demand MD_{ChP} (right).

8.4 Characteristic manufacturing cost analysis

An example of computations of the distribution both of the part costs k_j (left) and of the total annual costs $K_{b,j}$ (right) for a family of some 40 different parts is presented in Figure 8. The characteristic part costs k_{ChP} and the characteristic annual costs $k_{b,ChP}$ are shown by the vertical columns.
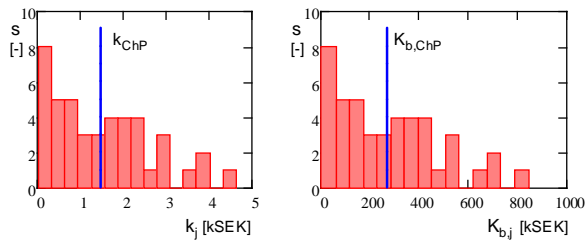
**Figure 8: Examples of the statistical distribution of the part costs k_j and of the total manufacturing costs per year $K_{b,j}$, as well as of the characteristic costs involved.**

On the basis of the values used in this case, the total sum of the characteristic part costs multiplied by the number of parts involved is 11.99 MSEK and the total manufacturing costs for all of the different products is 12.00 MSEK. The error in using a characteristic part in this case is less than 0.1%.

Figure 9 presents examples of the part costs, shown as a function of the batch factor f_{N0}, computed by use of equation 25, the discrete symbols in their entirety representing all of the parts involved, the continuous lines showing the results of computations based on the characteristic data. The computations were carried out here for two different levels of the downtime rate q_S. By increasing f_{N0} the total set-up time decreases making the part cost decrees.
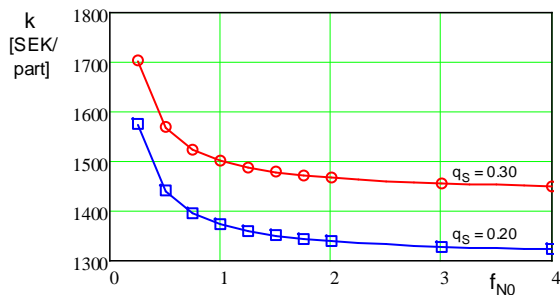
Figure 9: Examples of the part costs k, shown as a function of the batch factor f_{N0}, for two different downtime rates q_S.

Under conditions in which both the size of the series of parts N_{0M} that is manufactured and the total demand for the parts $MD_{tot} = \Sigma\ MD$ are constant, the part costs k_j are dependent in a straightforward way on the annual demand for the parts in question MD_j. An increase in the total demand leads to an increase in the length of time altogether that the equipment is made use of per year. This provides the basis for computations regarding the degree of occupancy of the equipment U_{RP}. In general terms, there is also a reduction in equipment costs as use of the equipment increases, through the basic investment in the equipment being distributed over a greater number of production hours. Figure 10 exemplifies changes that occur in the characteristic part costs as a function of the level the annual characteristic demand MD_{ChP} for the parts in question. The discontinuities in costs that are evident in

the figure can be explained in terms of the assumed length of the intervals between successive renovations of the equipment when the production time that is planned being allowed to vary.
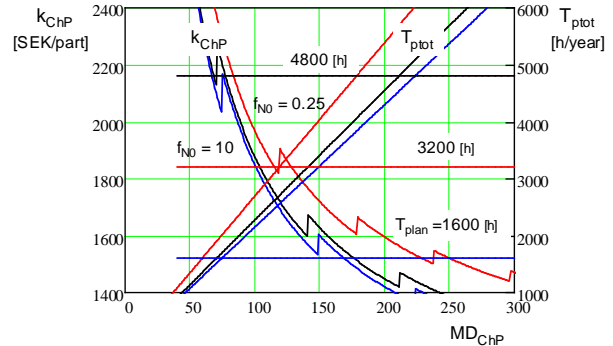
Figure 10: Examples of the characteristic part costs k_{ChP}, shown as a function of the annual characteristic demand MD_{ChP}, for f_{N0} = 0.25, 1.0 and 10, respectively, together with examples of the total production time needed for producing the family of details in question in its entirety, T_{ptot}, for f_{N0} = 0.25, 1.0 and 10, respectively and for values of the planned production time involving 1, 2 and 3 work shifts per day, the latter shown by the horizontal lines.

The y-scale located at the right in Figure 10 indicates the total production time T_{ptot} needed per year, this providing a basis for planning of the production time T_{plan} required, in line with equation 21. The effects of the batch factor f_{N0} on the total production time needed in the case at hand are shown in the figure. Figure 11, in turn, exemplifies how the characteristic part cost k_{ChP} can vary under conditions in which the paid and planned production time is constant. When this is the case, the degree of occupancy U_{RP} increases with the demand MD_{ChP} since if the degree of occupancy is reduced, for example, a part of the free time is added to the batch time.

Values of U_{RP} somewhat larger than 1.0 are often dealt with as involving overtime, due to the equipment costs being distributed then across a greater number of parts. This effect is illustrated in Figure 11 (the red curve). If, as is frequently the case, no account is taken, in computing the machine costs here, of the increase in machine costs that occurs under such circumstances, the part costs appear to remain constant when the level of the demand increases (the blue horizontal line). In the case at hand, no account was taken of the extra salary costs that came about when overtime was involved.
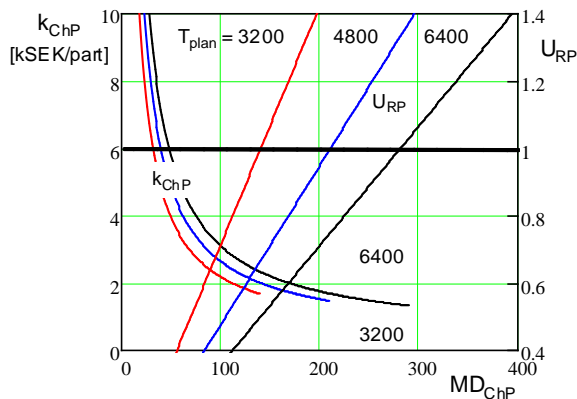
Figure 11: Examples of the part costs k_{ChP} and U_{RP}, shown as a function of the demand MD_{ChP}, for each of three different levels of paid and planned production time, T_{plan} = 3200 h (red), 4800 h (blue) och 6400 h (black).

Reductions in demand MD affect part costs negatively, as shown in Figure 12. The effects of reduced demand can be analyzed by use of cost derivatives, as described in [8,12,13]. A change in demand of 10 %, for example, would tend to affect the manufacture of all or virtually all parts and families of parts. It can be practical under such conditions to base analyses of the situation on characteristic parts.
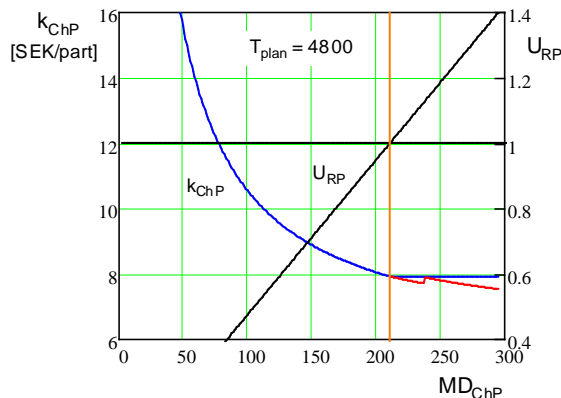
Figure 12: Examples of the part costs k_{ChP}, shown as a function of the demand, MD_{ChP}, for $U_{RP} > 1.0$, both with (the red curve) and without (the blue horizontal line) adjustment for the added machine-time costs (k_{CP} and k_{CS}) caused by the increase in total production time.

9. CONCLUSION

In industry it is usual to make calculations and estimations in connection with production design and planning on one or some few existing products representing the product range. With use of the characteristic part it is possible to take all products into consideration. Figure 2, 5, 6, 8, 9 demonstrate how calculations using the characteristic part relate to the product range it represents. It has been shown here that it is possible to use a characteristic part when making capacity estimates

and cost calculations. In Figure 3, 4, 7, 10-12 ways of analysing the data are shown. The simulations can be used in order to analyse the needed production hours and how the batch size and market demand affecting the part cost, giving the company information to use when making decisions on investment. However the model is based on production data that could be difficult to collect if the company in question possesses no adequate production monitoring systems and is unable to estimate the specific production conditions to each part. Any type of capacity calculations or estimates not using this kind of performance data is not likely to be correct.

There are both global and characteristic parameters that could be used in calculations. In the present case the number of parts n_{part}, the number of batches of each part n_b, and the total number of batches $n_{b,tot}$ are global, meaning it is not possible to manipulate the numbers and still get an adequate result.

Figure 2 illustrates the fact that the characteristic part (with its index ChP) can be used under appropriate conditions for describing the total production time required for each of the different parts. When rather large changes occur, such as in the relationship of market demand MD_j and batch size $N_{0,j}$ to one another, there tend to be rather large differences between the results of computations pertaining to the characteristic part and those pertaining to each and every part. The use of a characteristic part in this article is based on the fact that all the parts involved belong to the same family and that the same machine and the same operations can be used in machining all of them.

10. DISCUSSION

There has been a study of the economically optimal automation level [14], relating to this its representing a further development of the model presented in [8, 12, 13]. It is possible to combine the model there with the one presented in the present paper. This makes it possible to combine calculations of the optimal automation level with that of a characteristic part, making the planning of the production system more efficient. A situation when this kind of investigation could be very useful is when a company analyse different alternatives for relocating manufacturing sites. With the presented calculations a company would be able to do an in depth analysis of the needed capacity and final manufacturing costs based on each alternative's special condition. This makes it possible to compare different system both old and new ones, which is necessary in order to make a well based decision. This is in line with Park´s and Son´s statement. "A decision to install a new manufacturing system requires a comparison of the manufacturing performance of the old and new systems" [15, p. 2].

Future work could aim at construct a model for calculating the optimal batch size, on the basis of the characteristic part. A basic approach that could be taken here has been reported in [16], by J-E. Ståhl.

11. ACKNOWLEDGMENTS

12. REFERENCES

[1] Jianxion Jiao and Mitchell M. Tseng (1999) *A methodology of developing product family architecture for mass customization*, Journal of Intelligent Manufacturing vol. 10 p. 3-20

2] M. T. Martinez, J. Favrel and P. Ghodous (2000) *Product Family manufacturing Plan Generation and Classification*, Concurrent Engineering 8:12.

[3] Mosier C., Taube L., (1985) The Facets of Group Technology and Their Impacts on Implementation A State-of-the-Art Survey, International Journal of management Science, vol. 13, no 5, p. 381-391

[4] Roland G. Asktin, Subramantan P. Subramantan, (1987) *A cost-based heuristic for group technology configuration*, International Journal of Production Research volume 25 no. 1, p. 101-113.

[5] Boucher, T.O (1984) Lot sizing in group technology production systems, International Journal of Production Research, vol. 22, issue 1, p. 85-93.

[6] FC Foo, JG Wager (1983) Set-up times in cyclic and acyclic grouptechnology scheduling systems, International journal of production research, Vol. 21 no. 1, p. 63-73.

[7] Kullberg Gunnar, Eriksson Sven-Åke, Johansson Dan, Lumsden Kenth, (1976), *Samordnad Datorstödd Produktion – verkstans industrins framtid*, Ingenjörsförlaget AB, Stockholm (Swedish).

[8] Ståhl J-E, Andersson C., Jönsson M., (2007) *A basic economic model for judging production development,* SPS Gothenburg, Division of Production and Materials Engineering, Lund University.

[9] Foster George, Gupta Mahendra (1990) *Manufacturing overhead cost driver analysis* Journal of Accounting and Economics vol. 12 no. 1-3 p. 309-337

[10] Montazeri M, van Wassenhove L&N., (1990) *Analysis of scheduling rules for an FMS* International Journal of Production Research, vol. 28 no. 4 p. 785-802

[11] Vander Veen David J., Jordan William, (1989) *Analyzing trade-off between machine investment and utilization*, Management science vol. 35, no. 10, p. 1215-1226

[12] Jönsson M. (2012) *Cost-conscious manufacturing – Models and methods for analyzing present and future performance from a cost perspective*, Division of Production and Materials Engineering, Lund University

[13] Ståhl Jan-Eric (2009) *Industriella Tillverkningssystem del II*, Industriell Produktion (Swedish).

[14] Park Chan S. and Son Young K. (1988) *An Economic Evaluation Model for Advanced Manufacturing Systems*, The Engineering Economist: A Journal Devoted to the Problems of Capital Investment, vol 34, no. 1 p. 1-26

[15] Windmark Christina, Gabrielson Per, Andersson Carin, Ståhl Jan-Eric (2012) *A Cost Model for Determining an Optimal Automation Level in Discrete Batch Manufacturing*, The 45th CIRP Conference on Manufacturing systems.

[16] Ståhl J-E. (2012), *NEXT STEP in Cost-based Sustainable Production Development – Cases from different production operations*, International Conference on Advances in Manufacturing and Materials Engineering (ICAMME 2012) Kuala Lumpur: 3-5 July.