Shop floor design

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Chapter 2

Layout and investments

DECISION SUPPORT FRAMEWORK FOR THE SELECTION OF A MANUFACTURING LAYOUT[1]

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ABSTRACT

One of the most important design decisions in a firm is the choice for a manufacturing layout. This article shows which aspects have to be taken into account and suggests a systematic method for the decision problem. The method can be seen as a decision support framework, which links the various aspects. The framework is based on the AHP (Analytic Hierarchy Process) approach. A case study, concerning a Dutch firm, illustrates the applicability of the framework in a practical instance. Important advantages of applying the framework are: (1) the ability to decompose the complex decision problem in smaller problems, (2) the possibility of an efficient and effective employee participation, and (3) the detailed assessment of the selected layout alternative, which helps to define further improvement actions.

1. Introduction

The layout of a firm concerns the physical grouping of machines and workers. There are basically two different design philosophies with respect to the layout. In a product-oriented design philosophy, machines and workers are grouped according to manufacturing needs of product types. A group of machines and workers is responsible for the complete manufacturing of (a set of) product types. The various groups in a product layout are relatively independent from each other. In a process-oriented design philosophy, machines and workers are grouped according the various functions needed to perform all product types. The functionally based groups are highly dependent on each other. Products flow from group to group. Figure 1 gives a simplified example of a situation in which a choice has to be made between a product layout and a process layout. The products in this example move between the processes, or machines, A and B. It is possible to design product-oriented groups (AAB and ABB) or process-oriented groups (AAA and BBB).

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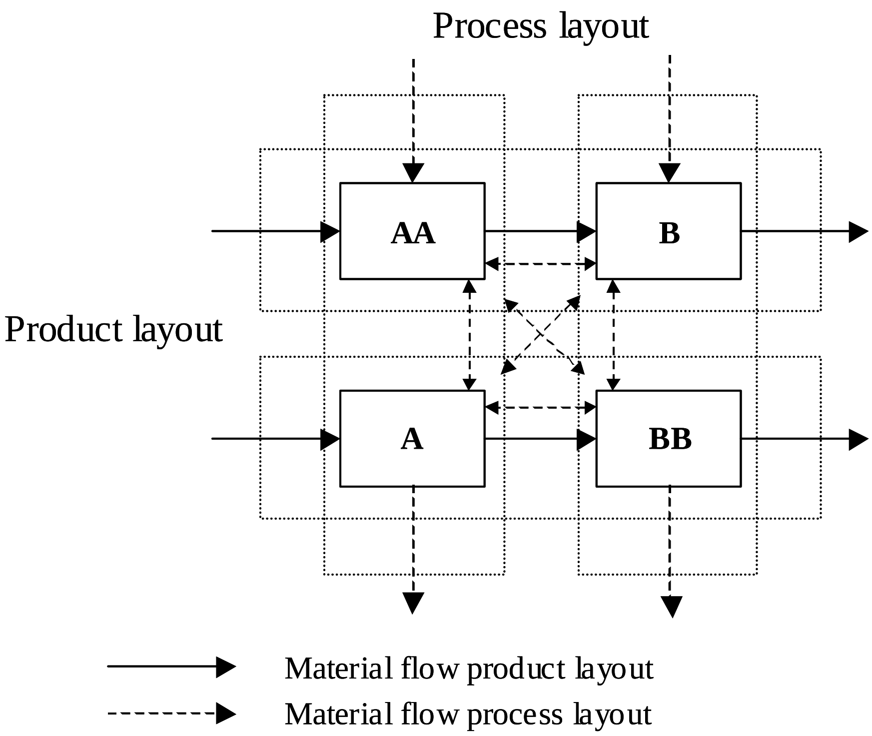

Figure 1. Product- versus process layout

The choice between a product- and a process-oriented layout is, many times, not an obvious decision. Case studies and survey articles (see e.g. Wemmerlöv and Hyer 1989, Burbidge 1992) illustrate the enormous advantages of the introduction of a product-oriented, cellular manufacturing layout (CML). Other case studies indicate that several firms move from a cellular manufacturing layout towards a process-oriented, functional layout (FL) (see e.g. Slomp 1998, Molleman *et al.* 2002). Numerous simulation studies have been performed in order to compare the performance of a CML and a FL in various situations (for an overview, see Johnson and Wemmerlöv 1996). These studies indicate important factors, which have to play a role in the layout choice. Johnson and Wemmerlöv (1996), however, state that the simulation studies cannot assist practitioners in making specific choices between existing layouts and alternative cell systems. They indicate various mismatches between the model world and reality and suggest that decisions to change the existing layout should be made on a case-by-case basis for each potential cell application. Reviews of simulation- empirical- and analytical studies comparing functional with cellular manufacturing layouts can be found in Shambu *et al.* (1996) and Agarwal and Sarkis (1998).

This paper presents a general decision support framework for the selection of a manufacturing layout. The framework is based on the AHP (Analytic Hierarchy Process) approach (Saaty, 1980). This approach is useful in multi-criteria situations where intuitive, qualitative and quantitative aspects play a role. The approach includes a hierarchical decomposition of the decision problem and a further decomposition of each decision level into pairwise comparisons of decision elements. Next, the "eigenvalue" method is used to estimate the relative weights of the decision elements. For a further explanation of the AHP method, we refer to Saaty (1980) or Zahedi (1986). The latter gives a brief explanation of the method and addresses some of the major extensions and criticism of the method. The AHP-approach is used extensively in the area of Operations Management. Davis and Williams (1994) use AHP to select a simulation software package. Labib *et al.* (1998) select maintenance rules. Barbarosoglu and Yazgac (1997) apply AHP to select the best supplier. Arbel and Seidmann (1984), Mohanty and Venkataraman (1993), Shang and Sueyoshi (1995), and Albayrakoglu (1996) use AHP to assess investment alternatives. Abdi and Labib (2003) use an AHP model to support management's strategies on planning and (re)designing manufacturing systems over their planning horizons. Our paper concerns the selection of a manufacturing layout and illustrates the applicability of AHP for a practical situation.

In section 2 of this paper, we present several performance objectives and discuss how the basic layout types influence these objectives. Various aspects of layouts will impact the manufacturing performance. The performance objectives and the various aspects are presented in the form of a decision hierarchy, according the AHP approach. Section 3 describes the way in which the decision hierarchy can be used to solve the decision problem. In this section, we further specify our AHP approach. Section 4 presents a case study. This study indicates the generic value of the decision hierarchy, presented in section 2. Finally, we reflect on the AHP methodology and draw conclusions in section 5.

2. Performance objectives

An essential condition in the selection of a layout is the ability of decision makers to link the strengths and weaknesses of each layout alternative with the market demands, or performance objectives, with which the firm has to deal. Slack *et al.* (2001) distinguish five major performance objectives: price, quality, speed, flexibility, and dependability. The flexibility objective can be further split in product/service flexibility, mix flexibility and volume/demand flexibility. These objectives have to play an essential role in the selection of a manufacturing layout. We have added the objective "quality of labour" to the set of objectives. This criterion is especially important in environments where labour is scarce. In the next subsections, we link the various performance objectives with aspects of the manufacturing layout. We will refer to the process- and product layout, as depicted in Figure 1, in the discussion of the various aspects. Important words in the next subsections are written in italics. This means that these words are elements of the summarizing figures and/or the summarizing table 1.

2.1. Price

From the perspective of a production manager, the price of a product has to be related to the manufacturing costs. A reduction of the manufacturing costs can be a reason to lower the price of products. Elements of the manufacturing costs are *equipment costs*, *personnel costs*, *material costs* and *inventory costs*. Several aspects of a manufacturing layout will have impact on these costs (see Figure 2). More *machines and tools* may be needed in a product-oriented cell layout in order to create independent, autonomous groups of workers and machines. A survey of 32 U.S. firms involved with cellular manufacturing, reported in Wemmerlöv and Hyer (1989), showed that new equipment and machine duplication was a major expense category for cell implementation. Specialization in a process layout may lead to a higher *production speed*, which may reduce equipment and personnel costs. On the other hand, *setup times* are usually lower in a product layout (see e.g. Flynn and Jacobs 1986, Wemmerlöv and Hyer 1989, Wemmerlöv and Johnson 1997) and reduce equipment and personnel costs in this type of layout. Furthermore, less *transport equipment* is usually required in a product layout because of the shorter transport distances. All these aspects have to be considered in order to estimate the impact on the equipment costs by the various types of layout. Personnel costs are, as mentioned above, related to the factors that have impact on equipment costs. Personnel costs in a product layout can also be lower than in a process layout because of a reduced need of *middle managers*. Farrington and Nazemetz (1998) indicate, by means of simulation studies, that a cellular system is easier to manage than a job shop. Empirical studies show the reduced need for indirect labour where firms convert from a functional layout to a cellular layout (Wemmerlöv and Hyer 1989, Burbidge 1992, Slomp *et al.* 1993). On the other hand, the *salaries* in a product-oriented layout may be higher, since more tasks are, probably, decentralized to the autonomous groups and workers need higher qualifications. These aspects of personnel costs should be taken into account when assessing the various layout alternatives. Material costs can be influenced by the layout through the effect of layout choice on *waste*. It is conceivable that workers in a product layout feel more responsibility for the reduction of the amount of waste. On the other hand, more advanced equipment and more specialized workers in a process layout may also reduce waste. Inventory costs can be lower in a product layout because of the smaller *lot sizes* that can be produced efficiently in this type of layout. This efficiency is due to the smaller setup times in a product layout. Further, *flow times* in a product layout are often lower than in a process layout and this reduces the work-in-process inventory. Reductions in throughput time and work-in-process inventory have been reported in surveys of plants that implemented cellular manufacturing (Wemmerlöv and Hyer 1989, Wemmerlöv and Johnson 1997).

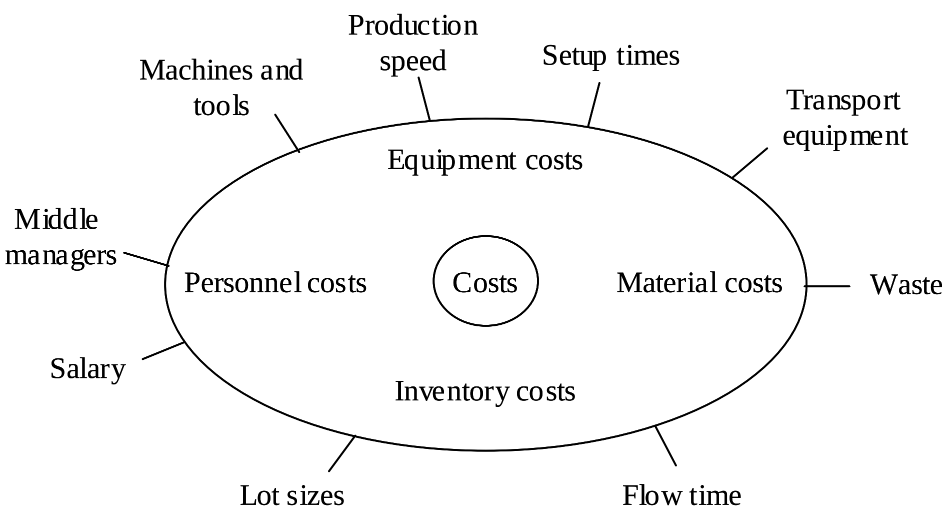

Figure 2. Impact of layout on manufacturing costs

2.2. Quality

The type of manufacturing layout can also influence the quality of products. In a process layout, workers are probably more *specialized* and will provide for a better product quality. In a product layout, experts are divided among the various groups and the best worker will not always be assigned to the most complex task. Furthermore, a process layout may apply more *advanced machinery*, which has a positive effect on the quality of products. On the other hand, the *control loops* in a product layout are short and may, in comparison to a process layout, have a positive effect on product quality.

2.3. Speed

Speed concerns the time needed to fulfil the needs of internal or external customers. The throughput time of an average job is a measure for speed. This throughput time consists of *transport*, *machining* and *waiting times* (see figure 3).

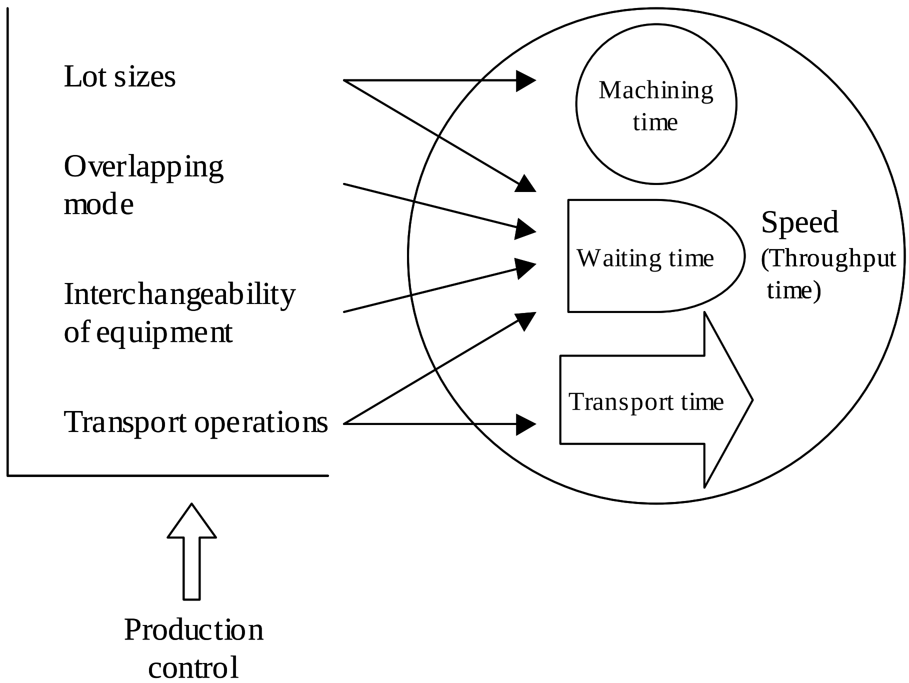

Figure 3. Impact of layout on speed

A product layout usually involves less *transport operations* for manufacturing jobs because of the proximity of the required machines. It may also be possible to produce in an *overlapping mode* (Shafer and Charnes 1993, Shafer and Meredith 1993), which reduces the “lot size” waiting times. This is more easily realized in a product layout. Problematic for the waiting times in a product layout may be the lack of pooling synergy (Suresh and Meredith 1994). Identical machines are probably split over more than one group and the *interchangeability of equipment* is less than in a process layout. The throughput time will also be influenced by the *lot sizes.* Reduced setup time, which can be realized in a CM environment, may make smaller lot sizes acceptable. This may have a positive impact on the throughput time (Suresh, 1991). *Production control*, finally, plays an important role in the ability to realize short throughput times. An inflexible control system, for instance, may frustrate the production in an overlapping mode. When assessing the effect of different manufacturing layouts on speed, it is important to consider the requirements with respect to the production control system.

2.4. Flexibility

As mentioned earlier, the flexibility objective can be further split in product/service flexibility, mix flexibility and volume/demand flexibility (Slack *et al.* 2001). The importance of these types of flexibility for a particular instance may differ substantially. Therefore, these types of flexibility have to be seen as different performance objectives. Flexibility, in general, can be defined as the ease (time, effort and/or money) by which changes can be realized. Two aspects determine the flexibility of a manufacturing layout: (i) *range* and (ii) *response*. “Range” refers to the scope of a layout and indicates the variety of situations that can be dealt with without a serious change of the production layout. “Response” indicates the speed by which the layout can be adapted to changing circumstances. Slack (1987) and Upton (1994) have observed that managers think along these lines with respect to the term flexibility.

Product flexibility indicates the ease by which new products can be introduced in a firm. This type of flexibility is higher in a product layout if the new product can be assigned to a single existing product group (quicker response). If a new product has impact on the design of the manufacturing cells, then a process layout is more stable and has more product flexibility (larger range).

Mix flexibility indicates the ease by which a firm can vary the mix of products. Important for the assessment of mix flexibility is insight in the effect of mix changes on the need of various manufacturing processes. A process layout is more range-flexible if the impact of mix changes on the need for manufacturing processes is limited. A product layout is range-flexible if work can be reallocated between the various groups. An important advantage of a product layout concerns the multi-functionality of workers: there are more capabilities at the work floor to deal with changes in the product mix.

Volume/demand flexibility concerns the ease by which the production volume can be increased or decreased. Temporary workers and the extension of working time are possibilities to increase the production volume. It is conceivable that autonomous teams in a product layout can respond more quickly to the need for additional capacity than functional groups in a process layout (i.e. response flexibility). The need for additional capacity is localized and only one group is involved in the need for more capacity for a particular product family. On the other hand, extension of capacity can be realized more easily in a process layout, because more workers with the same capabilities are eligible to work overtime (i.e. range flexibility). Also, temporary workers can probably best be integrated in a process layout.

2.5. Dependability

The performance objective “dependability” points to the importance of being dependable with respect to delivery times, the quality of the products, and such. To be dependable, it is important that the manufacturing activities can be buffered from all kinds of disturbances.

Machine breakdowns and unexpected absenteeism of workers may complicate the dependability of a manufacturing system. *Interchangeability of machines* (or the ability to subcontract) and the *possibility to replace workers* (or increase the working times of some workers) indicate to what extent a manufacturing system can be reliable in various circumstances. The interchangeability and the possibility to replace workers are probably higher in a process layout because of the clustering of identical capacities. Another aspect of dependability concerns the ability to *control* the flow of products. It is likely that the throughput times in a product layout can be controlled better; the control responsibility can be decentralized to autonomous groups which are able to respond quickly to disturbances.

2.6. Quality of labour

Quality of labour can be investigated in several ways. A well-known approach concerns the job characteristics model of Hackman and Oldham (1980). This model is used by Huber and Hyer (1985) and Shafer *et al.* (1995) to investigate human issues in cellular manufacturing. The job characteristics model distinguishes five task characteristics that have impact on quality of labour: (i) *skill variety*, (ii) *task identity*, (iii) *task significance*, (iv) *autonomy*, and v) *feedback*. Skill variety refers to the extent to which the work requires a variety of activities involving different skills and talents of the workers. Task identity concerns the extent to which the work enables the worker to complete a whole task from start to finish. Task significance relates to the impact of the work on other people within or outside of the organization. Autonomy indicates to what extent a worker has the freedom to plan, to organize, and to perform the tasks in his/her own way. Finally, feedback refers to the extent to which the worker receives information on the effectiveness of his/her performance.

A product layout likely supports a higher/better skill variety, more autonomy, and a better feedback mechanism: workers can perform a variety of tasks, they are responsible for the internal organization of the group, and they get a quick feedback on their activities. The task identity and task significance in a process layout is probably better: the tasks to be performed are clear for all workers and they will be respected because of their specialization.

3. Decision support framework

Section 2 presented major performance objectives of a manufacturing system and indicated which layout-related aspects play an important role. Table 1 summarizes these aspects. As can be seen, the performance objectives price and speed consist of several elements. These elements together constitute the related performance indicators. We do not distinguish aspects for these two performance objectives.

The ultimate goal is to select the best layout out of a set of alternative layouts. Based upon the scheme of Table 1, the selection problem can be split in three sets of questions:

1 What are the relative scores of the various alternative layouts on the aspects mentioned in Table 1? This question involves a comparison of the alternative layouts with respect to the various aspects. Answering this question requires knowledge of operational issues on the work floor and the ability to assess the impact of an alternative layout on the aspects. The answer to this question determines value $\pi(i, j)$, see Table 2.

2 What is the relative importance of the various aspects for the performance objectives? Table 1 gives an overview of all the aspects. The answer to this question determines value $\pi(j,k)$. The sum of the elements, mentioned in column 3 of Table 1, forms an indication for the performance of respectively the price and speed objective.

3 What is the relative importance of the various performance objectives for the firm? This is basically a strategic question, which has to be answered by the management of the firm. It requires knowledge about customers and competitors. The answer to this question determines value $\pi(k)$.

The answers to these sets of questions enable the calculation of the relative performance of the alternatives:

$$R(i)=\sum_j \sum_k \pi(i,j)\,\pi(j,k)\,\pi(k)$$

Table 1. Objectives, aspects and elements in the selection of a manufacturing layout

objectives	aspects	elements
price	costs	equipment costs personnel costs material costs inventory costs
quality	specialization of workers advanced machinery control loops	
speed	throughput time	transport time machining time waiting time
flexibility • product/service • mix • volume/demand	response range	
dependability	interchangeability of workers interchangeability of equipment control capacity	
quality of labour	skill variety task identity task significance autonomy feedback	

Table 2. Notation

$\pi(k)$	=	relative importance of the various performance objectives (k) for the firm, $\sum_k \pi(k)=1$;
$\pi(j,k)$	=	relative importance of the various aspects (j) for the performance objectives (k), $\sum_j \pi(j,k)=1$;
$\pi(i,j)$	=	relative scores of the various alternative layouts (i) on the aspects (j), $\sum_i \pi(i,j)=1$;
$R(i)$	=	relative performance of alternative i, $\sum_i R(i)=1$.

The three sets of questions and the way in which the relative performance of the alternatives are calculated can be seen as an example of using the weighted-score method (see e.g. Slack *et al.* 2001, p. 166). A major issue is the difficulty to "determine" the values of $\pi(k)$, $\pi(j,k)$, $\pi(i,j)$, and $R(i)$. It requires the ability to weight different types of issues.

The three sets of questions and the issue of weighting different types of issues fits in the AHP-approach of Saaty (1980). AHP forces the decision maker(s) to make all assessments explicit. The decomposition of the main problem in several smaller problems also enables an effective participation of employees in the decision problem, using their specific expertise and responsibilities. In the next section, we will illustrate the use of the AHP-approach for layout selection on hand of a practical instance.

4. Case study

The case study presented here concerns the sheet metal processing department of the firm Holec Algemene Toelevering B.V., a supplier of parts, tools, and services for the electro-mechanical industry. Before the layout study started, the sheet metal processing department consisted of four autonomous manufacturing cells with some exchangeability between the cells: (i) an automated flexible system for sheet metal working (<3 mm), (ii) numerical sheet metal working (>3mm), (iii) sheet metal construction processing (>5 mm), and (iv) conventional sheet metal processing. Basic processes to be performed in the cells are sawing, punching, cutting, tapping, squaring, welding, and bench work. The firm started to produce in manufacturing cells in 1987. This has led to significant improvements in manufacturing throughput time and efficiency. In the course of years, however, there were several reasons to move back to a more functional layout, such as the complexity and productivity of new equipment, the possibility of workers to operate more than one machine simultaneously, and the increased variety of part types. Other parts of the manufacturing facility of the firm were already transformed to a more process-oriented layout (see Molleman *et al.* 2002). A layout study at the sheet metal processing department started in 1997.

On the basis of a production flow analysis (Burbidge 1991, Slomp 1998), Posthumus (1997) generated four alternative layouts: (i) a group-technology-oriented alternative, (ii) a product-type-oriented alternative, (iii) a capability-oriented alternative, and (iv) a process-oriented alternative. These alternatives are schematically depicted in figure 4.

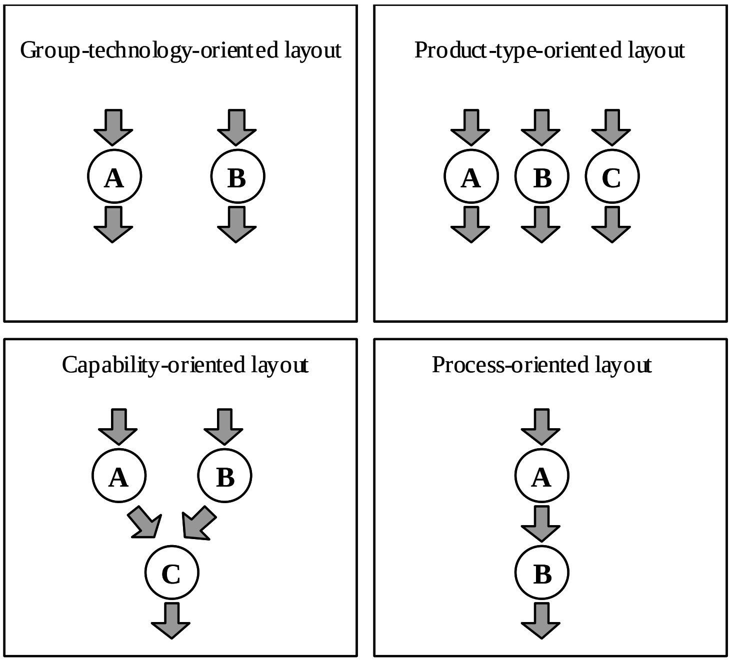

Figure 4. Layout alternatives

In the group-technology-oriented alternative, the department is divided in two relatively autonomous cells with minimal intercell movements. Some part types can be produced in both groups, which simplifies the balancing of the workload.

The product-type-oriented alternative consists of three manufacturing cells, each responsible for a particular type of product. Two cells are responsible for the production of repetitive part types, while one cell is mainly focused on the production of quick orders. An important advantage of this layout is that the production of repetitive part types is not disturbed by quick orders. This may simplify the production control. On the other hand, the cell that is responsible for the quick orders may face undesirable fluctuations of demand.

The capability-oriented alternative consists of three manufacturing cells. Basic viewpoint of this alternative is that all assembly work (welding and bench work) needs to be performed in one manufacturing cell (C). The other cells (A and B) are autonomous cells, which have their own product-oriented capabilities. Therefore, intercell movements are minimal.

The process-oriented alternative consists of two manufacturing cells. Sawing, punching and cutting is performed in cell A, while tapping, squaring, welding, and bench work is done in cell B. Each cell consists of small groups of identical machines.

The four alternatives are compared by means of the decision framework of Table 1 and by using the AHP methodology. We used the software package “Expert Choice”. Figure 5 presents the results of the comparisons of the four alternatives. The bars in figure 5 indicate the relative importance of the various performance objectives. The four lines in the figure show the relative scores of each alternative on the performance objectives. The position of the alternatives at “total” shows the final judgment of the alternatives. As can be seen, the process-oriented layout is preferred because of its positive effect on price, quality, mix flexibility and, to less extent, dependability. Especially price and quality are important reasons to select the process-oriented layout.

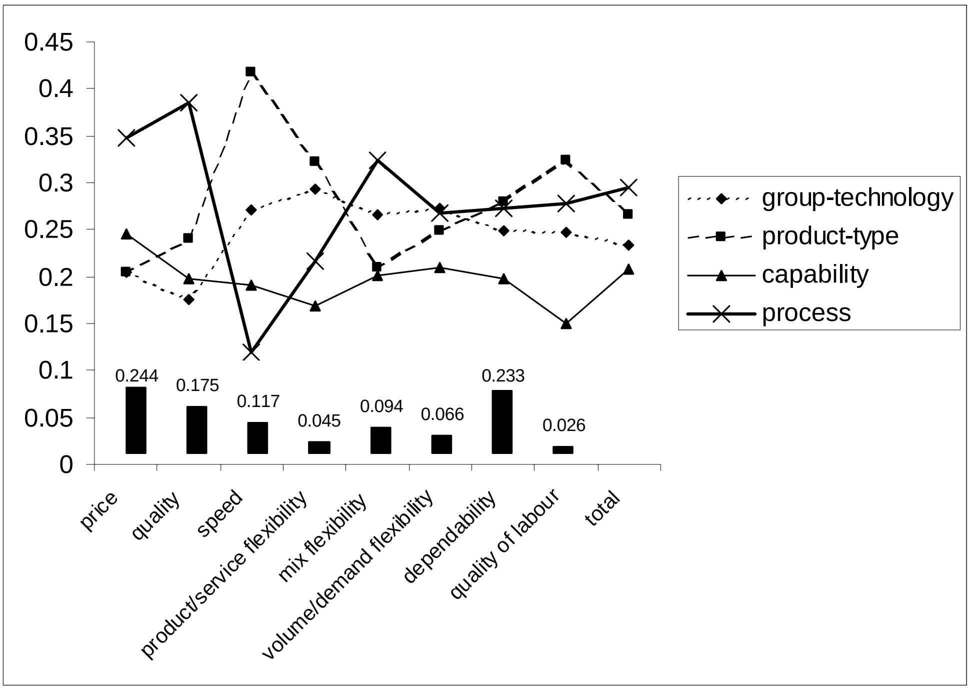

Figure 5. Scores of the four alternatives

It is interesting to see the almost equal end scores of the product-type-oriented and the process-oriented layout, despite their completely different orientation. The product-type-oriented layout performs well with respect to the performance objective “speed”. In the assessment, Posthumus (1997), and with him the managers of the firm, assumed that the production control in the process-oriented layout is more complex and will perform worse than in the product-type-oriented layout. At that moment, the firm did not have a good registration system (bar-coding system) on the work floor that is connected with the production control system. A better shop floor control system, which was under study at the firm and which has been implemented in 2000, would improve the score of the process-oriented layout on the performance objective “speed”. This kind of “sensitivity analysis” is also useful for the assessment of the scores on the performance objectives “quality” and “price”. In this particular case, the impact of control loops on the quality of the products is assessed as being minimal. This assessment has a negative impact on the final score of the product-type-oriented layout. The software package Expert Choice supports sensitivity analysis. It appears that if short control loops do have a major impact on the quality of the products, the product-type-oriented layout performs better than the process-oriented alternative.

In 2000, the firm changed the layout of the sheet-metal processing department, in conformity with the findings of Posthumus (1997), see also Molleman *et al.* (2002). The systematic approach of the selection problem is seen at the firm as a major help to canalize the discussions about the required layout of manufacturing departments.

5. Conclusions and reflection

This paper presents a systematic approach for the selection of a manufacturing layout. The approach includes the use of the AHP-methodology. Important element of the approach is the construction of a decision hierarchy and the pairwise comparisons of decision elements. In this section we will first reflect on the AHP methodology and next we will draw conclusions on the use of AHP for layout selection.

As in all Multi-Criteria-Decision-Methods, AHP is sensitive for issues such as the specification of the selection problem, its decomposition, and the scales used for the pairwise comparisons (see Pöyhönen *et al.* 1997). The quality of the outcome of an AHP analysis is largely determined by the quality of the problem specification. For instance, adding aspects or regrouping decision elements may lead to different outcomes. A particular problem concerns the issue of “rank reversal”. This means that the priority of alternatives may change if alternatives are removed from and/or other alternatives are added to the selection problem (see e.g. Belton and Gear 1983). The problem of rank reversal plays a role if almost identical alternatives are taken into consideration. Finally, the number of pairwise comparisons may be problematic and may lead to unreliable results. Employees who have to make the pairwise comparisons may get tired and lose the required concentration. Another issue, which has to be taken into consideration when applying the AHP approach, is the translation of verbal or graphical assessments in numerical figures. Pöyhönen *et al.* (1997) show that it is not advisable to mix different types of assessment within the levels of the AHP hierarchy.

This paper has presented a decision support framework based on the AHP approach for the selection of a manufacturing layout. The value of the framework is illustrated by means of a case application. Important advantages of using the AHP approach are (1) the ability to decompose the complex decision problem in smaller problems, (2) the possibility of an efficient and effective employee participation, and (3) the detailed assessment of the selected layout alternative, which helps to define further improvement actions.

Interesting point in the case study, as presented in this paper, is that opposite alternatives do have the best scores. This illustrates the group technology debate, as it takes place in practice. Both alternatives appear to be acceptable and have their pros and cons. The proposed approach has the advantage that it gives insight in whether the two alternatives do have similar scores. A debate about the differences on the scores of the various aspects will help the decision process and the acceptability of the final decision.

The systematic approach is developed in 1997 (see also Slomp *et al.* 1999a, b) and is applied in several practical situations. In our opinion, the content of Table 1 and the use of AHP form a robust framework for the selection of a layout in many situations.

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AN INTEGRATED MODEL FOR PART-OPERATION ALLOCATION AND INVESTMENTS IN CNC TECHNOLOGY[2]

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ABSTRACT

This study addresses the issue of investment appraisal of new technology, specifically computer numerical control (CNC) machine tools in conjunction with optimal allocation of parts and operations on CNC machines as the investments take place. Part-operation allocation is the allocation of parts and operations to either the conventional machines or to the new technology as they are acquired. It is shown that part allocation is an important consideration in the assessment of profitability from investments in CNC technology. A mixed integer programming model is presented to: 1) determine the optimal allocation of parts and operations to conventional machines and to new CNC machine tools; and, 2) determine the optimal investment sequence and timing of investments in CNC machine tools. The optimality criterion is based on a maximization of net present value (NPV) over a specified planning horizon. The application of the model is illustrated using a numerical example, and the implications for industrial practice are also indicated.

Key words: Economic Justification of CNC, Investment Appraisal, Part Type Selection, Advanced Manufacturing Technology

1. Introduction

The advent of global competition, increased customization of product offerings, shrinking product life cycles, increased product complexity, shorter delivery times, greater variety, smaller volumes, etc. have required more agility from manufacturing firms. Machine tool technology based on computer numerical control (CNC) technology has proved to be of significant value for firms in coping with these pressures. Over the years, CNC machine tools have also become much more affordable for small and medium-sized firms (Thyer, 1991; Luggen, 1994). The number of CNC machines sold within the Dutch market by *de Vereniging van Importeurs van Machines en Gereedschappen voor de Metaalindustrie* (VIMAG: a society of importers of CNC machines and tools for metal cutting industry) increased by 21.5% in 1998 compared to 1997 (MB Productietechniek, 1999). This indicates that the issue of economic justification of CNC technology is of importance for a growing number of firms.

Past justification approaches have generally assumed that when a CNC machine tool is installed, all existing parts for which the CNC machines are being considered will be manufactured in entirety on the new machine tool(s). However, investment in a CNC machine tool, or a set of CNC machine tools with varying degrees of system integration, presents a combinatorial complexity involving selection of a set of parts and operations to

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be transferred to CNC operations. This affects the economics of CNC operations significantly.

Economic justification methods proposed for CNC machine tools have also, for the most part, been along the lines of justifying traditional, single machine tools. Given that CNC machine tools are often employed as multi-machine systems, and each CNC machine typically serves to replace more than one traditional machine, CNC machine tools have to be justified as multi-machine systems, involving a strategic approach (Klahorst, 1983; Primrose and Leonard, 1985; Suresh and Meredith, 1985; Meredith, 1986; Hamblin and Hundy, 1986; Kaplan, 1986; Miltenburg and Krinsky, 1987; Leung and Tanchoco, 1987; Suresh, 1990).

A major objective of the model developed in this paper is to extend past work in this area by incorporating the *part-operation allocation problem* (defined in more detail below) into the CNC economic justification problem. This is a key economic question in the context of CNC investments which, in practice, still relies on subjective and intuitive decision processes to a large extent. The model developed below also captures some unique setup and processing characteristics of CNC machines. In essence, the model attempts to maximize the net present value (NPV) of the after-tax cash flows over a planning horizon. The NPV criterion, in conjunction with consideration of other strategic factors, is now generally accepted as the proper criterion for strategic justification of multi-machine systems (Hamblin and Hundy, 1986; Kaplan, 1986; Suresh, 1990). In the process of maximizing NPV of after-tax cash flows, the model captures relevant aspects of CNC-based multi-machine systems more comprehensively, and it serves to address the following decisions:

1 Which part types to manufacture (fully or partially), on new and/or current machines, and in what quantities, in each period of the planning horizon;
2 Given a set of candidate CNC machine tools for potential investment, which new CNC-machine(s) to invest in, and, in which periods during the planning horizon;
3 Which of the current machines to dispose of, and when should they be disposed of in the planning period, in order to maximize NPV as well as to ensure feasible production switchovers.

Thus the problem addressed in this paper is important for a number of reasons which include:

- Investment decisions for CNC machine tools are of importance to manufacturing firms in order to ensure agility and flexibility in the new dynamic marketplace;
- Given the high capital costs, it is even more important for the survival of small and medium-sized firms;
- Past economic justification approaches have assumed a single replacement of traditional machines with CNC equipment, without considering the combinatorial complexity surrounding part-operation transfers to CNC machines, and progressive integration.

This paper is organized as follows. In section 2, a brief literature review of past justification approaches is presented. In section 3, the model is developed, describing the problem context and the problem definition. Section 4 provides some unique economic characteristics of CNC machines over conventional equipment. In section 5, the model specifications are presented and a numerical example is given in section 6 to illustrate the use of the model, which is followed by the conclusions in section 7.

2. Literature Review and Background

The topic of investment appraisal in advanced manufacturing technology (AMT) has been addressed extensively in past literature. A wide range of tools and techniques have been developed (see Meredith, 1986). It is now generally agreed that a strategic approach, in conjunction with traditional financial appraisal methods are warranted for AMT investments (Primrose and Leonard, 1985; Suresh and Meredith, 1985; Meredith, 1986; Hamblin and Hundy, 1986; Kaplan, 1986; Miltenburg and Krinsky, 1987; Suresh 1990; Lefley, 1996; Lefley and Sarkis, 1997; Kakati, 1997). Narrow financial evaluation may lead to rejection of an AMT investment, for instance, whereas non-investment in AMT may be deemed as highly risky from a business strategy perspective. This is especially true when AMT contributes significantly towards closing the competitive and opportunity gaps (Kakati, 1997).

While some researchers have argued that all the potential costs and benefits of new technology can be included as a financial evaluation (Kaplan, 1986; Pimrose and Leonard, 1991), others have attempted to integrate strategic and financial evaluation into multi-objective decision models such as the analytic hierarchy process (AHP) (e.g., Falkner and Benhajla, 1990; Suresh and Kaparthi, 1992; Angelis and Lee, 1996). The work of Sarkis (1997) applies data envelopment analysis for this problem. Lotfi (1995) also uses a multi-objective decision model, addressing financial aspects as well as non-financial and other conflicting objectives, such as flexibility, firm disruption, and group homogeneity of new modules. Lefley (1996) examined various strategic models and approaches of investment appraisal in AMT and concluded that even though there is no single model that has been universally accepted, strategic implications should be taken into account in addition to financial techniques. Strategic implications include improved flexibility, synergy with other operations or technologies, reduced production lead times, improved quality, increased sales and other “intangibles”.

The problem addressed in this paper constitutes an extension of the modeling stream of Leung and Tanchoco (1987) and Suresh (1992). For an extended literature review of various other tools and techniques developed for this problem context, the reader is referred to works such as Meredith (1986), Azzone and Bertele (1989), Falkner and Benhajla (1990), Suresh (1990), Proctor and Canada (1992) and Sarkis (1997). In addition, a comprehensive bibliography is presented by Son (1992).

The issue of *selecting parts and operations*, considered explicitly in this paper, deals with the question of which of the parts, and which of their operations, can be manufactured using conventional and/or CNC technology. This is a somewhat different issue than what is generally known in the literature devoted to flexible manufacturing systems (FMS) as *part type selection*, though there are some similarities. For instance, Stecke (1985) describes problems and decisions that have to be addressed during the design, planning, scheduling and the control of a FMS. In developing an FMS design, a range of part types to be produced must be determined, and a subset of these part types must be identified to be manufactured on the FMS. In this context, part type selection is one of several FMS *production planning problems*, indicating the choice of a subset of part types for immediate and simultaneous manufacture from a set of specified part types for which production orders exist. This choice can be based on several criteria: meeting due dates and ensuring effective use of limited tool magazine capacities (Denizel and Sayin, 1998); due dates and profit maximization (Stecke and Toczyłowski, 1992); throughput and processing cost or makespan (Liang and Dutta, 1993); maximization of profits subject to constraints on capacity, pallets and fixtures (Chen, Ker and Kleawpatinon, 1995). Often part type selection is considered in conjunction with the loading problem (e.g., Nayak and Acharya, 1998; Guerrero, Lozano and Koltai, 1999). The loading problem is concerned with the allocation of operations and required tools to machines. Chen *et al.* (1995) also include outsourcing into their model, so that parts that have a higher profit when outsourced, will not be selected for in-house production with an FMS.

The part-operation selection problem addressed in this paper refers to a different issue faced at the investment decision stage, as described earlier. Unlike the FMS part type selection, which is a short-term problem, the part-operation allocation problem which is considered together with investment decisions, can be seen to be a medium- or long-term problem. It results in an optimum i.e., most profitable selection of part types and operations to be manufactured on current and/or new CNC machine types. This is an integral part of the economic justification of CNC machine tools.

3. Model Development

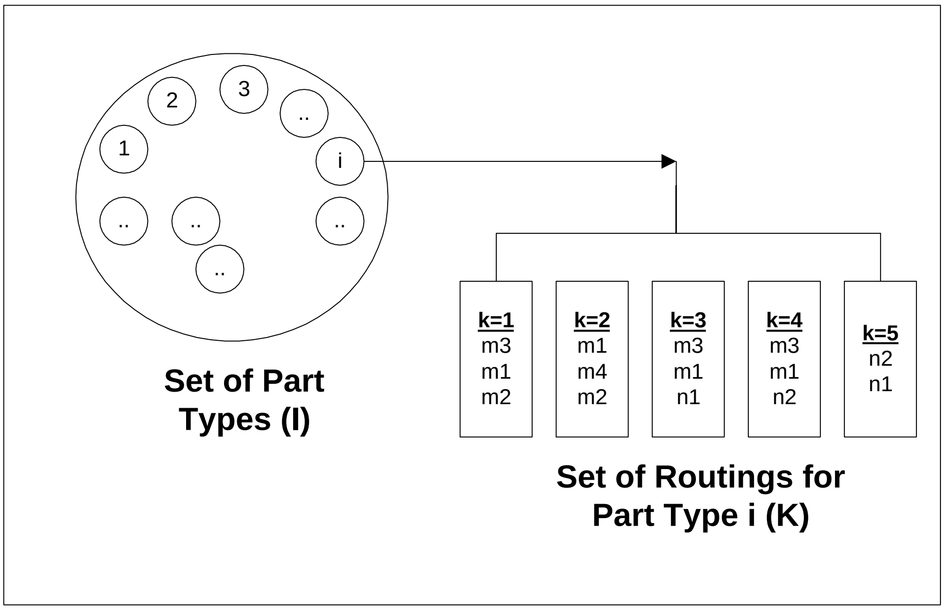
The intent of this section is to describe the problem context and define the problem.

3.1. Problem Context

Consider a set of part types $\{i=1,2,...,I\}$ which are manufactured using a set of current machine types $\{m=1,2,...,M\}$, as shown in Figure 1. For each part type, a set of routings $\{k=1-5\}$ is shown. These are alternative process plans based on several combinations of machine tools, with differing cost implications. For instance, the first routing for part type i involves three operations, to be carried out on current machines 3, 1 and 2, respectively. Likewise, the second routing involves current machines 1, 4 and 2, respectively.

At this juncture, assume that a set of CNC machine tools $\{n=1,2,...,N\}$ is considered tentatively for investment. For part type i, the third and the fourth routings involve one of these new CNC machine types for performing a subset of the operations. In other words, these two routings require partial manufacturing on CNC machines. The fifth routing involves complete manufacture on CNC machines. The number of operations is often reduced when CNC machine tools are used, given their versatility and multi-functional capabilities. The economics of manufacturing according to each of these routings may vary significantly based on part and operation characteristics, the capital and operating costs of the machines considered.

The capital costs of CNC machine tools continue to be high, and a progressive implementation requiring less capital outlays in each period is often adopted in practice. Phased implementation permits a slower transition and learning of CNC technologies, less operating risk, etc. A phased-implementation approach is considered here as a general solution for implementation sequences, with instantaneous installation of a fully-integrated CNC machine tool system forming a special case. A one-time installation of an integrated system, such as flexible manufacturing system (FMS), may certainly be economically and strategically justified under certain conditions (Suresh, 1990).



	Period					
	1	**2**	**3**	**..**	**..**	**T**
Current machines						
1	x	x	x	-	-	-
2	x	-	-	-	-	-
3	x	x	-	-	-	-
4	x	x	x	x	x	x
..						
m						
New machines						
1	-	x	x	x	x	x
2	-	-	x	x	x	x
..						
n						

Figure 1. CNC Machine Investment Context

The latter half of Figure 1 shows one example investment sequence for the new machines: machine type $n = 1$ is installed in the second year and machine type 2 is implemented in the third year. This is just one of many combinations of investment sequences possible. This investment sequence can dictate the cash flows significantly. The sequence shown in

Figure 1 also calls for the salvage of current machine 1 after three years, machine type 2 after one year, and machine type 3 after two years. This replacement or salvage sequence also has a major impact on the cash flows.

With the investment sequence shown in Figure 1, it may be seen that not all routings for part type i are feasible each year. For instance, routing 5 becomes feasible only in year 3. Often, a routing is selected based on the operational costs of producing on various machines, and the mix of jobs present in the shop at a given time. However, it may be seen that certain seemingly expensive routings, through conventional or CNC machines, may actually be preferred as the optimum solution from the larger perspective of maximizing cash flows over the planning horizon. In practice, such decisions are often taken myopically, based on production economics on an item-by-item basis and shop order status at a given time.

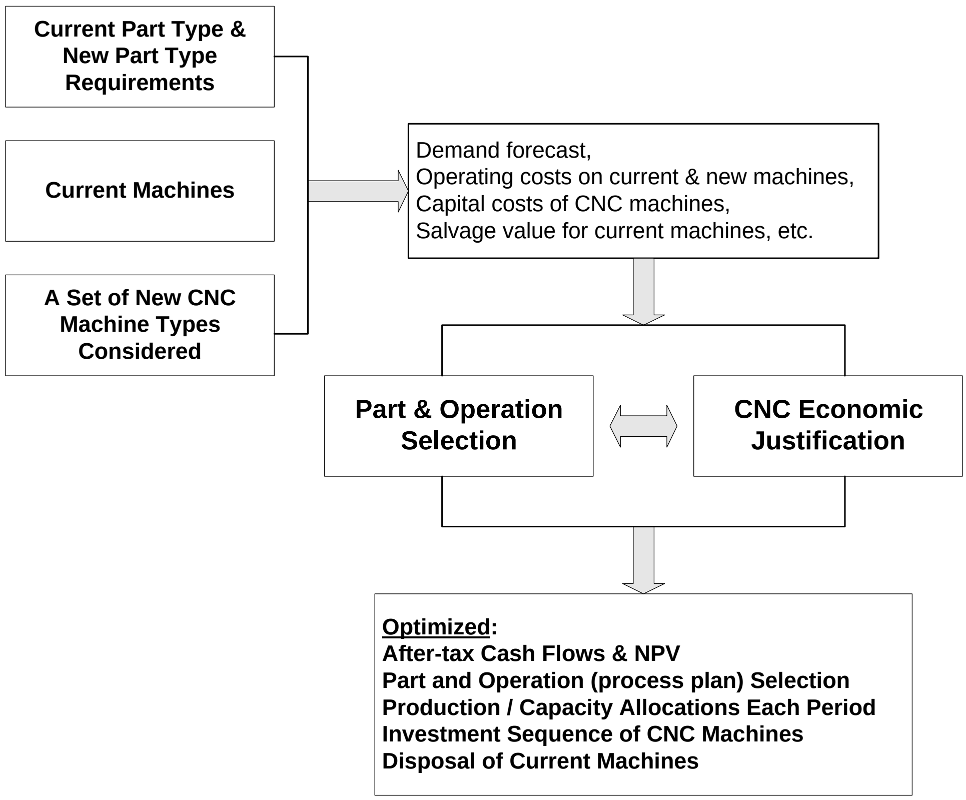


Figure 2. The Justification Model

An important aspect in the justification is the fact that CNC machines tend to expand the process envelope, permitting new part types to be manufactured in the future, which is often referred to as *product flexibility*. Potential for new revenues is created which has to be factored into the justification. For an extended discussion of such issues, the reader is referred to works such as those of Smith and Evans (1977), Steffy *et al.* (1973) and Suresh

(1990). At any rate, it is clear that to maximize the NPV, the optimal selection of parts and process plans becomes an integral part of the CNC investment decision. The capital costs and salvage values resulting from an implementation sequence also have a strong impact on the investment decision. In addition, the economics of manufacturing on CNC machine tools also play an important role on operating costs and benefits, and resulting cash flows during the planning horizon.

Figure 2 shows the overall inputs and outputs of the model developed, in line with the problem context described.

3.2. Problem Definition

We now formally define the problem as follows. Consider a set of part types, denoted by the index set $\{i=1,2,...,I\}$, which are currently produced using a set of machine types denoted by index set $\{m=1,2,...,M\}$. A set of new CNC-machines, represented by the index set $\{n=1,2,...,N\}$ have been identified to perform one or more of various operations required by the part types.

The planning horizon considered for this investment decision is denoted by the index set $\{t=1,2,...,T\}$. During this planning horizon, one or more of the current machines may be disposed of. The binary variables $y_{m,t}$ and $y_{n,t}$ equal 1 if the machine is available for production in period t, and zero if not. Thus, these variables specify the investment and replacement sequences, for current and new machines, respectively. It is assumed that the new CNC-machines are installed at the beginning of a period, and $C_{n,t}$ is the capital cost of a new machine n anticipated in time t. Likewise, $S_{m,t}$ denotes the salvage value of machine type m if replaced in time t. Thus, both capital costs and the salvage values can be made time-dependent.

Given the part types $\{i=1,2,...,I\}$, let $\{j=1,2,...,J_{i,k}\}$ be the index set of operations needed to produce a part type i. The part type can be produced through various routings (process plans) denoted by the index set $\{k=1,2,...,K_i\}$. The alternative routings may include current machines and/or the new CNC-machines considered for investment. As the new CNC-machines are installed, the part types may be produced using both the current machines and the CNC-machines. The routings are specified such that in a particular routing, each operation is performed by a specific machine type. Thus, if an operation can be performed on more than one machine, additional routings need to be specified for every combination.

An incidence matrix is used to represent routing capabilities: the matrix element z_{ijkn} is equal to 1 if operation j of part type i, belonging to routing k, can be performed on machine type n; and it is equal to zero otherwise. When part types are produced through routings that include CNC-machines, due to redesign or re-process planning, the number of operations will often be less than when produced through routings using conventional machines (Smith and Evans, 1977; Steffy *et al.*, 1973; Suresh, 1990). The setup and operation times are denoted by A_{ijkm} and t_{ijkm}, respectively, for current machines and by A_{ijkn} and t_{ijkn} for CNC-machines. The setup times for CNC-machines are generally significantly reduced compared to conventional machines, and operation times may also be less at times.

Let $D_{i,t}$ be the demand forecast for part type i for period t of the planning horizon. Given these demand requirements, the decision variables also include $X_{ijkn,t}$ and $X_{ijkm,t}$, which are the production quantities for operation j of part i through routing k on machine types n and m respectively, in time t. A quality factor, $\mathrm{QF}_{i,k,t}$ is considered, given that routings that include CNC-machines are generally of significantly higher quality (lower reject rates) than routings with conventional machines. Let $q_{ik,t}$ be the production lot size for part i through routing k in period t. The notation is summarized in Table 1.

Table 1. The notation.

$\{t=1,2,...,T\}$	Index set of periods in the planning horizon
$\{i=1,2,...,I\}$	Index set of part types
$\{j=1,2,...,J_{i,k}\}$	Index set of operations for part type i in routing k
$\{k=1,2,...,K_i\}$	Index set of routings for part type i
$\{m=1,2,...,M\}$	Index set of current machine types
$\{n=1,2,...,N\}$	Index set of new CNC-machines considered
$p_{i,t}$	Price of part type i in period t
$D_{i,t}$	Demand forecast for part type i in time t
$\mathrm{QF}_{i,k,t}$	Quality factor for part type i through routing k in period t
$\mathrm{MC}_{i,k,t}$	Material cost for part type i through routing k in period t
TR_t	Tax rate assumed for time t
w, r_t	Discount rate and discount factor $\left(=1/(1+w)^t\right)$
$\mathrm{DP}_{n,t}, \mathrm{DP}_{m,t}$	Depreciation computed for machine types n and m, respectively, in period t
$y_{m,t}, y_{n,t}$	1 if machine m or n is available for production, 0 if not
$S_{m,t}$	Salvage value of machine m in time t
BV_T	Book value of the assets at the end of the planning horizon
$C_{n,t}, C_m$	Capital costs for machine types n and m at the time of installation
$B_{m,0}$	Starting value of machine m (period 0)
$\mathrm{CK}_{i,n,t}$	One-off cost that occurs when part type i is manufactured (partially) for the first time on machine n
$\mathrm{CP}_{i,k,t}$	Costs per part type i, through routing k in period t
$\mathrm{CQ}_{i,k,t}$	Costs per lot of part type i, through routing k in period t
$\mathrm{MAKE}_{i,n,t}$	1 if part type i is manufactured (partially) for the first time on machine n, 0 if not
$q_{ik,t}$	Lot size for part type i through routing k in period t

$h_{i,t}$	Inventory holding costs per part per hour for a period t
O_{ik}	The transition time between operations per part per route
d_n, d_m	Straight-line depreciation factors for machine types n and m
$X_{ijkn,t}, X_{ijkm,t}$	Production quantity of operation j, part type i in time t on machine types n and m, respectively, through routing k
z_{ijkn}, z_{ijkm}	1 if operation j of part type i can be performed on machine types n and m, respectively, through routing k
t_{ijkn}, t_{ijkm}	Processing times for operation j of part type i on machine types n and m, respectively, through routing k
A_{ijkn}, A_{ijkm}	Setup times per lot for operation j of part type i on machine types n and m, respectively, through routing k
γ	Factor for routing flexibility
$K_{n,t}, K_{m,t}$	Capacity for machine types n and m, respectively, over time

Given the above parameters and variables, the objectives of the model are to maximize the overall net present value of the after-tax cash flows and, in the process, to determine:

1 Which part types to manufacture (fully or partially), on new and/or current machines, and in what quantities each period.
2 What new CNC-machine(s) to invest in and when;
3 Which of the current machines to dispose of, and when.

4. CNC Machine Characteristics

The model developed above may be seen to be consistent with the technical and economic characteristics of CNC equipment which are now widely known. Essentially, CNC machines contribute to an increase in the three main performance criteria of efficiency, flexibility and quality. The most distinct characteristics of CNC machines are that they are computer controlled, they integrate several operations and they may also have automatic part handling and transportation facilities (Thyer, 1991; Luggen, 1994). These characteristics have an inter-related impact on the three performance criteria, as shown in Figure 3.

Computer numerical control results in less direct employees, and thus the operating costs (including labor costs) will decrease, resulting in higher efficiency. By programming the machines it becomes possible to produce unattended or lightly attended for a period of time. This also adds to a higher level of efficiency. Furthermore, tasks can be done quicker with computer control. Processing times are reduced due to the fact that higher cutting speeds and revolutions per minute can be achieved by means of computer control. Given increasing user-friendliness of the NC-programming and increased self-handling of the machines, operating times have reduced even more over the years. As production times on the machines have decreased, the changing of tools and work pieces take up relatively more time. This increases the relative need to speed up the tool and work piece changing and reduce the number of set-ups. A development to reduce the number of set-ups is an increase in the number of axes. Machines equipped with several axes can tool work pieces multilaterally. The tool changeovers can be done faster, for example, with two-spindle machining centers: while one spindle can be used to process the work piece, the other can change its tool.

Characteristics	Impact	Performance
Computer Controlled	Shorter processing times Less direct employees Decreased setup time	Efficiency
Integration of operations	Higher accuracy Less WIP Smaller lot sizes	Flexibility
Automatic part handling and transportation	Less scrap/rework Less transportation Less operating costs Reduced throughput times	Quality

Figure 3. Characteristics of CNC machines and impact on performance.

The swift downloading of NC programs reduces the setup time, making it possible to produce in smaller lot sizes, which increases flexibility. Smaller lot sizes will also reduce WIP costs and thus increase operational efficiency. Other advantages of computer control are that repetitive products will be of a consistent quality, so there will be less scrap and rework.

There is also a pronounced tendency to integrate several manufacturing processes into one CNC machine. For instance, CNC lathes can perform milling operations, and lately, even grinding. The tooling of sheet iron work can be done on single machines that combine several operations, like a punching machine with bending and thread cutting possibilities, punching nibbling machines equipped with a laser for cutting, welding and marking and bending machines with (spot) welding possibilities.

There are several advantages from such integration, or multi-functional capability of CNC machines: reduction in setting time, elimination of floor-to-floor move times, reduction in the number of fixtures to be set up, etc. These result in savings in time (efficiency), as well as increased precision and thus improved quality. Furthermore, the reduction in setting time enhances producing in smaller lot sizes, which increases flexibility.

The automatic part handling and transportation facilities of CNC machines reduce the number of direct employees needed, resulting in higher efficiency. Furthermore, these facilities enable the machines to produce unattended or lightly attended for a period of time, by providing the system with parts to be processed and carry away finished parts. Other advantages of automatic part handling and transportation are less scrap/rework caused by transport, resulting in a higher quality of the parts.

Thus, the performance characteristics of CNC machines are significantly different from that of conventional machines. This results in different operating cost functions which need to be captured in CNC justification models.

$$\sum_k D_{ik,t} = D_{i,t} \qquad \forall i,t \tag{9}$$

$$\sum_j \sum_k \sum_{t^*=1}^{t} X_{ijkn,t^*} \le \Omega \sum_{t^*=1}^{t} \mathrm{MAKE}_{i,n,t^*} \qquad \forall i,n,t \tag{10}$$

$$\sum_t \mathrm{MAKE}_{i,n,t} \le 1 \quad \forall i,n \tag{11}$$

$$\sum_i \sum_j \sum_k t_{ijkn} X_{ijkn,t} \mathrm{QF}_{i,k,t} + \sum_i \sum_j \sum_k A_{ijkn} X_{ijkn,t} / q_{ik,t} \mathrm{QF}_{i,k,t} \le \gamma y_{n,t} K_{n,t} \qquad \forall n,t \tag{12}$$

$$\sum_i \sum_j \sum_k t_{ijkm} X_{ijkm,t} \mathrm{QF}_{i,k,t} + \sum_i \sum_j \sum_k A_{ijkm} X_{ijkm,t} / q_{ik,t} \mathrm{QF}_{i,k,t} \le \gamma y_{m,t} K_{m,t} \qquad \forall m,t \tag{13}$$

$$\mathrm{BV}_{TM} = \sum_m [B_{m,0} - C_m d_m T] y_{mT} \quad \text{if} \quad [B_{m,0} - C_m d_m T] \ge 0 \tag{14}$$

$$\mathrm{BV}_{TM} = 0 \quad \text{if} \quad [B_{m,0} - C_m dm\ T] < 0 \tag{15}$$

$$\mathrm{BV}_{TN} = \sum_t \sum_n (y_{nt} - y_{nt-1}) C_{n,t} - \sum_t \sum_n \mathrm{DP}_{n,t} \tag{16}$$

$$\mathrm{BV}_T = \mathrm{BV}_{TN} + \mathrm{BV}_{TM} \tag{17}$$

5.1. Objective Function: Cash Inflows

The present worth of cash flow from revenues generated by the parts can be written as

$$+\sum_t \sum_i [p_{i,t} D_{i,t}](1 - \mathrm{TR}_t) r_t, \tag{A}$$

where $p_{i,t}$ is the price. The above cash flow is on an after-tax basis, assuming a tax rate of TR_t, and it is time-weighted using the discount factor of r_t which is equal to $1/(1+w)^t$.

The after-tax cash inflow due to depreciation charges equal

$$+\sum_t \left(\sum_n \mathrm{DP}_{\mathrm{n,t}} + \sum_m \mathrm{DP}_{\mathrm{m,t}} \right) \mathrm{TR}_t r_t. \tag{B}$$

The depreciation amounts, $\mathrm{DP}_{\mathrm{n,t}}$ and $\mathrm{DP}_{\mathrm{m,t}}$, are computed in constraint sets (3) and (4, 5), which are explained further below.

Another cash inflow arises from possible disposal of current machines in each period of the planning horizon. This is stated using the variable $y_{m,t}$, which represents the current machines operated in each period, and the salvage value, $S_{m,t}$, as follows:

$$+\sum_t \sum_m (y_{m,t-1} - y_{m,t}) S_{m,t} r_t. \tag{C}$$

5. Model Specifications

The objective function attempts to maximize the net present value (NPV) of the after-tax cash flows over the planning horizon of T years, as stated above. The cash inflows are considered first.

Table 2. The model.

$$\text{Max } NPV =$$

$$+\sum_t \sum_i [p_{i,t} D_{i,t}](1-\text{TR}_t) r_t \qquad (\text{A})$$

$$+\sum_t \left(\sum_n \text{DP}_{\text{n,t}} + \sum_m \text{DP}_{\text{m,t}} \right) \text{TR}_t r_t \qquad (\text{B})$$

$$+\sum_t \sum_m (y_{m,t-1} - y_{m,t}) S_{m,t} r_t \qquad (\text{C})$$

$$+\text{BV}_T r_T \qquad (\text{D})$$

$$-\sum_t \sum_n (y_{n,t} - y_{n,t-1}) C_{n,t} r_t \qquad (\text{E})$$

$$-\sum_t \sum_i \left[\sum_k D_{i,k,t} \text{QF}_{i,k,t} \text{MC}_{i,k,t} \right] (1-\text{TR}_t) r_t \qquad (\text{F})$$

$$-\sum_t \sum_i \sum_n \text{CK}_{i,n,t} \text{MAKE}_{i,n,t} (1-\text{TR}_t) r_t \qquad (\text{G})$$

$$-\sum_t \sum_i \sum_k \text{CP}_{i,k,t} D_{i,k,t} \text{QF}_{i,k,t} (1-\text{TR}_t) r_t \qquad (\text{H})$$

$$-\sum_t \sum_i \sum_k \text{CQ}_{i,k,t} D_{i,k,t} / q_{ik,t} \text{QF}_{i,k,t} (1-\text{TR}_t) r_t \qquad (\text{I})$$

$$-\sum_t \sum_i \sum_k h_{i,t} D_{i,k,t} \text{QF}_{i,k,t} \left[\sum_j \sum_n q_{ik,t} t_{ijkn} + \sum_j \sum_m q_{ik,t} t_{ijkm} + O_{ik} \right] (1-\text{TR}_t) r_t \qquad (\text{J})$$

subject to

$$y_{m,t} \le y_{m,t-1} \qquad \forall m,t \qquad (1)$$

$$y_{n,t} \ge y_{n,t-1} \qquad \forall n,t \qquad (2)$$

$$\text{DP}_{\text{n,t}} = \text{DP}_{\text{n,t-1}} + (y_{n,t} - y_{n,t-1}) C_{n,t} d_n \qquad \forall n,t \qquad (3)$$

$$\text{DP}_{\text{m,t}} = y_{m,t} C_m d_m \quad \text{if} \quad \left[B_{m,0} - \sum_{t=1}^{t} C_m d_m \right] > 0 \qquad \forall m,t \qquad (4)$$

$$\text{DP}_{\text{m,t}} = 0 \quad \text{if} \quad \left[B_{m,0} - \sum_{t=1}^{t} C_m d_m \right] \le 0 \qquad \forall m,t \qquad (5)$$

$$X_{ijkn,t} \le z_{ijkn} D_{ik,t} \qquad \forall i,j,k,n,t \qquad (6)$$

$$X_{ijkm,t} \le z_{ijkm} D_{ik,t} \qquad \forall i,j,k,m,t \qquad (7)$$

$$\sum_n X_{ijkn,t} + \sum_m X_{ijkm,t} = D_{ik,t} \qquad \forall i,j,k,t \qquad (8)$$

Finally, the value of the assets at the end of the planning horizon is also treated as a cash inflow, and is stated as

$$+\mathrm{BV}_T r_T. \tag{D}$$

$\mathrm{BV}_T r_T$ is the value of the assets at the end of the planning horizon. We used the book value of the assets for this purpose, since this expresses the economic value of the assets for the firm. Another indication of the value of the assets would be the total salvage value of these assets at the end of the planning horizon. This, however, does not necessarily reflect the economic value of the assets as it is experienced by firms at the end of the planning horizon.

5.2. Objective Function: Cash Outflows

Cash outflows are due to capital expenses and operating costs. The cash outflow due to investment in new machines is considered first. The capital costs of the new machines, $C_{n,t}$, may differ from period to period. The variable $y_{n,t}$ denotes the operation, and hence, investments of machine n in period t. Thus, for the new machines the capital costs are given by

$$-\sum_t \sum_n \left(y_{n,t} - y_{n,t-1}\right) C_{n,t} r_t. \tag{E}$$

The material costs can be stated as follows:

$$-\sum_t \sum_i \left[\sum_k D_{i,k,t} \mathrm{QF}_{i,k,t} \mathrm{MC}_{i,k,t}\right] (1 - \mathrm{TR}_t) r_t. \tag{F}$$

where $\mathrm{MC}_{i,k,t}$ is the material cost anticipated for part i if routing k is selected in period t. This is dependent on the quality factor, $\mathrm{QF}_{i,k,t}$, mentioned earlier.

Next, we consider the operating costs. First, there are several costs that are incurred only when a part type is manufactured for the first time on machine n in period t ($\mathrm{CK}_{i,n,t}$). These costs include investments in fixtures and tools, the writing of new CNC-programs, and other one-off costs. $\mathrm{MAKE}_{i,n,t}$ is a binary variable that is 1 in the period t that part type i is manufactured for the first time on machine n and zero in all other periods. $\mathrm{MAKE}_{i,n,t}$ is computed by the constraint sets (10) and (11) which are explained later in this section. These costs can thus be given by

$$-\sum_t \sum_i \sum_n \mathrm{CK}_{i,n,t} \mathrm{MAKE}_{i,n,t} (1 - \mathrm{TR}_t) r_t. \tag{G}$$

Other operating costs can be calculated per product (part type x demand) made through routing k in period t ($\mathrm{CP}_{i,k,t}$). These costs include the cost of energy, and part of the labor costs. These costs concern amongst other things the machine handling costs per product. The demand is adjusted by the quality factor, requiring extra production to compensate for rejects.

Thus, these costs per product can be denoted by

$$-\sum_t \sum_i \sum_k \mathrm{CP}_{i,k,t} D_{i,k,t} \mathrm{QF}_{i,k,t} \left(1-\mathrm{TR}_t\right) r_t. \qquad (\mathrm{H})$$

In addition, several other costs are related to the number of lots, such as, setup costs, planning costs, inspection costs, and transportation to and from machines. These are stated in terms of the costs per lot, $\mathrm{CQ}_{i,k,t}$, as

$$-\sum_t \sum_i \sum_k \mathrm{CQ}_{i,k,t} D_{i,k,t} / q_{ik,t} \mathrm{QF}_{i,k,t} \left(1-\mathrm{TR}_t\right) r_t. \qquad (\mathrm{I})$$

where $q_{ik,t}$ is the typical lot size of part type i produced through routing k in period t.

The last part of the objective deals with the inventory carrying costs. These costs are given by

$$-\sum_t \sum_i \sum_k h_{i,t} D_{i,k,t} \mathrm{QF}_{i,k,t} \left[\sum_j \sum_n q_{ik,t} t_{ijkn} + \sum_j \sum_m q_{ik,t} t_{ijkm} + O_{ik} \right] \left(1-\mathrm{TR}_t\right) r_t, \qquad (\mathrm{J})$$

where $h_{i,t}$ is the inventory holding cost per hour for one unit of part type i in year t, $D_{i,k,t}$ is the customer demand of part type i through route k in period t, $\mathrm{QF}_{i,k,t}$ is the quality factor, t_{ijkn} and t_{ijkm} are the processing times for operation j of part type i on machine types n and m, and O_{ik} is the transition time between operations per part per route. Year-end inventory and year-to-year backlogging have not been taken into account. The impact of investments in CNC machinery on this type of inventory and on the year-to-year backlogging is likely negligible. Year-end inventory, furthermore, is low in case of a make-to-order situation, which is assumed here.

5.3. Model Constraints

The first two constraints deal with current and new machines to be operated. For current machines, only current machine types which existed in the last period can be disposed of, and after disposal, they do not reappear within the planning horizon. This is stated as

$$y_{m,t} \le y_{m,t-1} \qquad \forall m,t. \qquad (1)$$

Likewise, for new investments, the following constraint applies:

$$y_{n,t} \ge y_{n,t-1} \qquad \forall n,t. \qquad (2)$$

Next, depreciation values for the new machines, using a straight-line depreciation method, can be computed as

$$\mathrm{DP}_{\mathrm{n,t}} = \mathrm{DP}_{\mathrm{n,t\text{-}1}} + \left(y_{n,t} - y_{n,t-1}\right) C_{n,t} d_n \qquad \forall n,t. \qquad (3)$$

Note that the amount is based on the capital cost ($C_{n,t}$) at the time of installation. For the current machines, the depreciation amount can be written as

$$\mathrm{DP}_{\mathrm{m,t}} = y_{m,t} C_m d_m \quad \text{if} \quad \left[B_{m,0} - \sum_{t=1}^{t} C_m d_m \right] > 0 \qquad \forall m,t, \tag{4}$$

$$\mathrm{DP}_{\mathrm{m,t}} = 0 \quad \text{if} \quad \left[B_{m,0} - \sum_{t=1}^{t} C_m d_m \right] \leq 0 \quad \forall m,t, \tag{5}$$

where $B_{m,0}$ is the initial value of machine m and C_m the capital costs of machine m when acquired. If a machine is amortized ($B_{m,0} - \sum_{t=1}^{t} C_m d_m \leq 0$), or salvaged ($y_{m,t}$ = 0), the bookvalue will turn zero.

We next consider the assignment of production quantities. A production quantity can only be assigned to machine n in routing k if the machine is capable of performing the operation. This necessitates the following sets of constraints:

$$X_{ijkn,t} \leq z_{ijkn} D_{ik,t} \qquad \forall i,j,k,n,t, \tag{6}$$

$$X_{ijkm,t} \leq z_{ijkm} D_{ik,t} \qquad \forall i,j,k,m,t. \tag{7}$$

The total production quantity for a given part-operation produced through routing k should equal the demand for the part type produced through k:

$$\sum_n X_{ijkn,t} + \sum_m X_{ijkm,t} = D_{ik,t} \quad \forall i,j,k,t. \tag{8}$$

The sum of the demands for part type i per period for the routings k should equal the total customer demand per period for part type i:

$$\sum_k D_{ik,t} = D_{i,t} \qquad \forall i,t. \tag{9}$$

The $\mathrm{MAKE}_{i,n,t}$ variable should be 1 only in period t in which part type i is manufactured (partially) on machine n for the first time. This can be expressed by the following sets of constraints, where Ω represents a large value:

$$\sum_j \sum_k \sum_{t^*=1}^{t} X_{ijkn,t^*} \leq \Omega \sum_{t^*=1}^{t} \mathrm{MAKE}_{i,n,t^*} \qquad \forall i,n,t, \tag{10}$$

$$\sum_t \mathrm{MAKE}_{i,n,t} \leq 1 \quad \forall i,n. \tag{11}$$

The capacity constraints take into account the processing and setup times at each machine type

$$\sum_i \sum_j \sum_k t_{ijkn} X_{ijkn,t} \mathrm{QF}_{i,k,t} + \sum_i \sum_j \sum_k A_{ijkn} X_{ijkn,t} / q_{ik,t} \mathrm{QF}_{i,k,t} \leq \gamma y_{n,t} K_{n,t} \qquad \forall n,t, \qquad (12)$$

$$\sum_i \sum_j \sum_k t_{ijkm} X_{ijkm,t} \mathrm{QF}_{i,k,t} + \sum_i \sum_j \sum_k A_{ijkm} X_{ijkm,t} / q_{ik,t} \mathrm{QF}_{i,k,t} \leq \gamma y_{m,t} K_{m,t} \qquad \forall m,t. \qquad (13)$$

The book value of the assets is computed using the last four constraint sets. The book value of the conventional machines equals the starting value less the sum of the depreciation amounts, for all machines. If a current machine is disposed of during the planning horizon, the variable y_{mT} will be 0, so that the book value of that machine will be zero. The book value of all assets at the end of the planning horizon equals the sum of the book value of current and new machines at the end of the planning horizon.

$$\mathrm{BV}_{TM} = \sum_m [B_{m,0} - C_m d_m T] y_{mT} \quad \text{if} \quad [B_{m,0} - C_m d_m T] \geq 0, \qquad (14)$$

$$\mathrm{BV}_{TM} = 0 \quad \text{if} \quad [B_{m,0} - C_m dm\, T] < 0, \qquad (15)$$

$$\mathrm{BV}_{TN} = \sum_t \sum_n (y_{nt} - y_{nt-1}) C_{n,t} - \sum_t \sum_n \mathrm{DP}_{n,t}, \qquad (16)$$

$$\mathrm{BV}_T = \mathrm{BV}_{TN} + \mathrm{BV}_{TM}. \qquad (17)$$

6. An Illustrative Example

The following numerical example is designed to illustrate various elements and features of the model, and to present the results in an intuitive manner. Consider two part types to be manufactured, one of which is currently outsourced, while the other can be manufactured on three conventional machine types. Two new CNC machines are considered to either add to the set of current machines, or to replace them.

Table 3. Characteristics of current (m) and new (n) machines.

Type	Avail.	Capital cost (000s)	Starting value(000s)	Deprn. factor	Salvage Value (000s) $S_{m,t}$ in year		Net Capacity
m	$Y_{m,0}$	C_m	$B_{m,0}$	d_m	1	2	K_m
1	1	150	93.75	0.125	80	60	4000
2	1	250	187.5	0.125	162	130	4000
3	1	120	105	0.125	97	80	4000
4 (sub-contract.)	-	-	-	-	-	-	Unlimited

Type	Deprn. Factor	Capital costs (000s) $C_{n,t}$ in year		Capacity (Hours)
n	d_n	1	2	K_n
1	0.125	800	775	4000
2	0.125	750	735	4000

The characteristics of the current and new machines are given in Table 3. This data includes, for the current machines, the availability of the machines before the first period, the initial capital costs (at the time of the purchase of the machine), the current value of the machines, the depreciation factor, the salvage values and the net available capacity. Similarly, for the two CNC machines considered, the depreciation factor, the capital costs estimated at the various periods of introduction, and the net capacity available are provided. We assume the net capacity available of the machines to be constant over time. One could argue, however, that machines over time will have less capacity available, due to the fact that older machines often require more repair time.

The incidence matrices consisting of the z_{ijkm} and z_{ijkn} elements are given in Table 4. These matrices show the operations to be performed for each routing, and by which machines. Since there are two CNC machines considered to be invested in, we included, in this example, routings for both parts making use of the first CNC machine, of the second CNC machine and of both CNC machines. Data on setup times per lot and processing times is followed in Table 5. For example, for part one, the first operation in the second routing can be performed by the current conventional machine number two (Table 4). The setup time per lot is then 2.2 hours and the processing time equals 0.24 hour (Table 5).

Table 4. Incidence matrices

Part i	Routing k	Operation j	Current machines z_{ijkm}				CNC machines z_{ijkn}	
			1	2	3	Sub-contract	1	2
1	1	1	-	-	-	1	-	-
		2	-	-	-	1	-	-
		3	-	-	-	1	-	-
		4	-	-	-	1	-	-
		5	-	-	-	1	-	-
	2	1	-	1	-	-	-	-
		2	1	-	-	-	-	-
		3	-	-	-	-	1	-
		4	-	-	-	-	1	-
	3	1	-	-	-	-	-	1
		2	-	-	-	-	-	1
		3	-	-	1	-	-	-
		4	-	1	-	-	-	-
	4	1	-	-	-	-	-	1
		2	-	-	-	-	1	-
		3	-	-	-	-	1	-

Table 4. Incidence matrices (continued)

Part i	Routing k	Operation j	Current machines z_{ijkm}				CNC machines z_{ijkn}	
			1	2	3	Sub-contract	1	2
2	1	1	-	-	1	-	-	-
		2	1	-	-	-	-	-
		3	1	-	-	-	-	-
		4	-	1	-	-	-	-
		5	-	-	1	-	-	-
	2	1	-	-	1	-	-	-
		2	1	-	-	-	-	-
		3	-	-	1	-	-	-
		4	-	1	-	-	-	-
		5	-	-	1	-	-	-
	3	1	-	-	-	-	1	-
		2	-	-	1	-	-	-
		3	-	1	-	-	-	-
		4	-	-	1	-	-	-
	4	1	-	-	1	-	-	-
		2	1	-	-	-	-	-
		3	1	-	-	-	-	-
		4	-	-	-	-	-	1
	5	1	-	-	-	-	1	-
		2	-	-	1	-	-	-
		3	-	-	-	-	-	1

Table 5. Incidence matrices with setup times and processing times

Part i	Routing k	Operation j	Current machines $A_{ijkm};t_{ijkm}$				CNC machines $A_{ijkn};t_{ijkn}$	
			1	2	3	Sub-contract	1	2
1	1	1	-	-	-	-	-	-
		2	-	-	-	-	-	-
		3	-	-	-	-	-	-
		4	-	-	-	-	-	-
		5	-	-	-	-	-	-
	2	1	-	2.2; 0.24	-	-	-	-
		2	2.5; 0.18	-	-	-	-	-
		3	-	-	-	-	0.25; 0.22	-
		4	-	-	-	-	0.75; 0.17	-
	3	1	-	-	-	-	-	0.5; 0.21
		2	-	-	-	-	-	0.25; 0.17
		3	-	-	2.0; 0.24	-	-	-
		4	-	3.5; 0.20	-	-	-	-
	4	1	-	-	-	-	-	0.5; 0.30
		2	-	-	-	-	0.75; 0.26	-
		3	-	-	-	-	0.5; 0.22	-

Table 5. Incidence matrices with setup times and processing times (continued)

Part i	Routing k	Operation j	Current machines $A_{ijkm};t_{ijkm}$				CNC machines $A_{ijkn};t_{ijkn}$	
			1	2	3	Sub-contract	1	2
2	1	1	-	-	2.0; 0.16	-	-	-
		2	2.5; 0.25	-	-	-	-	-
		3	3.0; 0.22	-	-	-	-	-
		4	-	2.5; 0.19	-	-	-	-
		5	-	-	2.0; 0.20	-	-	-
	2	1	-	-	2.0; 0.16	-	-	-
		2	2.5; 0.25	-	-	-	-	-
		3	-	-	2.5; 0.24	-	-	-
		4	-	2.5; 0.19	-	-	-	-
		5	-	-	2.0; 0.20	-	-	-
	3	1	-	-	-	-	0.5; 0.36	-
		2	-	-	2.5; 0.24	-	-	-
		3	-	2.5; 0.19	-	-	-	-
		4	-	-	2.0; 0.20	-	-	-
	4	1	-	-	2.0; 0.16	-	-	-
		2	2.5; 0.25	-	-	-	-	-
		3	3.0; 0.22	-	-	-	-	-
		4	-	-	-	-	-	0.25; 0.35
	5	1	-	-	-	-	0.5; 0.36	-
		2	-	-	2.5; 0.24	-	-	-
		3	-	-	-	-	-	0.25; 0.35

A part can only make use of a routing, when all the machines required for the routing are present. Without investments in CNC machines, the first part type can only be outsourced. This is indicated by the first routing of that part, consisting of five operations (see Table 4). It will then make use of a fictitious outsourcing machine with unlimited capacity (M4), and the material costs will equal the price of the part, so that no monetary gain is involved (see Table 6).

Table 6. Characteristics of the two part types over two periods.

	Type 1			Type 2		
	Routing	Period 1	Period 2	Routing	Period 1	Period 2
Prices $(P_{i,t})$	1,2,3,4 (all)	120	117.6	1,2,3,4,5 (all)	99	94.54
Material Costs	1	120	117.6	all	28	28.84
$(\mathrm{MC}_{i,k,t})$	2,3,4	36	37.08			
Quality factor	1	1.00	1.00	1	1.10	1.10
$(\mathrm{QF}_{i,k,t})$	2	1.06	1.06	2	1.09	1.09
	3	1.05	1.05	3	1.06	1.06
	4	1.02	1.02	4	1.05	1.05
				5	1.03	1.03
Demand $D_{i,t}$	-	6000	6500	-	4000	4500

When investments are made in either one or both CNC machines, the first part type can be produced in-house through at most three routings (k = 2, 3, 4). We use this construction to simulate the likely increase in sales volume when investments in CNC technology are made. In the second routing, the first CNC machine takes over the last three operations, combining them into two operations (integration) while conventional machines perform the first two operations. In the third routing, the first three operations are taken over by the second CNC machine, which combines them in two operations, while the last two operations are done conventionally. The fourth routing includes both CNC machines and then only three operations are needed to manufacture the part.

The second part can be produced through two conventional routings (k = 1, 2) with five operations and three routings that combine conventional and CNC machines (k = 3, 4, 5). In the third routing, the first CNC machine takes over the first two operations (compared to the second routing), integrating them into one operation. In the fourth routing, the second CNC machine takes over the last two operations (compared to the first routing), integrating them into one operation. Finally, the fifth routing makes use of both CNC machines and integrates all operations to just three. The second operation still needs to be performed on a conventional machine.

Each routing of the two parts will be given a quality factor that represents the extra demand that has to be produced through the routing because of rejects. The prices are assumed to go down and the material costs are expected to increase over the years, as shown in Table 6. We assume the quality factor in this example to be constant over time. The demand for both parts increases over time.

Data on costs per part per routing, costs per lot per routing, transition times between operations per part per routing, and one-off costs per part per CNC machine are given in Table 7. We assume these costs to be constant over the two years. We will fix the lot size in this example to be 25, even though it can be argued that routings that include CNC machines can produce with smaller lot sizes. Further, we assume for all periods the tax rate (TR_t) to be 15%, the discount rate (w) 5% and the inventory holding costs ($h_{i,t}$) 0.001 dollar per product per hour.

Table 7. Different costs and the transition times

Part	Routing	Costs per product	Costs per lot	Transition times	Part	CNC machine	One-off costs
i	k	$CP_{i,k,t}$	$CQ_{i,k,t}$	O_{ik}	i	n	$CK_{i,n,t}$
1	1	0	0	0	1	1	2200
	2	25	110	6		2	1800
	3	24	90	6			
	4	21	50	2			
2	1	28	200	24	2	1	1500
	2	26	210	24		2	1950
	3	23	150	15			
	4	24	135	15			
	5	21	85	8			

For convenience in working with large problem formulations, a modeling language is particularly useful. For this example, the modeling language LINGO was used to solve the model presented in Section 5. It took about 5 seconds for LINGO to solve the problem, using a personal computer equipped with a MMX Pentium 200 MHz processor.

Table 8 shows three feasible solutions, and the optimal solution. In the first feasible solution, it is seen that part type 1 is to be produced using routing 4 in both periods, and also routing 1, to a small extent, in period 2. Part type 2 is to be produced using routings 4 and 5 in both periods. This provides some stability in terms of production processes employed. In terms of machine requirements, this solution calls for salvaging machine 2 at the beginning of period 1 itself, and keeping M1 and M3 for both periods. A small amount of outsourcing (M4) is called for in period 2. More importantly, this solution also calls for investment in both CNC1 and CNC2 in the first period itself. Thus, this represents an accelerated introduction of CNC technology. The NPV for this decision solution amounts to a profitable \$ 740,488.

The second feasible solution calls for a slower implementation of CNC machines, requiring investment in CNC1 in the first year, and CNC2 in the second year. No outsourcing (M4) is required in both periods. However, the two part types need to be produced using six different routings together during the two years, which may present some operational complexity. But the NPV is increased marginally to \$ 765,730.

The third feasible solution represents a slower implementation of CNC machines, requiring investments in CNC1 and CNC2 only in the second year, when machine type 1 is to be salvaged. Again, six different process plans are utilized for both parts during the two years. The NPV is seen to drop, however, to \$ 613,626.

Table 8. Three feasible solutions, and optimal solution.

	Period 1	Period 2
Solution 1, NPV = $740,488		
Part 1	< *k* =4: 6000>	< *k* =1: 52>; < *k* =4: 6448>
Part 2	< *k* =4: 2578>; < *k* =5: 1422>	< *k* =4: 3698>; < *k* =5: 802>
M1	X	X
M2	-	-
M3	X	X
M4	-	X
CNC1	X	X
CNC2	X	X
Solution 2, NPV = $765,730		
Part 1	< *k* =2: 6000>	< *k* =3: 2745>; < *k* =4: 3755>
Part 2	< *k* =2: 1356>; < *k* =3: 2644>	< *k* =3: 744>; < *k* =5: 3756>
M1	X	-
M2	X	X
M3	X	X
M4	-	-
CNC1	X	X
CNC2	-	X
Solution 3, NPV = $613,626		
Part 1	< *k* =1: 6000>	< *k* =3: 2745>; < *k* =4: 3755>
Part 2	< *k* =2: 4000>	< *k* =3: 744>; < *k* =5: 3756>
M1	X	-
M2	X	X
M3	X	X
M4	X	-
CNC1	-	X
CNC2	-	X
Optimal solution, NPV = $812,705		
Part 1	< *k* =3: 6000>	< *k* =1: 157>; < *k* =3: 6343>
Part 2	< *k* =2: 780>; < *k* =4: 3220>	< *k* =1: 1671>; < *k* =4: 2829>
M1	X	X
M2	X	X
M3	X	X
M4	-	X
CNC1	-	-
CNC2	X	X

Finally, the optimal solution, with a NPV of $ 812,705 is seen to require acquiring CNC2 in the first year and not acquiring CNC1 at all. Part type 1 is to be produced using routing 3 primarily, and part type 2, using routing 4. Thus, this solution calls for only a limited use of CNC machine tools overall.

This example is purely illustrative, to illustrate the full range of decisions involved in the context of investing CNC machines. With the rapid growth in computing power over the years, such mathematical programming problems are becoming solvable with personal computers. In larger, realistic problem contexts, many pragmatic factors can also be utilized to limit the solution space. Pragmatic factors to reduce the problem are, for instance, the combination of non-bottleneck machines with equal hourly costs, the combination of part types which will likely be produced at the same (combined) machines, and a limitation of the number of investment scenarios (i.e. at what time which CNC machine has to be purchased) to be studied.

7. Conclusions

In this paper, an integrated decision method was presented for investments in CNC machine tools. The objectives of the model are to maximize the overall net present value of the after-tax cash flows and, in the process, to determine: (1) which part types to manufacture (fully or partially), on new and/or current machines, and in what quantities each period; (2) what new CNC-machine(s) to invest in and when; and, (3) which of the current machines to dispose of, and when.

The model developed captures the relationship between investment appraisal for flexible automation technologies, and the optimal selection of parts and operations to be transferred to CNC operations. This is a key decision that impacts the economics of CNC machine use in most manufacturing firms.

From a practical point of view, one may regard the model as being large and complex. The concept however (i.e., exploring the NPV approach) is simple and we believe that sufficient transparency is gained by the clarification of the elements of the objective function and the various constraints in Section 5. In a practical situation, one may select the elements of the model, which are most dominant in the particular situation. Computer technology is evolving in such a way that it will be possible to solve reasonably sized problems.

Next to the application of the model for a practical situation, the model provides a useful reference for assessing the investment procedures applied in practice. In order to illustrate this, we studied the investment procedure used in a firm in the Netherlands and referred it to our model approach. In this firm, it was decided intuitively that there was a need to replace some old machines and/or to invest in new machines. The NPV criterion was used in the investment procedure, but only to calculate the expected profit of a single machine, at the time of investment. In our opinion and in line with our model, a more grounded decision would be taken if the investment procedure would encompass a time horizon of several years, by considering numerous new machines to invest in. The influence of part allocation on the performance of the firm was also minimally addressed in the investment procedure. Parts were intuitively assigned to the potential new machine and the impact of the part allocation on the load of the various other machines in the manufacturing department was not taken into account in the investment appraisal. In our opinion and in line with our model, the investment decision should be based upon an integral view on the effect of part allocation on the performance of the department.

Although the model provides a useful framework for investment appraisal, there are some limitations. The model presented in this paper is primarily based on a financial analysis of investments in CNC technology. Intangibles such as the learning of the organization and the image of the firm and characteristics of the various suppliers of CNC technology need to be factored into the final decision, and incorporated into a multi-objective decision framework proposed by other researchers in the past.

The model approach presented in this paper provides several opportunities for future research. The model can be seen, for instance, as the basis to study the impact of investments on the importance of the part allocation decision in firms. Also, empirical studies can be done as a follow up of this study. Keeping the basic general formulation as a foundation, it may be worthwhile to conduct empirical investigations in order to develop solid investment procedures that can be used in practice. An empirical investigation will also make clear what intangible aspects should be taken into account, and in what ways. The practical utility of such an investment is evident when one considers the amount of capital investment involved for such machine tool systems.

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