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ORIGINAL ARTICLE

E. Niemi

Optimal tool magazine operation. Part 2: rotating magazines with buffered tool change

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Abstract The paper examines the minimisation of the tool change waiting time of numerically controlled machine tools equipped with rotating tool magazines and buffering tool changers. The tool order in the various magazine operation concepts is optimised with the primary objective of minimising waiting time caused by tool change and magazine rotation. Other issues such as the total tool magazine travel are also considered. Numerical experiments are conducted and an industrial case is analysed. It was found that the optimisation is most beneficial if the magazine is large, cutting times short and the tool usage frequency distribution non-uniform. Waiting time savings of 50%–70% are typical compared to the case of random tool order in the magazine. A considerable reduction of idle times and magazine travels was reached in the industrial application described. The corresponding problem in the case of unbuffered tool change was studied in the earlier Part 1 of the paper.

Keywords Automatic tool changer · Machine tool · Tool location optimisation · Tool magazine

1 Introduction

In order to accomplish several process steps in a single sequence, numerically controlled (NC) machine tools use several automatically changed tools. Productive time is lost if the machine must wait for the tool change.

Part 1 of the paper [1] treated minimisation of the waiting time in the case of rotating magazines with unbuffered tool change.

This second part of the paper deals with waiting time minimisation of machines equipped with buffering tool changers. These typically appear in combination with large tool magazines so that the tools can be moved from and to the tool changer's loading position while the machine is cutting. Thus, productive time is wasted only if the cutting time of a tool is shorter than the time needed for the necessary tool change and magazine movement operations.

E. Niemi
Laboratory of Production Engineering,
Helsinki University of Technology (HUT),
P.O. Box 4200, 02015 Helsinki, Finland
E-mail: Esko.Niemi@hut.fi
Tel.: +358-40-5119596
Fax: +358-9-4513518

2 Tool magazines equipped with a buffering tool changer

By far the most common machining centre tool magazine types are the chain, disc, or drum magazine equipped with a double arm tool changer. These appear in machines that are used to machine workpieces requiring the use of many different tool types. This is particularly common in horizontal machining centres. Figure 1 shows such a machine tool with a typical double arm tool changer and chain magazine. The double arm and gripper act as an intermediate buffer that allows the magazine to be rotated while the tool loaded onto the spindle is cutting.

The tool change proceeds as follows: as the machining stops, the tool changer arm grips the tool on the spindle, removes it,

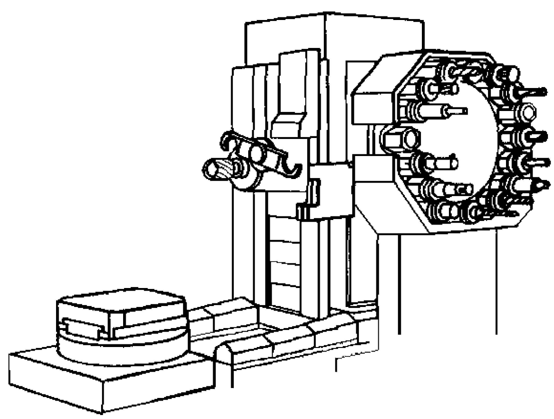


Fig. 1. Horizontal machining centre equipped with a chain magazine and a double gripper tool changer

turns 180°, loads a new tool onto the spindle and the spindle starts. The tool unloaded from the spindle is returned to the magazine, which is rotated until the tool to be used next is in the loading position of the tool changer. The tool is removed from the magazine and remains in the gripper of the tool changer until the spindle stops again. Meanwhile, the tool magazine rotates until the empty slot of the tool being used is again in the tool changer's loading position.

In order not to lose productive time, all of the above actions must take place during the ongoing process step. Unlike revolver type arrangements, the magazine must make two movements per tool change, which, on average, take twice the time of an equally sized unbuffered revolver type magazine. Variations of this procedure, with restrictions concerning the timing of the tool changer and magazine movements, appear in different makes of machine tools. Details of some of these are explained later in Sect. 3.1.

Machining centre magazines may be large; capacities of up to 200 tools appear in machine tools operating in flexible manufacturing systems (FMS). This increases the average distance between tool positions in the magazine. The tools are often heavy, and the chain magazine to be moved may weigh more than two tons. Therefore, the processing time of a tool can sometimes be much shorter than the time taken by parallel tool changing operations.

In a variation of the chain magazine concept described above, the tool unloaded from the spindle is always inserted into the empty slot of the tool to be used next. Thus, the advantages of short magazine travel of the revolver type magazine and the parallel operations of the chain type magazine are combined. The disadvantage of this concept is that, since large tools may not fit in adjacent positions, and the order of the tools in the magazine changes constantly, the tools might collide. In order to avoid this, the machine must be stopped for manual intervention. For example, in the 1970s, the Kearney&Trecker Milwaukee Matic machining centres experienced this problem. The problem is avoided by more intelligent control of the tool magazine or by using different sizes of tool slots in the magazine and corresponding control logic.

Foulds and Wilson [2] have formulated a tool magazine optimisation problem for a tool changer and magazine of the type described in the previous paragraph. In their formulation, rearrangement of the magazine is allowed during machining. They applied commercial software to the integer-programming problem obtained, and were able to solve problems of up to five tools and 30 process steps to optimality within a reasonable time.

In this paper, the tool order in the various magazine operation concepts is examined and optimised with the primary objective of minimising tool change waiting time. Other issues such as the total tool magazine movement are also considered.

3 Numerical experiments and results

The tool magazine concepts described in the previous section were examined by numerical experiments in the present study. The procedure used has been described in more detail in Part 1 of the paper. It is based on a generation of random data and application of the solution procedures, which were coded for the cases of the buffered magazines in the C programming language and run on a standard personal computer.

NC programs were generated as arrays of tool changes and cutting times. Large total numbers of tool changes were used in the experiments. These consisted of the tool changes for several repetitions of different NC programs. Since some tools are typically used more than others, in most cases an exponential distribution of tool usage frequency in the NC programs was selected. Uniform distributions were used alternatively in order to get reference results. The parameter determining the mean of the exponential distribution was set to 15% of the magazine size. In this way about 24.1% of the tools used represented 80% of all tool changes.

The cutting times were tool specific. The maximum cutting time was generated for each different tool and then the cutting time for each occasion was picked from a uniform distribution between this maximum and a fixed minimum. The cutting time unit used was the time required for the magazine to move between two adjacent tool slots.

The local search heuristic used for tool magazine optimisation was originally developed for facilities layout planning [3]. It starts with an initial solution, or tool order, for which all possible pair wise exchanges of tools are evaluated. In other words, the machine waiting time, which is the optimisation criterion, is calculated by simulating the entire magazine and tool changer operation sequence, using each tool order in the magazine obtained by exchanging the locations of two tools in the magazine. The tool order giving the lowest waiting time value is used again as the new initial solution. This procedure is repeated until no further improvement is found.

The procedure was repeated five times, starting with different initial solutions for each set of parameter values. Four of the initial solutions were random orders of tools in the magazine, and one was the order of descending tool usage frequency.

3.1 Magazines with fixed tool positions

The operating principle of a double arm tool changer used in connection with a chain magazine was explained in Sect. 2. A Gantt chart in Fig. 2 shows the operation sequence in the case where the magazine and tool changer arm can operate independently. Here, the magazine can rotate while the tool changer unloads and loads the spindle. Consequently, in order to calculate whether the spindle must wait for the next tool, one must simulate the entire process sequence.

In Fig. 2, tool number 1 is initially loaded onto the spindle and the machining starts. The magazine rotates until tool number 2 is in the loading position, after which the tool changer removes the tool from the magazine. The magazine starts to rotate in order to bring the empty position of tool number 1 to the loading position. While the magazine rotates, machining stops and the tool changer changes tool number 1 on the spindle to tool number 2, which was waiting in the gripper. When the magazine stops

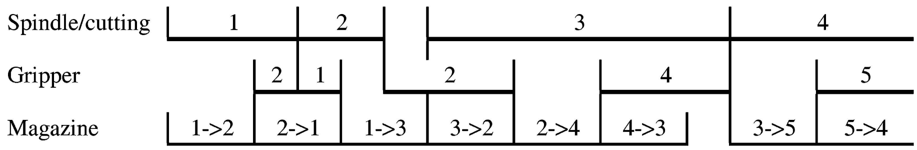


Fig. 2. Example operation sequence for a machine tool equipped with an asynchronous tool changer. The numbers represent the cutting tools on the spindle and in the tool changer grippers; for the magazine the tool slots moved to and from the load/unload position. The lengths of the lines are proportional to the durations of the associated events

moving, tool number 1 is inserted into its slot, and the magazine rotates toward tool number 3. The machining using tool number 2 stops before the next tool is in the loading position and the tool is removed from it, but the spindle remains waiting until tool number 3 is available. Tool number 3 is loaded from the magazine the instant it becomes available, but tool number 2 remains in the gripper because the magazine has not started to move toward its slot until now. The cutting time of tool number 3 is long, tool number 2 is loaded into the magazine, tool number 4 is brought to the loading position and removed from the magazine, and tool number 3's empty slot is rotated to the loading position. At this point, the magazine stops for the first time and waits until the spindle stops. Thereafter, tool number 3 on the spindle is changed to the waiting tool number 4, and the magazine starts rotating in order to bring tool number 5 to the loading position.

In certain older machine tools, the tool changer operation and magazine rotation do not occur simultaneously. The reason for this is the machine tool controller's lack of sophistication. In the sequence shown in Fig. 3, the magazine waits for the spindle to stop before it rotates the empty slot of the tool last used to the loading position. In Fig. 4, the unloaded spindle waits until the empty slot of the previously used tool is rotated to the loading position. In both cases, the two magazine movements must take place before the work can proceed and some time may be wasted compared to the operation sequence in Fig. 2. For the purposes of this study, the operating sequences of Figs. 3 and 4 are equal, and they are referred to as synchronous tool change operations in the following. Correspondingly, the operation sequence of Fig. 2 is referred to as an asynchronous tool change operation. Both types will be analysed in the light of the numerical experiments made.

In the experiments performed, the objective of the optimisation, i.e., the minimisation of the machine waiting time for tool change, was recorded in addition to the total magazine travel and the improvement from various initial situations. The operation sequences were simulated using computer programs written for the different magazine and tool changer operation types.

The parameters varied were magazine size, the average machining time in relation to magazine speed, and the tool usage distribution type, which was either exponential or uniform. Test data for magazine sizes 20, 40, 100, and 200 were generated and used.

3.1.1 Asynchronous tool change

The results of the experiments made assuming asynchronous tool change operation are shown in Figures 5 and 6. From Fig. 5, it can be seen that waiting times increase as the magazine size and the number of tools increase. This is due to the longer average tool distances in the magazine. The minimum cutting time is 10 units, the maximum 200 units, and the average is 55–64 units for results marked with B. These parameter values have been divided by two for parameter values A and multiplied by two for parameter values C. Both the increase of average cutting time and the exponential tool usage distribution compared to uniform one decrease the waiting time. Only results for average cutting time B are shown for the uniform distribution, but the effect of increase of waiting time is similar in that case.

The improvements gained by tool order optimisation compared to a random tool order are shown only for cutting times B. They are relatively smaller when the magazine is large, but in absolute terms they are always greater the larger the magazine. Compared to a random initial tool order, the improvement is greater when the tool usage is concentrated on certain tools. Not shown in the figure, the largest relative improvement can be gained when the cutting times are long, but in absolute terms, the improvement is greater when the cutting times are shorter.

The total magazine travel changes analogously as for the case of revolver type magazines discussed in Part 1 of this paper, except that the travel distances are approximately twice as long. The average magazine travel per tool change varies from 37% to 50% of the magazine size when the tools are used uniformly and from 20% to 30% when the tool usage frequency is exponentially

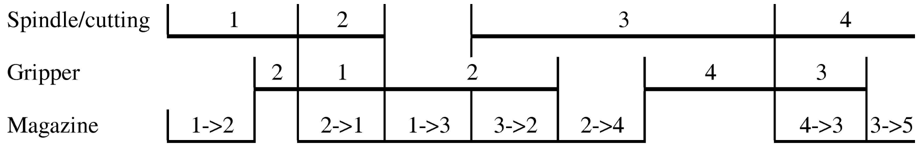


Fig. 3. Example operation sequence of a machine tool with a synchronous tool changer. In this case, the location of the previous tool is rotated to the loading position only after the new tool has been loaded onto the spindle

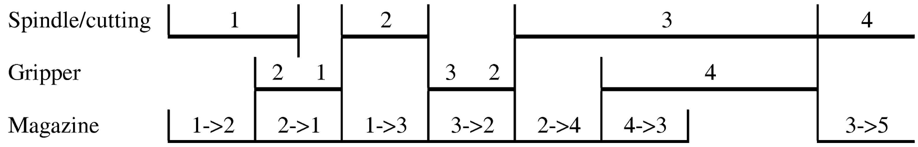


Fig. 4. Example operation sequence of a machine tool with a synchronous tool changer. In this case, the next tool is loaded onto the spindle only after the previous tool has been loaded into the magazine

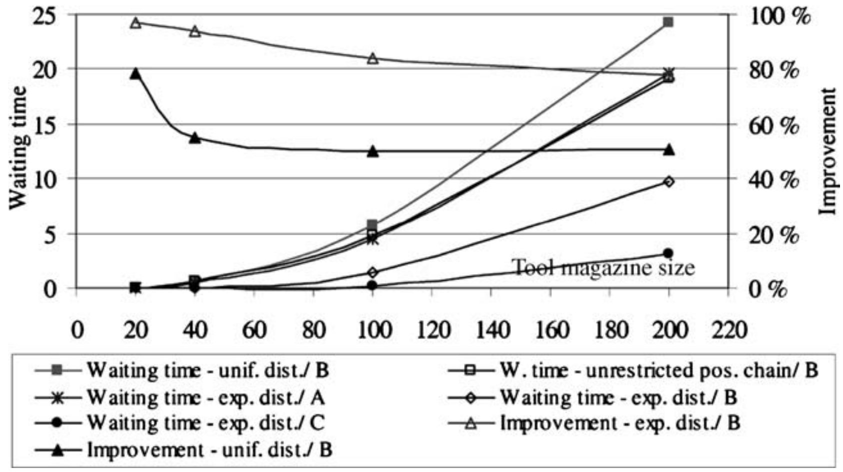


Fig. 5. Average waiting time per tool change after tool order optimisation, and the improvement gained compared to a random tool order for an asynchronous tool changer machine tool as a function of magazine size.

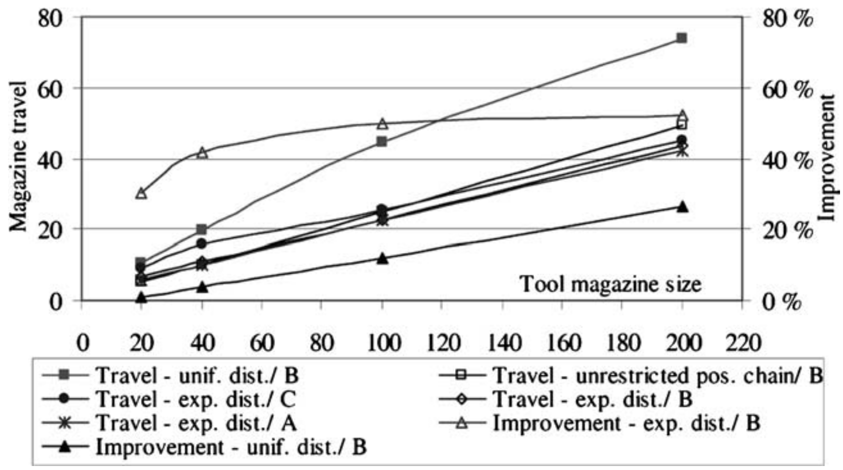


Fig. 6. Average magazine travel per tool change after tool order optimisation, and the improvement gained compared to a random tool order for an asynchronous tool changer machine tool as a function of magazine size. The results relate to the same experiments as in Fig. 5

distributed. Perfectly uniform tool usage should produce a result of 50% on average with a buffered tool changer. Cutting time has very little effect on the magazine travel. With longer cutting times, the travelled distance is slightly longer than that with shorter ones in the optimised tool arrangement. This is because there is more time available for the magazine to rotate while the tool is cutting.

The improvements in magazine travel gained by optimisation are also significant. Although the primary goal is the reduction of waiting time, the reduction of magazine travel is also important. Magazine wear, breakdowns, and noise are reduced when the magazine travel is reduced.

With small magazines, the waiting time is zero with certain parameter values. In the experiments made, magazine travel was not optimised after the shortest waiting time solution was found.

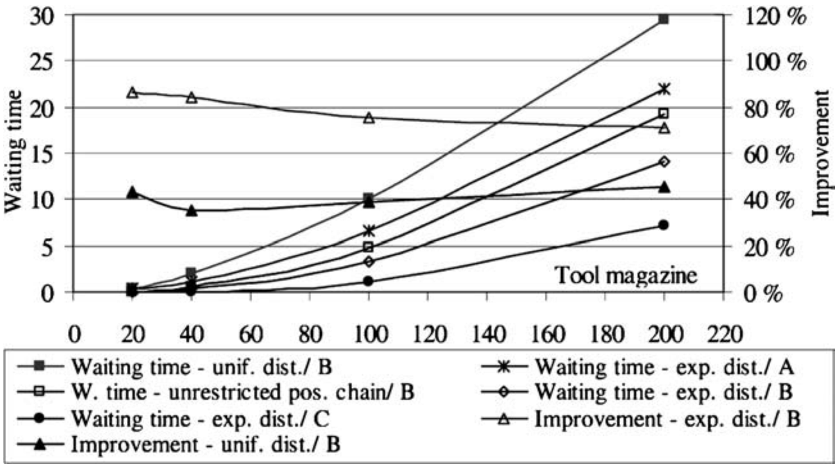
The optimisation time in the worst case, with a 200-tool magazine and approximately 4000 total tool changes, was on average approximately 5 h on a personal computer equipped with a 1.5 GHz Intel Pentium 4 processor. This can be considered acceptable, since the optimisation is not meant to be carried out frequently, and the computing times fall quickly when the size of the magazine is decreased.

The time saving gained by minimisation of magazine travel of a chain magazine was examined as an interesting side-path of the study. It was found out that most of the time saving available, about 80%–90%, can be gained by minimising the magazine travel, rather than the waiting time itself, if the tool usage is concentrated on certain tools. When the different tools are used evenly, the gain remains lower, about 40%–60% of that available in the experiments made. Since the former type of distribution is probably more common in practice, this result may be useful because the data required for optimisation of magazine travel is easy to collect. In this case, the cutting times are not required; only the order in which the tools are used needs to be known. Although commercial software for analysing NC programs exist, the work involved in collecting the cutting times for direct waiting time minimisation may be considerable.

3.1.2 Synchronous tool change

The results of the synchronous tool change type operation experiments are shown in Fig. 7. The data used is identical to the experiments with the asynchronous tool changer. The results are

Fig. 7. Average waiting time per tool change after optimisation of tool order and the improvement gained compared to a random tool order for a synchronous tool changer machine tool. The data used are identical to those in the experiments in Fig. 5



similar, but systematically worse, and the improvements gained by optimisation are smaller. This is a consequence of the extra waiting taking place from time to time with this tool changer type, as explained earlier in Sect. 3.1.

The magazine travel results are almost identical to those for the asynchronous magazine in Fig. 6, and therefore are not shown separately.

3.2 Magazines with unrestricted tool positioning

The type of chain magazine described in Sect. 2, where the previous tool is always returned to the same slot in the magazine from where the next tool to be used is fetched, was tested and compared to the other concepts. As with revolver type magazines, in this concept only one magazine movement is required, but it can be accomplished while the spindle is rotating. Waiting time is only generated if the magazine travel takes longer than the cutting operation. Because the tool order in the magazine changes randomly, tool order optimisation is not useful, and the travel distances can be long in connection with short cutting times. Figures 5 to 7 show the average waiting time and magazine travel for cutting times B. The results were obtained by simulating the magazine and tool changer operation using the same NC program data as with the other magazine types. Different initial tool orders were used. A comparison of the positions of the curves in the figures reveals that the strategy performs well compared to asynchronous and synchronous tool changers used with a uniform tool usage distribution. However, with exponential tool usage distribution, the optimised fixed tool location magazines perform noticeably better. Although not shown in the figures, the results change similarly to the fixed position magazines when cutting time parameters are changed.

In the case of exponential tool usage, the total magazine travel distance is not shorter than that in the other chain magazine concepts as one might expect; see the curve in Fig. 6. The magazine travel distances for uniform and exponential tool usage distributions are practically equal. The magazine travel shown in Fig. 6 is for NC programs with exponential tool usage distribution.

4 Analysis of an industrial case

The real-life case to be described in the following involves a Mazatech H630 horizontal machining centre used by a company manufacturing hospital appliance parts. The machine is equipped with a 120-tool chain magazine and a double arm tool changer of the synchronous type described in Sect. 3.1, and particularly of the type the operation sequence of which is shown in Fig. 3.

The NC programs of six high volume parts were selected for optimisation. These six programs used 50 different tools of a 110-tool standard set-up. A set of parts was selected, representing approximately one week's average production consisting of 200 NC program runs and 2780 tool changes in total. The tool usage frequency for these is shown in Fig. 8. The total machining and unavoidable tool changing time was 71.5 hours, and the waiting time for tool change was another 3.9 hours, or 11.7 slots per tool change in the current arrangement. The average cutting time per tool use was 93 seconds or 213 magazine speed units, since the measured average magazine speed was 2.3 slots per second. The cutting time distribution is shown in Fig. 9. The total

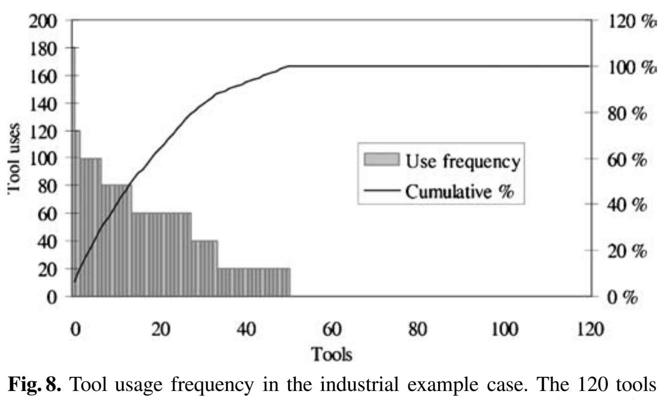


Fig. 8. Tool usage frequency in the industrial example case. The 120 tools are represented on the horizontal axis in descending order of usage frequency. The vertical axis on the left shows the number of times they are used during the week's production

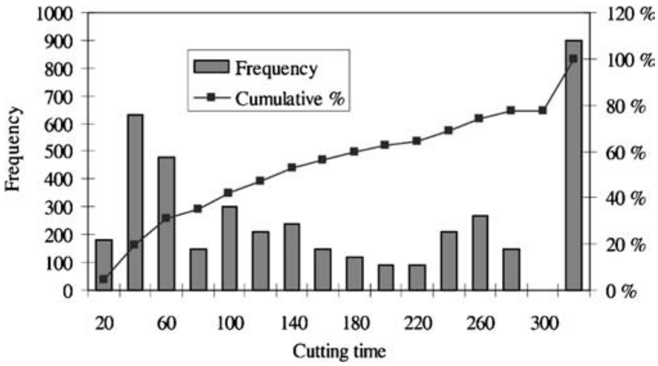


Fig. 9. Cutting time distribution of the tool uses in the part set of the example case

magazine travel was 125,300 tool slot distances, or 45 per tool change on average.

The current tool set-up was so organised that one segment of the tool magazine was reserved for drills, and other segments for centre drills, taps, broaches, shank mills, angle mills, boring tools, etc. The tools in each segment were typically in the order of increasing physical size of the tool. This is a common, and from the machine operator's point of view, a logical arrangement. However, if productivity is considered, it is far from optimal. From the point of view of magazine waiting time, the tool order was random, both within segments and overall.

Through the optimisation of the tool order in the magazine, the waiting time was reduced from 3.9 hours to 24 minutes, 1.2 tool positions per tool change on average, and the total magazine travel to 63 920 slot distances, from 45 to 23 per tool change on average. In the final arrangement, all 50 tools used by the NC programs that the optimisation was based on were located in adjacent positions in the magazine. An optimisation run took approximately 10 seconds on the personal computer equipped with a 1.5 GHz Intel Pentium 4 processor used in the other experiments.

The result is well in line with the graphs in Figures 6 and 7 if the following interpretations are assumed: the tool usage distribution shown in Fig. 8 can be considered roughly exponential, and the cutting time distribution in Fig. 9 relatively uniform. The average cutting time is effectively approximately 110 units, if the very long cutting times, which do not prolong waiting time, are neglected. In light of these remarks, the results obtained are close to the corresponding values in the stated figures.

The obtained magazine tool order was put into permanent operation by the company.

5 Conclusions

The numerous and extensive experiments made and results obtained provide a basis for evaluation and prediction of the performance and suitability of various tool change and magazine arrangements for different uses of numerically controlled machine tools. The magazines examined are of the rotating type, and the tool changers of the buffering type.

The results show how different tool change and magazine operation methods affect the waiting time for tool change and magazine travel. It appears that optimisation of tool order of a fixed tool position magazine decreases both waiting time and magazine travel significantly compared to a random tool order in the magazine. Even the largest magazines can be optimised efficiently in an acceptable time on a standard personal computer using a simple local search algorithm.

Indeed, it appears that optimisation is most beneficial when the magazine is large, cutting times are short, and the tool usage frequency is concentrated on certain tools. Waiting time savings of over 70% are typical compared to a random tool order in the magazine. If the tool usage is approximately uniformly distributed, savings of over 50% are typical.

Magazine travel reduction gained by optimisation of waiting time typically varies in the case of exponential tool usage distribution from 30% to 50%, the larger relative and absolute savings being achieved with large magazines. With uniform tool usage, the potential savings are essentially smaller.

It is also found that when tool usage concentration is high, most of the waiting time savings can be gained by optimising with the objective of minimising magazine travel. This may sometimes be useful because data collection is much easier in this case.

The type of chain magazine where the previous tool is always returned to the same slot in the magazine from where the next tool to be used is fetched, was compared to a fixed-position magazine. It was found to be less efficient than an optimised fixed-position magazine if the tool use was concentrated on certain tools, but more efficient if the tool use was uniformly distributed.

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