Study on Process Planning System for Holonic Manufacturing*
(Selection of Machining Sequences and Sequences of Machining Equipment)

Suyoto RAIS**, Nobuhiro SUGIMURA**
and Atsushi KOKUBUN**

New architectures of manufacturing systems have been proposed aiming at realizing more flexible control structures of manufacturing systems which can cope with dynamic changes in volume and variety of products. They are so called as holonic manufacturing systems, autonomous distributed manufacturing systems, random manufacturing systems and biological manufacturing systems. The objective of the present research is to develop an integrated process planning and scheduling system which is applicable to the holonic manufacturing systems. In the previous paper, procedures were proposed to recognize the machining features from the product model. A systematic method is proposed, in this paper, to select suitable machining sequences and sequences of machining equipment, by applying the genetic algorithm (GA) and the dynamic programming (DP) methods.

Key Words: Production System, Holonic Manufacturing System, Process Planning, Machining Sequence, Machining Features, Genetic Algorithm, Dynamic Programming

1. Introduction

New manufacturing system architectures for machine products are now being proposed aiming at realizing high productivity in high variety small batch productions with dynamic changes in volumes and varieties of products. The proposed systems carry out management and control tasks based on autonomous distributed decision making of intelligent manufacturing devices. They are so called as holonic manufacturing systems, autonomous distributed manufacturing systems, random manufacturing systems, and biological manufacturing systems*(1)-(9), and applied to scheduling problems. However, the process plans of the products, such as machining sequence and sequence of machining equipment, are assumed to be pre-determined and fixed in these scheduling problems.

The objective of the present research is to develop a distributed process planning system that can take into consideration of the machining schedules of the machining equipment. In the previous paper*(9), systematic procedures of workpiece holons were proposed to extract the machining features from the inputted product model data, referring to the machining functions of the machining equipment. This paper deals mainly with systematic methods to select suitable machining sequences of the machining features and sequences of the machining equipment based on the machining features of the workpieces and the machining functions of the machining equipment.

2. Basic System Architecture

2.1 System architecture

A process planning system shown in Fig.1 was
proposed in the previous paper\(^7\), which consists of three types of holons; they are, order holons, workpiece holons and machining equipment holons. The tasks of the holons in process planning are summarized in the followings;

2.1.1 Order holon The order holons represent the product orders, and have the attributes of types, volumes and due date of the ordered products. The order holon determines the information about the product lots by dividing and combining the product orders, and generates the workpiece holons representing the product lots which are manufactured simultaneously in the manufacturing systems.

2.1.2 Workpiece holon The workpiece holons corresponds to the individual product lots, and have the attributes of product model, due date and lot size. One product order may be divided into several workpiece holons, and the process planning tasks are carried out by the individual workpiece holons.

2.1.3 Machining equipment holon The machining equipment holons represent the machining equipment, such as machine tools, fixturing devices and cutting tools, and have the information about the machining functions and the machining schedules.

The individual workpiece holons in the above holonic architecture carry out the process planning tasks based on the machining functions.

2.2 Process planning procedure

This paper deals with the process planning tasks of the workpiece holons in the planning phase. The process planning tasks of the workpiece holons are basically carried out as shown in the followings.

2.2.1 Extraction of machining features

The machining features are defined here as the groups of the faces which are machined concurrently by the same combinations of the cutting motions, the feed motions, the fixturing positions, and the cutting edge types. The following steps carry out the extraction procedures of the machining features.

a) Extraction of faces to be machined

All the faces to be machined are extracted based on the product information. The elemental faces to be machined, such as plane faces, cylindrical faces, conical faces, torus faces and spherical faces, are derived from the three dimensional product models.

b) Selection of feasible machining functions of faces

Feasible machining functions are selected for the individual extracted machining faces. The machining functions of the machining equipment are defined, in the research, as the combinations of the cutting motions, the feed motions, the fixturing positions, and the cutting edge types.

c) Integration of faces to generate machining features

Machining features are generated by combining a set of faces which can be generated concurrently by the same machining functions.
2.2.2 Selection of feasible machining equipment for machining features

Feasible machine tools, fixturing positions and cutting tools are selected for the individual machining features referring to the machining functions of the machining equipment.

2.2.3 Determination of suitable machining sequences and sequences of machining equipment

Suitable machining sequences of all the machining features and sequences of the machining equipment are determined for the individual workpieces by selecting and arranging the machine tools, the fixturing positions and the cutting tools for all the machining features of the workpieces. The preference relations among the machining features are considered in the process.

The procedures to extract the machining features have been proposed in the previous paper\(^2\). Systematic procedures are proposed, in the paper, to select feasible machining equipment for the individual machining features and to select suitable machining sequences and sequences of machining equipment.

3. Selection of Suitable Machining Sequence and Sequence of Machining Equipment

3.1 Procedures

The machining features extracted from the product model have the following information\(^2\).

(a) ID numbers, areas and surface roughness of the faces composing the machining features, and
(b) Feasible machining functions that can generate the machining features.

Suitable machining sequences of the machining features and sequences of the machining equipment are selected by the procedures given in the followings.

STEP-1 Preference relations among machining features

Preference relations among the machining features are firstly determined based on the face ID, shapes and surface roughness of the machining features.

[i] If there are a rough machining feature and a finish machining feature, both of which are extracted from the same face of the product, high priority is given to the rough machining feature.

[ii] If there is a hole feature on a plane feature, high priority is given to the plane feature.

For example, if there are a rough plane feature and a finish plane feature, which are extracted from a same face of the product, high priority is given to the rough plane face. There may be other types of experimental preference rules in the machining processes, however, the rules above mentioned are considered in the research as the fundamental ones.

STEP-2 Selection of feasible machining equipment

Feasible machining equipment for the individual machining features are selected based on the surface roughness and the machining functions of the machining features. The selection process is carried out by referring to the files shown in Tables 1, 2 and 3.

The machining function file is given to the machining equipment holons. The machining functions are presented by the information about the combinations of the machine tools, the fixturing positions and the cutting tools. The surface roughness and the material removal rate are also given in the file, which specify the performance of the combinations of the machine tools, the fixturing positions and the cutting tools. The machine tool file describes the information about the cutting motion, the feed motion, and the maximum workpiece size. The characteristic features of the cutting tools are described in the cutting tool file. It includes such information about the tool types, the tool sizes and the cutting edge types.

The machine tool file is firstly retrieved to select feasible machine tools, which satisfy the cutting motions and the feed motions required by the machining features and also satisfy the sizes of the products. Feasible fixturing positions are also selected based on the main spindle directions and the directions of the machining features. Secondly, feasible cutting tools are selected by retrieving the cutting tools that satisfy the requirements on the cutting edge types. Finally, it is examined whether or not the selected combinations

<table>
<thead>
<tr>
<th>Machining Function ID</th>
<th>Machining Equipment</th>
<th>Roughness Ra</th>
<th>Removal Rate (mm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0101</td>
<td>MT01</td>
<td>65</td>
<td>8.0</td>
</tr>
<tr>
<td>M0102</td>
<td>MT02</td>
<td>25</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Table 1 Machining function file

<table>
<thead>
<tr>
<th>Machine Tool ID</th>
<th>Cutting Motion</th>
<th>Feed Motion</th>
<th>Range of Movement</th>
<th>Fixturing Device</th>
<th>Cutting Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>C(T)</td>
<td>A(X,Y)</td>
<td>90×80×75</td>
<td>F060</td>
<td>CT001</td>
</tr>
<tr>
<td>M02</td>
<td>C(T)</td>
<td>L0(X)</td>
<td>45×40×45</td>
<td>F080</td>
<td>CT002</td>
</tr>
</tbody>
</table>

Table 2 Machine tool file

<table>
<thead>
<tr>
<th>Cutting Tool ID</th>
<th>Tool Type</th>
<th>Size</th>
<th>Cutting Edge/</th>
<th>Feed Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT01</td>
<td>Tr Tool</td>
<td>D60</td>
<td>Point, Straight Line</td>
<td>L0(X,Y)</td>
</tr>
<tr>
<td>CT02</td>
<td>Gr Tool</td>
<td>D100</td>
<td>Circular Plane, Cylinder</td>
<td>A0(X,Y)</td>
</tr>
</tbody>
</table>
of the machine tools and the cutting tools satisfy the surface roughness required by the machining features, by retrieving the machining function files.

**STEP-3 Estimation of machining time**

The machining time $T_i$ of the individual machining features $MF_i$ are estimated for the combinations of the machine tools, the fixturing positions and the cutting tools, based on the following equation.

$$ T_i = A_i / MR $$  \hspace{1cm} (1)

Where, $A_i$ is the total area of the machining feature $MF_i$ and $MR$ is the material removal rate given in the machining function file. The material removal rates in the file specify the area that can be finished in a unit time by the individual combinations of the machine tools, the fixturing positions and the cutting tools.

**STEP-4 Selection of suitable machining sequence and sequence of machining equipment**

As the results of the STEP-1 to STEP-3, the following information is obtained.

1. Preference relations among machining features
   
The preference relations specify the constraints on the machining sequences. The preference relations are given in the binary relation form as shown in the following.

   $$ MF_i < MF_j \quad (i, j = 1, 2, \ldots, m) $$  \hspace{1cm} (2)

   where, $MF_i$ and $MF_j$ are the machining features, and the $MF_i$ should be machined prior to the $MF_j$, $m$ is the total number of the machining features.

2. Machining equipment of machining features
   
The individual machining features $MF_i$ have feasible machining equipment $ME_{ia}$, which are represented by the combinations of the machine tools $MT_{ia}$, fixturing positions $FI_{ia}$, and cutting tools $CT_{ia}$.

   $$ ME_{ia} = \{ MT_{ia}, FI_{ia}, CT_{ia} \} \quad (k = 1, 2, \ldots, n_i) $$  \hspace{1cm} (3)

3. Machining time of machining features
   
The machining time $T_{ia}$ of the machining features $MF_i$ are specified for all the feasible machining equipment $ME_{ia}$.

   $$ T_{ia} \quad (k = 1, 2, \ldots, n_i) $$  \hspace{1cm} (4)

   The suitable machining sequences and sequences of machining equipment are determined based on the information above mentioned, as shown in the following sections.

3.2 Selection of machining sequences and sequences of machining equipment

The objective of the problem considered here is to select suitable machining sequences of the machining features and suitable sequences of the machining equipment for the individual machining features. Equations (2), (3) and (4) give the constraints on the machining sequences and the sequences of the machining equipment.

The objective function of the problem is to minimize the total machining time which is the sum of the machining time of the machining features and the set-up time needed to change the machine tools, the fixturing positions, and the cutting tools. There have not yet been carried out the researches dealing with the problem to select both the machining sequences and the sequences of machining equipment concurrently. A procedure shown Fig. 2 is proposed to solve the problem. In the figure, the boxes and the arcs show the procedures and the information, respectively. The procedure includes the following two steps.

Sets of individuals representing the feasible machining sequences of the machining features are firstly generated by applying the GA (Genetic Algorithm), which satisfy the constraints on the preference relations among the machining features. The offspring is then generated from the initial populations by applying the crossover and the mutation operations. In the second step, an optimum sequence of machining equipment is generated, by selecting suitable machining equipment for each machining feature in one machining sequence, in order to select the individuals surviving to the next generation. The DP (Dynamic Programming) method is applied to select the sequence of machining equipment that minimizes the machining time and the set-up time.

Suitable machining sequences of the machining features and suitable sequences of the machining equipment

\[ \text{Generation of feasible machining sequences of machining features by Genetic Algorithm} \]

\[ \text{Selection of optimum machining equipment by Dynamic Programming for each machining sequence} \]

\[ \text{Optimum machining equipment of machining features} \]

\[ \text{Total machining times} \]

\[ \text{Suitable machining sequence of machining features} \]

\[ \text{Suitable machining equipment and total machining time} \]

![Fig. 2 Selection of suitable machining sequence and sequence of machining equipment](image-url)
equipment can be obtained by repeating the procedures.

3.3 Selection of machining sequences based on GA

The gene $L^3$ of the individuals $Z$ in GA is described in the following form, which gives a candidate of the machining sequence of the machining features.

$$L^3 = \{f^1, f^2, \ldots, f^n\}$$  \hspace{1cm} (5)

where, $f^i$ is an ID of the machining feature to be machined in the $i$-th process in the machining sequence. The following processes are applied to the individuals to generate the feasible machining sequences.

(1) Generation of feasible individuals

In the first step of GA, the individuals in the initial population are generated randomly as the first parent generation. The number of initial individuals is $a$. If the generated individuals do not match the preference relations among the machining features, they are removed.

(2) Crossover and mutation

In the second step, a set of offspring is generated from the parent population by applying the crossover operators. The number of populations generated here and the probability of crossover are $\beta (<a)$ and $P_o$, respectively. The mutation operation is also applied to the offspring for generating additional offspring. The number of populations and the probability of mutation are $\gamma$ and $P_n$, respectively. If the newly generated individuals do not match the preference relations among the machining features, they are removed.

All the individuals of the parent and the offspring are evaluated from the viewpoint of the total machining time, by applying the procedure presented in the next section. Suitable individuals are selected to survive to the next generation, and the crossover and mutation operators are applied repeatedly. After repeating the procedure mentioned above until the $D$-th generation of individual is generated, suitable machining sequences are obtained.

Various types of operations have been proposed for the crossover and the mutation. As regards the crossover, three types of operations have been verified in the research. They are, PMX (Partially Mapped Crossover)\textsuperscript{(8)}, CX (Cycle Crossover)\textsuperscript{(8)}, and EXX (Edge Exchange Crossover)\textsuperscript{(10)}. The methods have been applied to the scheduling problems and the traveling salesman problems. The calculation time needed to obtain the solutions by these methods has been verified through the numerical experiments, and the results are not so different. Therefore, the PMX method is applied in the research.

Three methods for the mutation called exchange, inverse and insertion\textsuperscript{(11)} have also been verified from the viewpoint of the calculation time, and much difference was not observed. The exchange is applied in the research for the mutation.

The numerical experiments were also carried out to select a suitable set of parameters in GA. In the experiments, the machining feature data shown in Eqs. (2), (3) and (4) were generated randomly, and the procedures of GA and DP were applied under the various conditions of the GA parameters, such as $a$, $\beta$, $\gamma$, $D$, $P_o$, and $P_n$. It was shown, through the experiments, that the objective function given by the total machining time is not rapidly improved after 2,000 generations. The parameters of GA were fixed as follows based on the experiments. $a=20$, $\beta=18$, $\gamma=2$, $D=2,000$, $P_o=0.5$, and $P_n=0.1$.

3.4 Selection of sequence of machining equipment based on DP

The problem to be solved here is summarized in Fig. 3. In the figure, the nodes in the upper part shows the machining features $MF_i$ to be machined in $i$-th process. The nodes $ME_0$, $ME_{n+1}$ and $ME_i$ in the lower part denote the two terminal nodes and the feasible machining equipment selected for $MF_i$. The arcs between the nodes $ME_0$ and $ME_{i+1}$ specify the sum of the machining time and the set-up time given in the following.

$$T_{i+1} = T_{i+1} + ST_{i+1}$$  \hspace{1cm} (6)

where, $T_{i+1}$ is the machining time of the machining feature $MF_{i-1}$ by the machining equipment $ME_{i+1}$, and $ST_{i+1}$ is the set-up time between the machining equipment of $ME_i$ and $ME_{i+1}$. The set-up time depends on the combinations of $ME_i$ and $ME_{i+1}$, however, the set-up time is assumed here to be constant as follows, for the ease of calculation.

$$ST_{i+1} = STM$$ (if the machine tools are changed)

$$STA$$ (if the fixtureing positions are changed)

$$STT$$ (if the cutting tools are changed)

0 (if the machining equipment is not changed)$$STT < STF < STM$$  \hspace{1cm} (7)

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig3.png}
\caption{Selection of suitable sequence of machining equipment}
\end{figure}
Table 4  Machining features extracted

<table>
<thead>
<tr>
<th>Machining Feature ID</th>
<th>Machining Equipment</th>
<th>Machining Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF01</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
</tr>
<tr>
<td>MF32</td>
<td>MT12-FI902-CT133</td>
<td>10,270</td>
</tr>
<tr>
<td>MF30</td>
<td>MT3-FI902-CT30</td>
<td>1,926</td>
</tr>
<tr>
<td>MF6</td>
<td>MT6-FI902-CT51</td>
<td>7,702</td>
</tr>
</tbody>
</table>

Table 5  Preference relations among machining features

<table>
<thead>
<tr>
<th>Proceeding</th>
<th>MF11</th>
<th>MF30</th>
<th>MF23</th>
<th>MF32</th>
<th>MF20</th>
<th>MF18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Succeeding</td>
<td>MF30</td>
<td>MF25</td>
<td>MF32</td>
<td>MF17</td>
<td>MF16</td>
<td>MF21</td>
</tr>
</tbody>
</table>

Fig. 4  Product model and machining features

The dynamic programming method is adopted to select an optimum sequence of the machining equipment which minimizes the total machining time including both the machining time of the machining features and the set-up time needed to change the machine tools, the fixturing positions and the cutting tools.

4. Case Study

A prototype of the process planning system has been implemented on PC by using Small-talk and Visual Basic. Some case studies have been carried out to verify the effectiveness of the procedures proposed here. Figure 4 shows an example of the product model of the machine product for the case studies. This figure also shows a part of the machining features extracted from the product model. Thirty-two machining features were extracted in this case. Table 4 gives feasible machining equipment and machining time for the machining features. The preference relations among the machining features are summarized in Table 5.

A suitable machining sequence and a sequence of machining equipment were obtained as shown in Table 6, by applying GA and DP. The set-up time needed for change the machine tools was set to be relatively large, therefore, the obtained machining sequence and the sequence of the machining equipment minimized the number of changes of the machine tools.

Table 6  Suitable machining sequence and machining equipment

<table>
<thead>
<tr>
<th>No</th>
<th>Machining feature ID</th>
<th>Machining equipment</th>
<th>Machining time</th>
<th>Setup Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MF20</td>
<td>MT14-FI403-CT135</td>
<td>3,898</td>
<td>1,000</td>
</tr>
<tr>
<td>2</td>
<td>MF02</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>MF01</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>MF04</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>MF05</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>MF09</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>MF07</td>
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<td>575</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>MF08</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>MF03</td>
<td>MT14-FI403-CT133</td>
<td>575</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>MF18</td>
<td>MT14-FI403-CT138</td>
<td>3,898</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>MF24</td>
<td>MT14-FI403-CT27</td>
<td>4,033</td>
<td>10</td>
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<tr>
<td>12</td>
<td>MF13</td>
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<td>1,720</td>
<td>0</td>
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<tr>
<td>13</td>
<td>MF12</td>
<td>MT14-FI403-CT27</td>
<td>1,662</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>MF15</td>
<td>MT14-FI403-CT27</td>
<td>84</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>MF22</td>
<td>MT14-FI403-CT140</td>
<td>84</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>MF31</td>
<td>MT14-FI403-CT140</td>
<td>84</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>MF36</td>
<td>MT14-FI403-CT140</td>
<td>84</td>
<td>0</td>
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<td>18</td>
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<td>MT14-FI403-CT140</td>
<td>84</td>
<td>0</td>
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<td>19</td>
<td>MF14</td>
<td>MT14-FI403-CT140</td>
<td>84</td>
<td>0</td>
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<td>20</td>
<td>MF39</td>
<td>MT14-FI403-CT140</td>
<td>84</td>
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<td>21</td>
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<td>22</td>
<td>MF39</td>
<td>MT14-FI403-CT23</td>
<td>356</td>
<td>10</td>
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<tr>
<td>23</td>
<td>MF23</td>
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<td>1,025</td>
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<td>24</td>
<td>MF09</td>
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<td>13,813</td>
<td>10</td>
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<tr>
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<td>MT3-FI302-CT81</td>
<td>1,628</td>
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</tr>
<tr>
<td>26</td>
<td>MF27</td>
<td>MT3-FI302-CT27</td>
<td>447</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>MF11</td>
<td>MT3-FI302-CT27</td>
<td>873</td>
<td>0</td>
</tr>
<tr>
<td>28</td>
<td>MF30</td>
<td>MT3-FI302-CT27</td>
<td>625</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>MF32</td>
<td>MT3-FI302-CT30</td>
<td>1,662</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>MF17</td>
<td>MT17-FI702-CT27</td>
<td>6,750</td>
<td>1000</td>
</tr>
<tr>
<td>31</td>
<td>MF25</td>
<td>MT17-FI702-CT27</td>
<td>1,668</td>
<td>0</td>
</tr>
<tr>
<td>32</td>
<td>MF21</td>
<td>MT17-FI703-CT27</td>
<td>7,796</td>
<td>100</td>
</tr>
</tbody>
</table>

Total machining time 86,280

5. Conclusions

Systematic procedures were proposed, in the paper, to select suitable machining sequences and suitable sequences of machining equipment based on GA (Genetic Algorithm) and DP (Dynamic Programming), aimed at realizing a process planning system for the holonic manufacturing systems. Following items are concluded.

(1) A systematic procedure was proposed to select feasible machining equipment and to estimate machining time for the individual machining features based on the information about the machining functions.

(2) A systematic method was proposed to select suitable machining sequences of the machining features and suitable sequences of the machining equipment based on the genetic algorithm and the dynamic programming. The method provides us to select solutions that minimize the total machining time including the machining time and the set-up time.

(3) A prototype of the process planning system has been implemented and applied to the process planning for the machine products. It was shown, through case studies, that the proposed methods are effective to generate suitable machining sequences and suitable sequences of the machining equipment based on the product model of the finished products. The process planning capabilities can be added to the
workpiece holons based on the procedures proposed here.

References