Development of Intelligent Mold Shop

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ABSTRACT

Presented in the paper is an approach to developing an intelligent mold shop as a means to overcome the difficulties faced by mold-makers due to skill shortages and increased global competition. A machine shop where as much as of the human skills are replaced by a set of intelligent systems is called an *intelligent machine shop*, and an intelligent mold-making machine shop is called an *intelligent mold shop (IMS)*. By analyzing the contents of operator's skill, three intelligent S/W stations have been designed: Technical Data Processing (TDP) Station, Loading Schedule Station, and Real-time Monitoring Station. A detailed architecture of the TDP station is described, and measures of effectiveness of IMS are elaborated.

Keywords: Intelligent mold shop (IMS), effectiveness measure of IMS, functional model of mold shop, loading scheduling, machining process monitoring, software architecture

1. INTRODUCTION AND MOTIVATION

These days almost all products are designed with sophisticated freeform shapes as the aesthetic aspect of product features is becoming more critical, and life cycles of these products are becoming shorter and shorter due to higher customer expectations and rapid technological developments. Since every product shape defined by CAD systems may have to be realized by molding dies, all the pressures of shape complexity and time squeeze are on the shoulders of mold makers. In other words, set makers are pressing hard the mold makers to supply more complicated molding dies at shorter lead times, of course, at a lowest possible cost and highest quality.

On the other hand, the mold-making industry itself is under severe global competition. According a survey report [1] by Korea Trade Commission, the world wide market for molds and dies in 2003 is about 63 billion US dollars (about 7 billion in the US; about 4 billion each in Germany, Japan, and Korea; about 3 billion in China) with an annual increase of 10%. By nature, most mold-making companies (in Korea) are small ones having less than 100 employees. To be competitive, mold-making companies have to invest in high tech equipment even under uncertain prospect of return on investment.

However, the most serious difficulty faced by mold-makers is shortage of skills. According to the above mentioned survey report, major difficulties of mold-makers are: 1) recruiting new operators, 2) retaining existing skilled operators, 3) high and rising labor costs, 4) keeping on-time delivery, 5) meeting reduced lead time, 6) meeting the high-precision quality requirements.

One approach to overcoming the mold-maker's difficulties would be to make the mold-making process less dependent on human skills. In a traditional mold-making company, the machining stage of mold-making process is heavily dependent on human skills. Thus, the primary target for skill-replacement is the machine shop. A machine shop where as much as of the human skills are replaced by a set of intelligent systems is called an *intelligent machine shop*. Further, an intelligent mold-making machine shop is called an *intelligent mold shop* for short. It should be pointed out that our approach is not based on a "theoretical" IMS concept such as holonic manufacturing [2].

Presented in the paper is an approach to developing an intelligent mold shop. How to design an IMS (intelligent mold shop) is described in section 2, and some details of "technical data processing station" which is the key component of IMS are presented in section 3. Measures of effectiveness of IMS are elaborated in the section that follows, and conclusions and discussions in the final section.

2. DESIGN OF INTELLIGENT MOLD SHOP

A traditional mold-making machine-shop consists of physical resources and human operators. Key resources required for mold-making are NC machines, die-spotting machine, coordinate measuring machines (CMM), and CAM software system as shown in Fig. 1. Human operators are responsible for information processing and physical handling using their brain, sensing mechanisms (eyes, ears, etc.) and muscles. As this machine shop relies heavily on human skills, it is often called a *skill-based machine shop*. An *intelligent machine shop* is a machine shop where as much as of the human skills are replaced by a set of "IMS S/W systems" composed of knowledge bases (KB), software modules and hardware components, as depicted in Fig. 1.

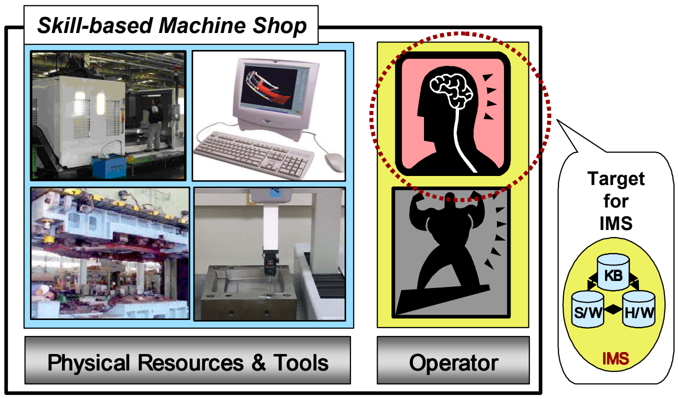


Fig. 1. Concepts of skill-based machine shop and intelligent machine shop

A mold-making process may be regarded as a series of information/physical transformation and quality assurance activities, as shown in Fig. 2(a). Starting from the CAD model of the item to be molded, major transformation activities include *Layout design* of mold set, *Detail design* of the stationary core and moving core, *Core machining, Polishing & assembly*, and *Tryouts*. Quality assurance activities involved are *Die-spotting* and *Sample evaluation*.
Shown in Fig. 2(b) are activities involved in core-machining. Starting from the CAD model of the core, 1) NC-data files are generated and verified; 2) the verified NC-codes are filtered for high-performance machining; 3) the core is machined while making in-process inspections; 4) the final shape of the machined core is measured on a CMM, and correction instructions are generated if necessary. For the CMM measuring, CMM instructions have to be provided based upon the CAD model.

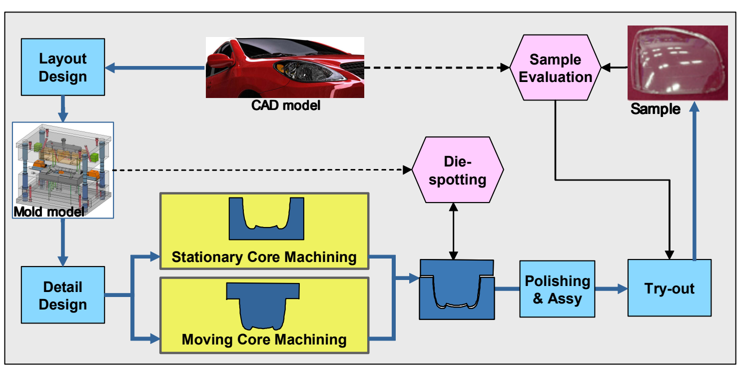


Fig. 2(a). Overall mold-making cycle and major activities

In order to design an intelligent machine shop for mold-making, human skills required to perform the activities in Fig. 2(b) need to be analyzed in detail. Among the activities in Fig. 2(b), **NC-codes filtering, NC-machining** including in-process inspection, and **Mold inspection** are carried out by the machine-shop operators. In addition, they are responsible for **Tooling** and **Setup** needed for NC-machining as well as **Loading-scheduling** of shop-floor operations (not shown in the figure). In the mold-shop we have studied, those machine-shop activities accounted for 40~50% of cost and lead-time.

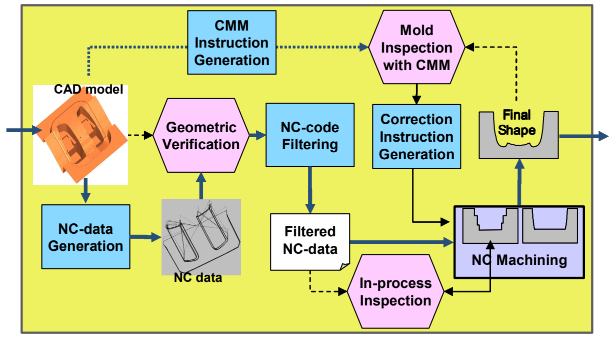


Fig. 2(b). Core machining activities

Listed in Tab. 1 are major machine-shop activities performed by operators in a skill-based machine shop, together with associated tasks and their contents (where the "shaded" tasks are to be covered by the IMS S/W systems):

1) Tooling: Tool spec planning and cutting tool preparation
2) Setup: Setup planning and actual setup
3) NC-code filtering: Cutting condition editing and ATC-file generation
4) NC-machining: Initial setting & adjustment, monitoring and in-process inspection
5) Mold inspection: CMM-file generation and measured data analysis
6) Loading scheduling: Loading planning and expediting

Activities	Tasks	Task contents
Tooling	Tool spec planning	Determine effective tooling spec (holder, sleeve, tool materials, etc) from nominal cutter spec
	Tool preparation	Preset & assemble a tooling set and install it on the tool magazine
Setup	Setup planning	Determine clamping positions/methods and checking points from given datum surfaces
	Setup	Setup the work-piece and set reference points using indicators and setting bar
NC-codes Filtering	Feed-rate/RPM editing	Adjust feed-rate and RPM values to avoid overloading and to increase productivity
	ATC-file generation	Generate ATC (auto tool-change) codes and combine them with NC-data to form an ATC file
NC-machining	Initial setting/adjusting	Start DNC-file transfer & machining, and adjust coolant position & gain control
	Monitoring	Watch the machining process for abnormal events (tool breakage, collision, overload, etc)
	In-process inspection	Inspect the machined surface after each machining stage
Mold Inspection	CMM-file generation	Plan probe-paths and generate CMM-file from given CAD model and inspection spec
	CMM operation	Setup the work-piece on CMM (coordinate measuring machine) and operate the CMM
	Measured data analysis	Analyze the errors (deviations) and make recommendation for rework, etc.
Loading Scheduling	Loading planning	Assign individual machining operations to NC machines based on process plan and due-dates
	Expediting	Monitor progresses and expedite delayed jobs

Tab. 1. Shop-operator's tasks in a skill-based machine shop

The structure of how these manual tasks are connected with each other in a typical skill-based machine shop (at least in Korea) is depicted in Fig. 3. Input data for the "machine shop" system are 1) Nominal NC-data for individual cutting tools, 2) Nominal cutter spec with cutter-size data only, 3) Drawings denoting datum surfaces, 4) Due dates and routing information, 5) CAD models, and 6) Assembly drawings

The shaded task-boxes in Fig. 3 are candidates for being replaced or aided by IMS (intelligent machine shop) S/W systems. Now the question is how to organize the IMS S/W systems. We use the term "station" for an independent IMS S/W system, and the term "module" is used for a software module in a station. Among the candidate tasks in Fig. 3, 1) Loading planning and Expediting are implemented as **Loading Schedule Station**, 2) Monitoring is implemented as **Real-time Monitoring (RTM) Station**, and 3) the remaining tasks are covered by **Technical Data Processing (TDP) Station**.

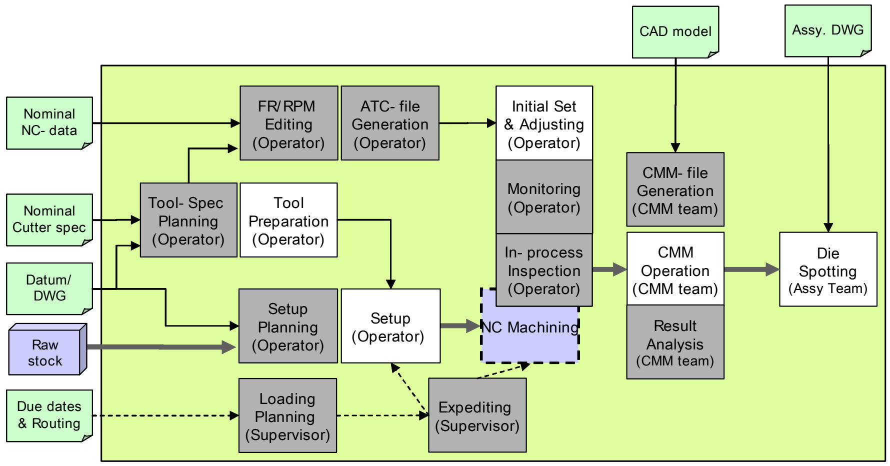


Fig. 3. Functional model of skill-based machine shop (AS-IS model)

TDP Station consists of three modules: 1) **NC-data Handler** covering Feed-rate/RPM editing, ATC-file generation, Tool-spec planning, and In-process inspection utilizing on-machine measuring (OMM) probes; 2) **Setup Planner** in charge of planning setups; 3) **Mold Inspector** responsible for CMM-file generation and CMM result analysis. With these IMS S/W systems, an intelligent machine shop for mold-making may be operated as depicted in Fig. 4.

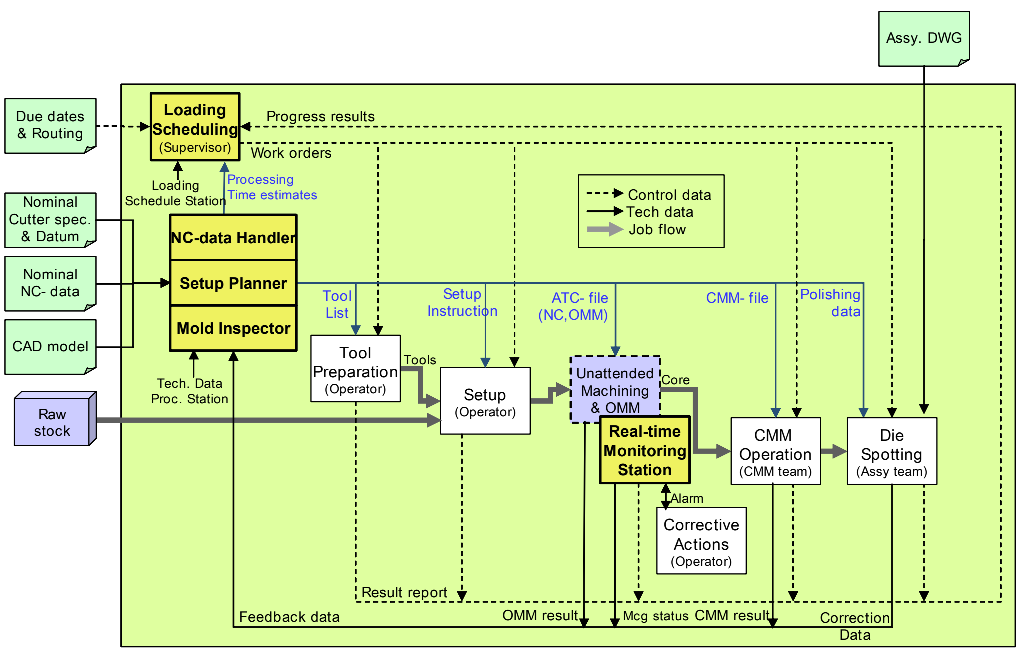


Fig. 4. Functional model of intelligent machine shop (TO-BE model)

Referring to Fig. 4, the "intelligent machine shop for mold-making", which we call ***Intelligent Mold Shop*** for short, is supervised by the *Loading Schedule Station*. It is a simulation-based real-time scheduling system whose commercial version is available in Korea, and some details of the loading scheduling method are described elsewhere [3-4]. The *Real-time Monitoring Station* in Fig. 4 is a PC camera based monitoring system that processes both sound signals and images obtained from a PC-camera attached to an NC machine. Depicted in Fig. 5 is the architecture of the RTM Station. Technical details of the RTM Station may be found in [5-6]. The *Technical Data Processing Station* will be described in the next section.

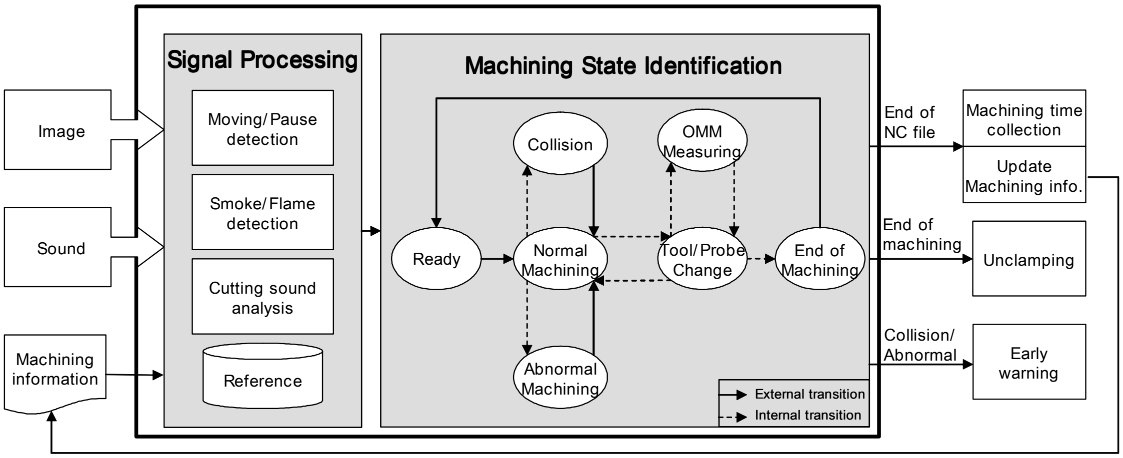


Fig. 5. Architecture of real-time monitoring (RTM) station

3. TECHNICAL DATA PROCESSING IN AN INTELLIGENT MOLD SHOP

The main part of our IMS (intelligent mold shop) is TDP station consisting of three modules as shown in Fig. 6: NC-data Handler in charge of NC-code optimization, tooling specification, and OMM (on-machine measuring) management; Mold Inspector handling CMM-data generation and virtual die-spotting; Setup Planner responsible for fixture planning and setup evaluation. More details of NC-data Handler will be given shortly.

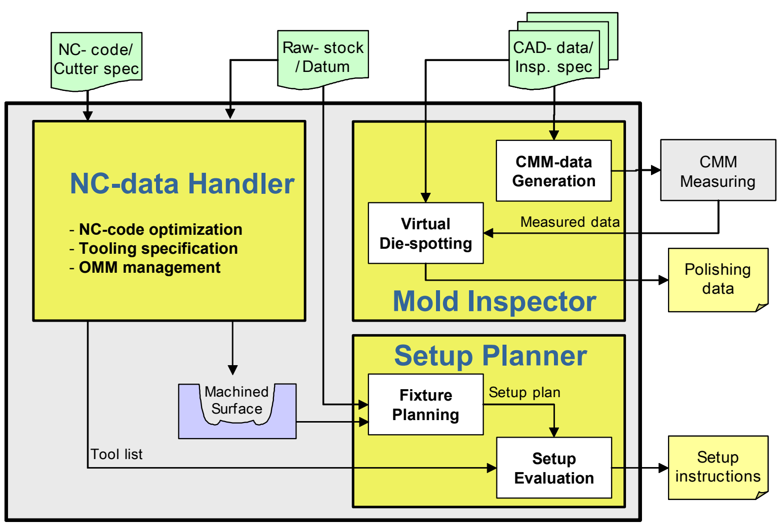


Fig. 6. Architecture of technical data processing (TDP) station

The **Setup Planner** is responsible for determining a fixturing assembly for setup and evaluating the suitability of a given setup. In general, setup planning for the machining of prismatic parts is a problem for finding minimum number of setups, which is not an easy problem. However, setup planning for molding die machining is a fixture planning task that can be carried out interactively by 1) determining a suitable fixturing configuration and 2) forming a fixture assembly for given orientation and datum from a predefined set of fixturing elements (dowel pin, rest pad, stud, strap clamp, etc.). Examples of fixturing configuration are given in Fig. 7, and more details of setup planning issues may be found in [7]. Geometric evaluation of a given setup may be carried out via virtual machining (i.e., cutting simulation), while kinematics stability can be checked by using screw theory [7].

(a) vise fixturing (b) base plate fixturing (c) strap clamp fixturing

Fig. 7. Examples of fixturing configuration

The **Mold Inspector** consists of CMM-data generator and virtual die-spotting function. Steps of generating CMM data are to 1) determine measure-points, 2) form a probe-path by connecting the measure-points, and 3) perform path filtering to obtain a collision-free path [8-9]. The measure-points for freeform object are defined on critical "feature regions" such as parting surface, concave fillet, convex round, etc. Some details on the concepts of features as well as of virtual die-spotting may be found in [10].

The core of the TDP station is the **NC-data Handler**. It takes 1) nominal NC-codes together with nominal cutter specs (i.e., cutter diameter and corner radius values) and 2) geometry of the raw stock together with datum surfaces as its input, and then it generates five types of output: 1) high-performance NC-data having optimal feed-rates with minimal idle traverses (GOO motions); 2) ATC files joining individual NC-files; 3) estimated machining times to be used for loading scheduling; 4) a list of tooling specs to be used for tool preparation; 5) OMM files for in-process inspection. A schematic architecture of the NC-data Handler is given in Fig. 8.

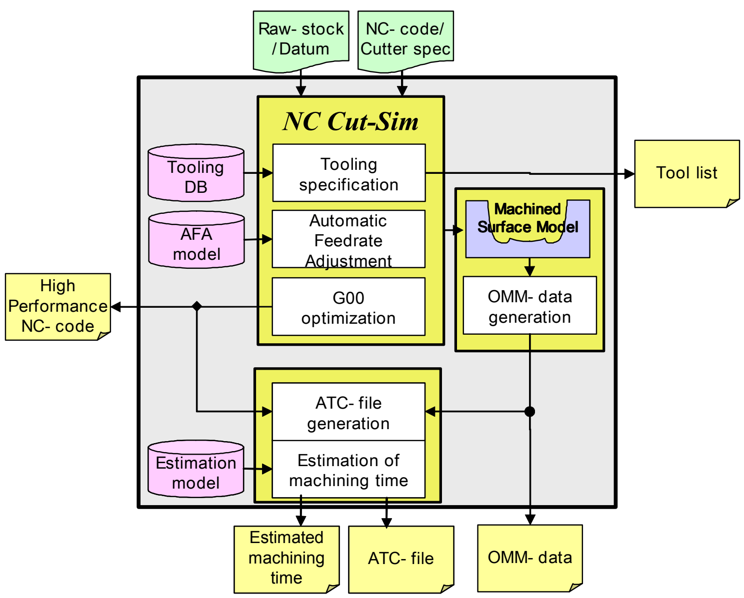
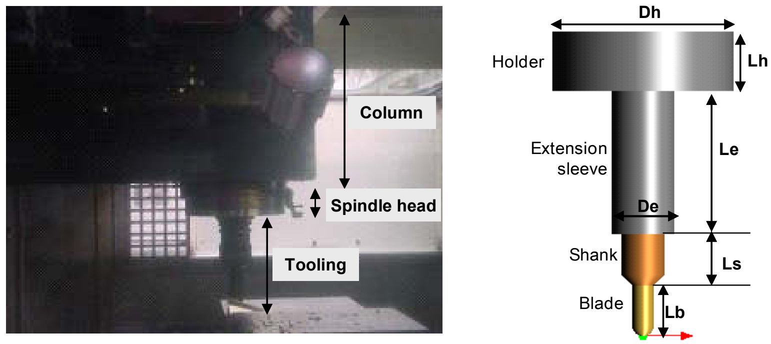


Fig. 8. Architecture of NC-data handler

Generation of high-performance NC-data with right tooling specs is based on "NC-data cutting simulation (NC Cut-Sim)". Going into the subject of NC Cut-Sim is beyond the scope of this paper, and interested readers are referred to [10]. When defining a tooling spec, one has to consider the machine geometry (column, spindle, and head) as well as tool-assembly geometry (holder, extension sleeve, shank, blade, etc.) as shown in Fig. 9.



(a) Machine (b) Tool assembly

Fig. 9. Machine and tool-assembly geometry for tooling specification

Generation of OMM-data is similar to that of CL-data for NC machining, and an OMM-probe assembly is treated like a tool assembly. As an OMM may be made after each NC machining, OMM files have to be combined with NC files via ATC files. Thus, a careful planning is required reflecting technical constraints of NC machining and in-process inspection. Once a combined set of NC-files and OMM-files is obtained, it is trivial to compute the nominal machining (& measuring) times. However, in sculptured surface machining, the actual machining time may differ considerably from its nominal time. Machining time estimation requires empirical investigation, and some details may be found in [11]. Technical issues related to OMM may be found in [12]

4. EFFECTIVENESS OF INTELLIGENT MOLD SHOP

The authors have been working for about one and half years with a local mold-making company to realize the IMS framework presented in this paper. While discussing with the management of the company, the six areas shown in Fig. 10 have been identified as KPI (key performance indexes) representing the effectiveness of implementing an IMS.

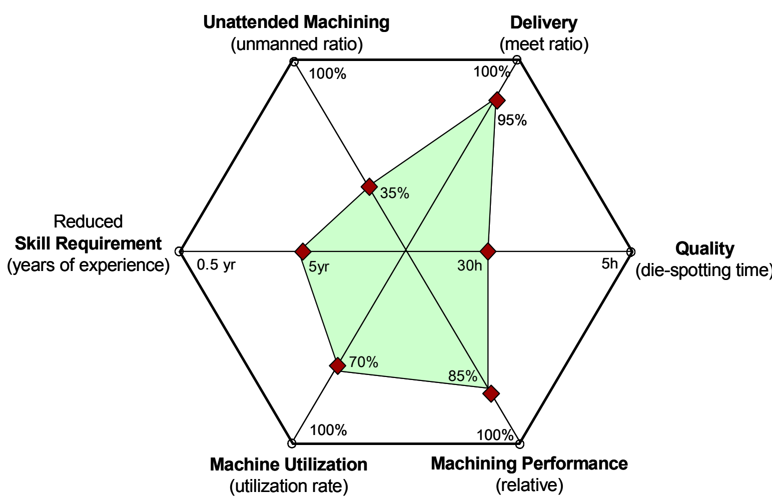


Fig. 10. Raider chart for the KPI of IMS

The six KPIs are 1) unattended machining ratio, 2) skill-requirement reduction, 3) machine utilization, 4) machining performance, 5) quality of machining, and 6) delivery performance. Currently, the NC machines in the machine shop are being tended by NC operators about 65% of the time (i.e., Unmanned machining ratio is 35%) and an NC operator is required to have at least 5 years of experience in order to perform his task satisfactorily by himself (there are no woman operators in the shop). NC machines are hoped to be in operation 20 hours per day, but they are in operation about 14 hours per day on the average now (i.e., their utilization is about 70%). The ultimate goal of IMS is to have the NC machines in operation 20 hours per day without being tended by human operators except during setup and tooling and each operator can carry out his tasks by himself after six months of experience.

The value of machining performance is defined as 100% if an NC machining is carried out utilizing the full power of the NC machine. The quality of machining is measured in terms of the die-spotting time needed to have a well-fit molding-die set. Delivery performance is defined as the ratio of in-time deliveries over the total deliveries. The IMS aims to achieve full-performance (100%) machining with a die-spotting time of less than 5 hours and 100% delivery performance.

5. CONCLUSIONS AND DISCUSSIONS

In this paper, an approach to developing an intelligent mold shop (IMS) is presented as a means to overcome the difficulties faced by mold-makers. Building an IMS requires a major transformation, from skill-based operations into system-based operations, which is more of a social and economic issue than a technical one. While working with a local mold-maker, it has been observed that most of required technologies for building an IMS are available to us but building an intelligent system (or management tool) using the technologies needs collaborative works with the end users. In order to realize the TO-BE model of Fig. 4, three "IMS S/W systems" are being developed and deployed: *Loading Schedule Station* has been fully developed and is being tested with shop-floor data; a prototype of *Real-time Monitoring Station* (Fig. 5) is put into operation; a sub-set of *Technical Data Processing Station* (Fig. 6) is being used by the mold-maker. The authors believe that the proposed IMS framework can be developed and deployed in full scale. However, in order to fully realize the proposed IMS framework, a considerable amount of "empirical" research may be needed, especially, in the areas of machining process monitoring [13], virtual die-spotting, fixture planning, OMM-data generation, and automatic feed-rate adjustment.

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REFERENCES

[1] Kim, J. D., Lee, H. S., Kim, B. K., Kim, J. S., Heo, Y. M., Lee, S. H., Lee, W. R., *Survey report on the competitiveness of die and mold company*, Korea Trade Commission, 2004 (in Korean)

[2] Holonic Manufacturing System (HMS) consortium, http://hms.ifw.uni-hannover.de/

[3] Choi, B. K., Kim, D. H. and Hwang, H., Gantt chart based MES for die & mold manufacturing, *Proceedings of IFIP WG5.7 Working Conference on Managing Concurrent Manufacturing to Improve Industrial Performance*, Seattle, WA, 11-15, September, 1995, pp 105–114.

[4] Choi, B. K., Kim, B. H., MES (manufacturing execution system) architecture for FMS compatible to ERP (enterprise planning system), *International Journal of Computer Integrated Manufacturing*, Vol. 15, No. 3, 2002, pp 274-284

[5] Lee, J. W., Development of PC camera-based monitoring system for NC milling, *KAIST Master's Thesis*, 2003 (in Korean)

[6] Song, S. Y., NC machining state detection using image and sound processing techniques, *KAIST Master's Thesis*, 2005 (in Korean)

[7] Joneja, A., Chang, T.-C., Setup and fixture planning in automated process planning systems, *IIE Transactions*, Vol. 31, 1999, pp 653-665

[8] Yau, H.-T., Menq, C.-H., Automated CMM path planning for dimensional inspection of dies and molds having complex surfaces, *International Journal of Machine Tools and Manufacture*, Vol. 35, No. 6, 1995, pp 861-876

[9] Ziemian, C. W., Medeiros, D. J., Automating probe selection and part setup planning for inspection on a coordinate measuring machine, *International Journal of Computer Integrated Manufacturing*, Vol. 11, No. 5, 1998, pp 448-460

[10] Choi, B. K., Jerard, R. B., *Sculptured surface machining: theory and applications*, Kluwer academic publishers, 1999

[11] Heo, E. Y., Kim, B. H., Kim, D. W., Estimation of sculptured surface NC machining time, *Transactions of the society of CAD/CAM engineers*, Vol. 8, No. 4, 2003, pp 254-261 (in Korean)

[12] Choi, J. P., Min, B. K., Lee, S. J., Reduction of machining errors of a three-axis machine tool by on-machine measurement and error compensation system, *Journal of Materials Processing Technology*, 2004, pp. 2056-2064

[13] Cho, D. W., Lee, S. J., Chu, C. N., The state of machining process monitoring research in Korea, *International Journal of Machine Tools and Manufacture*, Vol. 39, 1999, pp 1697-1715