Chapter 5
The Classification Methodology of IMS

5.1 Introduction

There are many current research activities in various directions in the area of IMS as described in section 2.6 (IMS technical framework). They are focusing on intelligent process controlling systems, machine tools condition monitoring system, real-time machining state detection using multi-axis force sensing, fail-safe system, tele-machining etc. However, most of them are still implemented only in the laboratory. Few of them can be practically implemented in real industrial environments since there are many different conditions between laboratory and factory.

Furness [6] describes that the current PLC and CNC equipment often utilizes proprietary hardware which makes integration between different systems difficult, if not impossible. Moreover, proprietary platforms also do not readily support integration of the necessary sensors and algorithm for IMS. It is obvious that to modify an existing machine to become an intelligent one is not easy and sometimes impossible. The trend towards utilizing open architecture systems for PLC and CNC controllers will enable implementation of IMS.

Suh [40] states that "*There is a prevailing notion that any machine can be made intelligent if we attach enough sensors and develop algorithms that can follow the 'IF*

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... THEN' type of logic that controls the machine. However, this is an unproductive way of creating intelligent machines." Based on Axiomatic Design Theory described in Chapter 3, he concludes that all intelligent machines must be either UNCOUPLED or DECOUPLED machines to be intelligent in performing a given set of tasks to satisfy their functional requirements.

5.2 Statement of the problem

As stated previously, to design an ideal intelligent machine and IMS is important but to practically implement IMS into an existing manufacturing system is also important. However, according to Suh [40] and Furness [6], it is clear that we should not make an intelligent machine by modifying an old design since it is very difficult or perhaps impossible to get a good intelligent machine. But, it is also difficult and may not be feasible for industries to invest a lump sum of money on any ready-made intelligent machine which is still very expensive.

To help the manufacturer to consider the feasibility of introducing the IMS, in terms of machine modification and investment, to their production system, this research proposes a classification methodology for evaluating the level of intelligence of a machine, a cell, and the entire system. The proposed methodology is based on Axiomatic Design Theory which will be able to evaluate the design in terms of "incompleteness". In addition, the proposed methodology is devised to provide a clear boundary for IMS and also can broadly answer how higher levels of intelligence can be reached from lower levels in terms of hardware and software investments.

Before discussing about the methodology, the following section will give a perspective idea of a classification of CIM which will be used as a guideline for the methodology.

5.3 Classification of CIM

Manabe et al.[20] classify CIM into six levels, as shown in Figure 5.1 :

1. **Equipment/machine**
2. **Cell**
3. **Line**
4. **Area**
5. **Factory**
6. **Entire company related management.**

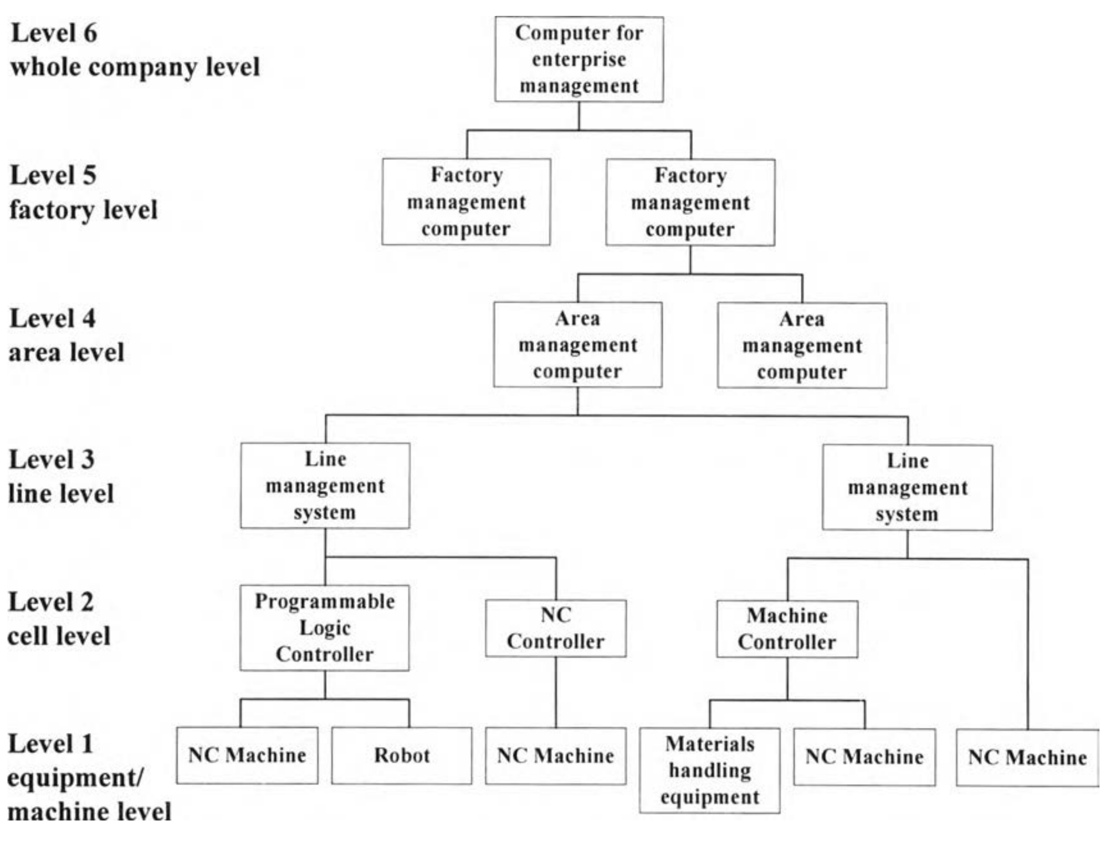
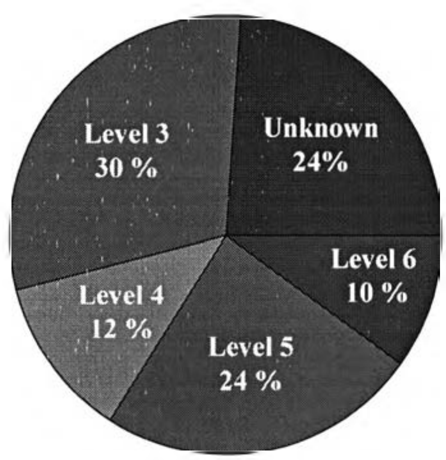


Figure 5.1 : CIM's six rank level and networking

They make a survey of systems on FMS/FA/CIM for metal forming processes in Japan in recent years and find that 10 percents of the firms are located in the level 6. Including the level 5, one third of all the systems are located higher than level 5. Figure 5.2 illustrates the classification of CIMs implemented into rank level in Japan.

It is obvious that the CIM for metal forming processes in Japan has been greatly progressing in the past decade. Although this research had done only on metal forming industries, it somehow indicate some degree of progression in CIMs for the other areas.



Classification of CIMs implemented into rank level

Figure 5.2 : Classification of CIMs implemented into rank level

5.4 Intelligence Density

Intelligence Density (ID) is a heuristic measure of the "army type" of intelligence proposed by Dhar and Stein [3]. They states that an organization can increase its intelligence in the same way that an army unit gathers "intelligence" about the movements of the enemy. A radar-tracking system that tells a military unit about the enemy's movements is providing intelligence.

ID is the amount of useful decision support information that a decision maker gets from using the output from some analytic system for a certain amount of time. It measures how many "utiles" (utility units) per minutes a particular output gives us.

If a decision maker examines Source A for 3 minutes and get the same quality decision as he or she does with Source B for 30 minutes, Source A can be said to have 10 times the ID as Source B. Conversely, if the time required to make a decision is fixed, and a decision maker can make a decision that is determined to be twice as good after examining Source X as those made based on Source Y, it can be said that Source X has twice the ID as Source Y.

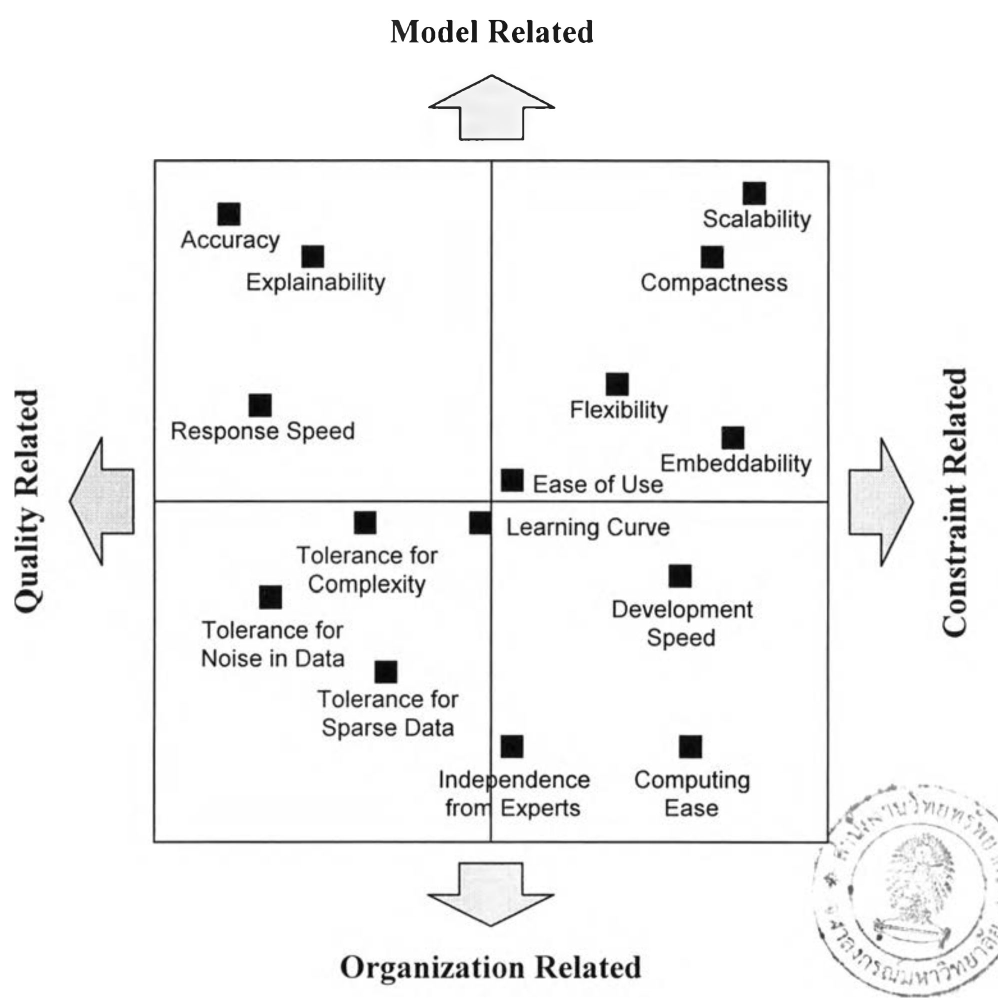


Figure 5.3 : Stretch Plot : A comprehensive View of Intelligence Density

Dhar et al. [3] classify all of the dimensions need to be considered in formulating and evaluating alternatives, in terms of ID, into 4 groups : **Quality of Model**, **Engineering Dimensions**, **Quality of Resources**, and **Logistical Constraints**. These groups can be plotted as shown in Figure 5.3. However, factors to be concerned in each group need not to be fixed or unchangeable. Not every factor is important for every problem. It's our responsibility to select a set of proper factors to be considered in each problem.

1. Quality of Model

The quality of the outputs should be adequate to meet the organization's needs. The followings are the factors need to be considered.

- **Accuracy** : Does the system need to provide optimal solutions in terms of accuracy or goodness ?
- **Explainability** : Does the decision maker need to know how the answer is derived ?
- **Speed/Reliability of Response Time** : Does the system provide responses within a reasonable amount of time ?

2. Engineering Dimensions

This is somewhat need to be considered as the long-term cost drivers. It relates to how well the solution is engineered when it is developed.

- **Flexibility** : How flexible is the system is allowing the problem specifications to be changed ?
- **Scalability** : How scalable is the system ?
- **Compactness** : How compact is the system ?

- **Embeddability** : How easily can the system be embedded into a larger system or the existing work flow of an organization ?
- **Ease of Use** : How easy is the system to use ?

3. Quality of Resources

This dimension deals with human resources and infrastructure which need to ensure that they are sufficient to undertake the whole system.

- **Tolerance for Noise in Data** : Are there good, high-quality electronic data available ?
- **Tolerance for Sparse Data** : Are there a lot of electronic data available ?
- **Learning Curve** : Is the organization far enough up the learning curve ?
- **Tolerance for Complexity** : How subtle and easily understood are interactions between the problem variables ?

4. Logistical Constraints

This group deals with considerations that can ensure that the organization can support the logistical requirements of the project.

- **Independence from Experts** : What is the access to experts, or conversely, how independent are you from them ? In particular, are experts readily available for advice and testing.
- **Computational Ease** : Are the computing infrastructure resources adequate for the problem ?
- **Development Time** : What development time can the organization afford ?

In Figure 5.3, the top half relate to the system or model itself and reflect requirements of the product being designed, while at the bottom half deal with the organizational environment in which the system will be developed and used. The left-hand side of the diagram relate to quality issues, while the right deal with practical constraints in system development and use.

Figure 5.4 shows an example of ID profile of a problem. The height of each bar indicates how much the score or importance of each intelligence factor need to be considered is. Notice that in each problem (machine design, or any system design), numbers of factors can be included or neglected arbitrarily if they are presumed significant to the system.

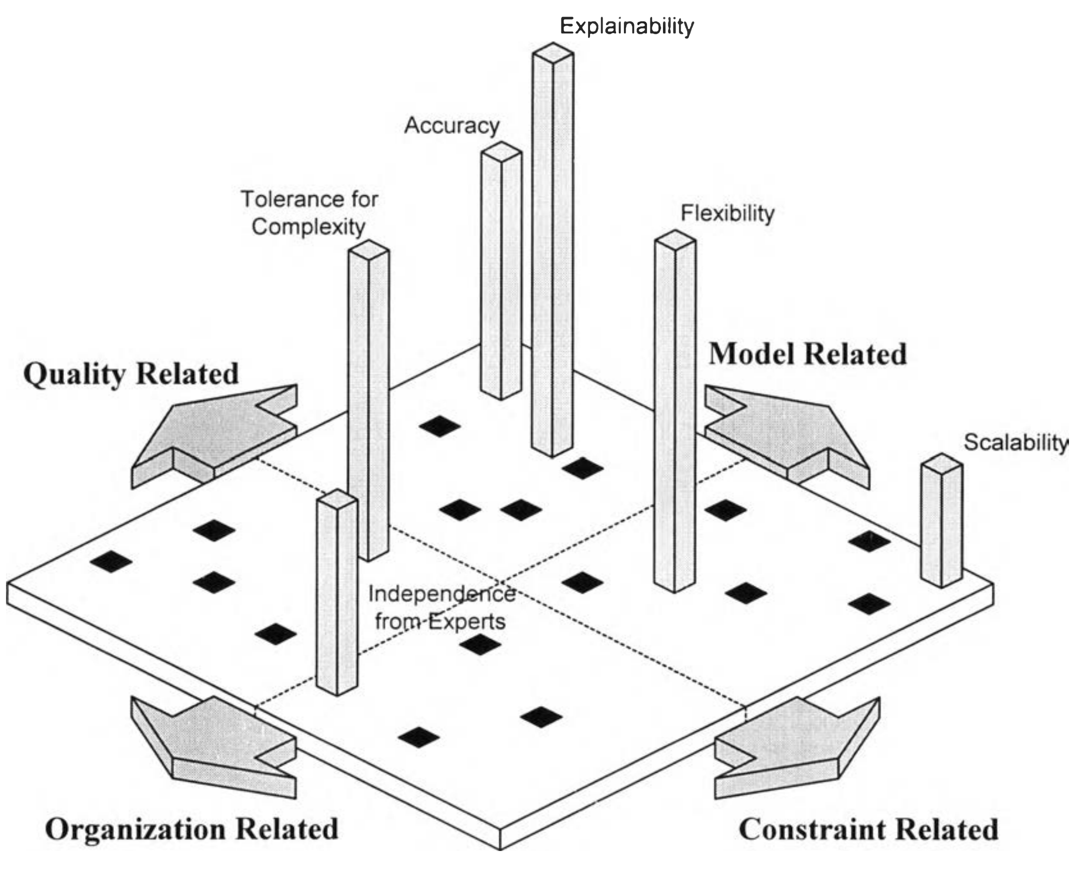


Figure 5.4 : An ID Profile for a Specific Problem

5.5 Characteristics of the Classification Methodology

The methodology proposed for classifying the level of intelligence of the IMS must be able to serve the following requirements or characteristics.

1. The methodology is used for classifying the level of intelligence of a proposed design. It does not deal with neither "*how to design a good intelligent system*" nor "*what we should concern when we design an intelligent system*". The methodology deals only with "*which level of intelligence a proposed system is*".
2. The methodology is developed based on management-oriented aspect, not the technical-oriented. Then the philosophy of the methodology indeed concerns with how to cope with technology management, especially with manufacturing industry, in a corporation.
3. Each machine/equipment, cell, line, etc. can be classified into level of intelligence by using a set of criteria and an appropriate evaluation technique which can be represented by an intelligence score.
4. At the equipment/machine level, it must be able to identify and classify the capability of a proposed design of an intelligent machine/equipment in terms of level of intelligence.
5. Stepping up to the higher level, it must be able to identify and classify the capability of a cell, line, area, factory, and the whole system which composes of a group of machines/equipments, cells, lines, areas, and factory, respectively. The upper level of each rank in the six rank levels of CIMs can be classify by the level of intelligence of the lower level.
6. Due to the rapid advancement in technology as the time goes by, new features of the equipment can be developed and implemented into a new

design. To make the methodology become flexible enough for the future, the criteria used for evaluating the level of intelligence of a specific kind of machine/equipment can be increased or a specific criterion can be dominated by the new one. It is known as the dynamic of criteria which will be static at the moment they are used for the evaluation.

7. When some of the criteria are changed, the total intelligence score (which is the result of the evaluation that used for classifying the level of intelligence) may be changed. The more score a machine/equipment gain, the more intelligence or chance it can be classified into a high intelligence level it is.
8. The intelligence score can be increased without the limit as the new features are added. We can set numbers of the criteria for the evaluation arbitrarily.
9. Number of level of intelligence should be relatively fixed.

5.6 A Classification Methodology of IMS

5.6.1 Conventional and Intelligent Machine

Before going through the classification methodology, it is better to show a perspective view of what the development direction of intelligent machine is. Figure 5.5 illustrates the development of intelligent machine tool from Moriwaki [29].

5.6.2 Evaluation Factors

Based on Dhar et al.'s work [3] on Intelligence Density, the following are the factors need to be considered for evaluating the level of intelligence.

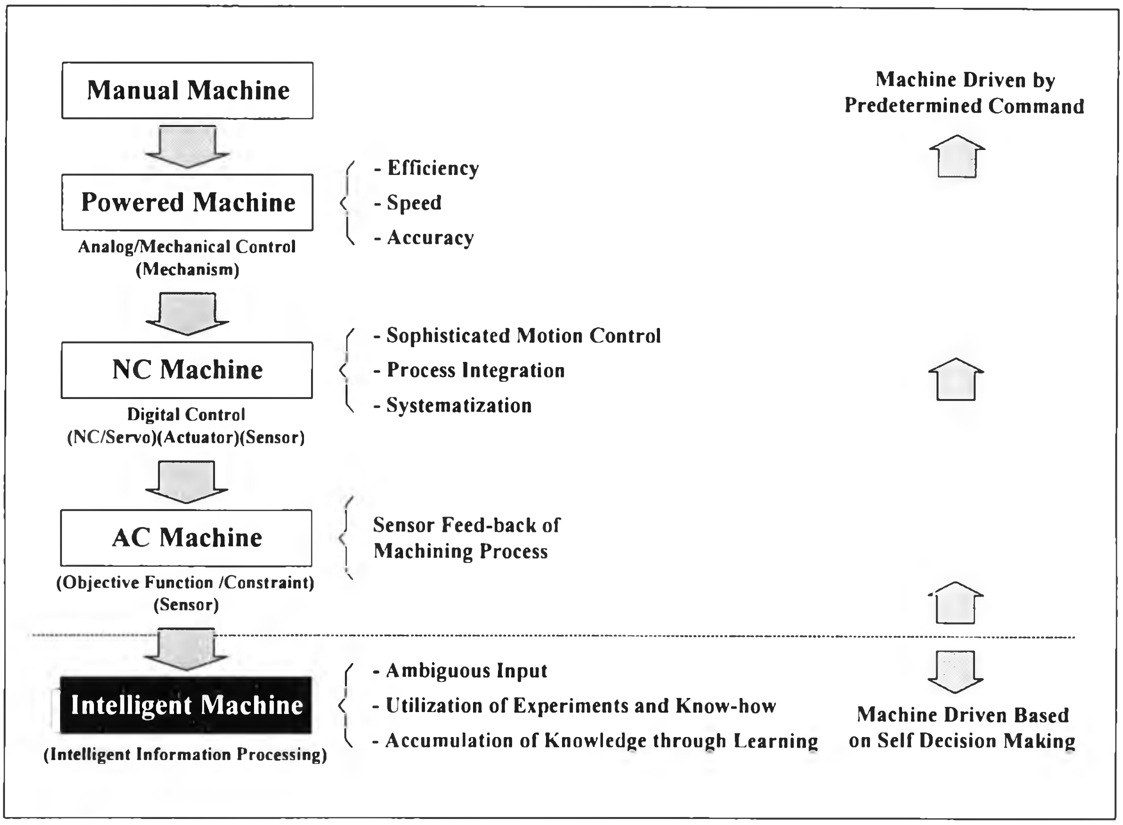


Figure 5.5 : Development of Intelligent Machine Tool from Moriwaki

Quality of Model

- **Accuracy** (1)
- **Explainability** (2)
- **Speed/Reliability of Response Time** (3)

Engineering Dimensions

- **Flexibility** (4)
- **Scalability** (5)
- **Compactness** (6)
- **Embeddability** (7)
- **Ease of Use** (8)

Quality of Resources

- **Tolerance for Noise in Data** **(9)**
- **Tolerance for Sparse Data** **(10)**
- **Learning Curve** **(11)**
- **Tolerance for Complexity** **(12)**

Logistical Constraints.

- **Independence from Experts** **(13)**
- **Computational Ease** **(14)**
- **Development Time** **(15)**

5.6.3 Convention of Factors Weighting

Each of the 15 factors has its own scoring technique and it's own weight which is different among different kinds of machine which are designed for different purposes.

It depends on what the machine is designed for which is different among different kinds of industries. Some industries may seriously encounter with high precision and high accuracy while others may encounter with flexibility and pay less attention in high precision.

This leads to different sets of weight of 15 factors. Each kind of machine has to be weighted by the expert(s) who deals with R&D or the user(s) who utilizes the system. It is impossible to show all of weights in this research since it is up to various kinds of industry. This research intends to guide a general methodology for industries to evaluate their own machines and manufacturing system. Most of unknown weight will be placed as the unknown variables. However, as an example in this research, weight of factors will be assumed equal for ease of calculation.

5.6.4 Intelligence Score

To make the evaluation, each of 15 factors has its own scoring technique that can be changed or dominated by a new one when it is developed.

The maximum score of each 15 factors is 100 points that indicate the ideal perfection (100% perfection) or "ideal intelligence". However, instead of giving the score in terms of perfection, say, "For, Accuracy, this machine gets 75 points or 75% of perfection.", it is better to give the score in terms of "Imperfection", say, "For Accuracy, this machine needs 25% more of improvement to gain perfection.". By this sense, the result will lead to the answer of what the company should do with the machines, cells, lines, areas, etc. to gain better performance of the whole system. The score ranges and their classes are listed in Table 5.1.

Intelligence Score	Percent of Imperfection	Imperfection Score	Class
91-100	0-10	0	Intelligence 7
81-90	10-20	1	Intelligence 6
71-80	20-30	2	Intelligence 5
61-70	30-40	3	Intelligence 4
51-60	40-50	4	Intelligence 3
41-50	50-60	5	Intelligence 2
31-40	60-70	6	Intelligence 1
0-30	70-100	7	Ordinary M/C

Table 5.1 : Classification of Intelligence Score

Remark here that the first step to make the evaluation is to consider the system itself. What kind the machine or system need to evaluate is, what direction the system is judged to be implemented (Quality of Model, Engineering Dimensions, Quality of Resources, and Logistical Constraints), the scale or range of classification, and how to quantitatively classify each machine or system into them.

The following are proposed criteria of giving score to each 15 factors. Notice that all of these factors can be adjusted arbitrarily up to the evaluation maker, kinds of machines (or systems), and the direction of development (see Figures 5.3 and 5.4).

1. **Accuracy**

In terms of Accuracy, IMS means the ability of the machine to repeatedly and precisely manufacture the products based on the functional requirement.

The level of Accuracy can be indicated by the quality of the products produced, in terms of accuracy of dimension and roughness. It indicates the level of precision of manufacturing process (e.g. machining quality) which varies from machine to machine, up to the machining technology, machining process, and skill of the technician.

The ultra-precision machining technology that implements single-point diamond turning (SPDT) is an example of a high precision machining. This kind of process being capable of producing components with micrometer to sub-micrometer form accuracy and surface roughness in nanometer range.

The level of Accuracy of IMS in the above sense can be recognized by various techniques. For example, in an ultra-precision machining technology, a superior surface finish is produced as a result of extremely high fidelity in transferring the machine motions and the tool path into a workpiece.

Another key to realize the high accuracy and high precision is to implement the intelligent sensors to monitor the whole system which in turn will help to control the accuracy and precision of the system.

Intelligent sensors have a better functionality than conventional sensors because they can respond to the special requirements of the machine tool or process they are monitoring. As stated before, an intelligent machine must be able to utilize experience and know-how accumulated during past operation, accumulates knowledge through learning and can accommodate ambiguous inputs. It can do some or all of the following things :

- self-calibration
- signal processing
- decision making
- fusion ability
- learning capability

An important characteristics of an intelligent sensor is that it should be able to learn from past information using neural network or other knowledge representation scheme in order to continuously increase its reliability and robustness.

However, it should be remarked here that for this factor, Accuracy, though a very high precision machine can make a very good quality product, but how accurate "precision" a machine is does not relate to how high its "Accuracy" is.

Accuracy in this classification methodology is depend on “functional requirement” (FR) of the system. If a product need to be manufactured is not expected to have an ultra-precision surface quality, there is no need to use an ultra-precision machine to manufacture it.

The following are table of grading system and some example questions used for evaluating how high Accuracy an intelligent machine is :

Level	Meaning	Score
0	Failure	30
1	Very Poor	40
2	Poor	50
3	Fair	60
4	Fairly Good	70
5	Good	80
6	Very Good	90
7	Excellent	100

Table 5.2 : Grading System

1. What is the percent of defection or percent of non-conformance to the specification (that caused by the machine’s errors) the machine produces, in terms of dimension and roughness ? (Percent of Defection)
2. Does the machine consistently maintain the machining quality during the normal condition ? (0-7)
3. When the machine makes its own decision to change tool path, feed rate, cutting speed or any machining parameters due to an emergency case that force the machine to take

actions, does the machine provide good result (machining quality) ? (0-7)

The score for Accuracy is the average of those 3 aspects. For example if a machine is judged to have 30 percent of defection (70 percent of acceptable functionality), Fairly Good machining quality, and Poor decision making.

$$\text{Accuracy Score} = \frac{70+70+50}{3}$$

$$= 63.33 \text{ points}$$

The Intelligence Score 63.33 points indicates that, for Accuracy, this machine has 36.67 percent of imperfection that is 3 point for Imperfection Score, and it is ranged at class 4 of Intelligence. (see table 5.1)

However, as stated previously, the numbers of aspect used for evaluation could be varied depending on what kind of machine is and how important those aspects are. The more and independent the aspects used for evaluation are, the more the accurate of the final score will be.

2. Explainability

As stated in section 1.7.3 that IMS is a kind of expert system implemented in manufacturing. Explainability is one of the desirable features of expert systems. It is the capability to explain how and why a decision or solution was reached. This will make the user of the system can understand the reasoning behind the action of the intelligent system. However, in most cases, it is harder to find techniques that satisfy "high" Explainability than it is to find techniques that have "low" Explainability [3].

In terms of the Explainability, an interesting point about implementing different techniques is that each AI technique has its own strength and weakness. For example, it is obvious that neural networks are generally unable to provide good explanations as to how they decide on a specific problem. On the other hand, rule-based systems are very good at explaining their results. However, for a more complex and hard to understand problem, neural networks are considered to be better in solving the problems, regarding to the development time.

The followings are the important assessing questions for considering the Explainability of an intelligent system. (refer to grading system in Table 5.2)

1. When the systems make a particular conclusion about something, **does it provide** any explanation why and how it reached ? (1-7)
2. For a conclusion the systems made, is it reasonable ? (1-7)
3. How much percent of reliability of the explanation ? How much percent we can believe the explanation ? (percent of reliability)
4. If the same machining condition or the same problem happened, does the system provide the same explanation ? Can the system utilize the accumulation of knowledge and learning to make better explanation ? (1-7)

3. Speed/Reliability of Response Time

It is the time an intelligent system takes to complete analysis at the desired level of accuracy. Dhar et al. [3] stated that in applications that require that results be produced within a specified time frame, missing that time frame means that no matter how accurate and otherwise desirable the results are, they will be useless in practice.

In most cases, "real-time operation" such as real-time controller is an important characteristic. However, the definition of "real-time" is needed to be clarified since the quantity of time spent in making an analysis is different for different systems. It depends on what kind of problem is encountering.

The followings are the important aspects for considering the Speed/Reliability of Response Time of an intelligent system.

1. In case of encountering with an abnormal machining conditions which need the machine's ability to generate a new set of proper cutting parameters, does the system provide the solution within a specified time frame ? (1-7)
2. With the signals sensed by the systems, how about the ability of the system to understand and take action with those signals ? (1-7)

4. Flexibility

Generally, "flexibility" means different things to different manufacturers. For FMS (Flexible Manufacturing System), flexibility can be broadly defined as "*the ability to respond effectively to* *changing circumstances*" whereas "changing circumstances" may vary considerably among manufacturers.

Luggen [19] states that flexibility, in terms of FMS, means :

1. **Variety of mix** : the combination of different parts the system can make at a time and various subsets of part types that can be made simultaneously
2. **Adaptability to design, production, or routine changes** : this refers to ease of accommodating engineering changes, expansion of the total universe of parts producible on the system, and the variety of routes or machines that can process the same part type
3. **Machine changeover** : the ease with which a machine within the system can automatically change from making one part type to another

However, in addition to IMS sense, most systems are not designed to be used once. They must be robust enough to update or adapt themselves to the new phenomena. It is obvious that many of the machining or even the business processes are not static, they change over time. Flexibility is the ability of the intelligent system to allow the problem specifications to be changed.

The followings are the important aspects for considering the Flexibility of an intelligent system.

1. As the controlled machining environment and machining parameters changed e.g. room temperature, time duration, cutting speed, material property etc., can the system adapt

itself to the new environment and properly perform its intelligence ? (1-7)

2. Can the machine easily changed from making one part type to another ? (1-7)
3. Due to the combination of different parts the system can simultaneously make at a time, can the system properly perform its intelligence to detect, classify, or operate any tasks with those different parts (Has the system got any limitation on different parts) ?
4. When the size, form accuracy, surface roughness or any specification of the workpieces changed to be more difficult to produce, can the machine be modified or adjusted to extend its functionality to produce them ? (1-7)

5. Scalability

It refers to how scalable the system is. Scalability involves adding more variables to the problem or increasing the range of values that variables can take. In most cases, when the interactions among variables increase rapidly in unpredictable ways, scalability problem will be recognized.

The followings are the important aspects for considering the Scalability of an intelligent system.

1. When the production quantity is changed (either increased or decreased), does the system maintain good or normal functionality, in terms of intelligent system ? (1-7)

6. Compactness

It refers to how small the system can be made. The system will be much more useful if it is not too bulky to be embedded in a format that makes it usable where and when it is needed.

1. **Utilization of working area** : For the size of the whole systems, e.g., machining center and its accessories, **does it utilize** proper working space (how much space needed for installing the whole system) ? (1-7)
2. **Utilization of computer resource** : For the AI technique used in the system, e.g. neural nets or rule-based system, does it consume much resource, such as disk space, RAM, etc. ? (1-7)
3. **Complexity of equipment** : For the equipment other than machine component, such as sensors, actuators, etc., that attached to the machine components, are they easy to install and re-install ? (1-7)
4. Can the system be encoded into a compact portable format ? (1-7)

7. Embeddability

It is the ability that the system can be incorporated into the infrastructure of an organization. On the other hand, it is the ability the systems can be attached or coupled as modules or components of the larger systems or other databases.

1. **Compatibility** : Technically, can the system be properly embedded to the main manufacturing system or the computer network without conflicts ? (1-7)
2. **Performance** : Does the system properly work after installed to the main system ? (1-7)
3. **Complexity** : Does it consume much time and other resource for installation ? (1-7)

8. Ease of Use

It describes how complicated the system is to use for the user who will be using it on a daily basis.

1. Is it an application or system that is easy to use or requires less of expertise and training ? (1-7)
2. Does the system or application equipped with the user-friendly interface ? (1-7)
3. Does the system provide help function key or wizard system to guide the user through the working process ? (1-7)
4. Is the system protected from human errors by equipping with "foolproof" or any other techniques ? (1-7)

9. Tolerance for Noise in Data

This is the ability of the system to encounter with the noise in electronic data . Is it affected by noise ?

1. Most of intelligent systems are equipped with various kind of sensors and actuators, do they properly work with noise in data they sense and interpret ? (1-7)
2. Is the system designed to handle noise in data processing, e.g. data processing after sensing various signals from sensors ? (1-7)
3. With noise in data or ambiguous input, does the system provide reasonable solution ? (1-7)
4. Is the system protected from serious damage after affecting by noise in data ? (1-7)

10. Tolerance for Sparse Data

This is the degree to which the quality of a system is affected by incompleteness or lack of data.

1. Can the system properly work with incompleteness or lack of data? (1-7)
2. With incompleteness or lack of data, does the system provide reasonable solution ? (1-7)
3. Is the system protected from serious damage after affecting by incompleteness or lack of data? (1-7)

11. Learning Curve

This is the degree to which the organization needs to experiment in order to become sufficiently competent at solving a problem or using a technique.

1. Is the organization far enough up the learning curve ? (1-7)
2. To implement an intelligent system, is the organization has a strong background (e.g. human resource, infrastructure etc.) to support it ? (1-7)

12. Tolerance for Complexity

This is the degree to which the quality of a system is affected by interactions among the various components of the process being modeled or in the knowledge used to model a process.

Notice that factor 9-12 are used for considering the quality of resource which does not directly relate to the intelligent system itself. They are related to the resources available in the organization required for supporting the system.

1. How easy the intelligent system can collect various kind of data sensed by the sensing system ? (1-7)
2. How easy the intelligent system can utilize various kinds of information collected by the sensing system (How about the complexity of their relationships) ? (1-7)

13. Independence from Experts

It is the degree to which the system can be designed, built, and tested without experts.

1. Are experts readily available for advice and testing ? (1-7)
2. How is it easy for the firm to have a new specialist or expert by in-house training ? (1-7)

3. How unnecessary is the system need to have an expert stand-by while the system is operating ? (1-7)

14. Computational Ease

Computational Ease is the degree to which a system can be implemented without requiring special-purpose hardware and software.

1. Are the computing infrastructure resources adequate for the system ? (1-7)
2. How independent the system are from any additional calculation equipment or process to handle the operation ? (1-7)

15. Development Time

It is the time that the organization can afford to develop a system or, conversely, the time a modeling technology would require to develop a system.

1. How much the time span of development the organization can afford ? (1-7)
2. How critical the development time affect to the organization in terms of investment ? (1-7)

5.6.5 Assumptions of the Model

For convenience of calculation and ease of interpretation, it is assumed that both the imperfection score and the intelligent class of each factor have the additive property. The total imperfection score of a machine/equipment can be calculated by adding the imperfection scores of each factor (15 IDs) whereas the intelligent class of a machine/equipment can be calculated from the average of 15 intelligent classes. Similarly, The total imperfection score of a cell can be calculated from the addition of the imperfection scores of each machine within it.

5.6.6 Classification of Machines/Equipment

By the aforementioned 15 factors, a machine/equipment can be graded as shown in Tables 5.3 and 5.4.

	Level								Score
	0	1	2	3	4	5	6	7	
	30	40	50	60	70	80	90	100	
1. Accuracy									
Percent of defection (convert to % of acceptable quality)									
Consistency of quality / Normal Con.									
Accuracy of intelligence									
2. Explainability									
Availability of explanation									
Reasonability of explanation									
Reliability of explanation									
Utilization of intelligence									
3. Speed/Reliability of Response Time									
Speed									
Reliability of response time									
4. Flexibility									
Flexibility to environment changed									
Flexibility to machine changeover									
Flexibility to variety of mix									
Flexibility to complexity									
5. Scalability									
Scalability of production quantity									

Table 5.3 : Machine/Equipment Evaluation Check Sheet

	Level								Score
	0	1	2	3	4	5	6	7	
	30	40	50	60	70	80	90	100	
6. Compactness									
Utilization of working area									
Utilization of computer resource									
Complexity of equipment									
Compactness of code									
7. Embeddability									
Compatibility									
Performance									
Complexity									
8. Ease of Use									
Ease of use									
Friendliness of user interface									
Help function									
Foolproof engineering									
9. Tolerance for Noise in Data									
Noise in sensing system									
Noise in data processing									
Intelligence over noise									
Self protection									
10. Tolerance for Sparse Data									
Functionality over incompleteness									
Intelligence over incompleteness									
Self protection									
11. Learning Curve									
Current position									
Infrastructure									
12. Tolerance for Complexibility									
Complexity of data collection									
Complexity of data itself									
13. Independence from Experts									
Availability of experts									
Possibility of training program									
Independence from experts									
14. Computational Ease									
Adequacy of infrastructure									
Independence from additional calculation equipment									
15. Development Time									
Time span of development									
Investment aspect									

Table 5.3 : Machine/Equipment Evaluation Check Sheet (Cont.)

	Intelligence Score (0-100)	Imperfection Score (0-7)	Class (0-7)
Quality of Model			
1. Accuracy			
2. Explainability			
3. Speed/Reliability of Response Time			
Engineering Dimensions			
4. Flexibility			
5. Scalability			
6. Compactness			
7. Embeddability			
8. Ease of Use			
Quality of Resources			
9. Tolerance for Noise in Data			
10. Tolerance for Sparse Data			
11. Learning Curve			
12. Tolerance for Complexibility			
Logistical Constraints			
13. Independence from Experts			
14. Computational Ease			
15. Development Time			
Total ⇨			

Intelligence Score	Imperfection Score	Class
91-100	0	Intelligence 7
81-90	1	Intelligence 6
71-80	2	Intelligence 5
61-70	3	Intelligence 4
51-60	4	Intelligence 3
41-50	5	Intelligence 2
31-40	6	Intelligence 1
0-30	7	Intelligence 0

Table 5.4 : Classification of Machines/Equipment

Tables 5.5 and 5.6 show an example of machine/equipment evaluation. Notice that each aspect of 15 factors are determined by an assessor which may be changed as the time goes by when the new technology is implemented.

	Level								Score
	0	1	2	3	4	5	6	7	
	30	40	50	60	70	80	90	100	
1. Accuracy									
Percent of defection (convert to % of acceptable quality)	85 %								
Consistency of quality / Normal Con.						✓			
Accuracy of intelligence							✓		**85**
2. Explainability									
Availability of explanation		✓							
Reasonability of explanation			✓						
Reliability of explanation					✓				
Utilization of intelligence					✓				**57.5**
3. Speed/Reliability of Response Time									
Speed						✓			
Reliability of response time							✓		**85**
4. Flexibility									
Flexibility to environment changed					✓				
Flexibility to machine changeover				✓					
Flexibility to variety of mix						✓			
Flexibility to complexity	✓								**60**
5. Scalability									
Scalability of production quantity					✓				**70**
6. Compactness									
Utilization of working area			✓						
Utilization of computer resource		✓							
Complexity of equipment			✓						
Compactness of code				✓					**50**
7. Embeddability									
Compatibility		✓							
Performance					✓				
Complexity			✓						**53.33**
8. Ease of Use									
Ease of use				✓					
Friendliness of user interface			✓						
Help function				✓					
Foolproof engineering					✓				**60**

Table 5.5 : Example of Machine/Equipment Evaluation Check Sheet

	Level								Score
	0	1	2	3	4	5	6	7	
	30	40	50	60	70	80	90	100	
9. Tolerance for Noise in Data									
Noise in sensing system						✓			
Noise in data processing							✓		
Intelligence over noise							✓		
Self protection							✓		**87.5**
10. Tolerance for Sparse Data									
Functionality over incompleteness						✓			
Intelligence over incompleteness					✓				
Self protection						✓			**76.67**
11. Learning Curve									
Current position				✓					
Infrastructure					✓				**65**
12. Tolerance for Complexibility									
Complexity of data collection					✓				
Complexity of data itself					✓				**70**
13. Independence from Experts									
Availability of experts						✓			
Possibility of training program				✓					
Independence from experts			✓						**63.33**
14. Computational Ease									
Adequacy of infrastructure					✓				
Independence from additional calculation equipment						✓			**75**
15. Development Time									
Time span of development			✓						
Investment aspect	✓								**40**

Level	Meaning	Score
0	Failure	30
1	Very Poor	40
2	Poor	50
3	Fair	60
4	Fairly Good	70
5	Good	80
6	Very Good	90
7	Excellent	100

Table 5.5 : Example of Machine/Equipment Evaluation Check Sheet (Cont.)

	Intelligence Score (0-100)	Imperfection Score (0-7)	Class (0-7)
Quality of Model			
1. Accuracy	85	1	6
2. Explainability	57.5	4	3
3. Speed/Reliability of Response Time	85	1	6
Engineering Dimensions			
4. Flexibility	60	4	3
5. Scalability	70	3	4
6. Compactness	50	5	2
7. Embeddability	53.33	4	3
8. Ease of Use	60	4	3
Quality of Resources			
9. Tolerance for Noise in Data	87.5	1	6
10. Tolerance for Sparse Data	76.67	2	5
11. Learning Curve	65	3	4
12. Tolerance for Complexibility	70	3	4
Logistical Constraints			
13. Independence from Experts	63.33	3	4
14. Computational Ease	75	2	5
15. Development Time	40	6	1
Total ⇨	998.33	46	59
Average ⇨			3.93

Intelligence Score	Imperfection Score	Class
91-100	0	Intelligence 7
81-90	1	Intelligence 6
71-80	2	Intelligence 5
61-70	3	Intelligence 4
51-60	4	Intelligence 3
41-50	5	Intelligence 2
31-40	6	Intelligence 1
0-30	7	Intelligence 0

Table 5.6 : Classification of Machines/Equipment

If it is assumed that the importance or weight of each factor is equal, then the average of intelligence levels is assumed the intelligence level of this machine.

The intelligence level of machine in table 5.6 is 3.93 scale 7.

5.6.7 Classification of Cells, Lines, Areas, and Factories

The methodology used for classifying a manufacturing cell is an extension of the methodology used in section 5.6.6. To demonstrate the methodology, suppose that there is a manufacturing system composed of factories, areas, lines, cells, and machines as illustrated in Figure 5.6.

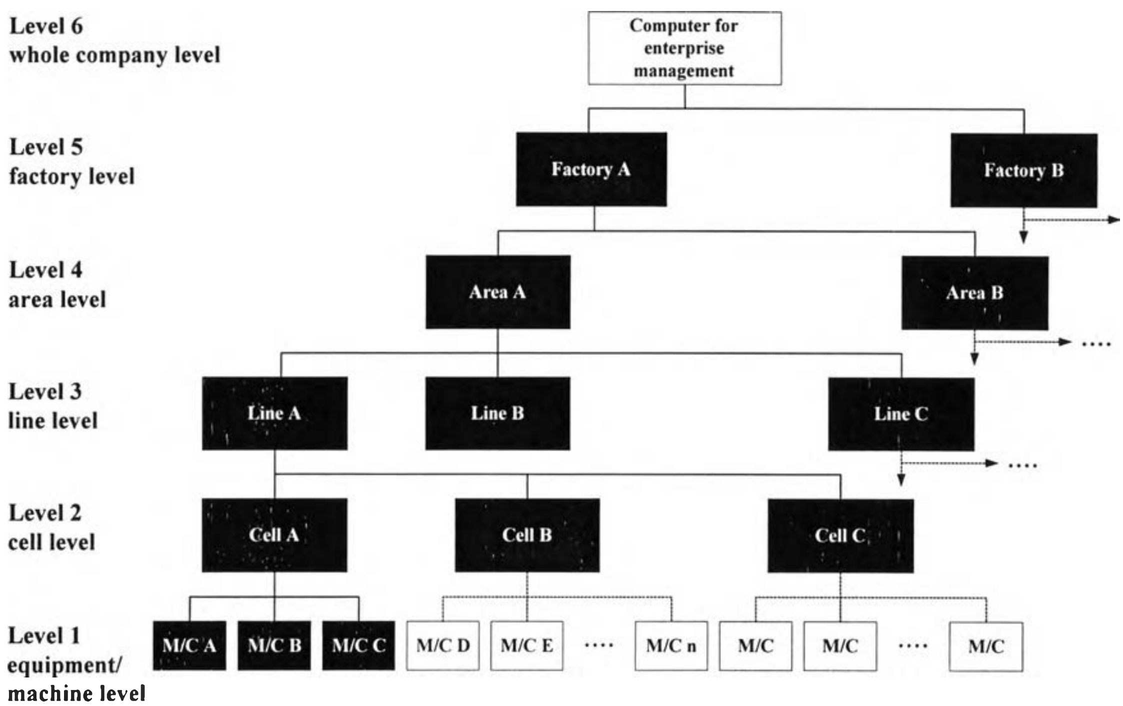


Figure 5.6 : An Example Structure of a Manufacturing System

The column of Imperfection Score and the Intelligence Class in Table 5.4 will be used as a tool to indicate the imperfection and intelligence level of a cell, a line, an area, and a factory, respectively.

Table 5.7 and 5.8 show an example of Imperfection Score and Intelligence Class of a cell (Cell A in Figure 5.6) that combined of 3 machines, Machine A, Machine B, and Machine C.

Cell A	Imperfection Score				
	M/C A	M/C B	M/C C	Total	%
Quality of Model					
1. Accuracy	1	1	2	4	3.45
2. Explainability	4	1	1	6	5.17
3. Speed/Reliability of Response Time	1	1	2	4	3.45
			Sub Total	14	12.07
Engineering Dimensions					
4. Flexibility	4	2	2	8	6.90
5. Scalability	3	3	2	8	6.90
6. Compactness	5	3	2	10	8.62
7. Embeddability	4	2	6	12	10.35
8. Ease of Use	4	2	5	11	9.48
			Sub Total	49	42.24
Quality of Resources					
9. Tolerance for Noise in Data	1	1	2	4	3.45
10. Tolerance for Sparse Data	2	2	1	5	4.31
11. Learning Curve	3	2	1	6	5.17
12. Tolerance for Complexibility	3	2	1	6	5.17
			Sub Total	21	18.10
Logistical Constraints					
13. Independence from Experts	3	5	1	9	7.76
14. Computational Ease	2	5	2	9	7.76
15. Development Time	6	6	2	14	12.07
			Sub Total	32	27.59
Grand Total	**46**	**38**	**32**	**116**	**100.00**

Remark : The last column shows the "Percent of Imperfection".

Table 5.7 : Imperfection Score of Cell A

Machine A, B, and C are classified by the check sheet shown in Table 5.3 and Table 5.5. The imperfection score of Machine A is in Table 5.6 which indicates that Machine A has 46 points or class 3.93 of intelligence.

From Table 5.7, the grand total of the imperfection score of Machine A is the summation of 15 imperfection scores which is 46 whereas the grand total of the imperfection scores of Machine B, Machine C, and the entire cell are also calculated by the same method.

Cell A	Intelligence Class			
	M/C A	M/C B	M/C C	Average
Quality of Model				
1. Accuracy	6	6	5	5.67
2. Explainability	3	6	6	5.00
3. Speed/Reliability of Response Time	6	6	5	5.67
			Sub Average	5.45
Engineering Dimensions				
4. Flexibility	3	5	5	4.33
5. Scalability	4	4	5	4.33
6. Compactness	2	4	5	3.67
7. Embeddability	3	5	1	3.00
8. Ease of Use	3	5	2	3.33
			Sub Average	3.73
Quality of Resources				
9. Tolerance for Noise in Data	6	6	5	5.67
10. Tolerance for Sparse Data	5	5	6	5.33
11. Learning Curve	4	5	6	5.00
12. Tolerance for Complexibility	4	5	6	5.00
			Sub Average	5.25
Logistical Constraints				
13. Independence from Experts	4	2	6	4.00
14. Computational Ease	5	2	5	4.00
15. Development Time	1	1	5	2.33
			Sub Average	3.44
Grand Average	3.93	4.47	4.87	4.42

Table 5.8 : Intelligence Class of Cell A

Since there are 4 directions for development, Quality of Model, Engineering Dimensions, Quality of Resources, and Logistical Constraints, there is an argument that it is no need and may be incorrect to calculate the total imperfection score of Cell A by the summation.

Under the actual conditions, those 15 factors may not have the additive property as the assumption. Nevertheless, if the total imperfection score is required, it is more reasonable to assume the additive property only among the factors within the same direction and find each summation. For example, the imperfection score of Cell A in the direction of Quality of Model, Engineering Dimensions, Quality of Resources, and the Logistical Constraints are 14, 49, 21 and 32, respectively whereas the total of the imperfection score of Cell A (which may be incorrect) is 116.

The above argument is considerably interesting but there is another advantage to find the total summation of imperfection score of Cell A. Since the classification methodology is devised to provide a tool for assessing the level of intelligent of a manufacturing system. It, in turn, will be a guideline for the improvement. The percent of the imperfection score that calculated from the grand total will be helpful for identifying which factor, group, or the direction a manufacturing need to be improved.

What the exact value of the imperfection score a machine, cell, line, area, factory, or the manufacturing system is, is not much important. It is more useful to get a perspective picture of how to manage the overall industry. This is why the total score is needed in this research.

However, Tables 5.7 and 5.8 only show the result of the combination of machines and equipment in terms of the imperfection score and intelligence level. It does not deal with any additional factors that affect to the integration such as the performance of the material handling systems or AGVs between the cells.

Obviously, the level of intelligence of a cell cannot be considered only by the combination of the functionality of the machines and equipment within it. Even though a cell is composed of a set of high performance intelligent machines but, in most cases, they cannot properly work together since they are controlled by an incompetent controller. In contrast, another cell that composed of lower performance machines but equipped with better cell controller may perform equal or higher functionality.

For the higher tier in IMS hierarchy, system integrity is considerably important and must be used as one of the evaluation factors.

Generally, an automated manufacturing system consists of two subsystems, **physical subsystems** and **control subsystems**.

For the physical subsystem, it includes the followings:

1. Workstations : NC machine tools, inspection equipment, part-washing devices, load and unload area, work area
2. Storage-Retrieval systems
3. Material handling systems : powered vehicles, conveyors, AGVs

For the control subsystem, it is divided into two categories:

1. Control hardware, which includes mini-computers and PCs, PLCs, communication networks, sensors, switching devices and many other peripheral devices such as printers and mass strorage memory equipment.
2. Control software consisting of a set of files and programs used to control physical subsystems. It is important to have hardware and software compatibility for efficient control of the whole system.

Accordingly, Singh [36] states that basic features of control component of a manufacturing system can be divided into the following control functions:

1. Work-order processing and part control system
2. Machine-tool control system including inspection machines
3. Tool management and control system
4. Traffic management control system

5. Quality control management system
6. Maintenance control system
7. Management control system
8. Interfacing of these subsystems with central computer

The classification methodology for higher tiers in IMS hierarchy, other than the machines/equipment, then must be included by another factor, **System Integrity**.

For the cell level, system integrity is the ability of the cell controller to control the PLCs or PCs, which in turn control a manufacturing cell or a series of machine tools as shown in Figure 5.7. Communication between various cells, other plant computers, and the factory floor can be either horizontally or vertically integrated.

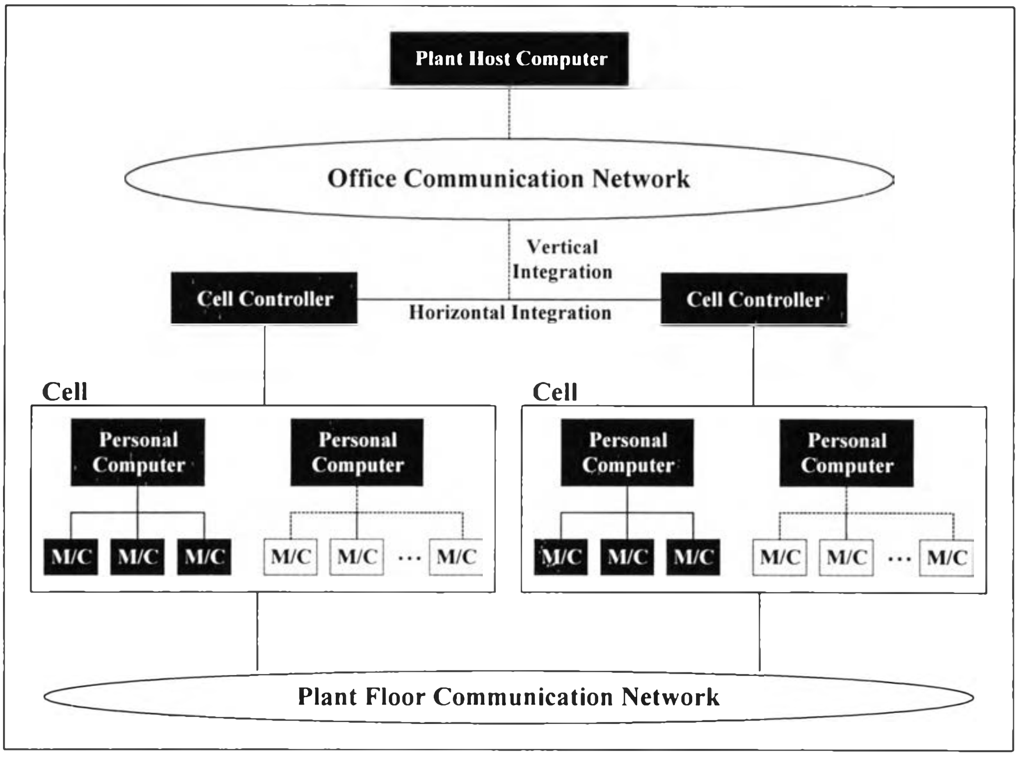


Figure 5.7 : Cell Controller, Vertical and Horizontal Integration

To find the intelligence score for system integrity of a cell, the following aspects will be considered and scored.

1. Work-order processing and part control system (1-7)
2. Machine-tool control system including inspection machines (1-7)
3. Tool management and control system (1-7)
4. Traffic management control system (1-7)
5. Quality control management system (1-7)
6. Maintenance control system (1-7)
7. Management control system (1-7)
8. Interfacing of these subsystems with central computer (1-7)

The average score of these aspects will be used as the intelligence score for system integrity. Table 5.9 shows the system integrity evaluation check sheet for a cell.

Cell	**Level**								**Score**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
	30	40	50	60	70	80	90	100	
System Integrity									
Work-order processing and part control system									
Machine-tool control system including inspection machines									
Tool management and control system									
Traffic management control system									
Quality control management system									
Maintenance control system									
Management control system									
Interfacing of these subsystems with central computer									
							Average Score		
							Imperfection Score		
							Intelligence Class		

Table 5.9 : System Integrity of Cell Evaluation Check Sheet

For cell A in Table 5.7 and 5.8, suppose that its system integrity is evaluated as shown in Table 5.10.

Cell A	**Level**								**Score**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
	30	40	50	60	70	80	90	100	
System Integrity									
Work-order processing and part control system						✓			**80**
Machine-tool control system including inspection machines				✓					**60**
Tool management and control system					✓				**70**
Traffic management control system							✓		**90**
Quality control management system					✓				**70**
Maintenance control system					✓				**70**
Management control system						✓			**80**
Interfacing of these subsystems with central computer						✓			**80**

Average Score	**75**
Imperfection Score	**2**
Intelligence Class	**5**

Table 5.10 : System Integrity of Cell A

The intelligence score for system integrity of Cell A is 75 which means it has 2 of imperfection score and class 5 of intelligence.

At this point, it is clear that system integrity is considerably different to those 15 evaluation factors. It cannot be accumulated for the combination of cells, lines, areas, and factories because the system integrity of cell does not significantly depend on the machines and equipment under it. Similarly, system integrity of a line also does not depend on the cells beneath it.

Every times a combination (or integration) of cells, lines, areas, or factories occurs, it is needed to make an evaluation for the system integrity of a line, an area, a factory, or an IMS, respectively. Thus there are 3 important tables for a cell, Tables 5.7, 5.8 and 5.10.

From Tables 5.7, 5.8 and 5.10, it can be concluded that ;

1. If Cell A that composed of Machine A, Machine B, and Machine C has to be improved, there is a sign indicates that Cell A need to be re-configure in Engineering dimension first since there is 42.24 percent of imperfection score on this direction.
2. Machine A has the maximum imperfection score that may affect to the cell's performance. Improving Machine A or replace it with another machine may make the cell's performance become more better.
3. Cell A is ranked at intelligence level 4.42. It may be ranked at higher level if improvement is adopted.
4. Percent of imperfection shows that Cell A has a good Quality of Model. This mean that the system was developed based on the functionality of the physical components and controlled software.
5. Based on the combination of machines, intelligence class of Cell A is 4.42 whereas the intelligence class of system integrity is 5. This indicate that Cell A has a Fairly Good to Good class of intelligence.

By the similar approach, classification of a Line that composed of Cells, an Area that composed of Lines, and a Factory that composed of Areas can be done as shown in Tables 5.11 - Table 5.19.

Line A	Level								Score
	0	1	2	3	4	5	6	7	
	30	40	50	60	70	80	90	100	
System Integrity									
Work-order processing and part control system					✓				70
Machine-tool control system including inspection machines			✓						50
Tool management and control system				✓					60
Traffic management control system							✓		90
Quality control management system							✓		90
Maintenance control system					✓				70
Management control system						✓			80
Interfacing of these subsystems with central computer				✓					60
								Average Score	71.25
								Imperfection Score	2
								Intelligence Class	5

Table 5.11 : System Integrity of Line A

Line A	Percent of Imperfection				
	Cell A	Cell B	Cell C	Total	%
Quality of Model					
1. Accuracy	3.45	3.67	3.82	10.94	3.65
2. Explainability	5.17	5.50	4.58	15.25	5.08
3. Speed/Reliability of Response Time	3.45	4.59	9.16	17.20	5.73
			Sub Total	43.39	14.46
Engineering Dimensions					
4. Flexibility	6.90	3.67	8.40	18.97	6.32
5. Scalability	6.90	6.42	3.82	17.14	5.71
6. Compactness	8.62	4.59	6.11	19.32	6.44
7. Embeddability	10.35	7.34	6.87	24.56	8.19
8. Ease of Use	9.48	9.17	3.05	21.70	7.23
			Sub Total	101.69	33.90
Quality of Resources					
9. Tolerance for Noise in Data	3.45	12.84	12.21	28.50	9.50
10. Tolerance for Sparse Data	4.31	4.59	9.16	18.06	6.02
11. Learning Curve	5.17	7.34	8.40	20.91	6.97
12. Tolerance for Complexibility	5.17	8.26	7.63	21.06	7.02
			Sub Total	88.53	29.51
Logistical Constraints					
13. Independence from Experts	7.76	6.42	3.82	18.00	6.00
14. Computational Ease	7.76	4.59	6.11	18.46	6.15
15. Development Time	12.06	11.01	6.86	29.93	9.98
			Sub Total	66.39	22.13
Grand Total	100	100	100	300	100.00

Table 5.12 : Percent of Imperfection of Line A

Line A	Intelligence Class			
	Cell A	Cell B	Cell C	Average
Quality of Model				
1. Accuracy	5.67	4.23	4.55	4.82
2. Explainability	5.00	5.58	5.56	5.38
3. Speed/Reliability of Response Time	5.67	6.03	6.45	6.05
			Sub Average	5.42
Engineering Dimensions				
4. Flexibility	4.33	5.33	4.55	4.74
5. Scalability	4.33	5.54	5.84	5.24
6. Compactness	3.67	4.23	5.35	4.42
7. Embeddability	3.00	5.98	4.21	4.40
8. Ease of Use	3.33	5.55	6.52	5.13
			Sub Average	4.78
Quality of Resources				
9. Tolerance for Noise in Data	5.67	6.36	4.95	5.66
10. Tolerance for Sparse Data	5.33	5.15	5.66	5.38
11. Learning Curve	5.00	4.95	5.76	5.24
12. Tolerance for Complexibility	5.00	3.50	4.66	4.39
			Sub Average	5.17
Logistical Constraints				
13. Independence from Experts	4.00	3.22	5.96	4.39
14. Computational Ease	4.00	2.33	5.35	3.89
15. Development Time	2.33	2.51	4.35	3.06
			Sub Average	3.78
Grand Average	4.42	4.70	5.31	4.81

Table 5.13 : Intelligence Class of Line A

Area A	Level 0 (30)	Level 1 (40)	Level 2 (50)	Level 3 (60)	Level 4 (70)	Level 5 (80)	Level 6 (90)	Level 7 (100)	Score
System Integrity									
Work-order processing and part control system			✓						50
Machine-tool control system including inspection machines				✓					60
Tool management and control system					✓				70
Traffic management control system					✓				70
Quality control management system					✓				70
Maintenance control system						✓			80
Management control system						✓			80
Interfacing of these subsystems with central computer						✓			80
							Average Score	70	
							Imperfection Score	3	
							Intelligence Class	4	

Table 5.14 : System Integrity of Area A

Area A	Percent of Imperfection				
	Line A	Line B	Line C	Total	%
Quality of Model					
1. Accuracy	3.65	5.80	6.47	15.92	5.31
2. Explainability	5.08	6.52	8.63	20.23	6.74
3. Speed/Reliability of Response Time	5.73	3.62	7.19	16.54	5.51
			Sub Total	52.69	17.56
Engineering Dimensions					
4. Flexibility	6.32	4.35	6.47	17.14	5.71
5. Scalability	5.71	8.70	6.47	20.88	6.96
6. Compactness	6.44	10.14	7.19	23.77	7.92
7. Embeddability	8.19	5.80	5.76	19.75	6.58
8. Ease of Use	7.23	6.52	5.04	18.79	6.26
			Sub Total	100.33	33.44
Quality of Resources					
9. Tolerance for Noise in Data	9.50	5.07	4.32	18.89	6.30
10. Tolerance for Sparse Data	6.02	7.25	3.60	16.87	5.62
11. Learning Curve	6.97	7.97	8.63	23.57	7.86
12. Tolerance for Complexibility	7.03	7.25	6.47	20.75	6.92
			Sub Total	80.08	26.69
Logistical Constraints					
13. Independence from Experts	6.00	5.80	9.35	21.15	7.05
14. Computational Ease	6.15	4.35	7.94	18.44	6.15
15. Development Time	9.98	10.86	6.47	27.31	9.10
			Sub Total	66.90	22.30
Grand Total	100	100	100	300	100.00

Table 5.15 : Imperfection Score of an Area

Area A	Intelligence Class			
	Line A	Line B	Line C	Average
Quality of Model				
1. Accuracy	4.82	5.23	6.36	5.47
2. Explainability	5.38	5.65	5.84	5.62
3. Speed/Reliability of Response Time	6.05	4.23	5.22	5.17
			Sub Average	5.42
Engineering Dimensions				
4. Flexibility	4.74	6.33	4.44	5.17
5. Scalability	5.24	4.25	4.63	4.71
6. Compactness	4.42	2.98	4.85	4.08
7. Embeddability	4.40	3.54	5.66	4.53
8. Ease of Use	5.13	6.36	6.02	5.84
			Sub Average	4.87
Quality of Resources				
9. Tolerance for Noise in Data	5.66	5.45	6.38	5.83
10. Tolerance for Sparse Data	5.38	5.23	5.89	5.50
11. Learning Curve	5.24	5.22	5.69	5.38
12. Tolerance for Complexibility	4.39	4.89	6.32	5.20
			Sub Average	5.48
Logistical Constraints				
13. Independence from Experts	4.39	5.63	5.64	5.22
14. Computational Ease	3.89	5.11	5.66	4.89
15. Development Time	3.06	5.24	3.25	3.85
			Sub Average	4.65
Grand Average	4.81	5.02	5.46	5.10

Table 5.16 : Intelligence Class of Area A

Factory A	Level 0 (30)	1 (40)	2 (50)	3 (60)	4 (70)	5 (80)	6 (90)	7 (100)	Score
System Integrity									
Work-order processing and part control system			✓						50
Machine-tool control system including inspection machines			✓						50
Tool management and control system					✓				70
Traffic management control system						✓			80
Quality control management system						✓			80
Maintenance control system						✓			80
Management control system					✓				70
Interfacing of these subsystems with central computer					✓				70
Average Score									68.75
Imperfection Score									3
Intelligence Class									4

Table 5.17 : System Integrity of Factory A

Factory A	Percent of Imperfection: Area A	Area B	Total	%
Quality of Model				
16. Accuracy	5.31	4.11	9.42	4.71
17. Explainability	6.74	6.85	13.59	6.80
18. Speed/Reliability of Response Time	5.51	10.27	15.78	7.89
			38.79	19.40
Engineering Dimensions				
19. Flexibility	5.71	9.59	15.30	7.65
20. Scalability	6.96	5.48	12.44	6.22
21. Compactness	7.92	6.16	14.08	7.04
22. Embeddability	6.58	7.53	14.11	7.06
23. Ease of Use	6.26	5.48	11.74	5.87
			67.67	33.84
Quality of Resources				
24. Tolerance for Noise in Data	6.30	5.48	11.78	5.89
25. Tolerance for Sparse Data	5.62	6.16	11.78	5.89
26. Learning Curve	7.86	6.85	14.71	7.36
27. Tolerance for Complexibility	6.92	6.16	13.08	6.54
			51.35	25.68
Logistical Constraints				
28. Independence from Experts	7.05	6.85	13.90	6.95
29. Computational Ease	6.15	7.53	13.68	6.84
30. Development Time	9.11	5.50	14.61	7.31
			42.19	21.10
Grand Total	100	100	200	100.00

Table 5.18 : Imperfection Score of a Factory

Factory A	Intelligence Class		
	Area A	Area B	Average
Quality of Model			
1. Accuracy	5.47	5.36	5.42
2. Explainability	5.62	4.56	5.09
3. Speed/Reliability of Response Time	5.17	6.89	6.03
	Sub Average		5.51
Engineering Dimensions			
4. Flexibility	5.17	6.00	5.59
5. Scalability	4.71	5.93	5.32
6. Compactness	4.08	4.85	4.47
7. Embeddability	4.53	5.66	5.10
8. Ease of Use	5.84	6.36	6.10
	Sub Average		5.31
Quality of Resources			
9. Tolerance for Noise in Data	5.83	6.38	6.11
10. Tolerance for Sparse Data	5.50	5.89	5.70
11. Learning Curve	5.38	5.63	5.51
12. Tolerance for Complexibility	5.20	6.32	5.76
	Sub Average		5.77
Logistical Constraints			
13. Independence from Experts	5.22	4.22	4.72
14. Computational Ease	4.89	5.60	5.25
15. Development Time	3.85	6.50	5.18
	Sub Average		5.05
Grand Average	5.10	5.74	5.42

Table 5.19 : Intelligence Class of Factory A

5.6.8 Classification of Intelligent Manufacturing Systems

Finally, the overall manufacturing system can be classified as shown in Tables 5.20 to 5.22. The example in this section shows that this manufacturing system is classified to level 5.36 of intelligence and level 6 of system integrity.

As described in section 5.6.2 and 5.6.6, this proposed classification methodology derived from Dhar et al.'s [3] 15 IDs and Singh's [36] 8 features of control function. These factors can be arbitrarily modified, added, or neglected by the assessor. They are not static. However, for the additional IDs used for evaluating the machines and equipment, which is the foundation of the IMS, it is essential to clarify where their position in the stretch plot are. (see Figure 5.3 and 5.4). Their positions in the ID profile will somehow indicate which direction an organization is encountering.

IMS	Level								Score
	0	1	2	3	4	5	6	7	
	30	40	50	60	70	80	90	100	
System Integrity									
Work-order processing and part control system							✓		90
Machine-tool control system including inspection machines							✓		90
Tool management and control system							✓		90
Traffic management control system						✓			80
Quality control management system					✓				70
Maintenance control system					✓				70
Management control system						✓			80
Interfacing of these subsystems with central computer						✓			80
									81.25
Imperfection Score									1
Intelligence Class									6

Table 5.20 : System Integrity of a Manufacturing System

IMS	Percent of Imperfection F/R A	F/R B	Total	%
Quality of Model				
1. Accuracy	4.71	9.38	14.09	7.05
2. Explainability	6.80	3.75	10.55	5.28
3. Speed/Reliability of Response Time	7.89	7.50	15.39	7.70
			40.03	20.02
Engineering Dimensions				
4. Flexibility	7.65	8.75	16.40	8.20
5. Scalability	6.22	5.63	11.85	5.93
6. Compactness	7.04	5.63	12.67	6.34
7. Embeddability	7.06	5.00	12.06	6.03
8. Ease of Use	5.87	8.75	14.62	7.31
			67.60	33.80
Quality of Resources				
9. Tolerance for Noise in Data	5.89	8.13	14.02	7.01
10. Tolerance for Sparse Data	5.89	10.63	16.52	8.26
11. Learning Curve	7.36	5.59	12.99	6.50
12. Tolerance for Complexibility	6.54	5.00	11.54	5.77
			55.07	27.54
Logistical Constraints				
13. Independence from Experts	6.95	5.63	12.58	6.29
14. Computational Ease	6.84	5.63	12.43	6.22
15. Development Time	7.29	5.00	12.29	6.15
			37.30	18.65
Grand Total	100	100	200	100.00

Table 5.21 : Imperfection Score of a Manufacturing System

IMS	Intelligence Class		
	F/R A	F/R B	Average
Quality of Model			
1. Accuracy	5.42	6.26	5.87
2. Explainability	5.09	6.33	5.98
3. Speed/Reliability of Response Time	6.03	5.66	5.42
	Sub Average		5.75
Engineering Dimensions			
4. Flexibility	5.59	6.33	5.75
5. Scalability	5.32	5.84	5.28
6. Compactness	4.47	6.36	5.22
7. Embeddability	5.10	5.23	4.88
8. Ease of Use	6.10	4.23	5.04
	Sub Average		5.23
Quality of Resources			
9. Tolerance for Noise in Data	6.11	4.89	5.36
10. Tolerance for Sparse Data	5.70	4.22	4.86
11. Learning Curve	5.51	5.69	5.54
12. Tolerance for Complexibility	5.76	5.65	5.43
	Sub Average		5.30
Logistical Constraints			
13. Independence from Experts	4.72	5.39	5.31
14. Computational Ease	5.25	5.87	5.38
15. Development Time	5.18	6.33	5.09
	Sub Average		5.26
Grand Average	5.42	5.62	5.36

Table 5.22 : Intelligence Class of a Manufacturing System

5.7 Conclusions

As mentioned at the very beginning of this thesis, intelligent manufacturing is a very new concept of production system. It concerns with the integration of the information technology and various kinds of intelligent machine tools to create a new production system which is completely 24-hour unmanned, flexible and easy-to-operate operation. However, for the industries, this new concept of production systems which is fully equipped with various kinds of advance manufacturing devices means "high investment".

The methodology proposed in this research is devised to be a guideline for evaluating the intelligent machines, cells, lines, areas, and the intelligent manufacturing system in order to clarify which subsystem in the overall system to be improved.

The core concept of the methodology is influenced by the intelligence density, ID, proposed by Dhar et al.[3]. Their works on intelligent system are based on the "army type" of intelligence.

The methodology is a hierarchy process of evaluation from the lowest tier, machines/equipment, to the topmost in the CIM structure.

At the lowest tier, machines and equipment will be classified by 15 IDs (15 factors) in Table 5.3 and 5.4 which leads to the value of imperfection score and the intelligence class.

Cell is the combination of machines and equipment that can be classified by the same technique, but since each cell in the manufacturing system need not to be articulated by the same numbers of machines and equipment. "The system integrity" which is the ability of a system to control and manage its own subsystem then has been adopted and the imperfection score is modified to be the percent of imperfection.

The intelligence scores of each ID are used for indicating the amount and the development direction of a proposed IMS whereas the imperfection score and the percent of imperfection are used for identifying which parts or subsystems are need to be improved or replaced. The perspective picture of these measures will be obvious from the stretch plot and the IDs profile in Figure 4.3 and 4.4.

To get a more clearer picture of how and which subsystem can be improved in order to create better level of intelligence of the overall system, the evaluation maker can arbitrarily adjust, modify, add, and neglect any ID in the 15 IDs used in the evaluation check sheet. In addition, the sensitivity analysis for each ID can be done if necessary.