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Axiomatic design of flexible manufacturing systems

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One of the major requirements of agile manufacturing strategies for the 21st century is to introduce intelligent information technology into manufacturing. The main contribution of this paper is an innovative new FMS design methodology. The operation-driven FMS design methodology is introduced, as the concept of concurrent product and process development is being widely used to enhance the productivity and quality of manufacturing. The new FMS design theory is developed from axiomatic design theory established by Suh (1990). The general design theory based on two design axioms and a set of theorems and corollaries is concretized for the FMS design. The proposed methodology works well as an effective decision support system for FMS designers in determining the appropriate FMS configuration at the design stage. This is illustrated via a successful implementation exercise resulting in configuring FMS in real manufacturing settings.

1. Introduction

A flexible manufacturing system (FMS) is a fully integrated manufacturing system consisting of computer numerically controlled (CNC) machines, connected by an automated material handling system, all under the control of a central computer. The design of the FMS is a complex decision making process that typically involves the planning of capacities, balancing of operations, transport analysis, storage planning and the like. Adequate solution of a manufacturing problem requires a comprehensive study of all these factors (in their interaction). The design of an FMS is concerned with obtaining good performance measures such as the optimal number of machines/resources, material handling transporters, number of operators, and so on (Sagi and Chen 1995).

Different tools such as mathematical modelling, simulation, artificial intelligence, neural networks have been used as decision support systems for FMS design. Simulation has been used as a popular tool in design of FMS. For the design of a FMS, simulation can be incorporated into the overall design procedure and used for the evaluation of design alternatives (Vujosevic 1994). Many reports on use of simulation in FMS design can be found (Pegden *et al.* 1984, Iwata 1984, Elmaraghy 1982, Del Taglia 1993). Basic limitations in using the simulation were the long model development time and the difficulty in analyzing the output. Different authors tried to overcome these limitations through coupling simulation and AI techniques.

Many FMS design systems reported in the literature are built by coupling expert systems and simulation. These systems use simulation models to generate experimental data for decision making. The design goals are expressed as limits of performance measures obtainable by simulation. The simulation outputs are analyzed to

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evaluate the performance of the FMS design. If some of performance measures are not within limits, the defined expert system performing bottleneck analysis is activated. The following reasons for bottlenecks in FMS are checked: inadequate loading/unloading of machines, and overutilized machines and machines with extremely long processing times (Wahab 1986). After bottleneck analysis expert system recommends modifications in the current FMS design and the new simulation run is done. The iterative process is repeated until the system design that meets design requirements is achieved.

Baid and Nagarur (1994) developed an intelligent simulation system (ISS) which incorporates three basic modules: an intelligent front end, a simulator, and an intelligent back end. The intelligent front end speeds up the modelling process. The simulator simulates the system and, in fact, is the heart of the ISS, in the sense that the whole ISS is built around this module. The intelligent back end makes appropriate changes in the model and runs it again for different scenarios. It can be also made to perform statistical analysis and validation.

Sagi and Chen (1995) described a framework for manufacturing system design with integration of simulation, neural networks and knowledge-based expert system tools. An operation/cost-driven cell design methodology was applied to concurrently consider cell physical design. Simulation was performed to estimate performance measures based on input parameters and given cell configurations. A rule based expert system was employed to store the acquired expert knowledge regarding the relation between cell control complexities, cost of cell controls, performance measures and cell configuration. Neural networks were applied to predict the cell design configuration and corresponding complexities of cell control functions.

The above analysis shows that the systems for the design of flexible manufacturing systems are based on the integration of neural network tools (example based), expert systems (rule based) and manufacturing simulators. An innovative approach to the design of manufacturing systems is to establish new design concept. This paper reports the results of research with a threefold objective: (1) to develop a new framework for FMS design based on axiomatic design theory; (2) to demonstrate the effectiveness of proposed approach through development of an intelligent system for FMS design; (3) to illustrate the practical applicability of the developed intelligent system for FMS design on examples from industrial environment. The new concept provides better organization of the design knowledge. The simulation is no longer used as a generator of experimental knowledge necessary for the decision making process. It is only employed to check the final solution at the end of design process.

2. Key concepts of axiomatic design

For the formalization of the FMS design process, axiomatic design theory developed by Suh (1990) was adopted. The design process consists of several steps (Kim and Suh 1991).

Step 1. Establishment of design goals to satisfy a given set of perceived needs.
Step 2. Conceptualization of design solutions.
Step 3. Analysis of the proposed solution.
Step 4. Selection of the best design from among those proposed.
Step 5. Implementation.

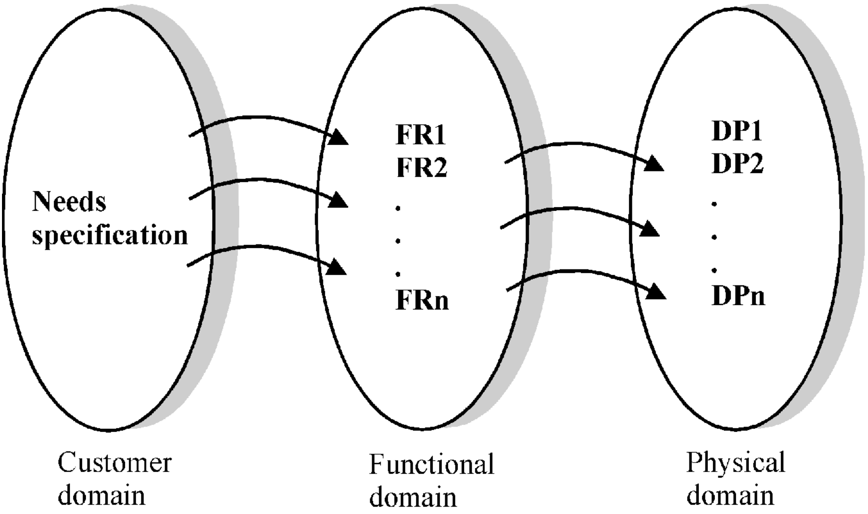


Figure 1. Concept of domain, mapping and spaces in axiomatic design.

These activities occur between and in different design domains. These design domains are illustrated in figure 1 (Kim and Suh 1991). The customer domain is where customer needs reside. These customer needs must be mapped into the functional domain where the customer needs are translated into a set of functional requirements (FRs), which constitute a characteristic vector. These FRs are then mapped into the physical domain, where design parameters (DPs) are chosen to control/satisfy the FRs.

The relationship between the domains is that the domain on the left is 'What we want' and the domain on the right is 'How we satisfy what we want' (Kim and Suh 1991). Going from one domain to another is called mapping, which is the synthesis phase of the design process.

The most important concept in axiomatic design is the existence of the design axioms, which must be satisfied during the mapping process to come up with acceptable solutions. The first design axiom is known as the Independence Axiom and the second axiom is known as the Information Axiom. They are stated as follows (Suh 1990).

Axiom 1—The Independence Axiom: *Maintain the independence of functional requirements.*

Axiom 2—The Information Axiom: *Minimize the information content.*

Axiom 1 distinguishes between good and bad design, or acceptable and unacceptable design. Axiom 2 is the criterion for the selection of the optimum design solutions from among those that satisfy Axiom 1.

Design is defined as the mapping process between the FRs in the functional domain and the DPs in the physical domain. This relationship may be characterized mathematically. As the characteristics of the required design are represented by a set of independent FRs, these may be treated as a vector FR with m components. Similarly, the DPs in the physical domain also constitute a vector DP with n components. The design process then involves choosing the right set of DPs to satisfy the given FRs, which may be expressed as (Suh 1990):

$$\{FR\} = [A]\{DP\}, \tag{1}$$

where $\{FR\}$ is the functional requirement vector, $\{DP\}$ is the design parameter vector, and $[A]$ is the design matrix. Each element A_{ij} of the design matrix relates a component of the FR vector to a component of the DP vector.

The information content is defined in terms of the probability of successfully achieving FRs. Information is defined as (Suh 1990):

$$I = \log_2\left(\frac{1}{p}\right), \tag{2}$$

where p is the probability of achieving the functional requirement FRi. In any design situation, the probability of success is given by what designer wishes to achieve in terms of tolerance (i.e. design range), and what the system is capable of delivering (i.e. system range). As shown in figure 2 (Kim and Suh 1991) the overlap between the designer-specified 'Design range' and the system capability range 'System range' is the region where the acceptable solution exists. Therefore, in the case of uniform probability distribution function, (2) may be written as (Kim and Suh 1991):

$$I = \log_2\left(\frac{\text{System range}}{\text{Common range}}\right), \tag{3}$$

From the two axioms of design, many corollaries can be derived as a direct consequence of the axioms. These corollaries may be more useful in making specific design decisions, since they can be applied to actual situations more readily than can the original axioms (Suh 1990). Here, the corollaries relevant for FMS design are only given.

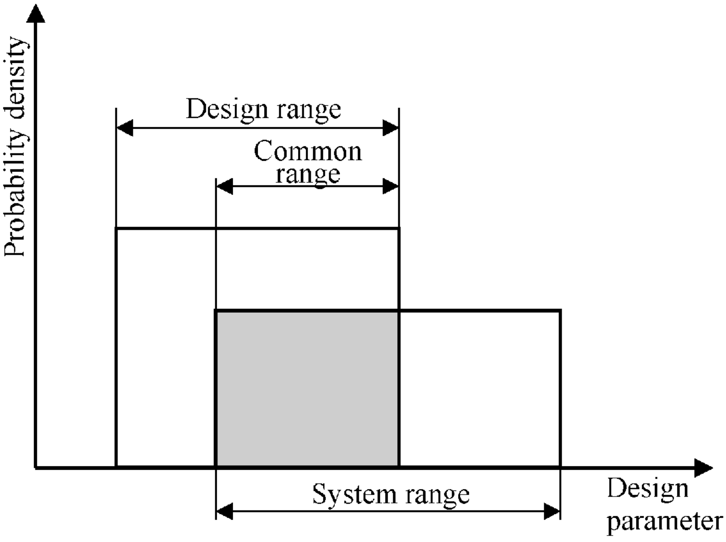


Figure 2. Probability distribution of a system parameter.

Corollary 2: *Minimization of FRs.*

Corollary 3: *Integration of physical parts.*

Corollary 6: *Largest tolerance.*

Corollary 7: *Uncoupled design with less information.*

These concepts will now be applied to FMS design.

3. Design of flexible manufacturing systems

3.1. *Design procedure*

The FMS design process can be divided into the following phases:

Specification of operations (SO): definition of overall manufacturing operations to be performed by the FMS. This defines the intended process flow.

Definition of functional requirements (FRs): the description of overall machine functions required to perform the manufacturing process. It states the detailed FRs at the individual FMS components level, such as machining type, accuracy, power requirements and the like.

FMS design: enumeration of machines, material handling equipment, determination of the number and capacity of each of these system components and layout of machines. The design task is performed based on SO and FRs.

FMS performance analysis: simulation is a popular tool for the evaluation of FMS designs. A specially developed visual FMS simulation system will be used to conduct simulation experiments. The inputs to a simulation model are the configuration of the system (number of machines, buffer size, layout description) obtained through previous step and part sequence defined by SO. The following performance measures are used to evaluate FMS design: percentage resource utilization, part flow time, time taken to produce a batch, queue at each resource, etc.

3.2. *Axiomatic design of FMS*

In accordance with axiomatic design theory the design process for FMS begins with the establishment of FRs in the functional domain to satisfy a given set of needs. The needs that FMS design should satisfy are defined by a set of parts that should be produced, batch sizes, etc. (Babic 1996). The needs specification and corresponding description of operations are the basis for the formation of FRs. Description of operations defines overall manufacturing operations to be performed by the FMS. This defines the intended process flow/sequence and related quality control requirements which are normally prepared by the manufacturing engineers as part of the generic manufacturing plan of the set of parts selected for running in the FMS (Sagi and Chen 1995).

The establishment of the functional domain starts with the creation of the individual functional requirement for each manufacturing operation from the overall set of operations. The functional requirements will be formed regarding machining type, required accuracy, required surface quality and part volume. During the specification of the required accuracy and surface quality, Corollary 6 (application of the largest possible tolerance) should be taken in mind. The FRs can be expressed in Prolog notation as:

FR (*Machining type, Accuracy, Surface roughness, Volume, Part_operation*) where *Part_operation* gives the connection between FR and operation from the set of operations via the part name and operation sequence number for the part.

Regarding Corollary 2, which emphasizes the need for minimization of number of FRs, in the next step the joining of similar FRs is performed. The final form for the FR in each functional domain is as follows:

FR (*Machining type, Accuracy, Surface roughness, Volume,* [*Part_operation*]).

where [*Part_operation*] is the list of *Part_operation* variables. Generally, each FR is associated with the list of operations from the overall set of operations.

The next step is the creation of physical space that is the space containing design parameters. Design parameters contain the characteristics of the machines, transportation devices and/or storage equipment. The design parameters are given in following form:

DP(*Machine name, Accuracy of machine, Maximal machinable part volume, Machine power, Machine cost per hour*).

After application of Axiom 1 the design matrix [A] is formed, i.e. each FR from functional space is associated with one or more DPs in physical space that can satisfy the FR concerned. Now, the DPs facts have the following Prolog notation:

DP(*Machine name, Number of machines, Accuracy of machine, Maximal machinable part volume, Machine power, Machine cost per hour*, [*Part_operation*]),

where *Number of machines* denotes the required number of machines of the same type, and the [*Part_operation*] list represents the connection to corresponding FR.

Due to a non-unique mapping process, more than one feasible solution will be obtained. Therefore the optimal solution should be selected. Axiom 2 and Corollary 7 give the criterion for the selection of the optimal solution based on the minimal information content. The methodology for the calculation of the information content of FMS is given in the following subsection.

The final step in axiomatic FMS design is the integration of physical parts based on the application of Corollary 3. Different FRs may be satisfied with the same or similar DPs, and that means the same or similar machines. Possible joining of machining jobs should be performed in order to decrease the number of machines and optimize the solution. The complete axiomatic design procedure described above is illustrated in figure 3.

3.3. *Methodology for the calculation of information content for FMS*

The information content for a system is the sum of partial information contents for individual parameters which are associated with FRs that should be satisfied. In the case of FMS the information content is calculated for two levels: (1) the machining station level; and (2) the system level.

At the machining station level the information content is the sum of the following partial information contents:

(1) Information content for geometrical accuracy
(2) Information content for surface quality
(3) Information content for production capacity
(4) Information content for production costs.

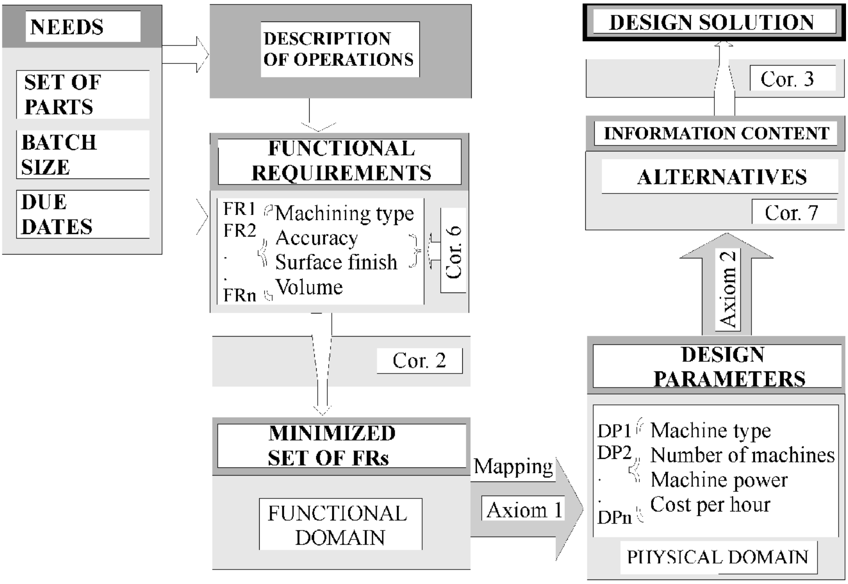


Figure 3. Axiomatic FMS design.

Information content at the machining station level is the criterion for the selection of machines. The system level information content considers part flow through the FMS (scheduling problem) and is the FMS integration measure.

3.3.1. *Information content for geometrical accuracy*

Equation (3) is the basis for the calculation of the information content. Consequently, for each particular case the system range and the common range should be defined. Let us consider machining some part to dimension $L \pm L/2$. The tolerance specified by the designer will be ΔL and the machine accuracy range will be from a_1 to a_2. This is illustrated in figure 4. As shown in the figure, the common range representing overlap between the specified tolerance and machine accuracy is equal to $\Delta L - a_1$ and the system range is equal to $a_2 - a_1$. Regarding (3), the formula for the calculation of information content for geometrical accuracy is:

$$I_{\mathrm{acc}} = \log_2 \left(\frac{a_2 - a_1}{\Delta L - a_1} \right). \tag{4}$$

3.3.2. *Information content for surface quality*

Illustration for the calculation of information content for surface quality is given in figure 5. In this case the designer specifies a maximal allowed surface roughness $R_{\max}$ The lower limit of the design range is taken to be 0. The minimal and maximal roughnesses achievable by the machine are a_1 and a_2 respectively. In accordance with (3) the following formula is derived:

$$I_R = \log_2 \left(\frac{a_2 - a_1}{R_{\max} - a_1} \right). \tag{5}$$

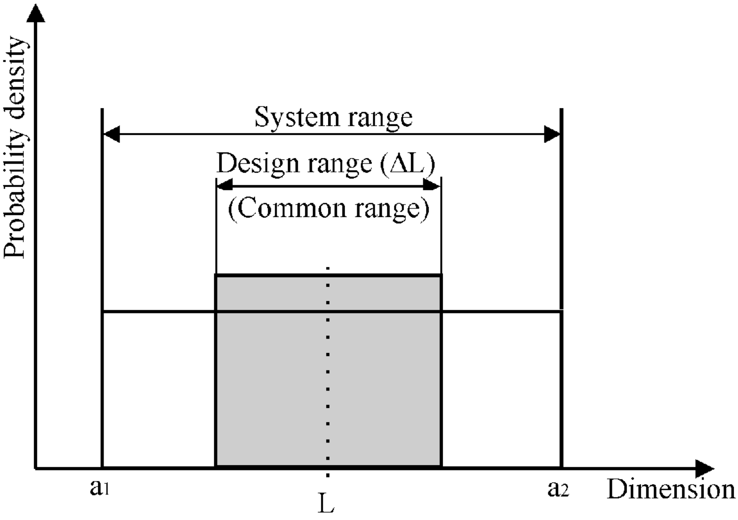


Figure 4. Probability distribution of a dimension.

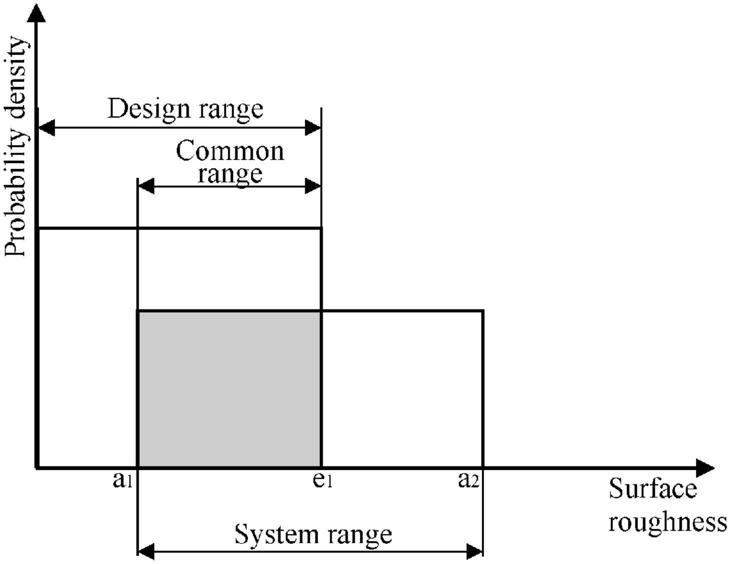


Figure 5. Probability distribution of surface roughness.

3.3.3. *Information content for production capacity*

Calculation of the information content for production capacity is based on the required capacity (design range) and the available capacity (system range). The number of parts to be machined on a machine and the machining time for the parts define the required capacity. The available capacity is defined by the number of machines of the same type and the efficiency of the machines. For the derivation of the necessary equations, the formula for the estimation of the required number of machines for the FMS cell given by Ranky (1983) will be used:

$$N = \left(\frac{T \times P}{60 \times D \times \eta}\right), \tag{6}$$

where N is the FMS cell requirements, i.e. the number of machines required; T is the part processing time; P is the production rate per machine (i.e. components manufactured per shift); D is the duration of an operating period (i.e. shift) in hours; η is the machine efficiency.

Equations for the calculation of design range bounds based on (6) are:

$$DR_{\max} = T_{\max} \times P, \tag{7a}$$

$$DR_{\min} = T_{\min} \times P, \tag{7b}$$

where $DR_{\max}$ and $DR_{\min}$ are the design range bounds; and $T_{\max}$ and $T_{\min}$ are the maximal and minimal estimated part machining times.

The system range lower limit is equal to 0 and the upper limit is calculated by the following equation:

$$SR_{ul} = N \times \eta \times D \times 60, \tag{8}$$

In accordance with (7a), (7b) and (8), equations for the calculation of the information content for production capacity follow:

$$I_{cap} = \log_2 \left(\frac{SR_{ul}}{SR_{ul} - DR_{\min}}\right) \tag{9a}$$

and

$$I_{cap} = \log_2 \left(\frac{SR_{ul}}{DR_{\max} - DR_{\min}}\right). \tag{9b}$$

Equation (9a) is valid for the case when $SR_{ul} < DR_{max}$ and Equation (9b) is for the case when $\mathrm{SR}_{\mathrm{ul}} > \mathrm{DR}_{\mathrm{max}}$.

3.3.4. *Information content for production costs*

The system range limits for production costs are calculated by:

$$C_{\max} = \mathrm{T}_{\max} \times C_{ph} \times Np/60 \tag{10a}$$

and

$$C_{\min} = T_{\min} \times C_{cp} \times Np/60, \tag{10b}$$

where $T_{\max}$ and $T_{\min}$ are the maximal and minimal estimated part machining times, C_{ph} is the machine cost per hour, and Np is the number of parts.

The design range upper limit is estimated by:

$$Cd_{\max} = \frac{\bar{C}_{\max} + \bar{C}_{\min}}{2}, \tag{11}$$

where $\bar{C}_{\max}$ and $\bar{C}_{\min}$ are maximal and minimal average production costs for the candidate machines. Then the information content may be written as

$$I_c = \log_2 \left(\frac{C_{\max} - C_{\min}}{Cd_{\max} - C_{\min}}\right). \tag{12}$$

The total amount of information for the FMS design is expressed by

$$I = I_{acc} + I_R + I_{cap} + I_c. \tag{13}$$

The information content for the FMS is the sum of four dimensionless partial information contents. Therefore the information for FMS is associated with many different attributes. Equation (13) takes into account the most important factors for FMS design and is the criterion for the selection of the optimal solution.

The minimum information criterion is a powerful tool in optimization of the design process when there are several variables with respect to which the solution must be optimized. Unlike many other optimization techniques, which typically deal with one variable, the information content measure can select the best solution among those proposed, regardless of the number of variables involved (Suh 1990).

Mathematical analysis of (4), (5), (9) and (12) would show that they are very sensitive to the change of input variables. For example examination of (4) shows that taking into consideration a too-inaccurate machine gives an infinite value for I_{acc} which means rejection of the machine. On the contrary, considering a too-accurate machine would give a high value for I_{acc}. Therefore we avoid choosing an inaccurate machine and a too-accurate machine. Optimal selection is forced. This is also true for (5), (9) and (12), and consequently for (13).

The other methods for the evaluation of manufacturing system design are based on the use of databases and pondering (Genschow and Harnisch 1988). These methods require complex databases and the designer's interaction is necessary during the decision process. Equations (4), (5), (9), (12) and (13) are quite suitable for computerization and are fully independent of the user's experience.

The practical applicability of the proposed method is illustrated in the example given in section 5.

4. Intelligent system for FMS design

In accordance with the axiomatic design concept, the architecture of the intelligent system for FMS design must involve the following four levels: functional requirements (FRs) definition level, design parameters (DPs) creation level, the level for analysis of design solution, and the level for checking the final solution (Babic 1996).

At the first level, a set of FRs are defined in the functional domain in order to satisfy perceived needs. Then a set of DPs are defined in order to satisfy the FRs defined at level 1. Subsequently proposed solutions are analyzed for acceptability. Finally, the fidelity of the final solution to the originally perceived needs is checked.

The basic model for the intelligent system for FMS design is given in figure 6. There are four knowledge processing modules, which are interconnected and used in the knowledge control unit: knowledge acquisition module, FRs recognition module, DPs recognition module, and construction module. The initial knowledge is divided into the following classes: knowledge about parts (dimensions and materials); knowledge about types of operation, surface description and tolerances; knowledge about potentially used machine tools; and knowledge about the lot size for release, required productivity, required utilization of machines. The main program representing the knowledge control machine is realized in Prolog and has the following coding form:

```
:- Module FMS_D M
       Reconsult ('Base.Ari'),
       Load_base,
       FR_recog,
```

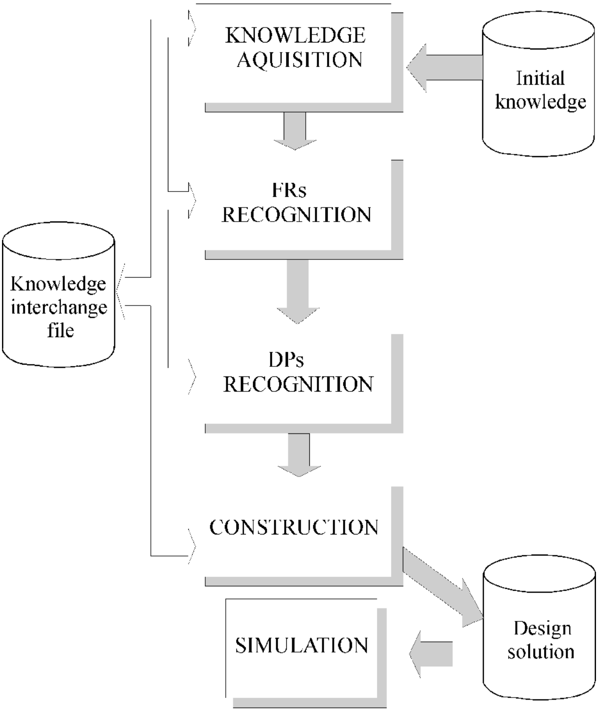


Figure 6. Architecture of intelligent system for FMS design.

DP_recog,
Construct.

The instruction *Reconsult*(*'Base.Ari'*) opens a file containing needs specification, a description of the operations, and the characteristics of available machines. The module *Load_Base* is the knowledge acquisition module which acquires knowledge from a previously opened file and organizes it in the form of Prolog facts. This knowledge is used for the definition of functional requirements. The modules *FR_Recog, DP_Recog* and *Construct* are knowledge processors. Generally these modules consist of a knowledge acquisition submodule for previously generated knowledge gathering, and a recursive submodule for knowledge processing. The knowledge acquisition submodule organizes previously generated knowledge in the form of the list. The knowledge processing submodule takes the 'head' of the list and processes it by the set of rules. The 'tail' of the list is processed in the next recursive call. Knowledge generated in each recursive call is written on the knowledge transition file and is available for use in the next recursive call as well as in the next knowledge processing modules. During the design process the knowledge transition file is used for knowledge interchange.

The first functional requirements are generated and written on the knowledge transition file. Then the design parameters recognition module (*DP_recog*) is called. This module performs mapping and generates design matrix.

The construction module uses the knowledge generated by the previous module. The construction module has two submodules: *Couple_m* and *Schedule*. The first submodule *Couple_m* integrates machine tools with the same or similar manufacturing tasks. The second submodule *Schedule* involves a scheduling process based on the time structure and the information content related to this time structure.

The final design solution contains the FMS layout structure and a schedule which is supposed to be optimal. The final solution is checked through simulation. The simulation module is a universal data-driven visual simulation system modelling a wide range of different layouts.

5. Application of intelligent system for FMS design

The established concept of the intelligent system for FMS design was fully realized in the program package FLEXY. For a better understanding of the proposed concept, the elementary example is given below. The example deals with selecting machines for cell manufacturing of the bolt shown in figure 7(a). Figure 7(b) shows surface groups to be machined (i.e. the machining sequence) with the required accuracy, surface roughness and estimated machining times. Data for candidate machines are given in table 1. The design ranges for each surface group are given in table 2. The upper limit for the dimensional accuracy of a machine is assumed to be twice the tolerance specified by designer $(2\Delta L)$. For the surface roughness the

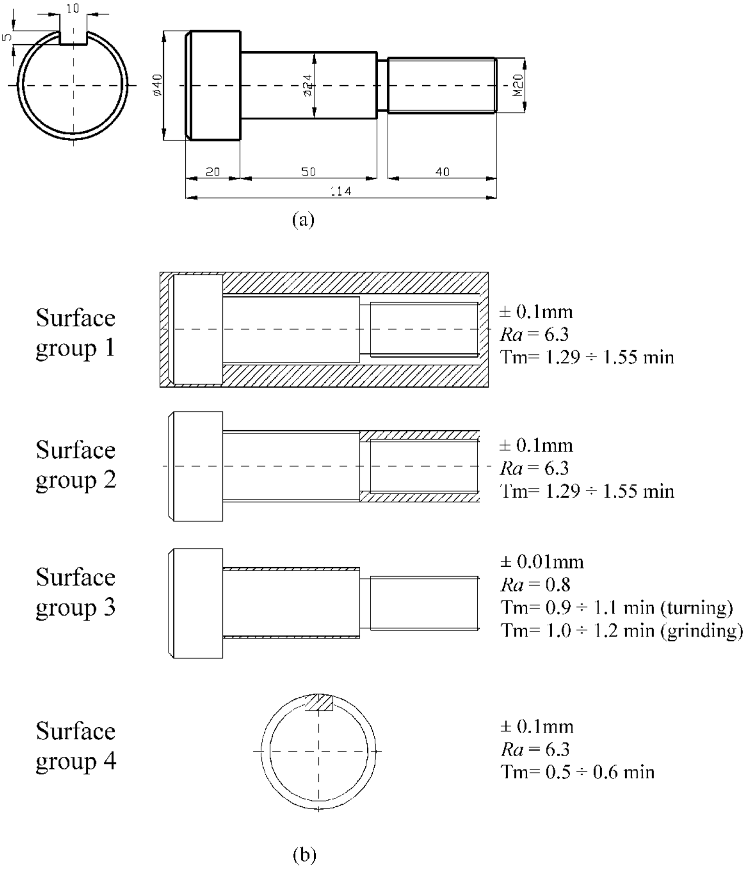


Figure 7. Bolt and related operation sequence for its manufacture.

Machine ID	Machine type	Max precision (mm)	Best surface roughness (μm)	Efficiency	Labour & depreciation rate ($/hour)
1	Cylindrical grinding machine	0.0025	0.5	0.65	80
2	Vertical milling machine	0.04	1.2	0.60	60
3	Horizontal milling machine	0.04	1.4	0.60	55
4	Lathe	0.02	4.0	0.70	60
5	High precision lathe	0.01	2.0	0.75	75

Table 1. Machine tool data.

Surface group	Tolerance (mm)	Surface roughness (μm)	
		Lower	Upper
1	0.2	0	6.3
2	0.2	0	6.3
3	0.02	0	0.8
4	0.2	0	1.6

Table 2. Design ranges for each surface group of a bolt.

Surface group	Candidate machines	I_{acc}	I_R	I_{cap}	I_c	I
1	4	0.925	0	4.87	0.062	5.857†
	5	0.963	0	4.97	3.22	9.153
2	4	0.925	0	5.97	0.061	6.956†
	5	0.963	0	6.07	3.22	10.253
3	1	0.907	0	5.13	3.83	9.867
	4	∞	–	–	–	∞
	5	0.584	2.41	5.49	0	8.484†
4	2	0.848	0	6.07	0.156	7.074
	3	0.848	0	6.07	0	6.918†

† The minimum information among candidate machines (i.e. selected machine).

Table 3. Partial and total information content for candidate machines.

upper limit is estimated as five times the lower limit (i.e. the best value). The calculated partial and total information contents for candidate machines are given in table 3. Selected machines are marked with asterisk. It is very interesting to analyze the selection of a machine for surface group 3. Candidate machines are a lathe, a high-precision late and a cylindrical grinding machine. The lathe is eliminated in the first step due to insufficient accuracy. The high-precision lathe has lower I_{acc} and that means it is a better choice from the accuracy point of view, i.e. the grinding machine is too accurate for this job. In the next step the information content for surface roughness is calculated. Here, the cylindrical grinding machine has lower I_R , meaning that it is easier to obtain the required accuracy by using this machine. The lower I_{cap} for the grinding machine denotes that the capacity of this machine is better used. Finally, the information content dealing with production costs shows that from the economic point of view it is better to use the high-precision lathe. The sum of partial information contents gives the total information content, which is lower for the high-precision lathe, and therefore the final choice for surface group 3 is this machine. In this case the high labor and the depreciation rate for the cylindrical grinding machine had the dominant influence.

The FLEXY package is used for the design of real manufacturing systems. One of them is a large scale FMS for machining parts for pumps used in the mining industry. This was a part of the project realized for the new factory of equipment for the mining industry. The major objectives in the design of such a manufacturing system stipulated by the management were to develop an efficient FMS that will: (1) meet production demand, (2) use least machinery, (3) minimize human interventions, and (4) be flexible for future expansion.

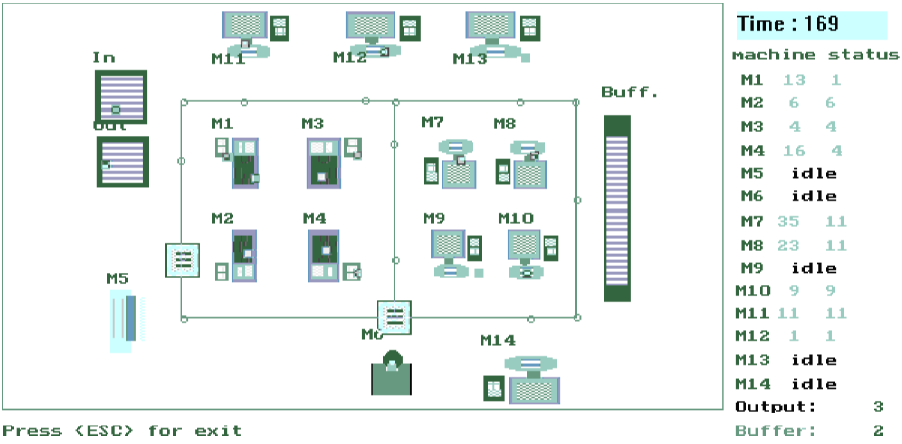
Data for this project are too complex to be elaborated in the paper. Therefore, for the illustration only the final layout generated by the FLEXY system, taken as a snapshot during the simulation of the design solution, is given in figure 8.

6. Conclusion

Until now three generations of decision support systems for FMS design have been recognized: (1) simulation models developed by using general purpose simulation languages or higher level programming languages; (2) special FMS simulation systems; and (3) simulation based expert systems.

To improve the productivity of the FMS design it is essential to set up a new concept based on the knowledge processing. The axiomatic design approach has been recognized as a viable means to establish a new framework for FMS design.

The axiomatic design of the FMS provides the conceptual frame, the criteria for an acceptable design solution, and a methodology for the FMS design. The concept



```
Time : 169
machine status
 M1  13   1
 M2   6   6
 M3   4   4
 M4  16   4
 M5   idle
 M6   idle
 M7 35   11
 M8 23   11
 M9   idle
M10   9   9
M11 11   11
M12   1   1
M13  idle
M14  idle
Output:      3
Buffer:      2
```

```
Press <ESC> for exit
```

Figure 8. Conceptual FMS layout for the manufacture of the pumps.

of FLEXY as the intelligent system for the FMS design is established on the frame, criteria, and methodologies. The software package was verified in an industrial environment. One of the examples is given in the paper.

The described methodology for the development of an intelligent designing system could be used to build similar systems in other engineering areas. The research presented in this paper is just a step in the development of a practical knowledge processing technology to meet challenges in the forthcoming knowledge-intensive industry.

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