ELEMENTS OF DESIGN OF PRODUCTION SYSTEMS – METHODOLOGY OF MACHINE TOOL SELECTION IN CASING-CLASS FMS

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Received: 15 December 2009
Accepted: 25 May 2010

Abstract

The work presents a new methodology of computer aided FMS machine tools selection. Flexible manufacturing systems (FMS) are systems which allow manufacturing of parts in small lot sizes, keeping a high level of productivity and low costs of production. Despite the fact that applied research on designing FMS systems has been continued for several years, there are no methodological solutions that can help design engineers to select machine tools for FMS in an optimal way. This article shows the main stages of the methodology which is based on computer database systems, as well as the principles of elimination and optimisation.

Keywords
flexible manufacturing system, machine tool selection, machine tool design, evolutionary system of multicriteria analysis.

Introduction

One of the principles of rationalisation of the production process which nowadays is more and more important is the principle of flexibility. It places emphasis on the necessity of fast and easy adaptation of the production process to new conditions which change depending on the specific situation and most often are connected with implementation of new processes. The result of the modern approach to the organisation of the production process, understood in this way, is the implementation of flexible manufacturing systems (FMSs), which combine automation and computerisation features and are characterised by huge possibilities of adaptation, in industrial practice [1].

Flexible manufacturing systems (FMSs) are a modern form of organisation of production which combines two inverse features of production systems:

1. high efficiency: the same as in a production line (in a system of rhythmic production),
2. variety of manufactured product range – the same as in technological seat (in a system of non-rhythmic production).

Thus, FMS allow to fill the gap between highly specialised production cells with inflexible automation of production and production cells with inflexible automation of production and production cells characterised by universal production – thanks to flexible automation.

Flexible manufacturing systems (FMS) design is still in the area of scientists’ interest and nowadays it is one of the basic directions of fundamental research in the science field of engineering and production management [2]. Up to now problems of FMS machine tools selection can be found in works by H.J. Warnecke [3], C.M. Harmonovsky [4], Z. Banaszak and L. Jampolski [5], S. Lis, K. Santarek and S. Strzelczak [6], T. Sawik [7], D. Borenstein,
J.L. Becker and E.R. Santos [8], R. Dorf and A. Kusiak [9], A.O. Harczenko [21], P.P. Mohanty [10], J. Honczarenko and I. Slaby [11, 12], and L. Zawadzka [2, 3]. Unfortunately, the solutions presented in those publications are still very general and the methodology of flexible manufacturing systems design is still at the stage of working out [13].

Flexible manufacturing system design is a complex and multistage process. The main problem of manufacturing subsystem design is the selection of machine tools for the designed FMS. It is the first and a very important stage which determines the system effectiveness to a large extent. Studies in the area of computer aided machine tools selection were undertaken in response to the needs of companies which were looking for a tool that would help in optimal machine tools selection taking into account real plant’s constraints. Proper selection of the machine tool subsystem could both significantly minimise investments for construction, as well as lead to minimisation of costs of system operation and permit the most efficient use of the machines. The purchased machinery stock directly determines the efficiency, automation and flexibility level of the whole FMS.

The research problem of selection of flexible machine tools subsystem FMS is equal to finding the solution (i.e. defining the type and the number of machine tools for the FMS) that would be optimal for the designed system. The authors of this article undertook a study aimed at developing a methodological solution which would permit optimal selection of machine tools for designed FMS and the main points of this methodology, based on computer software, are presented in this paper.

The essence of designing flexible manufacturing systems

Flexible manufacturing systems (FMS) are defined as a modern and prospective form of organisation of production created through evolution of conventional production systems due to market organisation changes taking place in the surroundings of manufacturing companies. FMS are production systems based on numeric-controlled machine tools (CNC), permitting high-efficiency machining of products from a specific group in any sequential order (as required), with significant positive effect on the economic indexes of productivity in the manufacturing of products in small batches of variable size [14].

The process of designing an FMS is a sequence of actions leading to the design of all functional subsystems of the FMS, with simultaneous design of material, energy and information flow streams. The sequence of designing the subsystems within the scope of design of the material flow streams subsystem is presented in Fig. 1.

Fig. 1. Schematic of the process of designing of the material flow streams subsystem in an FMS [7].
In the process of designing flexible manufacturing systems, the problems of designing the subsystem of manufacturing, and especially the selection of machine tools for the designed FMS, are of particular importance. It is the first stage of designing a system and it largely determines the system effectiveness. Proper selection of the subsystem of machine tools may significantly reduce the investment expenditure on the system construction, as well as contribute to the minimisation of the operating costs of the system or maximisation of the degree of utilisation of the machine tools. The machine tools purchased have also a direct effect on the efficiency, automation and level of flexibility of the whole FMS, and at the same time constitute an input to the design of the other subsystems of the flexible manufacturing system [15].Unfortunately, in spite of many years of research on designing FMS, until now no uniform methodology has been developed for the optimum selection of machine tools at specific assumptions of the system being designed [11, 12]. In the literature some methodological proposals of solution of this problem can be found, but they sometimes only touch the subject [16] or, within the wide range, omit the problem of optimisation in the process of selection [17, 18]. This paper presents a brief preliminary information on the new complex concept of a methodology which is based on the elimination algorithms and methods of multi-criterion optimisation.

Methodology of machine tool selection in casing-class FMS

The problem of selection of the machine tool subsystem of FMS consists in the identification of a solution (i.e. type and number on machine tools to be used in the FMS) that would be optimum for the adopted assumptions for the system being designed. The solution may vary depending on individual limitations, however, irrespective of the conditions and specific character of the company it must by based on the following criteria [19]:

1. The machine tools included in the manufacturing subsystem of the FMS should ensure the possibility of realization of all processes and treatments to be executed within the FMS at the required levels of accuracy,

2. The control systems of all individual machine tools must permit coordinated central control of the FMS,

3. The adopted solution should ensure minimisation of total costs of acquisition and operation of the machine tools and of the production costs involved in their use.

The developed methodology for the selection of the machine tool subsystem of a flexible manufacturing system constitutes a sequence of actions leading to the isolation, from among all machine tool groups available on the market, of a solution that will be optimum for the FMS being designed, i.e. to the identification of the types of machine tools on which the machining process will be realized. The proposed approach involves a four-stage process of selection of machine tools, based on the principles of elimination and optimisation [15]:

- **STAGE I: Acquisition and processing of information about machine tools**, representation of design knowledge, development of technological assumptions for the products to be machined in the FMS,

- **STAGE II: Elimination of machine tools that do not meet the critical technological-organisation conditions**, 

- **STAGE III: Development of possible variants of machining of the representative product; quantitative choice of machine tools for the particular variants**, 

- **STAGE IV: Optimisation analysis of the particular variants; selection of machine tools in accordance with the adopted optimisation criteria**.

A generalised schematic of the methodology is presented in Fig. 2.

**STEP 1**
- Record of knowledge about machine tools

The essence of the concept of computer-aided selection of machine tools in a FMS is the selection, from a set of any machine tools \( O = \{ o_1, o_2, \ldots, o_n \} = \{ o_i \} \), where \( i = 1, 2, \ldots, n \), of such machine tools (in both quantitative and qualitative sense) that will provide the optimum solution for the adopted design assumptions.

Therefore, the first step in the process of selection is the preparation of a record of knowledge about all machine tools from among which the choice is to be made. For this purpose a database has been created in MS Access, that permits accumulation and saving of data of technical nature (technical parameters), economic information (e.g. purchase price, costs of optional equipment etc.) and general information (e.g. name of manufacturer, website address of manufacturer/distributor, contact information of manufacturer/distributor).
STEP 2 – Record of design knowledge about products to be machined in the FMS

Information on the products to be machined in the FMS being designed is input data in the process of selection of the machine tool subsystem. Flexible manufacturing systems are designed for the production of specific classes of parts with similar technological features (e.g., parts of the class of casings, rotary-symmetrical parts, etc.). Moreover, they are created for groups of parts that are uniform within a specific range, e.g., parts with similar weight, similar range of dimensions, or within a specific range of accuracy classes. It should be emphasized that designing of an FMS is not viable for every group of parts.

The creation of a database on the products to be machined in a FMS should be preceded by a technical-economic analysis and selection of the
products to be machined in the system being designed. In the literature one can encounter certain methodological solutions permitting the identification of groups of parts to be produced in a flexible manufacturing system [3, 13]. In the case of such an identified group (set \( W = \{w_1, w_2, \ldots, w_t\} = \{w_\alpha\} \), where \( \alpha = 1, 2, \ldots, t \)) it is necessary to design and create a suitable database.

For such a purpose, a three-level database structure has been developed for the accumulation of information on products to be machined in a FMS (Fig. 3).

From Level 1 the user can input data of informative character, defining the product to be machined in the FMS being designed. In particular, the input data will include such items as the name of the product, product symbol, overall dimensions of the semi-finished product (including distances required for fixing the product on a machining palette or in a fixture), weight of the semi-finished product, assumed annual production program for the part.

Level 2 is used to define the datum areas for the machining of the part. The datum area is taken to mean an actual or a virtual plane within the machining space, defined in terms of position, permitting precise parameterisation of coordinates of features involved in the machining of a specific product. A uniform system of classification of machining datums has been developed for the purposes of description of datum areas in machining of parts.

Level 3 of the database is used to define the consecutive features to be machined, with relation to specific products from the casing class. In particular, there is a possibility of defining three basic types of machined features – planes, circles, or slots.

**STEP 3**

Development of technological process of the synthetic product (SP)

The structure of database on products to be machined in a FMS permits the accumulation of data that allow easy development of technical assumptions for the synthetic product (SP). The concept of the synthetic product is taken to mean a product that is characterised by design-technological-organisation parameters characteristic of all products to be machined in the FMS being designed (\( W = \{w_1, w_2, \ldots, w_t\} = \{w_\alpha\} \), where \( \alpha = 1, 2, \ldots, t \)).

The adopted method of notation of design knowledge in the run of the technological process permitted the elimination of the need for recording the dimensions and other parameters of the feature. For any operation we only need to define:

- number of operation (defining its place in the technological process),
- kind of machining (milling, drilling, reaming, etc.),
- machining precision (roughing, profiling, finishing, final),
- type of feature (plane, circle, slot),
- feature to be machined (via loading from database – design notation),
- allowance for machining (only in the case of roughing and finishing).

Information on the run of the technological process of the part is loaded by the user on the basis of the developed technological documentation. Once the feature has been defined for a particular machining operation, the system automatically reads in the required data on the position of the feature, its dimensions, accuracy of positioning and dimensions, surface roughness, etc.

![Fig. 3. Structure of database on products to be machined in a FMS.](image-url)
STEP 4
– Elimination of machine tools based on “critical” criteria

The essence of the second stage in the process of selection of machine tools for the FMS being designed lies in the elimination from the database of those machine tools that are incapable of producing the parts that are to be machined in the system, based on certain limit criteria ("critical" criteria). In accordance with the adopted assumptions, we should eliminate from the database those machine tools that:

1. Do not meet the limit conditions resulting from the technical parameters of products to be machined in the FMS.
2. Do not meet the limitations imposed by the user and/or designer of the flexible manufacturing system.
3. Do not have the design-technological capabilities to perform the machining operations provided for realization within the process of manufacturing.

In this case, the design capabilities are taken to mean the following:

- travel range of spindle axis or machining palette in axes X,Y,Z, permitting realization of particular machining operations,
- technological ability to realize specific machining operations (e.g. drilling, milling, reaming, etc.),
- spindle axis position and type of machine tool table permitting realization of machining operation for a specific side to be machined,
- sum of accuracies of positioning of machining palette and cutting tool permitting the achievement of required dimensional accuracy of the product.

Those machine tools that “remain” in the database after the stage of elimination constitute a set of machine tools that are taken into consideration at further stages of selection (\(X = \{x_1, x_2, \ldots, x_m\} = \{x_k\}, \text{ where } i = 1, 2, \ldots, m\)).

STEP 5
– Generation of “technological paths” for the synthetic product

As a result of realization of Stage II, in the database (set X) there remained machine tools capable of realizing at least one machining operation in the manufacturing process of the representative product. The objective of the next stage is the development of possible “technological paths”\(^1\) for the realization of the machining process of the representative product. The concept of a “technological path” is taken to mean the successive machine tools on which the technological process of the synthetic product is realized. For the purpose of generation of such paths, a suitable search algorithm has been developed, in the case of which in input is the matrix 0-1 defining the possibility of realization of a specific operation \(\delta_j\) on a given machine tool \(x_i\) [19]. The algorithm generates the technological paths in accordance with the principle of concentration of technological operations on a machine tool (Fig. 4).

Fig. 4. Developing “technological paths” in relation to representative object.

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\(^{1}\)The concept of a “technological path” is taken to mean the successive machine tools on which the technological process of the synthetic product is realized.
STEP 6
- Quantitative selection of machine tools for particular “technological paths”

Having data concerning the projected annual number of hours of operation for the system being designed, and information on the unit times of realization of particular operations on particular machine tools, it is possible to balance the loading of the particular machine tools in the system and to define the number of machine tools required in accordance with the condition of quantitative selection of machine tools relative to the index of loading of work stations [20]:

\[
\sum_{j=1}^{z} N_{wa}(t_{jkj} + \max(t_{wnk}; t_{wpk})) \leq F_{xk},
\]

where \( k \) – machine type index; \( j \) – cut index; \( N_{wa} \) – number of parts \( w_{\alpha} \) manufactured in one year time; \( t_{jkj} \) – time per cut \( j \) on the \( k \) machine tool (in hours); \( t_{wnk} \) – tool change time (chip to chip), \( t_{wpk} \) – pallet change time, \( F_{xk} \) – \( k \) machine tool work time of in one year time.

The input data for the load balance of machine tools are the values of unit times of realization of the individual machining operations on the particular machine tools included in set \( X \). The result of making the load balance of the machine tools is information on the required number of specific machine tools for the particular variants of technological paths (Fig. 5).

STEP 7
- Selection of “critical path” according to optimisation criteria

The essence of Stage IV is optimum selection of machine tools (choice of “technological path”) in accordance with the adopted optimisation criteria. For the solution of the present problem the methods of multi-criterion optimisation were applied, in particular, the Evolutionary System of Multi-criterion Analysis developed at the Lublin University of Technology. The system permits the identification of the best solution through the application of the methods constituting the System: Method of Threshold Value, Method of Ideal Point Definition, Method of Non-discernibleness and Method of Determination of Compromise Solutions.

The search for the optimum solution is realized on the basis of the following objective functions:

1. Minimisation of total costs of machine tools acquisition and operation (per annum)

\[
F_1 = \sum_{k=1}^{m} \left\{ L_k[(C_k \times a_{ok}) + k_{sk}] \right\} \rightarrow \text{min},
\]

where \( L_k \) – number of machine tools \( k \), \( C_k \) – total purchasing price of machine tool \( k \), \( a_{ok} \) – annual depreciation rate of machine tool \( k \), \( k_{sk} \) – average annual cost of service for machine tool \( k \).

2. Minimisation of time of machining (technological period) of synthetic product

\[
F_2 = \left\{ \max(t_{wnk}; t_{wpk}) + t_{1k} \right\} + \sum_{j=2}^{z} \{\lambda \times \max(t_{wnk}; t_{wpk}) \}

+ [(1 - \lambda) \times t_{wnk} + t_{jk}] \right\} \rightarrow \text{min},
\]

where the value of \( \lambda \) assumes the following values: \( \lambda = 0 \) when operation \( \delta_j \) is realized on the same machine tool as operation \( \delta_{j-1} \), \( \lambda = 1 \) when op-
operation $\delta_j$ is realized on another machine tool than operation $\delta_{j-1}$, $t_{\text{w}nk}$ tool change time “from shaving to shaving” on machine tool $k$; $t_{\text{wp}k}$ technological palette change time on machine tool $k$; $t_{1k}$ – unit time of realization of first operation in technological process of synthetic product on machine tool $k$; $t_{jk}$ – unit time of realization of operation $j$ on machine tool $k$.

Determination of the values of the objective functions for the specific variants (technological paths) permits the creation of a solution map and finding the optimum solution for the adopted objective functions (Fig. 6).

Fig. 6. Model of multi-criterion optimisation based on the method of ideal point definition.

Conclusion

In recent years one could observe numerous changes in the organisation of production systems that indicate a totally new understanding of the modern company (modern manufacturing system). Those changes result from two fundamental groups of premises that constitute the causative factors. The first of those groups originates from the changing demands put before the manufacturing companies by the market, while the second results from new possibilities created by the rapid advances of technology and organisation.

This situation imposes on the manufacturing companies the necessity of flexible adaptation to the new conditions, and also poses new challenges for research centres, aimed at the search for new and continually improved solutions that can meet the present and future requirements of the industry. Thus, research directions of high significance include the problems of design and operation of automated systems of manufacturing, modelling of processes, design of technologies and machining control for low-rigidity parts, and the design, implementation and evaluation of information technologies in the industry.

The presented methodology is a proposal of a solution that permits computer-aided optimum selection of machine tools for the adopted assumption of a FMS being designed. That solution includes the theoretical background (mathematical models, algorithms, optimisation functions), and is also already available in the form of the OPTSELECT software package based on a system of MS Access database management, the MATLAB system for engineering calculations, and the Evolutionary System of Multi-Criterion Analysis (ESMA).

Studies in the area of computer aided machine tools selection were undertaken in response to the needs of companies which are looking for a tool that will help in optimal machine tools selection taking into account real plant’s constraints. The authors of the methodology decided to develop a proper solution oriented at flexible manufacturing systems which are in the group of the fastest developing manufacturing systems in the world. The presented solution, implemented as the OPTSELECT software package, can find very wide applications among companies which are going to design and implement flexible manufacturing systems.

References


