The new method of process quality evaluation

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Abstract

Purpose - The purpose of the research is to develop a model or a method which allows to evaluate a manufacturing process quality on the basis of its many characteristics, i.e. process state measures, occurrences accompanying the process and diagnostic signals.

Methodology/approach – The paper shows the results of a conceptual research concerning the problem of process quality evaluation. The description of the problem, using the terminology of decision sciences, allowed to analyse the multicriteria decision making (MCDM) methods and to choice the apprioprate one.

Findings – It is possible to define the problem of process quality evaluation as the multicriteria decision problem and to apply one of the MCDM methods to its solution. There was indicated that the approach based on decision rules, using rough set theory, is the most applicable tool for the process quality evaluation made in a changeable, dynamic manufacturing environment, also for the sake of the ease of use and results interpretation.

Practical implications – The final aim of the research is to give a process operator a tool to evaluate the process quality online.

Originality/value – The originality of the concept consists in defining the problem of process quality evaluation as a multicriteria decision problem and in pointing out the approach based on decision rules using a rough set theory as the appropriate method of its solution.

Keywords process quality evaluation, multicriteria decision making

Paper type Research paper

1. Introduction

Factors which decide nowadays about chances of enterprises for surviving on the market are undoubtedly price and punctuality of supplies and quality of manufactured products as well. Making consumers trustful regarding ability of manufacturing products which meet requirements is possible only within the confines of properly functioning production process.

Thus, the evaluation of a production process state is one of the most important tasks for a process engineer. In this paper evaluation of process state is understood as evaluation of manufacturing process' quality.

With reference to manufacturing processes, quality requirements amount mainly to requirements concerning critical characteristics of a product. For example in manufacturing processes of machine parts these requirements concern dimension and shape accuracy of a product and properties of surface layer.

These characteristics must assure failure-free product used for a period predicted by designer and constructor. One of the means leading to reach this target – but with keeping economical efficiency of manufacturing – is a quality control in the whole product life cycle (Smith, 2002).

Quality control is based on utilizing data arising during widely concerned quality inspection. It consists in active and dynamic (adaptive) controlling manufacturing process runs in all phases of production: product conception, design, technical preparation forproduction, manufacturing, using, service and end of life. Recently an attitude to quality assurance issues has consisted in inspection and controlling activities after completing consecutive stages of production (for example quality inspection made after completing an operation) (Hamrol, 2008).

Today, quality control is carried out in a continuous way, during realization of production process already. It has a character of temporary activities, interventions and its purpose is operational assuring of required manufacturing quality. These activities can consist in: changing a tool, correcting a process, tightening some criteria of inspection, etc.

A basic issue conditioning correctness of functioning quality control in an enterprise is a skill of utilizing data generated on various stations in making decisions. In a company proper systems must exist to make correct data flow and its analysis possible. On the basis of this concluding and making decisions can take place.

These decisions can be (Hamrol, 2008):

- operational – made directly on the working station based on data received from a process (their result can be temporary correction of a process),
- tactical – allowing intervention into the quality of a manufactured product at the stage of planning and preparing for production – made by managers (systematic impact on quality of performance),
- strategic – oriented on realization of enterprise's targets defined as strategic (creating new products, reaching new markets, making technology more modern, employing specialists) – they involve predicting and planning of undertakings which from the perspective of quality system consist in interference in quality of design.

Generally, these decisions can be made basing on information gathered from (Hamrol, 2000):

- direct measurement of machined parts – measurement is carried out after completing an operation,
- from measurement of signals coming from phenomena accompanying the process (e.g. signal of force, temperature, vibrations) – measurement is made online,
- from observation of occurrences taking place during realization of a process (error of process operator, machine breakdown) – observed.

Information from measurement of machined parts is gathered as a result of 100 percent inspection, acceptance sampling and statistical process control.

Despite having advanced measurement technique and applying more and more user-friendly and advanced software to process results of quality inspection, the realizion of efficient information feedback between manufacturing process and remaining elements of the system is still a serious problem.

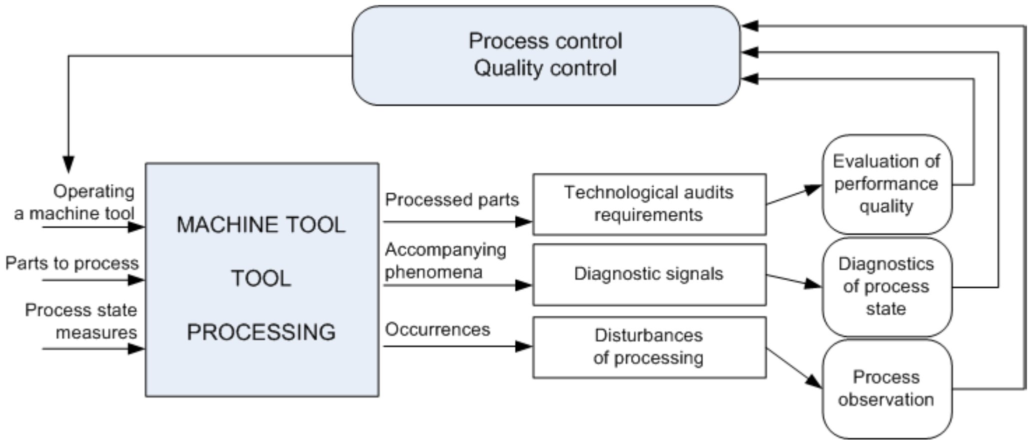

Fig. 1. Data sources for activities connected with quality control

In many cases data gathered from production in progress is wasted – it is used only for temporary regulation of a process, is often gathered only to fulfill consumers' requirements concerning so called quality records. Traditional tools of quality management often show many weaknesses. For example control charts and capability indices do not transfer information about causes of process disturbances and hints concerning a corrective action. It causes that potential possibilities of statistical process control are not exploited. In literature of this subject there is a lack of information which would indicate a solution making it possible to use diagnostic information and data about occurrences in the evaluation of a process.

Hence, there is a need to make some work in order to eliminate or at least limit these weaknesses and use wisely gathered information about a process (measurements, diagnostic signals and occurrences) in making decisions about the process state.

2. Problem

Data and information gathered from a process can concern parameters of machine set-up, process state measures, values of specified product characteristics or statistics (mean, standard deviation etc.), capability indices' values, set of information concerning causes of process maladjustment (e.g. dressing of cutting edge, wear land, mistake in service, etc.) and corrective actions taken (replacing a tool, correcting adjustment, changing the depth of a cut, etc.).

The main problem in evaluation of process state is finding a model or method which would allow to make this evaluation taking into account many characteristics (e.g. diagnostic data, critical characteristics' values, occurrences in process). From this point of view process state evaluation becomes a problem of making decision taking into account many criteria.

Using methods from Multicriteria Decision Making (MCDM) area which let a process state be qualified to predefined classes seems justifiable.

3. Multicriteria decision making – the main characteristics

Multicriteria decision making (MCDM) is a scientific discipline whose aim is to make a decision maker equipped with tools enabling him to solve problems considering many, sometimes opposing, points of view. Multicriteria decision problem (MDP) is a situation in which, having defined a set of actions (solutions, objects, decisions, variants, candidates) and a family of criteria, decision maker aims to either choice the best action (choice problem) or sort the actions to the predefined classes (classification problem), or rank the actions from the best to the worst (ranking problem). A decision maker (DM) who solves multicriteria decision problem is expected to compare many actions with different values of separate criteria. A classic idea of optimization does not have an application in this case because it is not possible to find optimal solutions, i.e. the best ones from all points of view. To find the final recommendation (solution) it is necessary to build and then exploit the preference model (criteria aggregation model) of a decision maker (Vincke, 1994).

There are three ways of representing of the preference information:

- function (e.g. additive utility function),
- relational system (e.g. relation of outranking),
- set of decision rules (Greco *et al*., 2004; Słowiński 2007).

Multicriteria decision problems are solved in 4 steps:

1. Specifying actions and type of issue (choice, classification and ranking).
2. Constructing consistent family of criteria and modeling decision maker's preferences.
3. Synthesis of decision maker's preferences model:
   - to one criterion (model in the form of function),
   - to relational system,
   - to system of rules.
4. Exploitation of decision maker's preferences model in the confines of proper issue.

MCDM as a scientific discipline worked out many methods to solve multicriteria decision problems. The most general classification accepted by many experts distinguishes the following groups of multicriteria decision aiding methods (Vincke, 1994):

- methods of multi-attribute utility theory – named also as "methods of synthesis to single criterion" – they do not take into account incomparability of variants. The most well-known methods from this group are AHP (Saaty, 1980) and UTA (Jacquet-Lagreze & Siskos, 1982)
- methods based on outranking relation – named as methods of outranking synthesis where incomparability is accepted. The most well-known methods from this group are methods from ELECTRE family (I-IV) (Benayoun, *et al*., 1966).
- interactive methods + named as methods of local dialogue assessment based on trial-and-error attitude in consecutive iterations, e.g. LBS. (Jaszkiewicz & Słowiński, 1995).

In the recent years the approach basing on the decision rules joined these groups (Greco, *et al*., 2004; Słowiński, 2007).

4. The evaluation of the manufacturing process state as multicriteria decision problem

As mentioned above, the task of evaluation of the manufacturing process state can be considered as a multicriteria decision problem. In the present chapter there was placed the description of the investigated research problem using the terminology of decision sciences.

The task of the evaluation of the manufacturing process state, formulating it in the most general way, can be defined as follows: in order to estimate the quality of items being currently manufactured the evaluation of the manufacturing process state should be determined on the basis of many characteristics of the process (state measures, occurrences and diagnostic signals), in other words determining the probability of obtaining a product of a given quality class .

The decisive variant here is obtainable in real conditions realization of the manufacturing process, i.e. the vector *a* of concrete values of process state measures (M), occurrences (O) and diagnostic signals (S) representing the manufacturing process state, $a = [M_1,M_2,...M_x,O_1,O_2,...O_y,S_1,S_2,...S_z]$, where x means the number of considered state measures, y the number of occurrences and z the number of considered diagnostic signals. The criteria of evaluation of the concrete realization of the process are process state measures, occurrences and diagnostic signals (M, O, S). The preference information is data concerning earlier realization of the process (i.e. the evaluation of quality of parts or products manufactured in a certain process state described by a certain vector *a*). The task is shown schematically in the table No. I.

The particular actions (here process realizations) are represented by the rows of the table – the vector $a_i = [M_{i1},M_{i2},...M_{ix},O_{i1},O_{i2},...O_{iy},S_{i1},S_{i2},...S_{iz}]$, where i=1,2,...,m means the i-th action (the i-th process realization). Having in mind that M, O and S are criteria, whereas x+y+z=n, the following notation for a_i is also possible $a_i= [c_{i1},c_{i2},...,c_{ix},c_{i(x+1)},...,c_{i(x+y)},c_{i(x+y+1)},...,c_{i(x+y+z)}]$, where i=1,2,...,m means the i-th action.

In the columns of the table the values of a given criterion for each individual action are contained (columns 1-n), while the 2 last columns represent the solution of the decision problem in the symbolic form of an hypothetical assignment to the predefined classes (column n+1) or in the form of additive utility function (column n+2).

Table I. The task of the evaluation of the manufacturing process state (process quality) as a MDP

	Criterion 1 c_1 (state measure 1)	Criterion 2 c_2 (state measure 2)	...	Criterion x c_x (state measure x)	Criterion x+1 c_{x+1} (occurrence 1)	...	Criterion x+y c_{x+y} (occurrence y)	Criterion x+y+1 c_{x+y+1} (signal 1)	...	Criterion n c_n (signal z) **where n=x+y+z**	ASSIGNMENT TO ONE OF QUALITY CLASSES (e.g. 1,2,3)	QUALITY quality evaluation (function of criteria)
Action 1 a_1 process realization 1			...			...			...		Class 1	Quality of action 1 $Q_1=\sum f_i (c_{1i})$
Action 2 a_2 process realization 2			...			...			...		Class 1	Quality of action 2 $Q_2=\sum f_i (c_{2i})$
...	...	...	...			...			...	...		...
Action m a_m process realization m			...			...			...		Class 2	Quality of action m $Q_m=\sum f_i (c_{mi})$

This task, according to the authors, should be solved in two steps. In the first step the evaluation of the manufacturing process state would be done, done through the estimation of partial quality of manufactured items (taking into account only one characteristic of the part – e.g. roughness) on the basis of process state measures, occurrences and diagnostic signals occuring during the manufacturing process. In other words the probability of obtaining, as a result of the manufacturing process being in a certain state, parts that meet quality requirement (i.e. requirement relating to one characteristic) is determined (let us call this step the subtask 1). This step should be executed for each characrteristic that is taken into consideration (in case of machining there could be for instance roughness, waviness, rectilinearity, hardness, bending strength, etc.)

Next, the global evaluation of the quality of the part (global evaluation of the process state) should be determined on the basis of its partial quality evaluations, i.e. either measurements of each individual characteristic of the manufactured part and/or their evaluation took by an expert, or on the basis of the received as the result of subtask 1 probabilities of obtaining parts that fulfil each quality requirement (in the form of assigning to the class or aggregated numerical value). Let us call step 2 the subtask 2.

Formulating it generally, in the task of evaluation of the manufacturing process state that is conducted in order to estimate the probability of obtaining parts fulfilling quality requirements, two stages can be distinguished: the stage of determining partial evaluation of quality on the basis of diagnostic data of the manufacturing process (subtask 1) and the stage of obtaining the global evaluation of part quality (the evaluation of the manufacturing process state and connected with them probability of obtaining parts that meet all quality requirements) on the basis on partial evaluations of the quality received in the previous stage (subtask 2).

Both subtasks should be considered as separate decision problems. The subtask 1 that consists in the obtaining of partial evaluation of quality of the manufactured part on the basis of process state measures, occurrences and diagnostic signals belongs to the group of sorting problem (classification), i.e. its solution consists in assigning of each action to one of the predefined classes, in this case the quality classes of the item (e.g. very good, good, poor). But in the particular case the desicion maker (here e.g. machine operator) could care about something more than „only“ the assigning of the manufactured part to the quality class, namely about the obtaining of the precisely numerical evaluation of the manufactured part. If the problem is stated in such a way, the methods dedicated for a multicriteria ranking or choice (e.g. UTA) should be used. These methods base on additive value function, i.e. aggregate the partial evaluation on each criterion to one global evaluation of a given action so the resulted evaluation has a numerical form.

In the subtask 1 occur the same actions and criteria as in the main research problem (original task) desribed earlier. The preference information make up the data concerning the earlier process realization but as opposed to the original task there are evaluations of the partial (not global) quality (e.g. regarding roughness) of the parts that were manufactured in a specific process state described by certain vectors *a*.

The subtask 1 was schematically illustrated in the table no. II.

The interpretation of the rows and columns of the table is the same as in the case of original task, with the difference in 2 last columns. They represent here the solution of the subtask 1, i.e. the hypothetical assignment to the predefined classes of partial quality (column n+1) and the additive utility fuction (column n+2) determined for partial quality.

Table II. The subtask of partial evaluation (focused on one characteristic of the product) of the manufacturing process state as a MDP

	Criterion 1 c_1 (state measure 1)	Criterion 2 c_2 (state measure 2)	...	Criterion x c_x (state measure x)	Criterion x+1 c_{x+1} (occurrence 1)	...	Criterion x+y c_{x+y} (occurrence y)	Criterion x+y+1 c_{x+y+1} (signal 1)	...	Criterion n c_n (signal z) **where n=x+y+z**	ASSIGNMENT TO ONE OF PARTIAL QUALITY CLASSES (e.g. 1,2,3)	PARTIAL QUALITY **partial quality evaluation (e.g. „quality = roughness")**
Action 1 a_1 process realization 1			...			...			...		Class 1	Partial quality of action 1 $Qp_1=\sum f_i (c_{1i})$
Action 2 a_2 process realization 2			...			...			...		Class 1	Partial quality of action 2 $Qp_2=\sum f_i (c_{2i})$
...	...	...	...			...			...	...		...
Action m a_m process realization m			...			...			...		Class 2	Partial quality of action m $Qp_m=\sum f_i (c_{mi})$

In the subtask 2 which consists in determining the global evaluation of the quality (the whole evaluation of the process state) on the basis of the values of partial qualities the evaluation criteria are values of those parts' characteristics ($c_1, c_2, ... c_n$) that are taken into consideration during the evaluation of the part's quality (e.g. roughness, waviness, rectilinearity, hardness, bending strength, etc.) or partial quality evaluations determined for

the sake of those particular characteristics. Speaking about the action (decision action) the authors mean in this case the possibility to obtain in reality vector of „quality"characteristics of an item (combination of partial quality evaluation of a part), a = $[c_1,c_2,...c_n]$. The preference information given by the decision maker is a global quality evaluation of a product specified for each part from a certain reference group, that is the evaluation of the chosen actions (here items) building the so called reference action set. The subtask 2, like a subtask 1 is a classification problem, however in order to obtain the precisely numerical evaluation of the quality of manufactured parts, obtained as a result of the running process, the approach that aggregates the evaluations to the one utility function should be applied.
The table III exemplifies the above characteristics of subtask 2.

Table III. The subtask of the evaluation of global quality of the product on the basis on its partial qualities as a MDP

	Criterion 1 c_1 (roughness)	Criterion 2 c_2 (endurance)	...	Criterion n c_n (hardness)	ASSIGNMENT TO ONE OF QUALITY CLASSES (e.g. 1,2,3)	GLOBAL QUALITY global quality evaluation (function of partial quality evaluations)
Action 1 a_1 (part 1)			...		Class 1	Quality of action 1 $Q_1=\sum f_i (c_{1i})$
Action 2 a_2 (part 2)			...		Class 3	Quality of action 2 $Q_2=\sum f_i (c_{2i})$
...	...	...	...	...		...
Action a_m (part m)			...		Class 3	Quality of action m $Q_m=\sum f_i (c_{mi})$

The rows of the table represent the particular actions (here manufactured parts) in the form of a vector $a_1 = (c_{i1},c_{i2}...c_{in})$, where i=1,2,...,m mean an i-th action. The columns of the table contain values of the given criteria for each individual actions (columns 1-n), while 2 last colums represent the solution of decision problem in the symbolic form of an hypothetical assignment to the predefined classes (column n+1) or in the form of additive utility function (column n+2).

5. The choice of the MCDM method

After the research problem has been defined using the concepts of decision sciences, the methods elaborated by decision sciences can be applied. The choice of the method to be implemented in the production environment is influenced by the following factors:

- type of the problem (in this case: classification),
- required type of preference information (e.g. the examples of decisions or the pairwise comparisons of all actions and criteria, or preference, indifference and veto thresholds),
- requirements respecting the necessary knowledge of the decision maker about the used method,
- ease of interpretation and acceptation of the results.

For this reason the authors regard the decision rules based approach as the best solution of the problem of the evalutation of the manufacturing process state. This approach can be applied to all types of decision problems, but it is especially suitable for classification.
The models using decision rules “if..., then” allow to give the examples of decision as the preference information (Greco *et al*., 2004; Słowiński, 2007) while people are more inclined to show examples of their decisions rather than explain them by giving model parameters.
The understanding by the decision maker (the user of the method - here the machine operator or process engineer) of the way of the exploitation of the preference model aggregated to the set of decision rules does not require a great cognitive effort from him. The mined decision rules can be also easily interpreted or even (in a special case) rejected as incorrect by the decision maker .
Furthermore, Greco, Matarazzo and Słowiński (2004) stated that the decision rule aggregation (preference model) is the most general among the known aggregation operators (preference models).

The generality and resulting from it flexibility of the logic rule approach makes it seemingly the most useful tool in the evaluation of the manufacturing process state which is changeable and described by the characteristics of various nature (e.g. binary, modeled by unlinear function).

6. Decision rules approach using Rough Set Theory

The decision rules are widely used by expert systems to represent the knowledge of an expert. The researchers from the domain of multicriteria decision making developed the approach of decision rules mining using the rough set theory (RST). The concept of rough sets was proposed by Pawlak (1982) and allows to deal with uncertain and vague data which follow from data granulation. The classical definition of a set is replaced by two – lower and upper - approximations of it. The lower approximation of X is composed of elements which certainly belong to X, while the upper approximation consists of elements which may belong to X (i.e. in the light of available knowlegde it is not possible to exlude their belonging to X). The objects having the same description, expressed by means of some attributes, are indiscernible - they are in the indiscernibility relation (Greco, *et al.*, 2001).
Several attemps were made to apply the RST to the decision support (Pawlak & Słowiński, 1994) but it was finally made possible after extension of the classical RST by Greco, Matarazzo and Słowiński consisting in substitution of the indiscernibility relation by a dominance relation in the rough approximation of decision classes to consider the preference order of data). An important consequence of this fact was a possibility of inferring from exemplary decision the preference model in terms of decision rules being logical statements of the type “if..., then” (Greco, *et al.*, 2001).
The approaches based on RST are called in the MCDM literature the Classical Rough Set Approach (CRSA) and the Dominance-based Rough Set Approach (DRSA), respectively. A detailed description of RST and decision support approaches based on it exceedes a framework of this paper and it is to be found in the cited literature.
The authors decided to apply the DRSA approach to the evaluation of the manufacturing process quality. The experimental investigation will be undertaken as the next step of the presented conceptual research on the problem. Initially the DRSA will be applied to the subtask of the evaluation of the global quality of the product on the basis of its partial qualities (illustrated in the table III).
Generally speaking, the procedure of evaluation consisting of the classification of a product to the quality class will include the following steps:

1. gaining of the exemplary decision from an expert (so-called “learning set”) in the form: if $c_1(a)=r$, $c_2(a)=p$, ... $c_n(a)=q$, then $a \rightarrow$ Class 1

2. discretization of attributes (criteria) values, if necessary
3. induction of decision rules based on the Dominance-based Rough Set Approach (the method mines three types of rules: certain, possible and approximate rules)
4. verification of the rules by an expert (decision maker)
5. application of the decision rules to new objects (to so-called “testing set”).

The presented approach to the multicriteria classification has many advantages described in the above chapter. They are connected with the use of the preference model in the form of decision rules. The preference information in the form of exemplary decisions or ease of results interpretation belong to the most important from the point of view of a method user, who is in this case a machine operator or a process engineer. It is also worth mentioning that RST allows to reduce the initial set of attributes (criteria) and to evaluate their importance, which is particularly useful in the evaluation of the manufacturing process, that can be described by many various attributes.

The CRSA and DRSA approaches are still gaining the followers from various research areas (e.g. management, medicine, engineering). They found their application also in technical diagnostics and quality control (Shen, *et al.*, 2000; Tseng, *et al.*, 2004; Sawicki & Żak, 2007) what is especially interesting and promising from the authors point of view, but are still not widely applied in these domains.

7. Summary

Nowadays the effective quality control of manufacturing has to be based on data coming from two basic sources: quality inspection of manufactured parts and also from measurement and observation of manufacturing process, whereas one of the key issues conditioning the correctness of this process is the ability to use data generated on various stands to make decisions. The data describes manufacturing process which allows to infer about the probability of obtaining, as a result of the running process, parts that meet quality requirements. The authors have classified the task of the evaluation of the process quality to the multicriteria decision problems and proposed its solution using decision rules based on Dominance-based Rought Set Approach. In the selection of the method the authors were guided by the possibility of the solution’s application in the manufacturing environment (there was paid the attention on the ease of defining the decision maker preferences and the ease of results „acceptation“ in the proposed method). The issue being elaborated is a part of a more comprehensive research project consisting in elaborating „the system of control of production flow and quality for small and medium enterprises“.

References

1. Benayoun, R, Roy, B, & Sussmann, B, (1966), “ELECTRE: Une méthode pour guider le choix en presence de points de vue multiples” *Technical report, SEMA-METRA International, Direction Scientifique,* Vol. 49, Paris.
2. Greco, S, Matarazzo, B & Słowinski, R, (1998), “A new rough set approach to multicriteria and multiattribute classification”, *Lecture Notes in Artificial Intelligence* 1424, 60-67.
3. Greco, S, Matarazzo, B, & Słowinski, R, (2001), “Rough set theory for multicriteria decision analysis”, *European Journal of Operational Research,* Vol. 129, No. 1, 1-47.
4. Greco, S, Matarazzo, B, & Słowinski, R, (2004), “Axiomatic characterization of a general utility function and its particular cases in terms of conjoint measurement and rough-set decision rules”, *European Journal of Operational Research,* Vol. 158, No. 2, 271-292.
5. Hamrol, A, (2000), “Process diagnostics as means of improving the efficiency of quality control*”, Production Planning and Control*, Vol. 11, No. 8, 797-805.

6. Hamrol, A, (2008), *Zarządzanie jakością z przykładami*, PWN, Warszawa.
7. Jacquet-Lagreze, E & Siskos, J, (1982), “Assessing a Set of Additive Utility Functions for Multicriteria Decision Making, the UTA Method”, *European Journal of Operational Research,* Vol. 10, No. 2, 151-164.
8. Jaszkiewicz, A & Słowiński, R, (1995), “The Light Beam Search - outranking based interactive procedure for multiple-objective mathematical programming”, In: Pardalos, PM, Siskos, Y & Zopounidis, C, (ed.), *Advances in Multicriteria Analysis*, Kluwer Academic Publishers, Dordrecht.
9. Pawlak, Z, (1982), „Rough sets”, *International Journal of Information & Computer Sciences,* Vol. 11, 341-356.
10. Pawlak, Z & Słowiński, R, (1994), „Rough set approach to multi-attribute decision analysis”, *European Journal of Operational Research*, Vol. 72, 443-459.
11. Roy, B, (1990), *Wielokryterialne wspomaganie decyzji*, WNT, Warszawa.
12. Saaty, T, (1980), *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation,* McGraw-Hill International, New York.
13. Sawicki, P & Żak, J, (2007), “Technical diagnostic of a fleet of vehicles using rough set theory”, *European Journal of Operational Research,* doi:10.1016/j.ejor.2007.10.053.
14. Shen, L, Tay, F, Qu, L & Shen, Y, (2000), “Fault diagnosis using Rough Sets Theory”, *Computers in Industry*, Vol. 43, No. 1, 61-72.
15. Słowiński, R, (2007), „Zbiory przybliżone we wspomaganiu decyzji”, In: Kulczycki, P, Hryniewicz, O & Kacprzyk, J, (ed.), *Techniki informacyjne w badaniach systemowych*, WNT, Warszawa.
16. Smith, GM, (2002), *Statistical Process Control and Quality Improvement*, Pearson Prentice Hall.
17. Tseng, TL, Jothishankar, MC & Wu, T, (2004), “Quality Control Problem in Printed Cuicuit Board Manufacturing – An Extended Rough Set Theory Approach”, *Journal of Manufacturing Systems*, Vol. 23, No. 1, 56-72.
18. Vincke, P, (1994), *Multicriteria decision-aid*, John Wiley&Sons, Chichester.