XVIII ICIEOM 2012
International Conference on Industrial Engineering and Operations Management
Guimarães - Portugal
July 9 - 11, 2012

A New Multi-criteria Method for Selection of Metal Casting Process with Aggregation of Information though Fuzzy Operator

Dalmarino Setti[a], Carla Schwengber ten Caten[b], Gilson Adamczuk Oliveira[a], Marcelo Gonçalves Trentin[b]

[a] Department of Mechanical Engineering, Federal Technological University of Paraná, Via do Conhecimento, km 1, Pato Branco, Brazil
[b] Department of Industrial and Transportation Engineering, Federal University of Rio Grande do Sul, Av. Osvaldo Aranha 99, Porto Alegre, Brazil
[c] Department of Electrical Engineering, Federal Technological University of Paraná, Via do Conhecimento, km 1, Pato Branco, Brazil

Email: dalmarino@utfpr.edu.br, tencaten@producao.ufrgs.br, gilson@utfpr.edu.br, marcelo@utfpr.edu.br

Abstract

In metal casting processes, selecting the most suitable process may become a complex task due to the large number of processes available, which differ greatly in terms of capabilities, advantages and limitations on design, quality, production, cost and environmental performance. The correct selection of the casting process contributes for reduced development time, increases quality, reduces cost and increases the competitiveness of the product. This paper presents a multi-criteria method for the selection of metal casting process (M3CPS). This method contemplates: fifteen selection criteria, fifteen main metal shape casting processes, six classes of metal alloys most used in the production of cast components, database information in the form of trapezoidal membership functions and the treatment of sources of information through a fuzzy aggregation operator. The operational steps are: aggregation of information, initial screening, determination of criteria weights and technical ranking. The determination of the weights of criteria is developed based on Analytic Hierarchy Process (AHP). Due to the large amount of information and mathematical operations the M3CPS was implemented using a computational tool. Two case studies are presented to demonstrate the proposed method as well as to compare with previous research. The case studies showed the operation of the computational tool of the M3CPS and the effect of aggregation of information on the selection results.

Keywords: manufacturing process selection; information aggregation; multi-criteria method; metal casting.

1 Introduction

There are many processes used to make metal castings. What differentiates one process from another is the material from which the mold is made, the type of pattern used (permanent or expendable), and the amount of pressure or force that is used to fill the mold cavity with molten metal (Kay 2004). The metal casting is one of the simplest, direct and less costly to obtain metal products with a near or net shape (Rundman, 1999). According to the Department of Energy (2005) metal casting enables the production of simple and complex parts that meet a wide variety of needs. Nearly all manufactured goods contain one or more cast components. The applications of cast components range from simple household items to critical components for aircraft and automobiles.

The selection of manufacturing processes that occur in the early stages of the component design aims to provide manufacturing options in terms of form, material and cost. According to Creese *et al.* (1992), in the early stages of design (conceptual design), the incurred costs are only 5-7 percent of the total costs whereas the committed costs are 75-85 percent of the total cost. So there are great opportunities to reduce costs early in the design of the component - the earlier the problems are prevented at this stage, via an appropriate development, the fewer problems will be fixed later, when the solution is expensive and more difficult to achieve.

Several authors have presented different approaches to solving the problem of the metal casting process selection. An early attempt used were expert systems, such as selection methods described in the works of Sirilertworakul *et al.* (1993), Darwish and El-Tamimi (1996) and Er and Dias (2000). The database adopted in such systems, using unique values to the capabilities of processes in which the selection rules are based, does not reflect the reality of the information of casting processes. According to Ravi (2005), what best describes the capabilities of metal casting process is obtained by fuzzy mapping of process capability. The works of Akarte *et al.* (1999), Karthik *et al.* (2003) and Daws *et al.* (2008) present selection methods in which information of metal casting processes are in the form of membership functions (fuzzy mapping of process capability). But even in these works in which the representation of information processes is adequate, there is concern over the treatment of information sources to be used in your selection methods.

This study presents a method of selection of metal casting processes using multi-criteria decision making, which includes the treatment of sources of information (aggregation of information) as a preliminary step, which aims to increase the accuracy and reliability of the multi-criteria decision making method.

2 Multi-criteria Method for the Selection of Metal Casting Process (M^3CPS)

The M^3CPS is structured in a sequence of operational steps (initial screening and technical ranking) to promote the selection of the most suitable process of metal casting, for the component under analysis. The key innovation introduced by M^3CPS consists in treating different sources of information used in the operational steps through a fuzzy aggregation operator. The operational steps are: aggregation of information, initial screening, determination of criteria weights and technical ranking. The mathematical equations and details of the steps are presented in the following sections.

2.1 Aggregation of information

The amount of information of the metal casting processes is quite large, which makes it difficult to choose what information to use in selection. The proposed solution is to make use of all available information and perform an aggregation procedure to obtain a unique data. The aggregation procedure aims to increase the accuracy and reliability of the results obtained by M^3CPS.

The information in the database of metal casting processes used in M^3CPS is in the form of trapezoidal membership functions *Trap (a, b, c, d,* μ(x)). Thus it was used a fuzzy aggregation operator (weighted mean), shown Eq. (1)

$$\mu_{ij} = \sum_{k=1}^{l} \gamma_k . \mu(x)_{ijk} \qquad (1)$$

Where:

μ_{ij} = the value of membership function for the process *i* in relation to evaluated criterion *j* (aggregated information);

γ_k = relative importance assigned to the database *k*, $\sum_{k=1}^{l} \gamma_k = 1$;

$\mu(x)_{ijk}$ = the value of membership function for the process *i* in relation to evaluated criterion *j* in the database *k*;

Equation (1) allows a large amount of information from different sources such as handbooks, catalogs, technical and process data provided by foundries, can be treated and aggregated into unique information to be used in M^3CPS. According Vaníšek *et al.* (2009) weighted mean operator can be useful in this situation to weight each answer according to the qualification or/and the competence of experts, in this case, according to the reliability of the information source.

2.2 Initial screening

The purpose of the initial screening step is to remove the metal casting processes that do not meet the basic requirements of the component under analysis. The seven criteria listed in Table 1 are characteristic of each shape casting processes, and therefore can be used to determine the exclusion of those who do not meet the requirements of the component under analysis.

Table 1: Selection criteria used in the M^3CPS

Criteria of initial screening	Group of criteria for technical ranking	Criteria of technical ranking
Material	Shape (φ_1)	shape complexity (ω_1)
Weight (kg)		dimensional tolerance (ω_2)
Maximum length (mm)	Production (φ_2)	*Lead time* (ω_3)
Maximum section thickness (mm)		lot size (ω_4)
Minimum section thickness (mm)	Metallurgical quality (φ_3)	Relative level of porosity (ω_5)
Maximum surface roughness (μm) Ra		Relative level of mechanical properties (ω_6)
Minimum angle of extraction (degrees)	Environmental impact (φ_4)	Gas emissions (ω_7)
		Toxicity waste (ω_8)

Source: Authors

At this step, the criteria do not have weights, because the main objective is to discriminate the processes in relation to the requirements of the component. At this stage, only the information available will be used, i.e. it is not necessary to enter all the information pertaining to the seven criteria to perform the initial screening. However, with the use of all criteria, the screening process may be more precise.

The initial screening step uses the information processed in the step of aggregation of information. A metal casting process that does not meet one of the criteria listed in Table 1 shows a membership function for this criterion of zero (μij = 0), disabling it for the production of the component under analysis. Whether a process can meet all the initial screening criteria at the same time can be determined by the product of all membership functions of this process. Eq. (2) describes this procedure.

$$S_i = \left[\prod_{j=1}^{m_{si}} \mu_{ij}\right]^{1/m_{si}} \quad ,j = 1,2,\ldots,m_{si} \tag{2}$$

Where:

S_i = Screening index for the *i* process in relation to m_{si} criteria used in this step;

μ_{ij} = the value of membership function for the process *i* in relation to evaluated criterion *j*.

The Eq. (2) is a conjunctive aggregation function (Beliakov *et al.*, 2007). Only processes that have the screening index greater than zero will be considered in the technical ranking step. If none of the metal casting processes considered in the M^3CPS presents a screening index greater than zero, that is an indication that the requirements of the component under analysis are not suitable for the manufacturing of metal casting, and should be reviewed.

2.3 Determination of criteria weights

Initially, the weight for each group of criteria is determined (Table 1), and from these, the weights of other criteria used in technical ranking step. The Analytic Hierarchy Process (AHP) proposed by Saaty (1977) was the tool used for this evaluation. For the application of AHP, the initial step is the construction of the comparison matrix (4 x 4), according to the four sets of criteria.

To construct pairwise comparison matrix A, the groups of criteria are compared in pairs based on an appropriate numerical scale, as shown in Table 2. The elements a_{ij}, above the main diagonal of the matrix,

are obtained by *n.(n-1)/2* comparisons (n=4). The elements from the main diagonal are equal to 1. The elements below the main diagonal are reciprocals of the values obtained above the main diagonal, i.e, $a_{ij} = 1/a_{ji}$.

Table 2: Pairwise comparison scale for preferences

Important level	Numerical rating
Extremely not important	1/5
Not important	1/3
Equally important	1
Important	3
Extremely important	5

Source: Chou (2009)

After obtaining the matrix of comparisons, calculations should be performed to find the normalized values for the weight of each group of criteria. In this step, additive normalization method (SRDJEVIC, 2005) is the adopted procedure. To obtain the priority vector φ_j by this method, divide the elements of each column of matrix A by the sum of that column (i.e. normalize the column, Eq. (3)), then add the elements in each resulting row and finally divide this sum by the number of elements in the row (Eq. 4).

$$a'_{ij} = a_{ij} / \sum_{i=1}^{m} a_{ij}, i,j = 1,2,\dots,m. \quad (3)$$

$$\varphi_j = \frac{1}{m} \sum_{j=1}^{m} a'_{ij}, i,j = 1,2,\dots,m. \quad (4)$$

Where:

a_{ij} = element of the comparison matrix;

a'_{ij} = normalized element of the comparison matrix;

φ_j = normalized weight of the group of criteria *j*.

After determining the weight of the groups of criteria, the AHP is used within each group (i.e. by applying the equations (3) and (4) obtaining (ω_j)). The weight of each criterion in the technical ranking (ω'_j) is obtained by multiplying the weight of the criterion group (φ_j) by the result of the comparison within the group's discretion (ω_j).

The consistency of priority vector is calculated by using the harmonic consistency index (HCI) proposed by Stein and Mizzi (2007). HCI is recommended as a consistency measure if the additive normalization solution method is used. The HCI is calculated by Eq. (5).

$$\mathrm{HCI} = \frac{[(\mathrm{MH_s} - \mathrm{n}).(\mathrm{n}+1)]}{\mathrm{n}.(\mathrm{n}+1)} \quad (5)$$

Where:

HCI = harmonic consistency index;

$MH_{(s)}$ = harmonic mean of the sum of the columns of the comparison matrix;

n = order of the comparison matrix.

If we divide the HCI by the appropriate HRI from Table 3 the result is called the consistency ratio (CR). The rule-of-thumb generally used is that if a matrix has a CR up to 0.10 (0.05 for n = 3 and 0.08 for n = 4) then it is sufficiently close to being consistent that the eigenvector priority vector is meaningful (Saaty, 1994).

Table 3: Harmonic random consistency index (HRI)

	n										
	3	4	5	6	7	8	9	10	15	20	25
HRI	0,550	0,859	1,061	1,205	1,310	1,381	1,437	1,484	1,599	1,650	1,675

Source: Stein and Mizzi (2007)

2.4 Technical ranking

The technical ranking is performed based on information from the aggregation of information step. Initially a matrix with number of rows equals to the number of metal casting processes adopted at the initial screening step is created and with eight columns, one for each of the criteria of the technical ranking. This matrix needs to be normalized so that the values are comparable (YOON and HWANG, 1995; LING, 2006; KAHRAMAN *et al.*, 2008). Eq. (6) shows the normalization procedure.

$$\mu'_{ij} = \mu^2_{ij} \Big/ \sum_{i=1}^{n} \mu^2_{ij}, i = 1,2,\ldots,n. \tag{6}$$

The ranking of the metal casting processes is obtained by additive weighting, in which membership functions are associated with the normalized weights of each criterion to obtain the technical ranking. This procedure is shown in Eq. (7).

$$R_i = \sum_{j=1}^{m} \omega'_j . \mu'_{ij}, j = 1,2,\ldots,m. \tag{7}$$

Where:

R_i = Technical ranking index for the *i* process in relation to *m* criteria used in this step.

ω'_j = normalized weight of of criteria *j* in the technical ranking.

The only processes ranked will be the ones which obtain a value of R_i greater than or equal to 1/*n*, where *n* represents the number of metal casting processes which were approved at the initial screening step.

3 Application

3.1 The Computational Tool

The computational tool to implement the M^3CPS is composed by three main elements: a spreadsheet software (Microsoft Excel) which performs every mathematical operations necessary for the development of operational steps in the M^3CPS; a database, freeware SQLite, responsible for storing information used in M^3CPS, and the graphical user interface (GUI), which acts as a link between the database, the spreadsheet software and the user.

The M^3CPS covers the fifteen main metal shape casting processes: green sand – hand molding (P1), green sand – mechanized molding (P2), green sand - automatic molding (P3), silicate-CO_2 (P4), air-set/nobake (P5), shell molding (P6), plaster molding (P7), ceramic mold (Shaw process) (P8), investment casting (lost wax) (P9), lost foam (P10), centrifugal casting – metallic mold (P11), permanent mold-gravity (P12), permanent mold-low pressure (P13), die casting (P14) and squeeze casting (P15) as the set solution for the selection process. The M^3CPS includes the six classes of metal alloys most used in the production of cast components: steel, cast iron, aluminum alloys, copper alloys, magnesium alloys and zinc alloys, suitable for metal shape casting processes. The metal alloys are input data in the M^3CPS.

The computational tool of the M^3CPS was developed with equal relative importance (γ) for all sources of information. The database was formed from handbooks of the metal casting processes and foundry technical data (presented on their websites). The complete database used in this paper can be found at Setti (2010).

3.2 Components for Application

The application of the M^3CPS was collected through the use of the computational tool described in the previous section. The components used in the application were the same used for Er and Dias (2000) in validation of their method of selection. Table 4 presents the requirements of the components.

Table 4: Requirements of the components used in the application of M^3CPS

Component requirements	Component 1	Component 2
Material	Aluminum	Aluminum
Weight (kg)	4,5	1,25
Annual batch size (parts)	> 100.000	-400
Maximum length (mm)	400	250
Maximum section thickness (mm)	12	15
Minimum section thickness (mm)	2,5	1,75
Maximum surface roughness (μm) Ra	8	1
Minimum angle of extraction (degrees)	Not informed	Not informed
Dimensional tolerance (mm)	± 1,0	± 0,75

Source: Er e Dias (2000)

3.3 Utilization of the Computational Tool

The component 1 (Table 4) was used to present the use of graphical interfaces of M^3CPS. The graphical interface of the initial screening step is shown in Fig 1. All the fields for entering the values of the seven criteria used in the initial screening are on the top left side of the graphical interface. After entering information about the component (Table 4), *the process select* button is pressed. The results of the selected processes are shown on your right. Thirteen metal casting processes were considered able to produce the component 1. Only plaster molding and squeeze casting processes were eliminated in this step. It should be noted that not all fields must be completed to perform the screening process, but the more information the greater the accuracy achieved.

The next operational step to be performed is to determine the weight of the criteria. The user is responsible for determining the weight of the criteria, according to the type of application of the analyzed component. The AHP is used to determine the weights, as described in 2.3. The judgments are operationalized through the selection box, according to the user's decision. Following the conclusion of the six judgments to determine the corresponding weights of the groups of criteria, the user must press the button *determine weights of criteria sets*. If the judgments made are inconsistent, they must be redone. Once the consistent groups of consistent criteria are achieved the last action of this operational step is held, which consists in determining the weight within each group of criteria. In this step, the judgments are conducted within the group of criteria, requiring only a paired comparison within each group to obtain the result. In conducting these judgments no problems in relation to consistency exist because only one trial is held within each group, as there are only two criteria in each group. Fig.2 shows the final result of this operational step, i.e. the weights of all the given criteria.

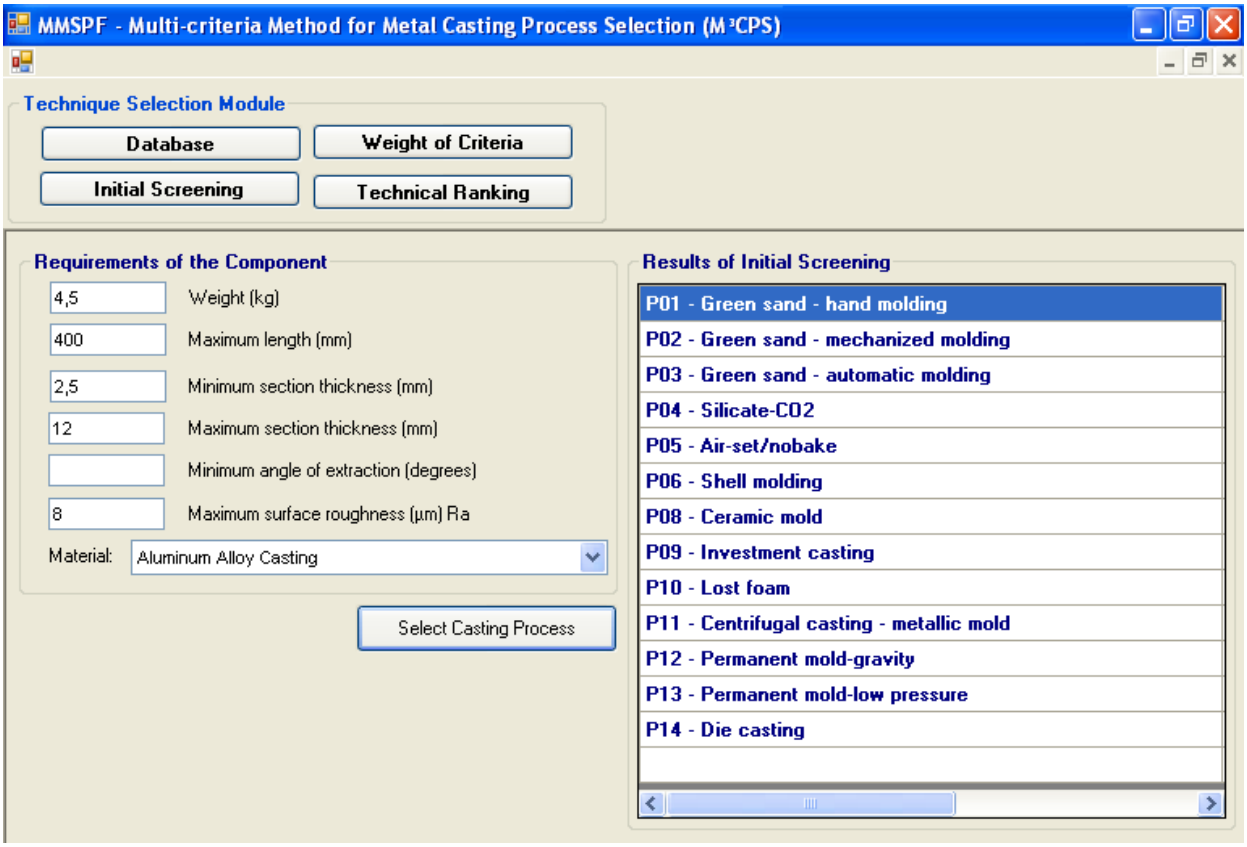

Figure 1: Graphical user interface of the initial screening step. M^{3}CPS computational tool.

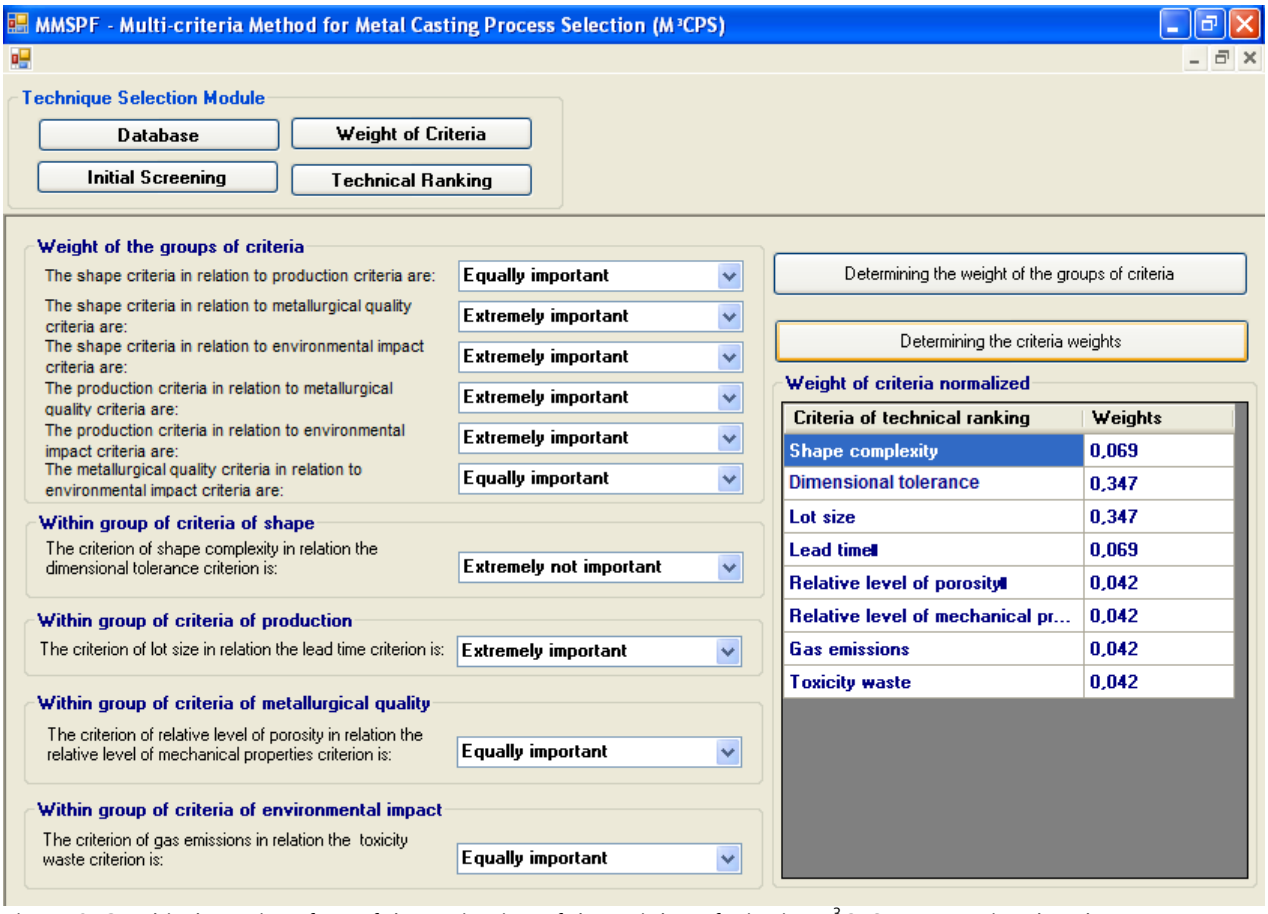

Figure 2: Graphical user interface of determination of the weights of criteria. M^{3}CPS computational tool.

With the weights determined, the step of technical ranking is performed. The information used in this step is: (*i*) the shape complexity, with two options of selection: low or high; (*ii*) the lot size to be produced annually; (*iii*) the dimensional tolerance for the component (*iv*); lead time for production of the first sample. The other four criteria used in technical ranking are evaluated according to the preferences expressed by the designer of the component through the weights of the criteria. The M^3CPS considers that the relative level of mechanical properties and porosity, gas emissions and toxicity waste, are hallmarks of the metal casting processes, and cannot be changed, independently on the component to be produced in the process. The effect of these criteria in the technical ranking is a function of the importance attributed to them by the weights. Figure 3 shows the result of technical ranking for component 1.

Thirteen processes approved in the initial screening, but only six were selected in technical ranking for presenting technical compatibility in the production of a component 1. The classified processes and their respective technical ranking index are: (*i*) die casting (0.144), (*ii*) green sand - automatic molding (0.143), (*iii*) shell molding (0.104), (*iv*) permanent mold-low pressure (0.096), (*v*) permanent mold-gravity (0.092) and (vi) silicate - CO_2 (0.082). The die casting process was selected by the computer application of M^3CPS as the metal casting process most suitable for manufacturing component 1, the same result was obtained in the work of Er and Dias (2000).

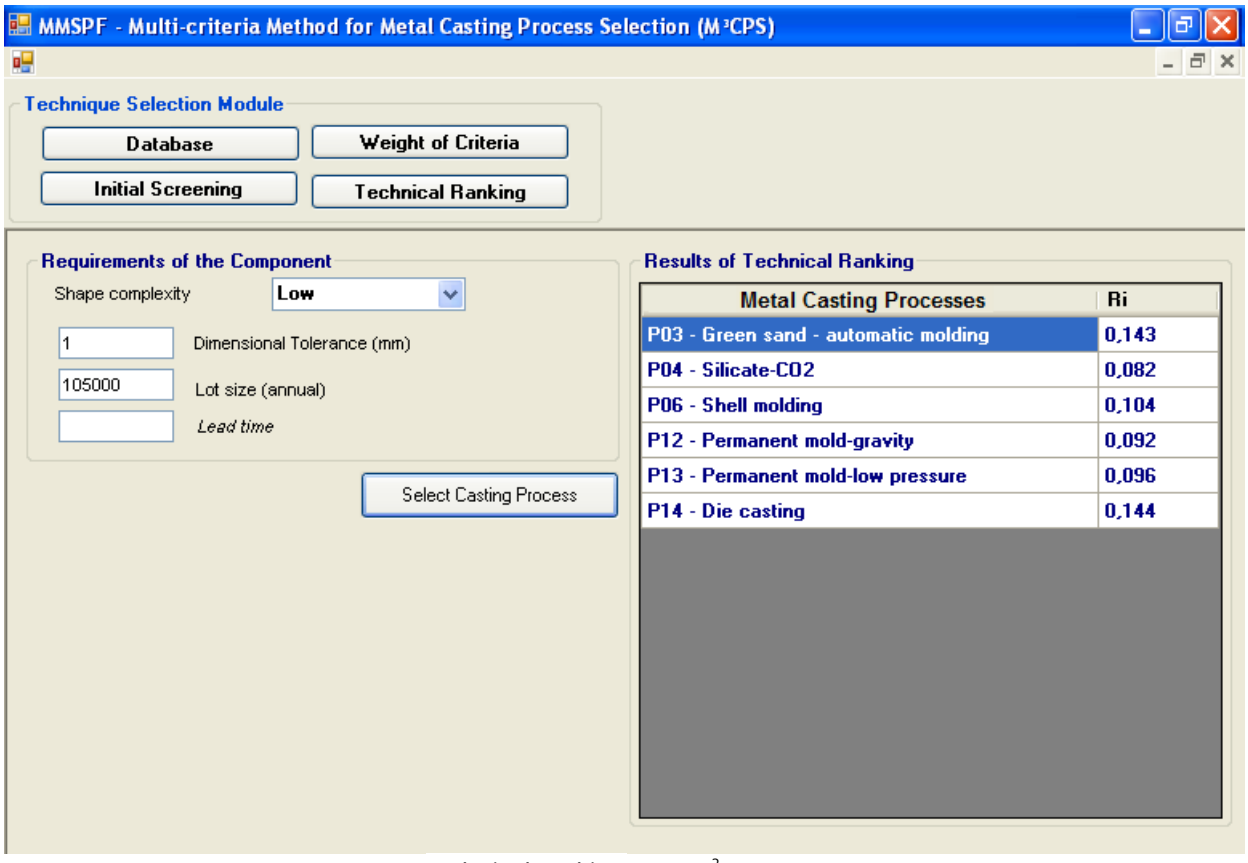

Figure 3: Graphical user interface of the technical ranking step. M^3CPS computational tool.

3.4 The Effect of Aggregation of Information in the Selection

To evaluate the effect of aggregation of information on the process selection the second component was used. Table 5 presents the results provided by the computational tool of M^3CPS.

Table 5: Results provided by the M^3CPS for the component 2

Results of initial screening	Results of technical ranking		
	Scenario 1	Scenario 2	Scenario 3
Shell molding	Not classified	Not classified	Not classified
Plaster molding	Not classified	Not classified	Not classified
Ceramic mold (Shaw process)	(0,285)	(0,275)	(0,287)
Investment casting (lost wax)	(0,262)	(0,267)	(0,306)
Die casting	Not classified	Not classified	Not classified

Only the processes shell molding, plaster molding, ceramic mold (Shaw process), investment casting (lost wax) and die casting were considered able to produce the component 2. Of the five processes approved in the initial screening, only two were selected in the technical ranking for presenting technical compatibility in the production of the component 2. At this operational step the effect of aggregation of information on the final outcome of the selection was evaluated.

In scenario 1, where all sources of information available to these processes were used, the ceramic mold (Shaw process) was chosen with a technical ranking index of 0.285. In scenario 2, only one source of information was used (criteria of greater weight) privileging the ceramic mold process (Shaw process), being chosen, again, this process with a technical ranking index of 0.275. In scenario 3, a source of information was used (criteria of greater weight) privileging the process investment casting (lost wax). The result obtained in this scenario was changed, with the investment casting (lost wax) being selected with technical ranking index of 0.306. Thus, the result of selection is directly dependent on the values of the information sources used. Based on the results shown in Table 5 the treatment of sources of information used in the selection methods cannot be disregarded. In the work by Er and Dias (2000) the process investment casting (lost wax) was chosen as most suitable to manufacture the component as in scenario 3.

4 Conclusions

A method for metal casting process selection (M^3CPS) is developed in this paper to select suitable metal casting process to assist designers of cast components. The key innovation introduced by M^3CPS consists in treating different sources of information used in the operational steps (initial screening and technical ranking) through a fuzzy aggregation operator. The initial screening step is responsible for eliminating processes that do not meet the requirements of the component based on seven criteria. The determination of criteria weights step for the technical ranking is based on Analytic Hierarchy Process (AHP). The technical ranking is performed through an additive weighting. The processes approved in the technical ranking are the ones with Ri value greater than or equal to $1/n$, where n represents the number of metal casting processes which were approved at the initial screening step. The M^3CPS was implemented in a computational tool and successfully tested on industrial parts of a previous research. The database (SQLite) used by M^3CPS can be easily customized with technical data of foundry of the user's preference.

The case studies showed the operation of the M^3CPS's computational tool and the effect of aggregation of information on the selection results. With the appropriate sources of information and the decision maker's preferences well defined, the M^3CPS is an important tool to assist designers of cast components in the proper selection of metal casting processes.

Acknowledgements

We are grateful to CAPES and the Araucaria Foundation, for their financial support which enabled this study to be conducted.

References

Akarte, M. M., Ravi, B., & Creese, R. C. (1999). Casting process selection using AHP and fuzzy logic. *International Seminar on Manufacturing Technology, Beyond 2000*, Bangalore, 468-482.

Beliakov, G., Pradera, A., & Calvo, T. (2007). *Aggregation Functions: A Guide for Practitioners*. Berlin: Springer, (pp. 123 – 270).

Chou, J. S. (2009). Web-based CBR system applied to early cost budgeting for pavement maintenance project. *Expert Systems with Applications*, 36, 2947-2960.

Creese, R. C., Adithan, M., & Pabla, B. S. (1992). *Estimating and Costing for the Metal Manufacturing Industries*. New York: Marcel Dekker, (pp. 99-193).

Darwish, S. M., & El-Tamimi, A. M. (1996). The selection of casting process using expert system. *Computers in Industry*, 30, 77-86.

Daws, K. M., Al-Dawood, Z. I., & Al-Kabi, S. H. (2008). Selection of metal casting processes: A fuzzy approach. *Jordan Journal of Mechanical and Industrial Engineering*, 2, 45-52.

Er, A., & Dias, R. (2000). A rule-based expert system approach to process selection for cast components. *Knowledge-Based Systems*, 13, 225-234.

Kahraman, C., Birgün, S., & Yenen, V. Z. (2008). Fuzzy Multi-Attribute Scoring Methods with Applications. In C. Kahraman (Ed.), *Fuzzy Multi-Criteria Decision-Making: Theory an applications with recent developments* (pp. 187-208). New York: Springer Science e Business Media.

Kay, I. M. (2004). Metalcasting processes. In H. Geng (Ed), *Manufacturing Engineering Handbook* (pp. 19.1-19.16). New York: McGraw-Hill.

Ling, Z. (2006). Expected value method for fuzzy multiple attribute decision making. *Tsinghua Science and Technology*, 11, 102-106.

Ravi, B. (2005). *Metal Casting: Computer-aided Design and Analysis*. New Delhi: Prentice-Hall of India, (pp. 102-112).

Rundman, K. B. (1999). *Metal Casting*. Houghton: Michigan Technological University, (pp. 1-7).

Setti, D. (2010). Método multicriterial para seleção de processos de fundição de metais. *Doctor Thesis*, Federal University of Rio Grande do Sul, Brazil: http://www.lume.ufrgs.br/bitstream/handle/10183/28785/000772499.pdf?sequence=1

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, 15, 234-281.

Saaty, T. L. (1994). How to make a decision: The Analytic Hierarchy Process. *Interfaces*, 24, 19-43.

Sirilertworakul, N., Webster, P. D., & Dean, T. A. (1993). A knowledge base for alloy and process selection for casting. *International Journal of Machine Tools & Manufacture*, 33, 401-416.

Srdjevic, B. (2005). Combining different prioritization methods in the analytic hierarchy process synthesis. *Computers & Operations Research*, v. 32, 1897-1919.

Stein, W. E., & Mizzi, P. J. (2007). The harmonic consistency index for the analytic hierarchy process. *European Journal of Operational Research*, 177, 488-497.

United States Department of Energy. (2005). *Metal Casting Industry of the Future: Fiscal Year 2004 Annual Report*, Washington.

Vaníšek, J., Vrana, I. & Aly, S. (2009). Fuzzy aggregation and averaging for group decision making: A generalization and survey. *Knowledge-Based Systems*, 22, 79-84.

Yoon, K., & Hwang, C. L. (1995). *Multiple attribute decision making: an introduction.* Thousand Oaks: Sage Publications, (pp. 15-16).