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Methodology for Metalcasting Process Selection

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ABSTRACT

Today, there are several hundreds of manufacturing processes available to the designer to choose from, and the number is constantly increasing. The ability to choose a manufacturing process for a particular user need set in the early stage of the design process is necessary. In metalcasting alone, there are over forty different processes with different capabilities. A designer can benefit from knowing the manufacturing process alternatives available to him. Inaccurate process selection can lead to financial losses and market share erosion.

This paper discusses a methodology for selection of a metalcasting process based on a number of user specified attributes or requirements. A model of user requirements was developed and these requirements were matched with the capabilities of each metalcasting process. The metalcasting process which best meets these needs is suggested. The selection is based on the weighted algorithm that considers both the relative importance of each user requirement as well as the relative ease of meeting the requirement by different metalcasting processes.

The method has been deployed on the web and can be easily accessed by a browser with minimal client side deployment. The implementation is currently limited to the most common metalcasting processes and materials.

INTRODUCTION

A major problem faced by both designers and procurement personnel is the selection of the appropriate metalcasting process from among the 40 different processes. The problem is made acute by the wide variation in different processes regarding “User requirements” like dimensional tolerance, surface finish and thin/thick section capabilities. Apart from these, processes are limited by other constraints like weight, economical quantity and shape complexity.

Metalcasting Process Advisor (MPA) is a web based advisory system that attempts to consider these criteria to suggest an appropriate metalcasting process. Unlike usual methods at metalcasting process selection, MPA uses a weighted approach that allows the user to state the relative importance of each criterion on a scale of 1 to 5. It also differentiates between what the process normally does (Typical limits) and what it can do with special equipment or additional costs (Extreme limits).

The weighted approach is a recognized decision making approach when no “Yes-No” answers can be applied to criteria that influence decision-making. The weighted approach has been suggested as valuable tool for material selection [5] . The MAS program [11] uses the weighted approach that considers the relative importance of input criteria for process and material selection, although it does consider all the metalcasting processes MPA does. MPA also differs in that it differentiates between the typical and extreme limits of the process.

The weighted approach that MPA uses considers material, quantity, weight, thin/thick Sections, tolerance and surface finish as the most important “input criteria” for selecting the metalcasting process. A frequent approach employed in earlier papers [1,9] for process selection is to select the process which meets all input critera. This ignores the fact that some input criteria may not be important always or may not be as important as some other input criteria. For Example, Surface finish is important when making a casting for the sealing surface of an aircraft structural casting [4], but may not be important in case of castings used as counter weight. Some castings would necessiate close control of tolerances without much attention to surface finish and in other castings a good finish is vital compared to tolerances. Another factor to consider is that the relative ease of meeting an input criterion may vary from process to process. For Example, Aluminum Sand casting using waterless green sand molds can manufacture to a finish as low as 90 μ inches while Aluminum Shell castings can manufacture to a finish as low as 125 μ inches [3]. However, Green Sand casting typically operates between 250 - 1000 μ inches whereas Shell castings can produce a finish between 125 –300 μ inches. If the user desires a finish of 150 μ inches, MPA suggests Shell casting as a better candidate to manufacture the part followed by Sand casting since the relative ease of casting it is easier in Shell casting.

As another example, Plaster casting can be used to cast between 0.05 lbs to 2200 lbs, but typically operates between 0.2 lbs to 150 lbs [8]. MPA has a mechanism wherein the probability that Plaster casting would be suggested as an appropriate process is higher where the part weight is in the range where it is typically cast or the relative ease of casting the part is better.

In effect, the weighted approach favors a process that can cast the part in the "Typical limits" of the process. The choice is not favored towards a process that can cast it outside the Typical limits but within the "Extreme limits" of the process. MPA is expected to give better results when compared to other approaches that consider only one range and do not consider the importance the user attaches to the input criteria. The program has been developed using Java server pages (JSP) technology using the Oracle 9i database.

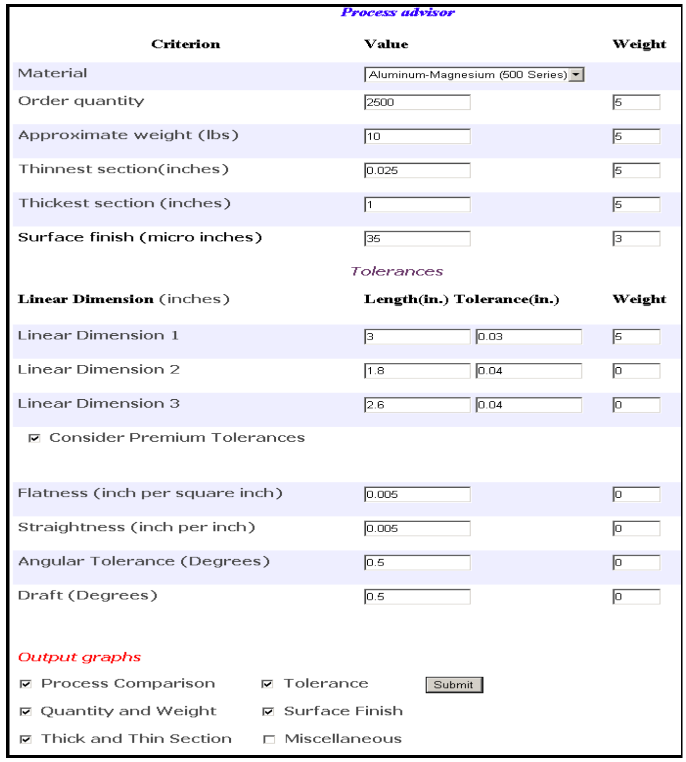
METHODOLOGY OF THE WEIGHTED APPROACH

Each input criterion (such as "Surface finish" or "Tolerance") is assigned a weight between 0 to 5 with 0 being "Unimportant" and 5 being "Very important". This weight is used for two purposes:

1. To indicate importance of an input criterion relative to other criteria. Higher the weight assigned to an input criterion, more likely it is that MPA will favor a metalcasting process that can satisfy the criterion at the expense of not satisfying other criteria with lesser weight.
2. To favor a process known to meet the input criteria within the normal or typical limits of the process.

The input form for MPA is given in Figure 1. A default weight, which can be changed by the user, is next to each criterion. By default, all factors other than surface finish is considered very important for process selection. Only processes capable of casting the metal are chosen. Each metalcasting process is checked to see whether it satisfies the specified criteria. For example, consider the values shown in Figure 1. The user wants to order 2500 Aluminum alloy castings. The approximate weight of each part is 10 lbs. The thinnest section of the casting is 0.025 in. and thickest section is 1 in. The desired tolerance is 0.03 in. over a linear dimension of 3 in. The second and third linear dimensions are optional.

A score is the weight assigned to the metalcasting process for an input criterion depending on how well the metalcasting process can satisfy the particular criterion. Scores for each individual criterion are summed up to arrive at an overall score for each metalcasting process with the maximum possible score being 100. If the metalcasting process cannot satisfy an input criterion fully, then the score for that criterion is not added to the overall score. Figure 2 gives a simplified method to assign the overall score to a metalcasting process.


Process advisor

Criterion	Value	Weight
Material	Aluminum-Magnesium (500 Series)	
Order quantity	2500	5
Approximate weight (lbs)	10	5
Thinnest section(inches)	0.025	5
Thickest section (inches)	1	5
Surface finish (micro inches)	35	3

Tolerances

Linear Dimension (inches)	Length(in.)	Tolerance(in.)	Weight
Linear Dimension 1	3	0.03	5
Linear Dimension 2	1.8	0.04	0
Linear Dimension 3	2.6	0.04	0

Consider Premium Tolerances

Flatness (inch per square inch)	0.005	0
Straightness (inch per inch)	0.005	0
Angular Tolerance (Degrees)	0.5	0
Draft (Degrees)	0.5	0

Output graphs

Process Comparison
Tolerance
Submit
Quantity and Weight
Surface Finish
Thick and Thin Section
Miscellaneous

Figure 1: Input form of the Metalcasting process Advisor

For example, if Investment casting cannot cast a finish of 50 μ in., its score would have been ((28 –3)/28)*100= 89.2. If it is able to meet all requirements, then its score would have been 100.

Similiarly, other metalcasting processes are evaluated on how well they meet user requirements and all processes are ranked in decreasing order of their scores. The metalcasting process with the highest overall score is suggested by the advisor. For example, if the overall scores for Sand casting, Die casting and Investment casting are 85, 80 and 88 respectively, then Investment casting is recommended as a possible process.

As will be demonstrated later, the advisory system does more than simply add weights. The MPA output for the input from Figure 1 is shown in Figure 3. Investment casting with an overall score of 98.2 out of a maximum of 100 is shown as the suggested process from among more than 10 processes .

The bar chart shows the scores achieved by different processes. It indicates that Plaster casting with a score of 97.5 comes close to Investment casting in meeting the requirement. For the material shown in the input form in Figure 1, only processes which can make the material is shown in the bar graph.

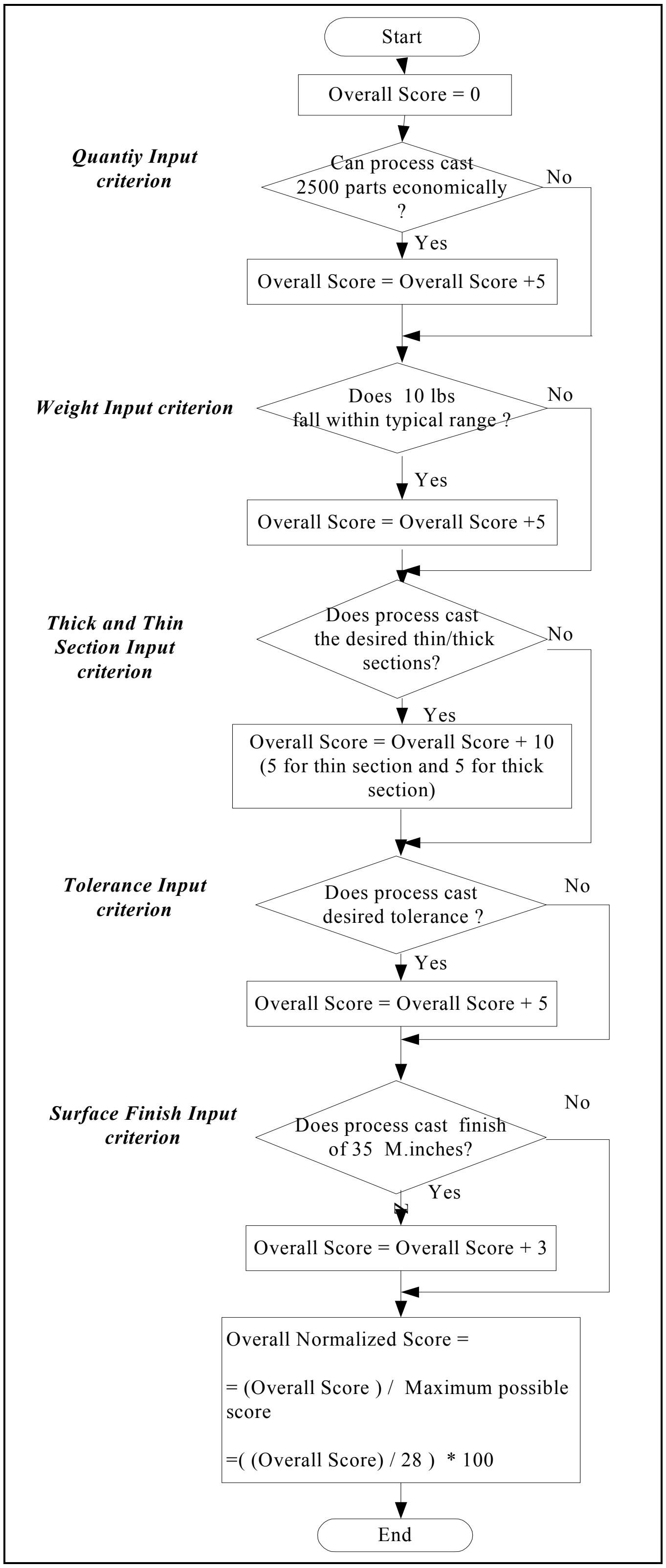


Figure 2: Simplified flowchart to assign score to a process for input form in Figure 1

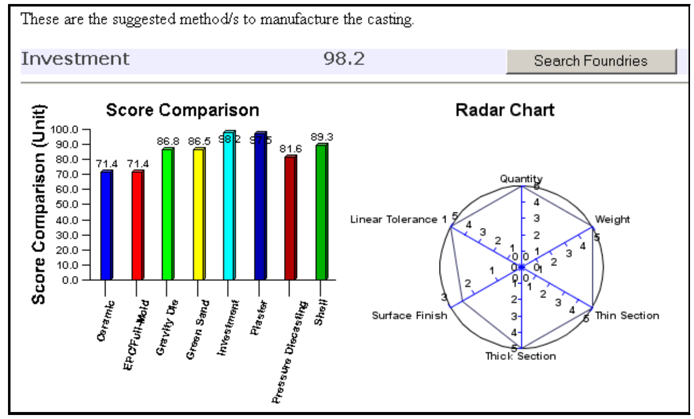


Figure 3: Web based output of the Metalcasting process Advisor

The chart on the right in Figure 3 shows a 6 dimensional radar graph showing how well Investment casting satisfies the various input critera. Each of the six axis starts with 0 and ends with the weight assigned by the user to the input criterion.

The lines connect the different axis and indicates the scores assigned by MPA to that particular input criterion. The line connecting the 6 dimensions is slightly skewed inwardly (does not touch the circumference) when it crosses the criterion “Surface finish” (Refer arrow in figure). This means that a Surface finish of 35 μ inches is not typically cast using investment casting. Typical finish obtainable from investment castings is around 50 μ inches, although finishes as low as 32 μ inches can be obtained. Therefore MPA assigns a value of 2.5 rather than the maximum score of 3 for the input criterion “Surface finish”.

ASSIGNMENT OF SCORES TO METALCASTING PROCESSES

Relationship between process and economical quantity

Material is treated as a “Go-Nogo” decision and any metalcasting process that cannot cast the material is eliminated. MPA’s database repository consists of more than 25 broad Metal/Alloy categories including Aluminum, Iron, Magnesium etc and 16 metalcasting processes.

Swift and Booker (8) have published Process Information Maps (PRIMA) which give information on the metalcasting processes suitable for a given metal and economical quantity. The PRIMA was extended to accommodate 2 more metalcasting processes and this information was stored in the database. Sample records from the database is shown in Table 1.

The PRIMA looks at manufacturing process at an extremely broad level and exceptions can happen. The MPA assigns the maximum score possible to the process for the input criterion “Quantity” if the process falls within the “Economical region”.

Table 1: Storing "Economical Region" for Process-Material combination

Metal	Process	Lower quantity	Upper quantity
Aluminum alloys	Pressure die	1000	No Upper limit
Gray iron	Shell	100	No Upper limit
Magnesium	Gravity die	100	No Upper limit
Corrosion resistant iron	Lost Foam	5000	20000

For Example: For Aluminum alloys, the economical region for Die casting is above 1000 units and economical region for the same metal for Sand casting is above 1. If the user wants to buy 500 castings, then Sand casting will be assigned a score of 5 and Die casting will be assigned a score of 0 since Die casting is not in the economical region.

Interpreting MPA's graphical output

Figure 4 shows MPA's web based output for "Quantity". The User input (2500) is given by the blue line. Green bars denote typical quantities where the process is economical and the red bars indicate uneconomical regions. Since quantity is being considered at a very broad level, there is always a risk that the user will input a value slightly lesser than the "Lower quantity" which may cause the process to be rejected. For instance, for the figures in Table 1, if the user input were 950, then Die-casting would have had a score of zero assigned to it for "Quantity". In such cases, the user can set a weight of zero to the input criterion "Quantity" and resubmit the JSP (Java Server Page). This will cause MPA to ignore quantity and arrive at a decision by considering other factors. The graph shows that apart from EPC/Full mold and Ceramic casting, all other castings fall into the feasible region.

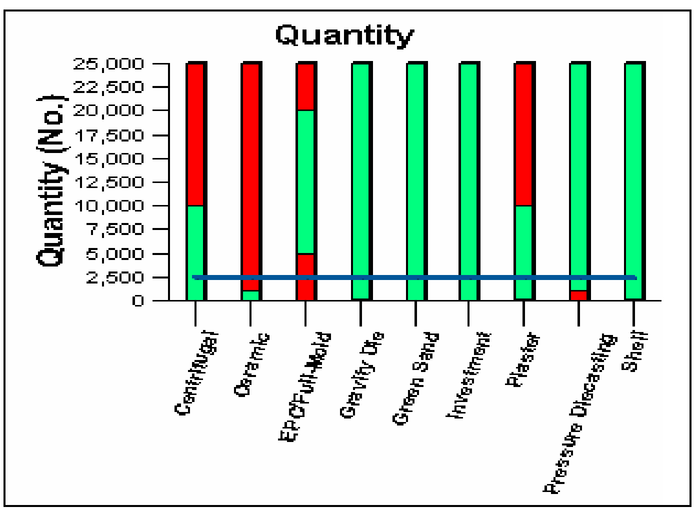


Figure 4: Capability to cast input "Quantity" for different metalcasting processes

Dimensional Tolerance capability

Tolerance is defined as the acceptable variation to the ideal or nominal dimension. These are described by the system of Geometric dimensioning and tolerancing (GD&T) and are based on the ASME standard Y14.5M-1994.
Tighter tolerances than normal will lead to increased cost and lead-time. For Example, an AFS study [3] for Plaster Mold aluminum castings gave the tolerance guideline specified in Table 2.

Table 2: Tolerances for Plaster Mold castings

Dimension	Under 1 in.	Add per in. over 1 in.
Across parting line	+/- 0.010	+ 0.0015

The study estimated that if the parting line tolerance above were reduced to +-0.010 in. plus 0.001 in, production costs would decrease by about 14-17%.
Generally, tolerances depend on the geometry of the part. However, foundries generally state the tolerances that can be obtained by using its processes and provide guidelines to the designer to work towards these tolerances. These tolerances are called "As cast" tolerances because they are obtained without any additional processes such as machining or using additional equipment. MPA considers linear, angular, flatness and straightness tolerances. Linear tolerances are usually most important of all the tolerances when determining a suitable metalcasting process.

Tolerances in the Metalcasting process advisor

Metalcasting tolerances greatly depend on both the metal and the process. MPA uses a database of casting tolerances to suggest an appropriate casting process. The format in which MPA stores linear tolerances in the database is given in Table 3. Table 3 indicates that for dimensions from 0 to 6 inches, the tolerance obtained is 0.032 in. After that, it linearly increases from 0.032 in. to 0.13 in.

Table 3: Format of storing linear tolerances

Process	Metal/ Alloys	From-To dimension (in.) *	Lower tolerance (in.)	Upper tolerance (in.)
Sand	Aluminum	0 – 6	0.032	0.032
Sand	Aluminum	6 – 40	0.032	0.13

Additionally, the database stores the tolerance obtained from metalcasting processes for linear dimensions that cross the parting line (Table 4) and for dimensions affected by cored regions. The parting line tolerance is added to the normal tolerance of the process for features that cross the parting line.

Table 4: Format of storing parting line tolerances

Process	Metal	Across Parting Line (in.)
Sand	Copper	0.020

Other tolerance related parameters considered include Flatness, Straightness and Angular tolerance. These parameters are not mandatory inputs. Table 5 indicates the format for storing these tolerances. The default weight for these is zero or unimportant, meaning that it is only used to highlight differences between metalcasting processes without considering it for process selection.

Table 5: Format of storing other tolerances

Process	Flatness (In. per sq in.)	Straightness (In. per in.)	Angular tolerance (Degrees)
Investment	0.003	0.003	$0^0 15'$

Consideration of Premium Tolerances

Tighter linear tolerances than available in the chosen casting process can be obtained by secondary processes such as machining. For Example: In Investment casting, there are several ways to obtain a tolerance tighter than what can be commonly obtained. Some of the methods displayed on one Investment casting foundry website [12] are:

1. Part redesign, including addition of tie bars, ribs, and gussets to certain shapes.
2. Tuning of wax injection tooling after the first sample to meet the nominal dimensions.
3. Straightening after casting
4. Gauging and hand fitting
5. Machining
6. Other secondary operations.

MPA can alert the user that an additional amount may have to be paid to obtain tolerances specified on the drawing. However, MPA favors the process that meets tolerance requirements within normal process capabilities.
Statistical analysis of premium tolerances is complicated because they are dependent on the foundry, process and part geometry. Some of the difficulties encountered are graphically displayed in Figure 5. The figure shows the premium tolerance expressed as a percentage of the tolerance that could be obtained for a given linear dimension for three Investment casting foundries sampled [13,14,15]. As can be seen from the diagram, the premium that may have to be paid to achieve the desired tighter tolerance for a given linear dimension varies from foundry to foundry.

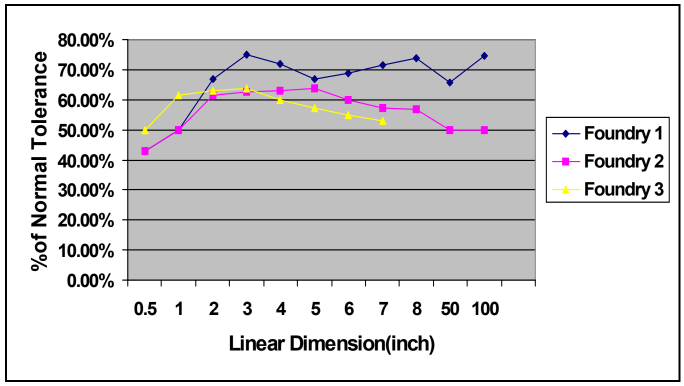


Figure 5: Premium tolerance as a percentage of normal tolerance

In order to know whether a premium has to be paid, MPA uses the graphs designed by Swift and Booker [8], which specify regions below the normal tolerance capability of the process as tolerances that cannot be normally achieved by the process. If the desired tolerance falls in this region, then secondary processing or additional cost is warranted. This region is used by MPA to indicate if tolerances are too tight to be achieved by a particular process.

Assigning Score to a process for "Tolerance":

MPA favors the process where the tolerance requirement can be fulfilled without going into the premium range. This is done by assigning higher scores to processes that can normally meet the tolerance requirement without additional equipment as compared to processes that fall within the premium range. The flowchart for this is given in Figure 6.
A future improvement in the model includes making the lower weight (2.5) as a user input. This will allow the user to set the sensitivity of the model to variations from what is typical for the process. Figure 7 displays the scores assigned to Investment casting where 0.005 in. is the achievable tolerance for given linear dimension and the region between 0.005 in and 0.002 in. is the premium range.

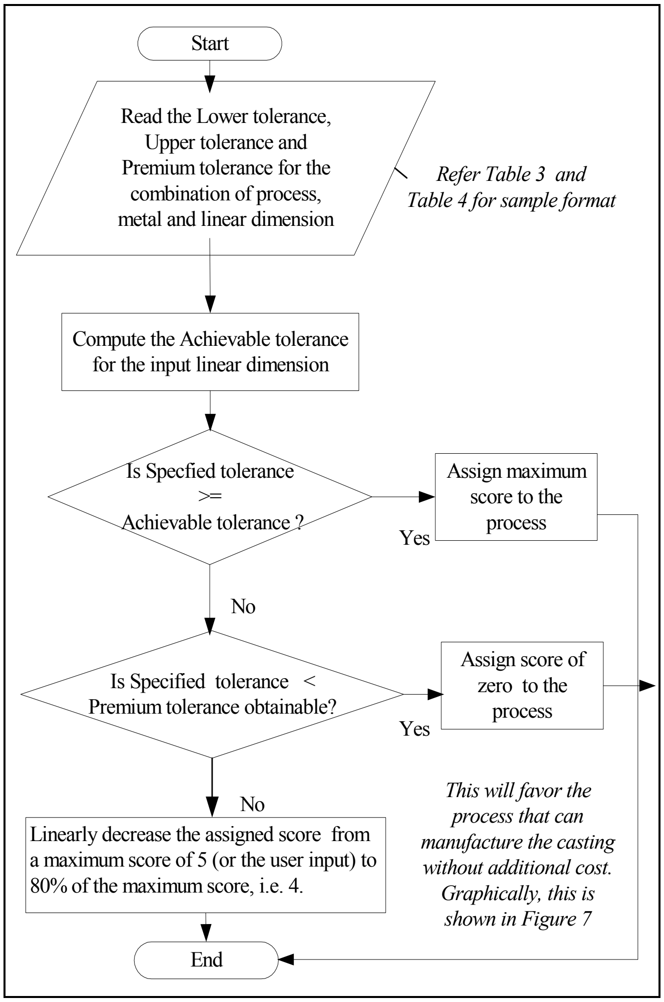


Figure 6: Flowchart for assigning scores to a process for "Tolerance"

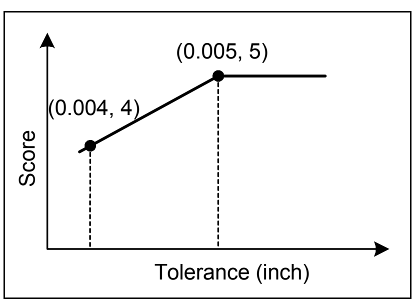


Figure 7: Variation of assigned score vs. specified tolerance for Investment casting

At the end of the algorithm outlined above, an internal array of all the metalcasting processes is built with its assigned score regarding its tolerance capabilities. Two such processes along with their score for tolerance are given in Table 6 for the input form in Figure 1.

Table 6: Assigned score to metalcasting processes for tolerance

Process	Assigned score
Investment	5.0
Plaster	5.0

Interpreting MPA's graphical output

Figure 8 shows graphical output for tolerances. Achievable tolerances are indicated by green bars, Unachievable tolerances by red bars, and premium tolerances by blue bars.

For Example, for the input form in Figure 1, MPA indicates that the tolerance across the first dimension (Linear tolerance 1) can be achieved normally by any process except Green sand where a premium may have to be paid. Across the second and third dimensions (Linear tolerance 2 and 3), the tolerance can be achieved by any process.

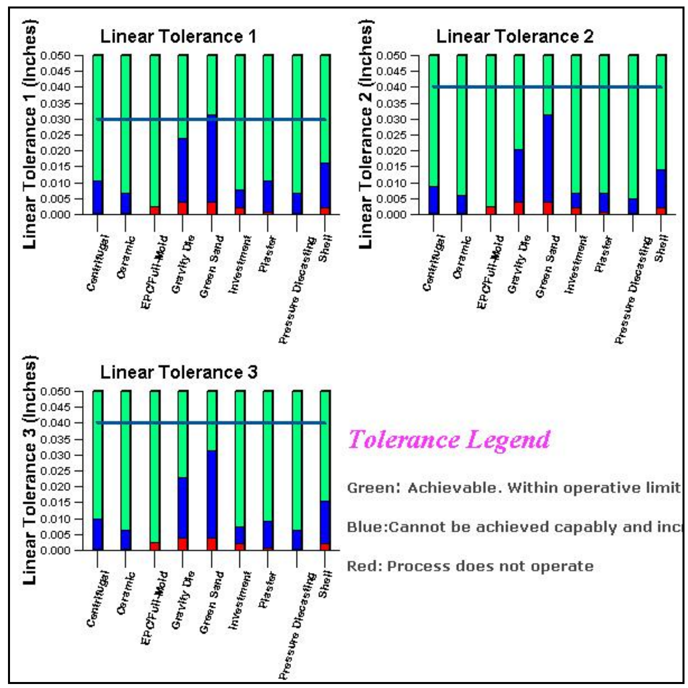


Figure 8: Capability to cast input "Tolerance" for different metalcasting processes

Part weight

Each metalcasting process has a range of casting weights that it can produce under normal conditions. While handling part weights, it may be incorrect to simply consider the upper and lower bound of each process regarding the maximum and minimum weight that can be cast. With the increasing pace of technology improvements, larger parts are being cast with processes earlier known for casting only parts with a small or medium weight. However, it is still true that every metalcasting process is most advantageous over a certain weight range. Outside this range, the process may still be feasible, but may no longer be advantageous. MPA considers this by defining the typical and extreme limits for each metalcasting process as shown in Table 7. Figure 9 gives the flowchart for assigning scores metal casting processes for the criterion “Weight”.

Table 7: Typical and Extreme limits for input criterion “Weight” for Plaster casting

Process	Lower extreme (lbs)	Lower typical (lbs)	Upper typical (lbs)	Upper extreme (lbs)
Plaster	0.05	0.2	150	2200

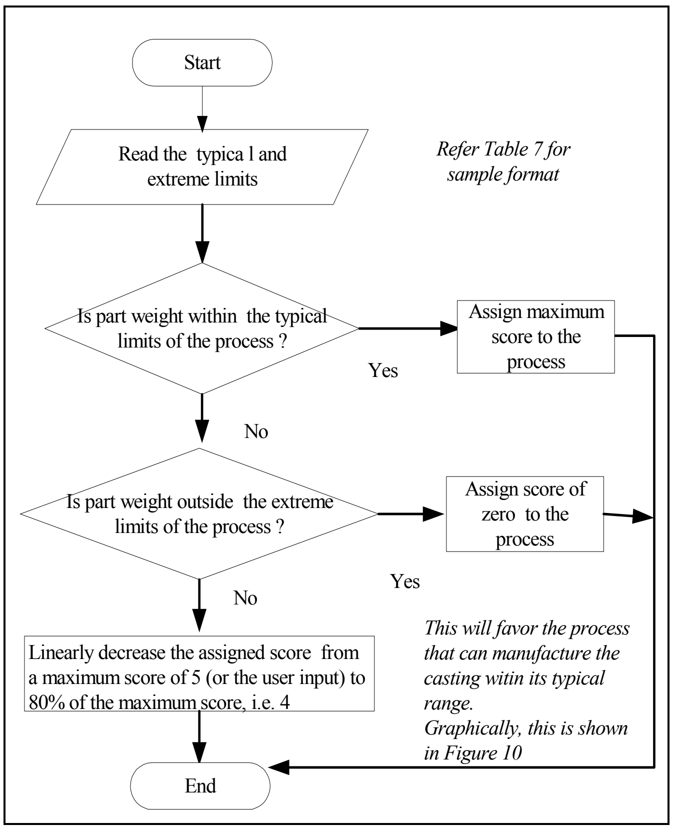


Figure 9: Flowchart for assigning scores to a process for “Weight”

Interpreting MPA’s graphical output

The estimated weight of the cast part is indicated by a blue line. Green bars indicate the region where the process normally operates. The Yellow bar indicates the region where scores are linearly decreased i.e., the region of uncertainty where the weight that can be cast depends on one or more of the factors - metal, geometry and foundry. In these cases, it is suggested that the appropriate foundry be contacted to determine whether the process can manufacture to the desired weight. The red bars indicate the region where the process cannot operate. Figure 11 shows that the user input of 10 lbs can be met easily by all processes.

At the end of the process, an internal array is built up showing the score that was assigned to different metalcasting processes for the input criterion weight. A sample of the array for the input form in Figure 1 is shown in Table 8.

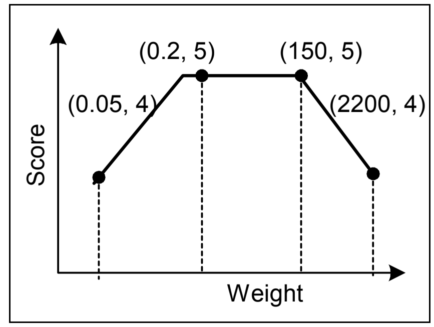


Figure 10: Variation of Assigned score vs. Weight for Plaster casting

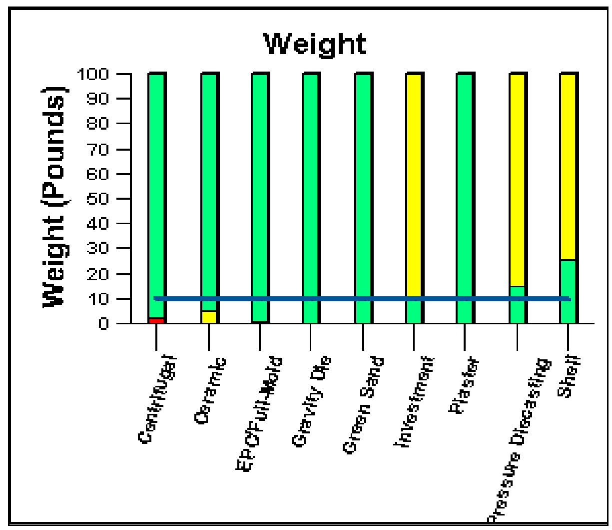


Figure 11: Capability to cast input “Weight” for different metalcasting processes

Table 8: Assigned score to metalcasting processes for input criterion “Weight”

Process	Assigned score
Plaster	5
Investment	5

Section size capability

The American Society for Metals casting design handbook lists the following advantages of thin walled sections [4]:

1. Contribute to a more favorable Strength to Weight ratio.
2. Help lower casting costs, especially when an expensive alloy is being cast.

When evaluating the feasibility of metalcasting processes to manufacture a given section thickness, the following uncertainties are faced:

1. The capability to manufacture thin sections varies from foundry to foundry, even within a given metalcasting process. For Example, some Green Sand foundries may be able to manufacture thinner sections than others.
2. The ability to make a thin wall section also depends on the Metal to be cast and the foundry capabilities. Example: Investment castings can cast thin walls ranges from 0.009 in. to 0.04 in. These two are internally defined as lower thin section and upper thin section. The lower thin section and upper thin section are stored in the database for all metalcasting processes.

Figure 12 shows the flowchart for assigning scores to processes based on the capability to manufacture thin sections.

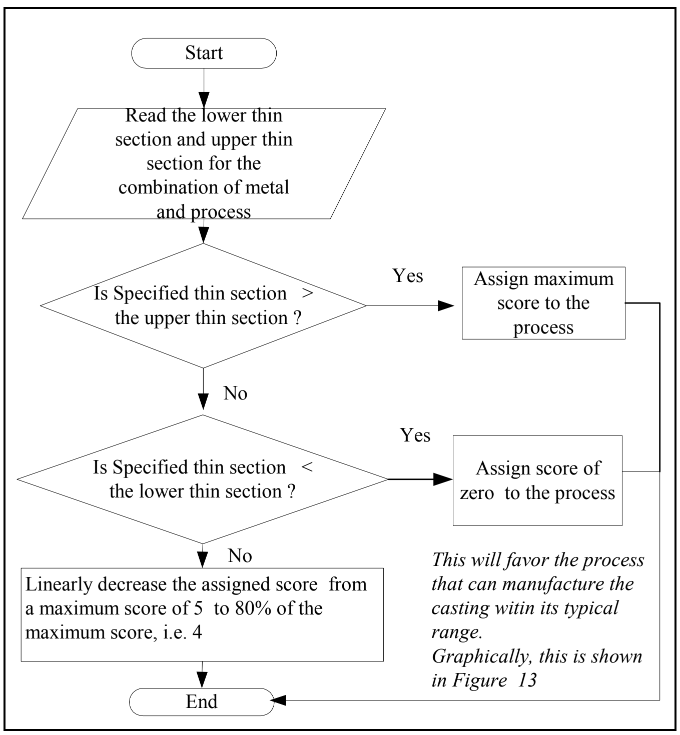


Figure12: Flowchart for assigning scores to a process for Thin Section

An internal array of the thin section capability score that is assigned to all processes, as shown in Table 9. For die-casting, the user input is between the lower and upper thin sections. Hence, the score assigned is 4.2.

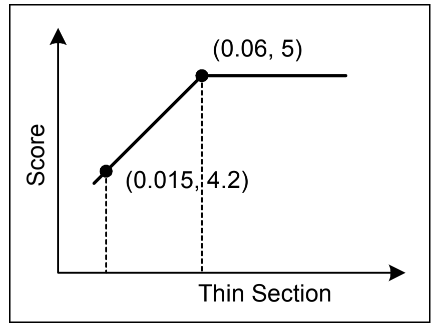


Figure 13: Graph to assign score to Pressure Die Casting for "Thin Section"

Table 9: Assigned score to metalcasting processes for input criterion "Thin Section

Process	Assigned score
Investment	5
Pressure die	4.2

<u>Interpreting MPA's graphical output</u>

In Figure 14, the input criterion is indicated by a blue line. The Yellow bar indicates the region where scores are linearly decreased, i.e. the region of uncertainty where the thin section the process can manufacture to depends on the metal and the foundry. In cases where achieving a thin section is uncertain and the input criterion passes the yellow bar, it is suggested that the foundry be contacted to determine whether the process can manufacture the specified thin section. Thick sections are handled the same way.

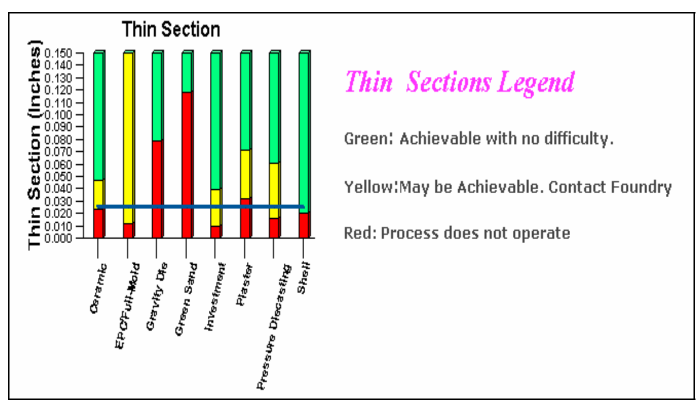


Figure 14: Capability to cast input "Thin section" for different metalcasting processes

Surface Finish capability

Surface finish is either computed based on the Centerline Average (CLA) or the arithmetic average based on the deviation from the mean surface. The arithmetic method is followed more in computing surface finish.

MPA considers only "As Cast" surface finishes. It does not favor processes that need secondary processes that can be used to give a better surface finish. For example, Investment castings typically provide a "As cast" surface finish that varies from 50 μ in to 125 μ in. In extreme cases, finishes of up to 32 μ in can be obtained. Secondary processes such as Glass bead blasting or Automatic grit blasting may be used to give a better surface finish is ignored.

Processes overlap with regard to finish that can be obtained from them. Suppose the designer wishes to obtain an "As cast" finish of 75 μ in. Neglecting other considerations such as weight, tolerance etc. and considering only surface finish, the designer is faced with several processes which can give the desired finish: Pressure die casting, Investment casting, Plaster casting, Shell casting and Ceramic casting. A lower extreme indicating the best possible finish and typical finish obtainable is defined for each process (Table 10). MPA favors the process for which the user input is equal to or greater than the typical lower finish and assigns the maximum score possible for the criterion "Surface finish". Between the lower finish and the lower bound, scores are linearly decreased to 80% of the maximum score possible. An example of this is illustrated in Figure 15.

Table 10: Typical and Extreme limits for input criterion "Surface finish" for Investment casting

Process	Lower extreme (μ in)	Typical lower (μ in)	Typical upper (μ in)
Investment	32	50	125

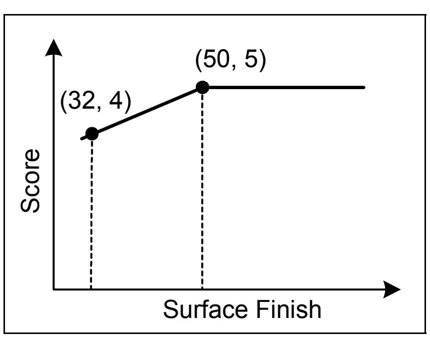


Figure 15: Graph to assign score to Investment casting for "Surface finish"

Finally, an internal array (Table 11) is built by the program giving the assigned scores to various metalcasting processes.

Table 11: Assigned score to metalcasting processes for input criterion "Surface finish"

Process	Assigned score
Investment	5
Pressure die	3

Interpreting MPA's graphical output

As can be seen from the Figure 16, the input criterion of 50 μ in (indicated by a blue line) can be made by Investment casting For plaster and shell casting, it falls in the uncertain range and determination of whether it can be made by would depend on the foundry, metal chosen and geometry of the part.

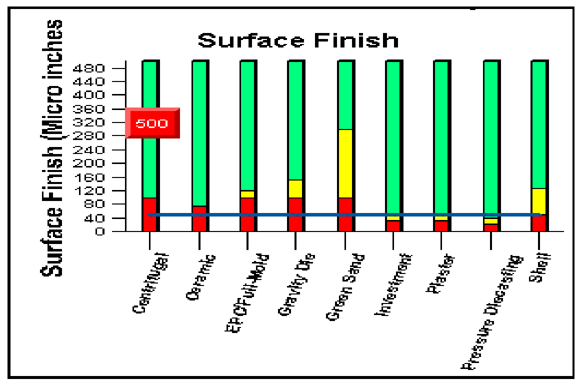


Figure 16: Capability to cast input "Surface finish" for different metalcasting processes

RESULTS

The overall score of each process is the normalized sum of scores assigned to different criterion for that process. So at the end of the algorithm, an internal array is constructed, five rows of which is shown in Table 12. The metalcasting process suggested is the one with the highest overall score, namely Investment casting. Plaster casting is suggested as an alternative with nearly the same score.

Table 12: Overall score of casting processes

Metalcasting process	Computed Score
Investment casting	98.2
Plaster casting	97.5
Shell casting	89.3
Green Sand	86.5

CONCLUSION

Initial model validation of MPA has given positive results. The advisory system has been tested with examples found in casting handbooks as well as foundry drawings. More extensive model validation needs to be done to fully prove the advantages of a weighted approach over the conventional "Yes/No" approach. Foundries will be asked to use the MPA over the web and the feedback will be used to further refine the model.

Another main contribution of the MPA is the detailed modeling of the capabilities for the different metalcasting processes. The main database consists of data regarding the capabilities for 16 main metal metalcasting processes along with tolerance and economical quantity relationships for around 500 process–metal combinations. This database is being expanded to include more metalcasting processes. It is envisioned that this database will be one of the most comprehensive databases for metalcasting capabilities accessible through the Internet.

The MPA is being extended to include geometry complexity as another factor along with the production rate and lead-time of various processes. The data for premium tolerances and parting line tolerances is being updated to encompass all metalcasting processes. Cost will also be integrated into the process advisor.

DISCUSSION

The design professional nowadays is given more responsibility to not only design for functionality, but also design for manufacturability and design for recycling. The MPA is a web-based tool that effectively models metalcasting capabilities for a wide range of processes. This information is converted into useful knowledge that the design professional and buyer can use to make informed purchasing decisions. This promotes the ability of the OEM to effectively engage in a meaningful dialogue with the supply chain.

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