

# RELIABILITY-BASED CASTING PROCESS DESIGN OPTIMIZATION

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## Abstract

Optimum casting designs are unreliable without consideration of the statistical and physical uncertainties in the casting process. In the present research, casting simulation is integrated with a general purpose reliability-based design optimization (RBDO) software tool previously developed at the University of Iowa. The RBDO methodology considers uncertainties in both the input variables as well as in the model itself. The output consists not only of a reliable optimum design but also of the knowledge of the confidence level in this design. An example is presented where the design of a riser is optimized while considering uncertainties in the fill level, riser diameter, and the riser pipe depth prediction. It is shown that the present reliability-based method provides a much different optimum design than a traditional deterministic approach.

## Introduction

Casting process simulation has become an invaluable tool in the production of economical and high performance cast components. Its application by experienced and knowledgeable operators leads to reduced castings defects, casting yield improvement, and reduced trial and error iteration in development of a casting's rigging. Increasingly casting simulation is being used as a collaborative tool between component designers and casting producers to reduce lead times, to develop casting friendly component designs, and to produce better castings. The majority of casting simulation is being used in a purely deterministic approach, replacing iterative trial-and-error process development on the shop floor with iterations on the computer. In this purely deterministic approach, the experience and knowledge of the engineer operating the software determines to a great extent that the software is used effectively, and that the casting process developed is the best it can be.

To maximize the effectiveness of casting simulation and improve the likelihood of an operator achieving an optimal solution, automatic optimization algorithms for casting process development are being researched [1-4], and commercial software such as MAGMAfrontier [5-8], OPTICast [9] and AutoCAST-X [3,10,11] have been developed. The most common application found in all of these automatic process optimization tools is the solution to the problem of casting feeding system optimization. In optimization of the casting feeding system, optimal sizes and locations of feeders are determined such that casting yield (ratio of mass of casting produced to mass of metal poured) is maximized and the desired quality level is met, which is typically defined as an absence of, or low level of, shrinkage porosity in the casting. Despite the power and promise of these developments in casting process optimization there are major shortcomings in these purely deterministic optimization approaches: neither the reliabilities of the casting production process nor the reliabilities of the casting model are considered. Uncertainties in the casting process conditions and variables, and in the casting

model parameters and properties must be considered since these will affect the feasibility of the optimized solution. Casting process optimization where the feasibility of the process solution is not considered is termed Deterministic Design Optimization (DDO). In DDO, the probability of success or failure of the solution is not known, and based on the software operators' experience they must judge the feasibility of the optimized solution and make adjustments if needed. Here the authors present an optimization study for a casting feeding system using a general purpose *Iowa Reliability-Based Design Optimization (I-RBDO)* software [12-15]. By considering uncertainties in the casting production process and models in the *I-RBDO* software, not only does the software tool provide a reliable optimal casting process design, but it also provides a measure of the design's confidence level. The resulting reliability-based design optimization (RBDO) solution for the optimal casting feeding system will be compared with a DDO solution and a solution as might be developed by a casting simulation operator based on a riser piping safety margin.

### Optimization Methods

Whether by DDO or RBDO methods, casting process design optimization inherently involves multiple variables, multi-objectives and multi-constraints. Many of the objectives conflict, such as achieving a porosity-free casting with the smallest size feeders. As such, the most successful multi-objective optimization algorithms developed for casting process optimization with conflicting objects have been the multi-objective evolutionary algorithms (MOEA) [1] or multi-objective genetic algorithms (MOGA) such as modeFRONTIER [16], which has been implemented in the casting process optimization software MAGMAfrontier [5-8]. As has been demonstrated in [6], given casting process and model variables (i.e. initial rigging, metal and mold properties, heat transfer coefficients (HTCs), pouring temperature and time, etc.), and given process constraints (i.e. porosity level, other defects, customer requirements, alloy, etc.), an optimized process can be determined to meet required objectives (i.e. maximum casting yield, required mechanical properties, etc.).

For reliability-based casting process optimization, both the multi-objective aspect of the problem and the uncertainties in casting process and model variables must be defined. In the *I-RBDO* software used in the current work, uncertainties and variations in the casting process variables and the casting modeling software variables and parameters are described via statistical distributions. Normal, Lognormal, Weibull, Gamma, Gumbel, and Extreme I and Extreme II distributions may be used in the *I-RBDO* software. Assuming the variations in the variables follow normal distributions, a standard deviation is sufficient to define the variability about a mean value. The desired confidence level, the probability that the optimized casting process solution will be successful, is also defined in the *I-RBDO* software. For example, a 95% confidence level for the RBDO solution would mean there is a 5% probability of failure.

### Description of Example for Casting Process Feeding System Optimization

The example case study application presented here to compare the DDO and RBDO methods for casting feeding system design is shown in Figure 1. The casting is a 600mm long by 100 mm wide by 50 mm thick bar. A cylindrical-shaped riser is assumed as shown in green in the figure. The average porosity within the casting must less than 0.1%; this is the constraint. The riser volume is to be minimized; this is the objective function. Hence the casting yield is to be maximized while keeping the average porosity in the casting to a low level. The two design variables to be optimized are the radius  $R$  and height  $H$  of the riser. Since a sample-based

optimization method is used, the sensitivities of the riser volume to the radius and height are not needed by the software. For the RBDO analysis the uncertainties in  $R$  and  $H$  must be defined. In this example problem, it is assumed that there is much less control in the process of filling the riser to a given height than to form the riser radial dimension during the molding process. The distributions for  $R$  and  $H$  to be used in the RBDO analysis are shown schematically in Figure 1. Here the uncertainty in  $R$  is defined by assuming it follows a normal distribution with a standard deviation of 3 mm, and to define the uncertainty in  $H$  a standard deviation of 10 mm is used. The results from the DDO and RBDO cases will be compared to a case termed here as “typical practice”, where the riser diameter is set to the plate width and the riser height was determined using a 10 mm safety margin, defined as the distance between the end of the riser pipe and the casting cope surface.

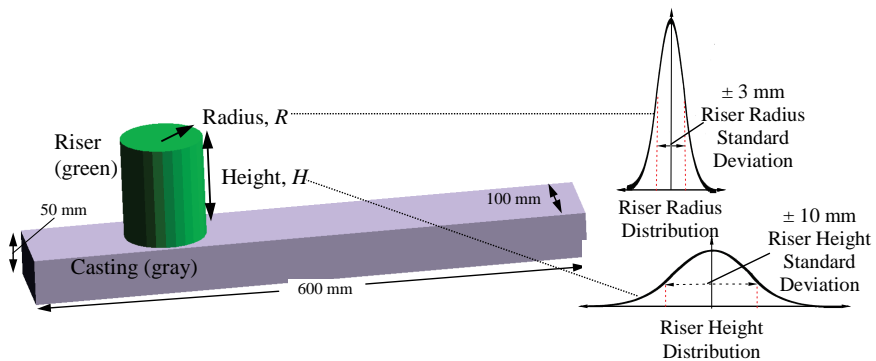


Figure 1. Casting (shown in gray) with dimensions and riser (shown in green) used in the casting feeding system design case study. Distributions for the riser radius and height assumed for the RBDO analysis are also shown.

The typical practice cases were run first to determine the shortest riser height that satisfies the margin of safety condition. Once  $R$  and  $H$  for the “Typical Practice” case were found, those dimensions were used as the starting point for the DDO analysis. For the DDO and RBDO analyses, search ranges for  $R$  and  $H$  were defined in the software as: 30 to 65 mm for  $R$ , and 60 to 190 mm for  $H$ . The DDO analysis was run first using the *I-RBDO* software and the commercial casting simulation package *MAGMAsoft* in an iterative fashion. Output from the *I-RBDO* software are the values of  $R$  and  $H$  that are to be simulated in the casting model. When the total casting porosity is determined from the casting simulation, for a given set of values of  $R$  and  $H$ , the porosity and riser volume are passed back to *I-RBDO*. Porosity and riser volume are the performance measure responses to the requested sets of variables  $R$  and  $H$ . The sequential quadratic programming algorithm was used in the optimization analysis for both the DDO and RBDO methods. The *I-RBDO* software uses normalized tolerances, and these were set to values recommended by its developers. In the DDO analyses the tolerances for the objective function and variables were set to 0.001, and the constraints to 0.05. In the RBDO analysis all tolerances were 0.05 as will be discussed below. The RBDO analysis used a sampling-based method with a dynamic kriging surrogate model.

## Casting Process Feeding System Optimization Results

In Figure 2, sections are shown through the mid-width section of the casting and riser to visualize the feeding “shrinkage pipe” for the three approaches used to design the risers. The shrinkage pipe is the gray (empty) v-shaped region in the riser that transitions through the blue (porous) region to the white (sound) region. A low carbon steel with properties from the *MAGMASoft* database was the cast metal used in these studies. This v-shaped shrinkage pipe forms as metal is drained from the riser to make up for solidification shrinkage in the casting. In Figure 2(a) the result is shown for the typical practice case with riser diameter equal to the plate width and using a 10 mm safety margin to determine the riser height. The resulting riser dimensions, riser volumes, average porosity predicted and casting yield are given for each feeding system design method in Figure 2.

A summary of results from the casting feeding system design studies for all three design methods is provided in Figure 3(a) for the riser dimensions and aspect ratios, and in Figure 3(b) for the casting yield and probability of failure results. The casting yield for the typical process safety-margin design approach is about 75% and its probability of failure was found to be 5.6%, as seen in Figure 3(b). This casting yield is relatively high for the steel foundry industry, where typical yields are in the 50% to 60% range. Because of this, the increase in casting yield for the optimized casting process is not as dramatic as it would be in applying optimization to most industrial casting feeding systems. Bearing this in mind, the optimized casting process solution

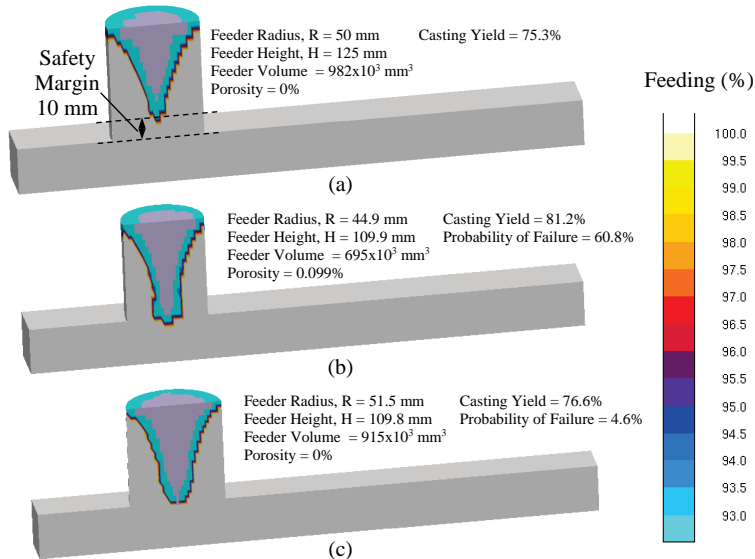


Figure 2. Mid-width sections showing riser pipes via the *MAGMASoft* feeding percentage result for (a) the case run using a 10 mm safety margin to determine the riser height with riser diameter equal to plate width, (b) the resulting riser piping and results for the DDO analysis, and (c) the results and predicted riser piping for the RBDO case.

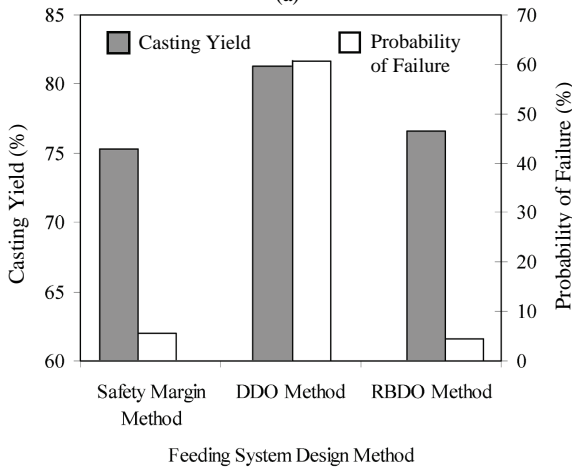
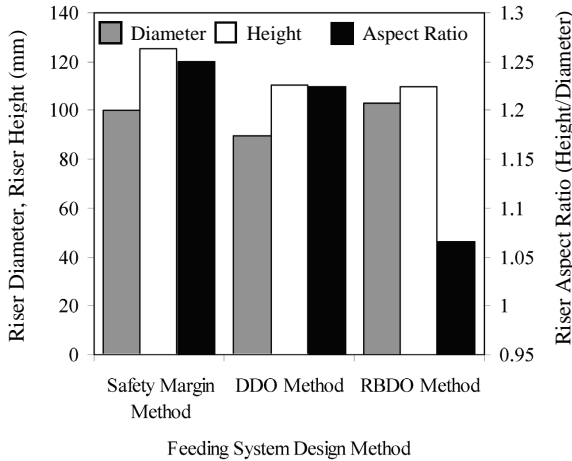


Figure 3. Summary results from casting feeding system design studies for the three design methods (a) riser dimensions and aspect ratio and (b) casting yield and probability of failure of design to meet the porosity constraint.

from the DDO method is shown in Figure 2(b) and in the summary Figure 3 by the middle bars. The DDO solution required 115 runs of the casting simulation software to determine the solution. In the DDO result, both  $R$  and  $H$  are markedly reduced from the safety margin method;  $R$  is reduced from 50 to 44.9 mm, and  $H$  is reduced from 125 to 109.9 mm. The DDO solution maximizes the casting yield shown in Figure 3(b) while keeping porosity in the casting to just

less than 0.1%. The DDO solution has an average porosity of 0.099% whereas the safety margin method had 0%. The casting yield in the DDO solution is 81.2%, about a 6% increase over the safety margin method as seen in Figure 3(b). Qualitatively speaking, the shrinkage pipe of the DDO solution feeder in Figure 2(b) appears much flatter at the bottom than the safety margin one, and it has no margin for error that it might extend down into the casting and violate the constraint. Therefore it is not surprising that the probability of failure for the DDO solution was determined to be 60.8% as shown in Figure 3(b). The RBDO solution riser pipe and results shown in Figure 2(c) required an additional 125 casting simulations. The probability of failure of the RBDO solution is only 4.6%, which is much lower than that of the DDO solution and slightly lower than that of the safety margin method. The large probability of failure for the DDO solution is not surprising. DDO solutions are typically found to have a probability of failure in the neighborhood of 50% when analyzed using the *I-RBDO* software, according to its developers. The small difference in the probability of failure between the RBDO and the safety margin case is insignificant from a practical point of view. For the RBDO solution the casting yield decreases to 76.6%, which is 4.6% less than the DDO solution, and is 1.3% higher than the safety margin solution as seen in Figure 3(b). These results indicate that the 10 mm safety margin design approach gives a reasonably safe design, but that it is less economical than the RBDO solution. Clearly from Figure 3(b), the DDO method is offering a dramatic increase in casting yield (or decrease in riser volume), but it is not feasible.

Note that in Figures 2 and 3(a) for the RBDO solution the  $H$  is nearly identical to that in the DDO solution (109.8 versus 109.9 mm for RBDO and DDO, respectively), and  $R$  is increased from 44.9 mm in the DDO solution to 51.5 mm in the RBDO solution. The uncertainty for  $H$  is much larger than that for  $R$ , and to prevent the shrinkage from piping into the casting one might wrongly think that  $H$  should be increased to be sure it is large enough to prevent this. However, foundries know from experience that the radial dimension should be increased to prevent piping into the casting. The resulting RBDO solution is seen to agree with foundry practice and achieves its solution by increasing  $R$  to a large enough value that the solution is insensitive to a large change in  $H$ .

The aspect ratio (AR) of a riser is its height divided by its diameter. For top risers used in steel casting (the type of riser examined here) the AR is recommended to be at least 1, and for side risers (with contact to the side rather than the top of a casting) as large as 1.5. If the AR exceeds 1.5 there is no benefit to the riser's feeding effectiveness arising from the additional height and the additional wasted metal in the riser is uneconomical. In addition, secondary under-riser shrinkage may form in steel casting with ARs greater than 1.5. The AR results of this study are shown in Figure 3(a). The safety-margin approach gave an AR of 1.25, the DDO result was only marginally smaller with an AR of 1.22, while the AR for the RBDO solution was 1.07. As a result from the RBDO analysis, ARs closer to 1.1 for casting feeding systems with top risers can be used and appear to be more efficient and reliable.

The sets of  $R$  and  $H$  values requested by the *I-RBDO* software in the solution process are presented in Figure 4. Here, values for  $R$  and  $H$  selected for casting simulation runs by the *I-RBDO* software are plotted for the DDO analysis in Figure 4(a), and for the RBDO analysis in Figure 4(b). Lines in Figure 4 indicate the optimal solution values for  $H$  and  $R$  found for each variable and optimization method. It is evident from the sets of  $R$  and  $H$  values in Figure 4(a) that the software performs the DDO analysis searching throughout the allowable ranges of the variables until it homes in on the solution. Note, there are many simulation runs in the neighborhood of the DDO solution, indicating the tolerances in *I-RBDO* could probably have

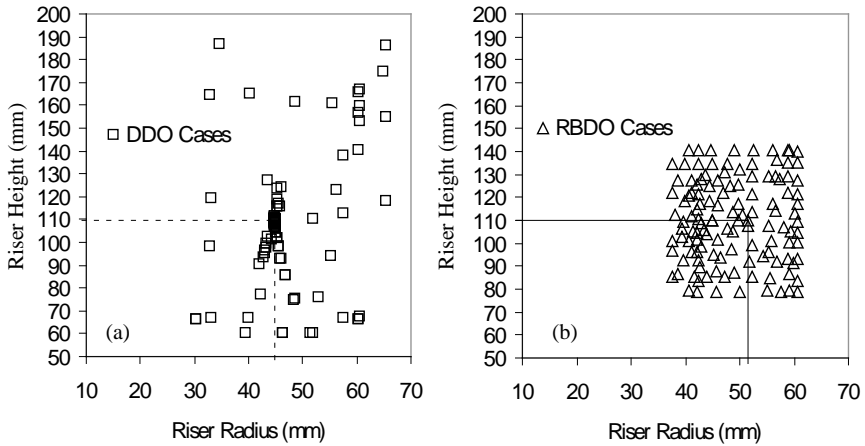


Figure 4. Values for  $R$  and  $H$  selected for casting simulation runs by the *I-RBDO* software as part of (a) the DDO analysis, and (b) the RBDO analysis. Lines indicate the optimal solutions found for each variable and optimization method.

been relaxed. For this reason, the RBDO tolerances for the objective function and variables were increased to 0.05 from the 0.001 tolerances used in the DDO analyses. This demonstrates the importance of gaining experience with the *I-RBDO* software and its parameters for a given problem in using it efficiently. In Figure 4(b) the RBDO sets of values appear to be more uniformly distributed in the search window. This is due to the construction of the surrogate model used in the reliability analysis.

### Conclusions

Application of optimization methods to casting process design provides more than just optimal solutions. It provides an overview of possible solutions, some of which might be novel and innovative. It gives foundry engineers insight into the sensitivity and stability in both the actual process, and process models, to variables and parameters. Here reliability-based design optimization and casting simulation are integrated to go a step further in the development of optimization methods by including uncertainties in process and model variables, and determining an optimal solution with a known probability of success. For a typical approach to riser design using a safety margin of 10 mm, the probability of failure was 5.6% based on assumed uncertainties in riser height and radius. This probability of failure was found to be slightly greater than that from the RBDO method, which was 4.6%. The safety margin design approach gives a reasonably safe design, but is less economical than the RBDO solution, which had a 3% casting yield improvement over the safety margin approach. It has been demonstrated that a purely deterministic optimal solution offers a remarkable 6% increase in casting yield over typical design practice, but had an unacceptable 61% probability of failure. The advantages of the RBDO method are that its output consists not only of a reliable optimum design but also of the knowledge of the confidence level in this design. An additional insight from this study is that the RBDO solution determines, on its own, the practice followed by most foundries that

increasing the radial dimension of risers, rather than the height, is the most reliable way to resize a riser that is not feeding a casting adequately.

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