

## **Casting Simulation and Optimisation: Benefits, Bottlenecks, and Best Practices**

**Dr. B. Ravi**, *Professor*

Mechanical Engineering Department

Indian Institute of Technology, Bombay, Mumbai

Phone: +91.22.2576.7510, E-mail: b.ravi@iitb.ac.in

### **ABSTRACT**

Casting simulation has become a powerful tool to visualize mould filling, solidification and cooling, and to predict the location of internal defects such as shrinkage porosity, sand inclusions, and cold shuts. It can be used for troubleshooting existing castings, and for developing new castings without shop-floor trials. This paper describes the benefits of casting simulation (both tangible and intangible), bottlenecks (technical and resource-related), and some best practices to overcome the bottlenecks. These are based on an annual survey of computer applications in foundries carried out during 2001-2006, which received feedback from about 150 casting engineers, and detailed discussions involving visits to over 100 foundries. While new developments such as automatic optimisation of method design are coming up, a national initiative must ensure that the technology is available to even small and medium foundries in remote areas.

Keywords: Casting, Computer-aided Design, Simulation, Optimisation, Defects.

### **1. INTRODUCTION**

Simulation is the process of imitating a real phenomenon using a set of mathematical equations implemented in a computer program. Metal casting, which has been compared to natural phenomena such as sea wave splashing and volcanic flow (Fig. 1), is subject to an almost infinite number of influences. A few major factors related to casting geometry, material, and process, are listed below.



*Fig.1. Metal casting is often compared to volcanic eruption and wave splashing*

**Geometry:** (i) Part features, including convex regions (external corners), concave regions (internal corners), cored holes, pockets, bosses, ribs, and various junctions (2D and 3D), all of which affect the flow and solidification of metal, (ii) layout in mould, including number of cavities, and their relative location (inter-cavity gap and cavity-to-wall gap), which affect the amount of heat absorbed by the mould, (iii) feedaids, including number, shape, size and location of insulating sleeves and covers, chills (external or internal), and padding, which affect the rate of heat transfer from the relevant portion of the mould.

**Material:** (i) Thermo-physical properties of the metal/alloy, including its density, specific heat, thermal conductivity, latent heat, volumetric contraction during solidification, coefficient of linear expansion, viscosity and surface tension, (ii) thermo-physical properties of mold, core and feedaid materials, including density, specific heat, thermal conductivity, coefficient of linear expansion, and modulus extension factor, (iii) changes in properties with composition and temperature, relevant transformations (grain shape, structure, distribution), and resultant mechanical properties.

**Process:** (i) Turbulent flow of molten metal in the mould with splashing, stream separation and rejoining, oxidation of advancing front of metal, mould erosion, gas generation and escape through venting, coupled with heat transfer leading to reduced fluidity, (ii) casting solidification with multiple modes of heat transfer (conduction, convection and radiation) involving non-uniform transient heat transfer rate from metal to mould, including latent heat liberation and moving liquid-solid boundary, (iii) solid state cooling with changes in mould shape and dimensions, leading to residual stresses and/or deformation in cast part, and different grain structures affecting the final

properties in different regions, (iv) process parameters including actual composition of metal/alloy, mould size, mould compaction, mould coating, mould temperature, pouring temperature and rate, mould cooling, shake out, etc.

It is no surprise that a complete and physically accurate simulation of metal casting process is so difficult that it is referred to as ‘rocket science for rocket scientists’. The key to developing a practically useful simulation program is to determine which are the most important factors. It is to the credit of several dedicated researchers, that they have worked for several decades to understand the phenomena, develop and fine-tune relevant equations, and implement them in computer programs [1]. Some of the well-known casting simulation programs currently available to foundry engineers are listed in Table 1. Among these, AutoCAST, MAGMASoft, ProCAST, and SOLIDCast have the largest installation base in India.

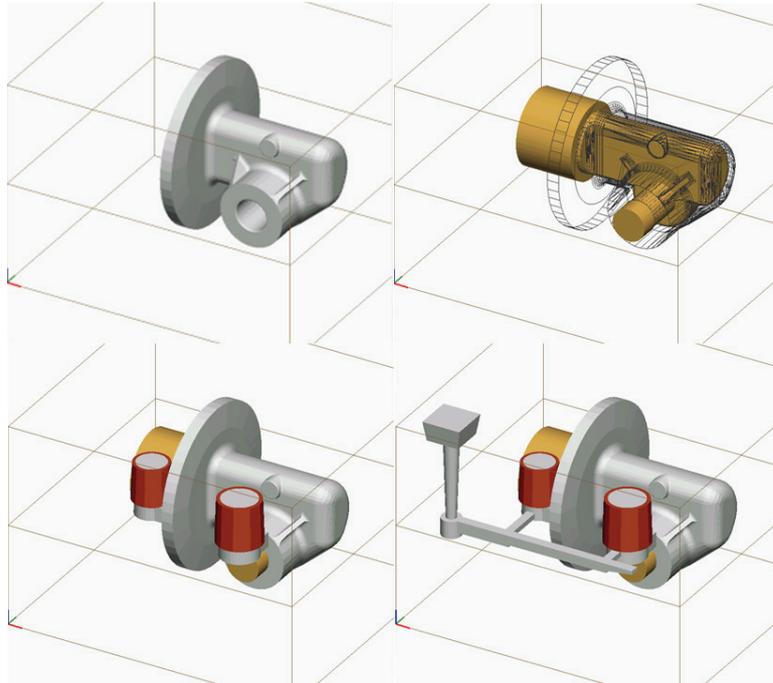
**Table 1. Casting simulation programs**

<b>Software Program</b>	<b>Company and Location</b>
AutoCAST	Advanced Reasoning Technologies P. Ltd., Mumbai
CAP/WRAFTS	EKK, Inc., Walled Lake, Michigan, USA
CastCAE	CT-Castech Inc. Oy, Espoo, Finland
Castflow, Casttherm	Walkington Engineering, Inc., Australia
JSCast	Komatsu Soft Ltd., Osaka, Japan
MAGMASoft	MAGMA GmbH, Aachen, Germany
MAVIS	Alphacast Software, Swansea, UK
Nova-Solid/Flow	Novacast AB, Ronneby, Sweden
PAM-CAST/ProCAST	ESI Group, Paris, France
RAPID/CAST	Concurrent Technologies Corp., USA
SIMTEC	RWP GmbH, Roetgen, Germany
SOLIDCast	Finite Solutions, Inc., Illinois, USA

In the following section, we will review the inputs, outputs and applications of casting simulation programs. Then we will highlight their benefits and bottlenecks faced by the majority of our foundries. This is based on the consolidated analysis of the feedback from about 150 casting engineers in annual surveys during 2001-2006. Finally, we will describe the best practices for using simulation programs, based on our interaction with over 100 foundries.

## 2. INPUTS, RESULTS, AND APPLICATIONS

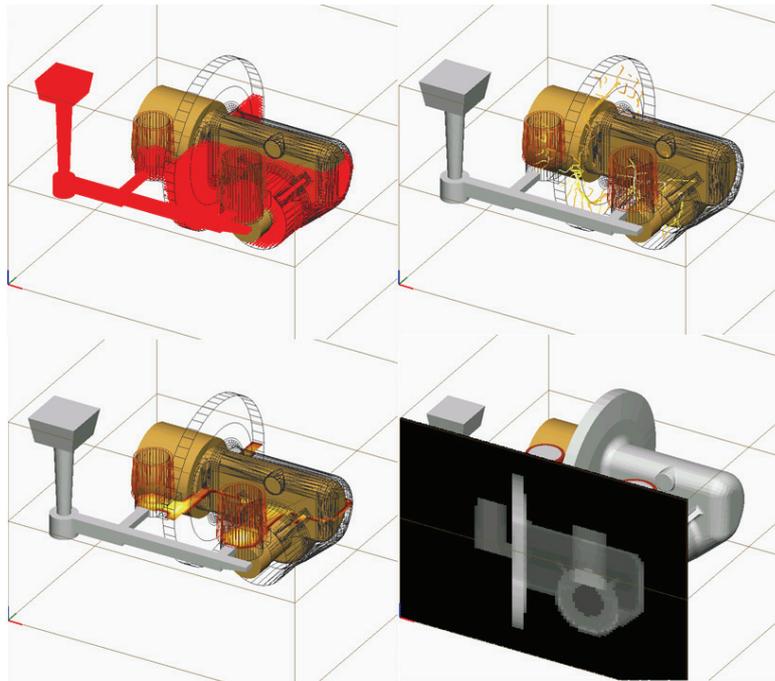
The main input to a simulation program is the 3D CAD model of the casting. The CAD model of part can be obtained from OEM customers, but it has to be modified by removing holes that are created by machining (not by cores), and adding draft and various allowances (shrinkage, machining, distortion, etc.). This is followed by the design and modeling of mould, cores, feeders, feedaids (if any), and gating system (Fig.2) [2]. Other inputs to the program include specification of materials (cast metal, mould, core, feedaids), and process parameters (type of mould, metal-mould heat transfer coefficient, pouring temperature, etc.).



*Fig.2. Part model import followed by core, feeder and gating design (Courtesy: AutoCAST)*

The main outputs of simulation programs include animated visualisation of mould filling, casting solidification, and further cooling to room temperature (Fig. 3). Mould filling simulation helps in predicting the total filling time, mould erosion (leading to sand inclusions), incomplete filling (cold shuts and misruns), and air entrapment. Blow holes caused by entrapment of gases (dissolved and from combustion) owing to poor venting are still difficult to predict. Casting solidification simulation shows the temperatures, gradients and cooling rates inside the casting, which are used for predicting the location

of shrinkage porosity based on Niyama and other criteria. Further cooling to room temperature can also be simulated, which is useful for predicting microstructure, mechanical properties, residual stresses, and distortion. Multi-physics simulation involving simultaneous solution of equations for mould filling, solidification, and stresses is now becoming possible. This is required mainly for thin walled parts produced in metal moulds (ex. high pressure die casting).



*Fig.3. Visualisation of filling, feedpaths, cooling, and radiography (Courtesy: AutoCAST)*

It is important to realize that simulation only predicts the effect of a given method design on casting quality and yield. It can provide a better insight than actual trials, since we can ‘look through’ the virtual mould. However, it can not improve the method by itself. The results must be interpreted by an experienced method engineer, who has to decide the modification to the method and carry out the iterations until satisfactory results are obtained. In other words, a casting simulation program can greatly enhance the productivity and success of a method engineer, but can not replace him.

There are three main applications of casting simulation programs, briefly described here.

**Casting Troubleshooting:** This is needed for existing castings that have unusually high or unexpectedly varying level of internal defects (mainly shrinkage porosity, sand inclusions,

cold shuts, etc.), or are suspected to have poor yield. The exact method used in foundry for producing the casting is modeled and simulated on computer. The simulated and actual location of defects are compared to see how well they match, and calibrate the program parameters, if necessary. The cause of the defects becomes very clear: for example, an inadequate size or location of feeder or gate. Often, simulation reveals defects at locations that have not been carefully inspected in practice. The reverse: too many or oversize feeders leading to poor yield also becomes apparent with simulation.

Method optimization: This is useful for both existing castings, and those under development for the first time, by eliminating shop-floor trials (Fig.4). The method design (casting orientation, mould layout, feeders, feedaids, and gating) is modified on computer, and simulated to check for defects, if any. Several iterations are carried out until the desired quality and yield are achieved. Even minor improvements in existing castings that are produced in large numbers, can lead to significant improvements in utilization of material, energy, equipment and labour resources. Simulation is also critical for large heavy castings under development, since their cost of trials or repair is prohibitive. A few programs have incorporated algorithms for automatic (user-guided) optimization of feeders and gating channels [3].

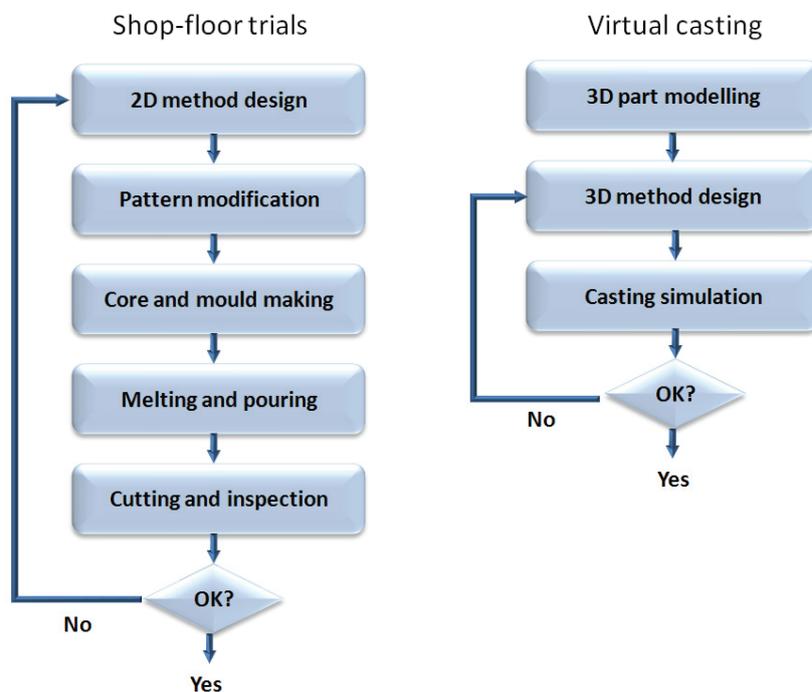


Fig.4. Comparison of manual and computer-aided method optimization

Part design improvement: This is driven by the realization that the part design usually ‘decides the fate’ of a casting to a large extent. Casting simulation of a part at an early stage in product design can point out features prone to defects. For example, excessive thick junctions and long thin sections will be prone to shrinkage porosity and cold shuts, respectively. These can be modified to prevent expensive remedial measures at the foundry stage, such as additional feeders (lower yield) and padding (additional machining) for the above two problems. Minor changes to part design can significantly improve its manufacturability without affecting its functionality. But these decisions can be taken only by the part designer, in consultation with the foundry, assisted by simulation programs.

### 3. BENEFITS OF CASTING SIMULATION

The benefits as well as bottlenecks in various computer programs for foundry applications are shown in Fig. 5. Both tangible and intangible benefits are described below. Tangible benefits mainly lead to cost reduction, and intangible benefits lead to value addition.

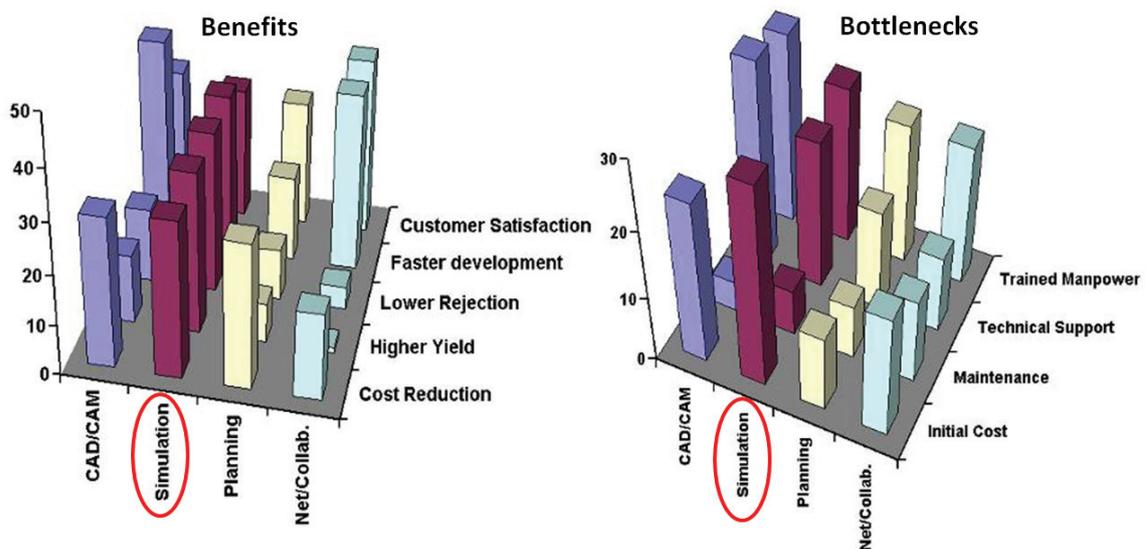


Fig.5. Survey of computer applications, benefits and bottlenecks in Indian foundries

Improved quality and/or yield: Simulation and method optimization of castings already in regular production leads to improvement in their quality, or yield, sometimes both. Every casting, by virtue of its geometry, material and process, has an optimal method. The method of most castings is incorrectly designed, under-designed, or over-designed. This can be clearly visualized by simulation, and verified by matching the simulated and actual observations. Often, only minor changes to the method are required: such as placing a

insulating sleeve on a feeder, or a chill at a suitable location. Even a small improvement in yield can give significant saving of resources, or higher productivity (more saleable castings from the same resources) over a period. The cost of poor quality (machining, transportation, repair, replacement) is becoming substantial, which can be considerably reduced by simulation and optimization.

Reduced shop-floor trials: Shop-floor trials for developing a new casting not only add to its cost, but also divert resources from regular production of other castings. The cost of a shop-floor trial includes tooling modification, melting, pouring, fettling, inspection, and some loss of materials (which can not be recycled). In the case of large ferrous castings the melting cost is higher, where as for complex-shaped non-ferrous castings produced in metal dies the tooling modification cost is higher. In either case, virtual casting trials on a computer are less expensive and faster, implying that more trials can be carried out to achieve better quality and yield. At the end, only a single foundry trial is required to verify the method design and simulated results.

Value addition: Simulation programs enhance the level of confidence in a foundry for taking up more difficult castings (complex, large), which typically command a higher margin. They also provide a scientific and documented basis for quality assurance and certification. For example, simulation can point out all probable locations of internal defects, which can be more carefully observed by sectioning or NDT methods. Indeed many overseas customers prefer to do business with foundries equipped with or having access to casting simulation facility. Thus simulation programs become a valuable aid to marketing the capabilities of a foundry, leading to more and higher value orders.

Knowledge management: This is an important, but less appreciated benefit of casting simulation. Since the computer automatically stores all inputs and results of each virtual trial, it can be readily recalled months or years later, and reused for new projects similar to a previous one. The project reports and presentations can also be used to train new engineers. Finally, the use of CAD and simulation tools in a foundry makes it more attractive for hiring and retaining younger engineers.

#### **4. BOTTLENECKS IN CASTING SIMULATION**

Our survey showed that most foundry engineers are fairly aware of the tangible benefits of casting simulation. However, the actual use of simulation programs within the surveyed

group was less than 30%, compared to nearly 100% use of Internet, and over 75% use of CAD/CAM. The overall penetration of casting simulation in Indian foundries is estimated to be less than 5%, which is very low compared to an estimated 90% in German foundries, and 75% in American foundries. This is owing to technical as well as resource-related factors, described here.

Cost of implementation and operation: Most simulation programs are in the range of Rs. 2-5 million. Some as available as annual lease (typically 25-35% of full cost), but even this is prohibitive for most SME foundries. The programs require high-end computer hardware. Training and database customization can take several weeks before the software can be used on a regular basis by foundry's own engineers. The software has to be upgraded annually, which typically costs 20-30% of the cost of the original license.

Technical manpower and support: Most simulation programs require qualified technical manpower to ensure proper execution (inputs and outputs), interpretation (for method design modification and quality assurance), and maintenance (database customizing, annual upgradation, etc.). A good knowledge of CAD and FEM (Finite Element Method), coupled with previous experience in methoding a variety of castings is required. The simulation engineer should also be able to effectively communicate with the technical support team of the software provider for troubleshooting and ensuring proper running of the software program.

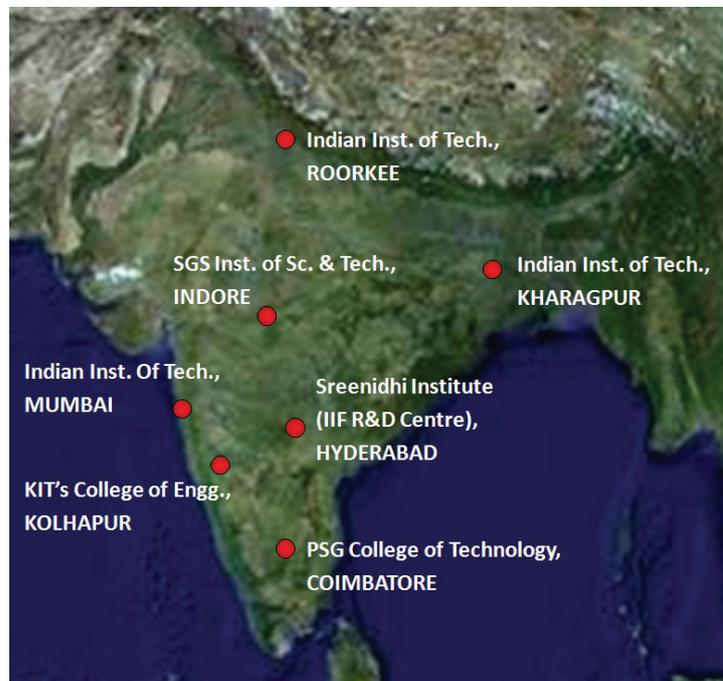
Solid modeling: A 3D CAD model of the as-cast part, the most important input to any casting simulation program, has to be created using a solid modeling program. The foundry can request its OEM customer to send the original part CAD model, which can be modified by the foundry to derive the as-cast part model as described earlier. However, most OEM firms are reluctant to send their original CAD models to foundries owing to security reasons, and the foundries are forced to model the parts again from 2D drawings. If the foundry does not have its own solid modeling program, they can get the model done from a local CAD service firm. This is fast (1-2 hours) and inexpensive for simple parts, but for large and complex parts, it can take several weeks and cost several thousand rupees. Still, a solid modeler is required for creating feeders, feedaids, gating system, etc., and the user has to switch between the solid modeling program and simulation program for each iteration.

## 5. BEST PRACTICES

Here we describe a few best practices to overcome the above bottlenecks and get the best out of simulation programs.

Acquiring a simulation software: Most of the ‘unknowns’ and ‘surprises’ in a simulation software can be countered by insisting on a live demonstration involving a casting of the foundry with internal quality problems, and comparing the simulated and actual results. The live demonstration provides a fairly good idea of the inputs, outputs, user interface, hardware required, time taken, and various skills required. Even a paid benchmarking exercise is well justified.

Cooperative Simulation Centres: Two or more foundries can get together and share the cost of acquiring a simulation software, hiring suitable technical manpower, and maintaining the facility. The foundry clusters coming up in different parts of the country are already planning such common facilities for simulation and other resources. Another approach is to set up such facilities in engineering colleges, which can also provide solid modeling, consultancy, training, technical support, and manpower to local foundries (Fig.6).



*Fig.6. Several engineering colleges have set up casting simulation facilities*

Casting simulation services: Most vendors of casting simulation software, as well as some CAD/CAM consultants are now providing casting simulation services. Foundry engineers can sit with simulation consultants and guide them to select or modify the method (feeders, feedaids and gating system design) until satisfactory results are obtained. Foundries do not have to worry about maintaining expensive software, or attracting and retaining high level technical manpower. Security concerns can be handled by insisting that all the relevant files are deleted after the method has been optimized and the results copied to portable media (CD or flash drive), which is handed over to the foundry.

Solid modeling: The problem of part solid modeling can be handled by asking the OEM customers to send an 'STL' file of the part, which is an approximate model and cannot be modified (thus addressing the security concerns), but good enough for casting simulation and method optimization. If this is not possible, then the part can be modeled by a local CAD/CAM consulting firm. It is important to check that the values of volume and critical thickness in CAD model match those of actual casting. The foundry should still have an easy-to-use solid modeling program to create the shapes of feeders, feedaids and gating channels, since it is very time consuming to go to a CAD firm for every method layout.

## **6. CONCLUSION**

Casting simulation technology has sufficiently matured and has become an essential tool for casting defect troubleshooting and method optimization. It enables quality assurance and high yield without shop-floor trials, and considerably reduces the lead-time for the first good sample casting. Productivity is improved, higher value castings can be taken up, and internal knowledge can be preserved for future use and training new engineers. However, the high cost of simulation programs, coupled with the need for attracting and retaining qualified engineers, has prevented their widespread use in our foundries. This can be initially overcome by using the simulation services offered by software vendors and consultants, and by setting up cooperative simulation centres by foundry clusters. A proper benchmarking of simulation programs by live demonstration can prevent many unpleasant surprises later. The programs are gradually become more powerful, by including method design suggestions, automatic modeling of feeders and gating system, and user-guided optimization for achieving the desired quality at the highest yield. In near future, we will be able to get the castings right first time, every time, in real time.

## REFERENCES

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