

Casting Simulation – Best Practices

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Abstract

Guidelines for effective implementation and the best practices for efficient use of casting simulation technology are presented here. These are based on a comprehensive review of about 200 industrial projects carried out by simulation consultants associated with IIT Bombay. The projects are of two types: (a) quality or yield improvement of existing castings, and (b) rapid development of new castings. The guidelines cover all major metals and processes, and deal with five stages of simulation projects: data gathering, methods design, numerical simulation, methods optimization, and project closure. Major concerns: how to obtain accurate results, reduce total lead time, and ensure data security are addressed, and illustrated with industrial examples. This compilation is expected to be useful to consultants taking up such projects, as well as to foundries already using or planning to use casting simulation technology.

Key Words: *Casting, computer-aided design, methods, simulation, optimisation, quality, yield.*

1. Introduction

Once considered a luxury, computer-aided design and simulation of castings is becoming an integral part of foundry operations, necessary to achieve consistently high quality castings with optimal yield¹. New and expanding foundries are planning casting simulation as an essential facility like melting and moulding units. Others are outsourcing this task to either simulation centres or to independent consultants. A recent survey of 215 foundries all over India² revealed that use of CAD/CAM and simulation reduced the average lead time for first good sample casting by 30%: from 10 weeks to 7 weeks, and halved the average rejection rate: from 8.6% to 4.1%. Other reported benefits included higher yield, cost reduction and customer satisfaction (*Fig. 1*).

Casting simulation can, however, be an agonizing experience for novices. The programme may not accept the user inputs, other data may not be comprehensible or available, the computer can hang up or take a very long time to produce the results, and the results may not match shop floor observations. Even regular consultants sometimes experience such problems. A poor knowledge of solidification physics and inadequate training in simulation technology becomes a handicap in

successful utilization of simulation technology. Thus a foundry setting up a simulation facility may end up only showcasing it to visitors. This sets a poor example for others, who delay their learning curve of exploring this important tool. As the simulation programmes get more sophisticated every year, it becomes even more difficult to adopt and adapt the technology in their foundries.

In this paper, we present guidelines and the best practices for effective implementation and efficient utilization of casting simulation technology. This is based on our experience of guiding over 50 foundries in implementing casting simulation, and supervising over 200 casting simulation projects for others (*Fig. 2*). Another rich source of knowledge is from interactions with 1200 senior and middle-level foundry engineers who attended our professional course on 'casting design and simulation' every September since 2000, and ten casting simulation clinics conducted all over India during 2008-2009³.

We first outline situations which necessitate simulation (not all castings need to be simulated). Then guidelines for establishing a casting simulation facility are presented. The simulation protocol (step-by-step procedure) is described next, highlighting all important inputs required along the way. Best practices for obtaining accurate

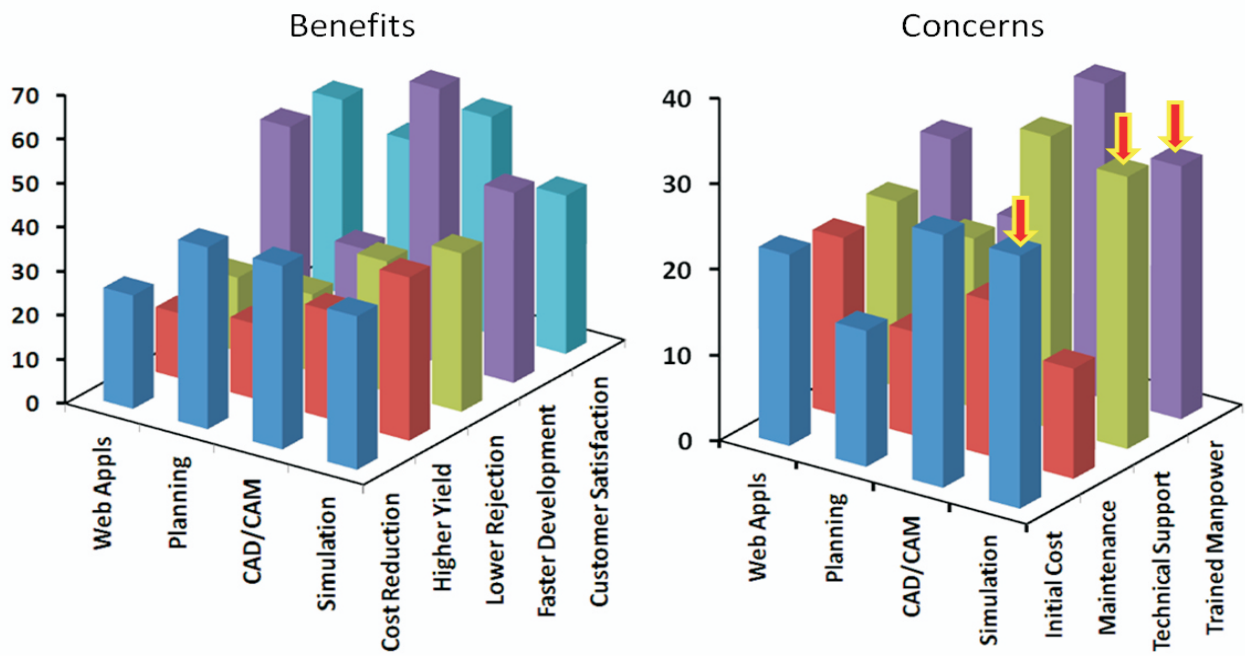


Fig. 1 : Benefits and concerns of IT applications in Indian Foundry Industry

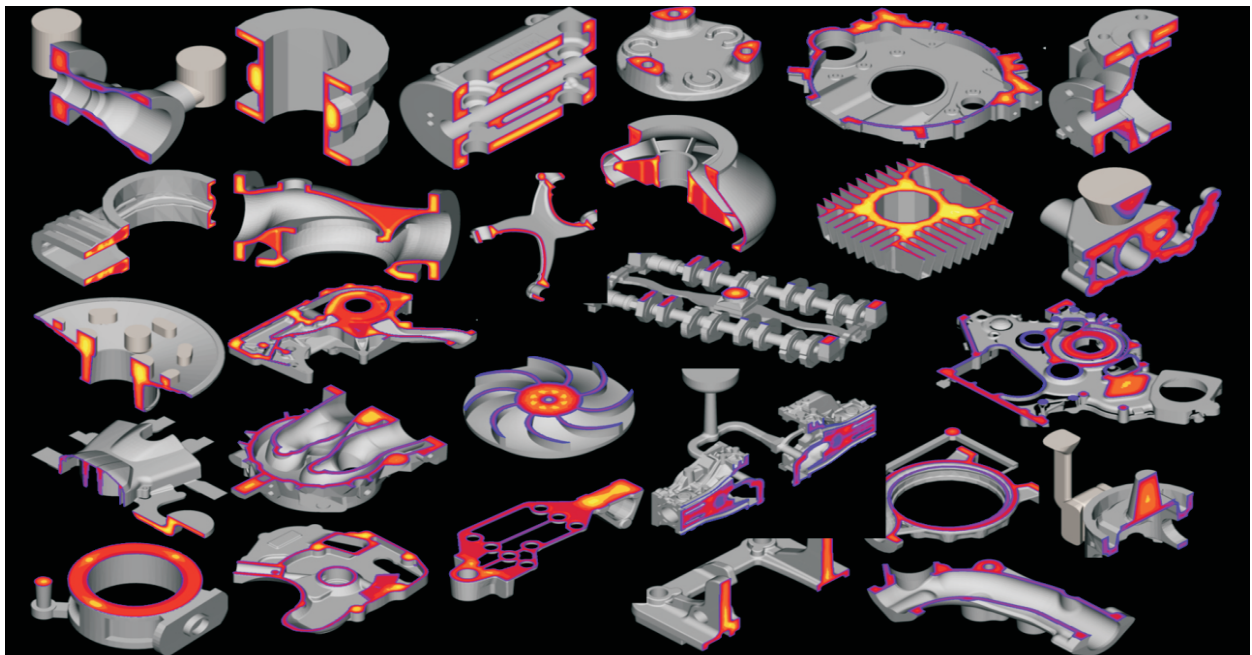


Fig. 2 : Some of the casting simulation projects (left to right : Steel, SGI, CI, and Aluminium)

results, minimizing the total lead time, We first outline situations which necessitate simulation (not all castings need to be simulated). Then guidelines for establishing a casting simulation facility are presented. The simulation protocol (step-by-step procedure) is described next, highlighting all important inputs required along the way. Best practices for obtaining accurate results, minimizing the total lead time, and ensuring data security are presented. We conclude with future developments in this area, and how foundries can prepare themselves to benefit from the same. Although most of our experience is with AutoCAST, the casting methods design and simulation software developed at IIT Bombay, the guidelines have been generalized to cover all simulation programmes, metals, processes, casting shapes and sizes.

2. When is the Simulation Necessary?

Casting simulation should be used when it can be economically justified for at least one of the following three reasons:

- **Quality enhancement** by predicting and eliminating internal defects like porosity
- **Yield improvement** by reducing the volume of feeders and gating channels per casting
- **Rapid development** of a new casting by reducing the number of foundry trials

The corresponding cost benefits can be estimated.

- **Quality improvement** reduces the (avoidable) costs associated with producing defective castings, including their transport, and warranty or penalties.
- **Yield improvement** reduces the effective melting cost per casting, and increases the net production capacity of the foundry (without adding melting or moulding units).
- **Faster development** of castings through virtual trials eliminates the wastage of production resources, and improves the rate of conversion from enquiries to orders, giving foundries an opportunity to select higher value orders.

Not all defects can be accurately simulated. Solidification shrinkage defects (macro, micro and centerline shrinkage) can be predicted fairly accurately. Flow-related defects (cold shuts and blow holes) can be simulated

but may not always match actual observations. Cooling stress related defects (cracks), micro-structure and mechanical properties are difficult to simulate, and extensive calibration experiments may be needed for practical use.

From the above it is clear that it is advisable to start with solidification simulation, which requires relatively less inputs, gives fairly reliable results, has a high impact on quality (shrinkage accounts for nearly half of all defects) as well as yield (feeder size optimization), and thus gives a high benefit to cost ratio.

There are at least three other secondary (long term) benefits, which accrue after using simulation for some time (few months to years). The corresponding cost benefits are relatively more difficult to estimate, and these reasons are not normally used for justifying setting up a simulation facility.

- Manufacturability improvement by part re-design in consultation with OEM
- Methods knowledge management by re-using simulation projects
- Brand image enhancement by using the simulation facility as a marketing tool

High capacity foundries (over 5,000 tonnes/year) with a large number of jobbing orders (more than 100 per year) require in-house casting simulation facilities, preferably one for each foundry unit (*Fig. 3*). Two or more medium capacity foundries, who have fewer jobbing orders, can share common facilities. Small foundries with less than ten new projects per year should set up co-operative

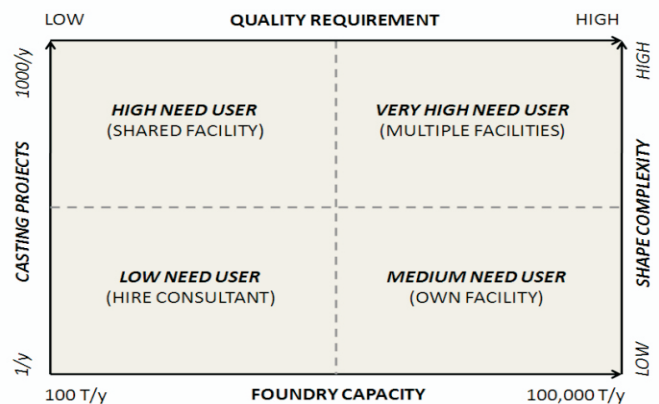


Fig. 3 : Types of casting simulation users based on various factors

simulation centres in their cluster, or approach casting simulation consultants.

New, large and complex-shape castings in aluminium, steel and SG iron for demanding applications (such as automobile, machine tool, aerospace, and medical) usually have a higher rate of rejections and penalties. Even SME foundries producing such castings should consider having their own simulation facility.

3. Setting up a Simulation Facility

Three types of resources are required for setting up a casting simulation facility: hardware, software, and ‘human-ware’. The choice of the hardware depends on the software. The choice of the software depends on the requirements of the foundry (discussed above) and personnel available for running the software. This is best ascertained by a benchmark project.

The benchmark should be an older casting with a known history of problems (internal defects). The software should be used to exactly model various methods layouts attempted in the foundry, and the simulated result compared with the known location of defects. The software should be able to correctly predict all major defects. False positives (simulated defect not observed in actual casting) may be acceptable, but there should be no false negatives (simulation did not catch an observed defect). The simulation should be carried out in front of the methods engineer who would be running the software later, so he

can evaluate the user interface, various inputs required by the programme, and the time and skill involved.

The most popular casting simulation programmes available in India include: AutoCAST-X, MAGMA, ProCAST and SolidCAST. Some of these are available on hire (monthly, quarterly or annually), which is useful for benchmarking. Major modules of a typical casting simulation software are shown in Fig.4 (not all modules are available in all programmes).

The programmes employ different methods for casting simulation are shown in Fig.5 :

- (i) Finite Difference Method (ex. SolidCAST),
- (ii) Finite Volume Method (ex. MAGMASoft),
- (iii) Finite Element Method (ex. ProCAST), and
- (iv) Vector Element Method (ex. AutoCAST).

While the underlying physics is the same, they differ in terms of the discretisation (division) of space and time continuum, handling of various material properties (ex. latent heat), boundary conditions (metal-mould interfacial heat transfer coefficient), and the numerical technique employed.

The FDM and FVM use cubic or brick-shaped elements, FEM uses tetragonal or hexagonal elements, and VEM uses a combination of cubic and pyramidal elements. The FEM can model the casting shape more accurately (using fewer elements), but may require manual effort to

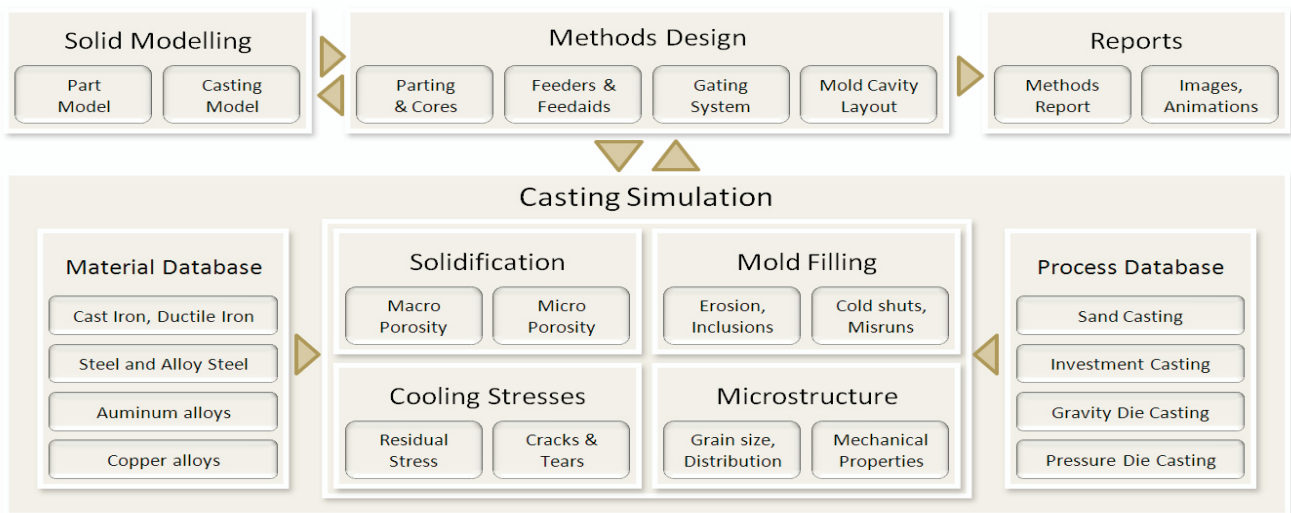


Fig. 4 : Different modules in Casting Simulation System

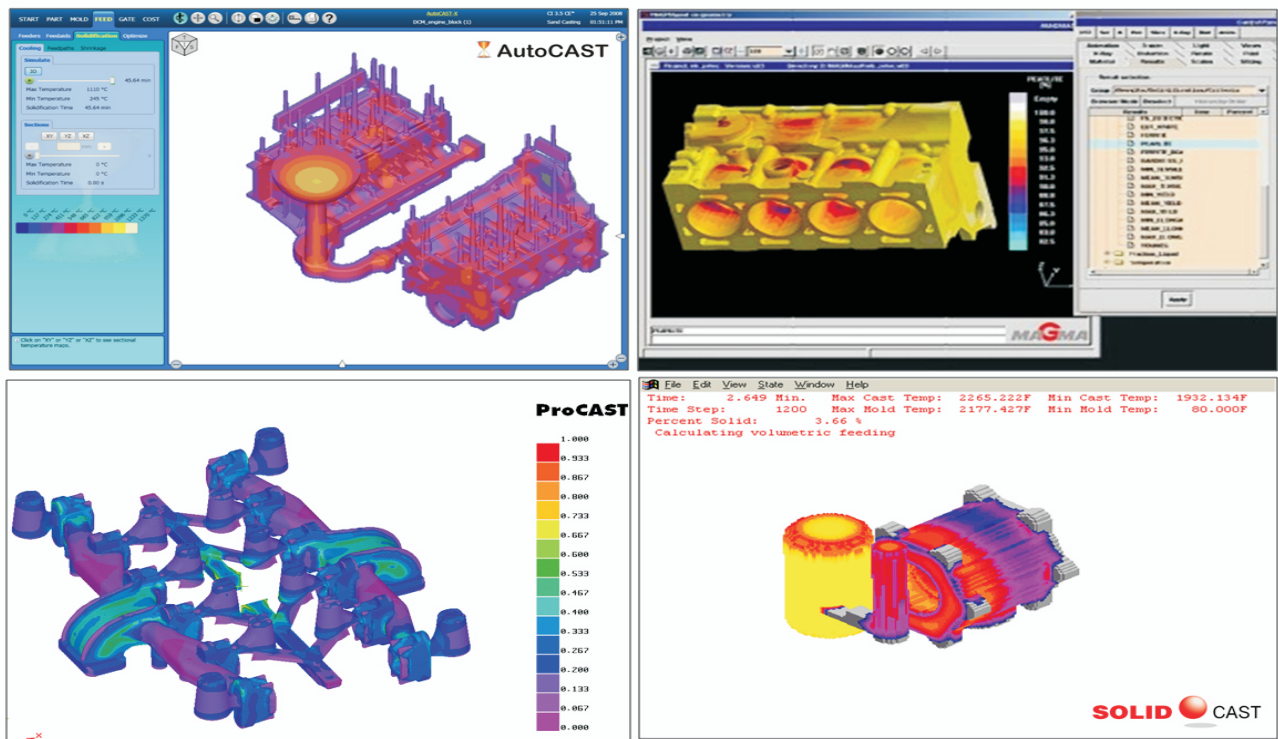


Fig. 5 : User interface of popular casting simulation programmes (AutoCAST, MAGMA, ProCAST and SolidCAST)

correctly generate the element mesh, which can sometimes take more time than the computation itself.

A separate 3D CAD programme is needed for solid modeling of as-cast parts, the main input for simulation programmes. Popular CAD programmes include AutoCAD, CATIA, I-DEAS, Pro-Engineer, SolidWorks, SolidEdge, and UG-NX. Most of them offer similar features, and their prices have reduced owing to a large market and fierce competition. The main difference remains in terms of user interface. Since solid modeling can take a lot of time, especially for complex-shape castings, it is best to acquire one which has an intuitive user interface, and familiar to the tool designer working in the foundry. Solid models can also be requested from the OEM customer, or outsourced from a local CAD/CAM agency, reducing the load on the foundry designer.

Computer hardware power has significantly increased over the last few years. Today, notebook computers are faster than desktop computers available 10 years back. Still, coupled simulation (flow + solidification + stress), especially for complex shape castings with thin walls using a fine mesh can take 40-80 hours. Multi-CPU computers with 4 GB or more RAM can reduce the

computation time, if the software is designed for parallel computation and addressing larger memory. A large display monitor (19" or more) is useful for better visualization and discussions with team members.

A frequently asked question is: "How to select a Simulation Engineer for a foundry?". The following qualifications are required in increasing order: computer skills, knowledge of solidification physics, and methods experience. Computer skills are the easiest to develop within a few days. Solidification physics can be learnt by reading and continuing education over a few weeks. Methods experience, however, takes years to accumulate. Hence senior methods engineers having a scientific attitude and basic computer skills make the best simulation experts. Ideally, at least 2-3 persons should be trained in simulation, including a senior methods engineer and a younger tool or CAD engineer.

4. Simulation Protocol (Flow Chart)

There are five distinct stages in casting simulation projects: data gathering, methods design, numerical simulation, methods optimization, and project conclusion (Fig. 6). Keys tasks and basic guidelines for each stage are described here.

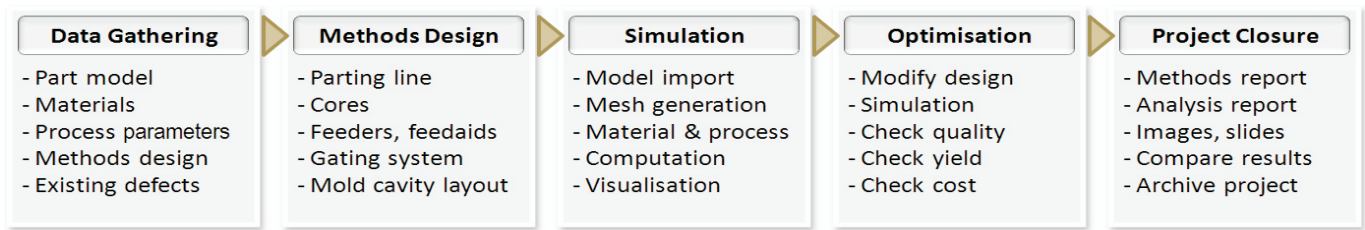


Fig. 6 : Major stages in Casting Simulation and Optimization

Data gathering: This is the most important stage, since incorrect or incomplete data will lead to inaccurate simulation and wrong conclusions. The problem must be defined first, to ascertain the need and type of simulation. Here we focus on two types of projects: (a) quality or yield improvement of an existing casting, and (b) rapid development of a new casting. The following inputs are required *before* simulation:

- **CAD model of casting:** It should be a 3D solid (not surface) model of the *as-cast* part. The model must be saved in an exchange standard like STL, which can be either in ASCII (text) or Binary format. The former is easy to verify manually, by opening it in a text editor.
- **Cast metal properties:** These include: density, thermal conductivity, specific heat, latent heat, volumetric shrinkage, viscosity and surface tension of cast metal, as a function of temperature. Properties of all major alloys are usually available in the programme database.
- **Mould property and process parameters:** Temperature-dependent values of density, thermal conductivity, and specific heat of mould materials (including cores, chills and insulation); and process parameters like pouring time and temperature are needed.
- **Methods design data:** For quality assurance or yield improvement of an existing casting, the methods design used in the foundry is required. This includes details about mould parting, cores, feeders, gating system, cavity layout, and feed-aids. Photographs of the full casting and cut sections or radiographs showing internal defects should be collected. In the case of new casting development, the suggested methods design may be provided as a starting point.

Methods design and modelling: In this stage, the methods design is solid modeled to convert the *as-cast* part model into a 3D model of the mould containing part cavities as well as feeders, gating channels, cores and feed-aids. If the methods design is not available, then the simulation engineer has to first design the above elements based on his experience and foundry practice. This requires both methods knowledge as well as CAD skills. Also, after each round of simulation, the methods design has to be modified based on the results, and the solid model of the mould has to be created again. In most of the simulation programmes available today, there is no provision of methods design or solid modeling of mould elements.

Some have provision for solid modeling of simple shapes of feeders and gating channels. The AutoCAST programme includes both methods design and solid modeling of mould elements, saving considerable time and effort required by simulation engineers, and reducing the possibility of related errors.

Numerical simulation: This is the main stage in casting simulation, wherein some more critical inputs are required from the user. The first is the correct generation of FEM mesh. The element size must be optimal, and the mesh must cover the entire model without gaps. The second set of inputs involves factors for various boundary conditions, like the interfacial heat transfer coefficients. There are mainly three types of interfaces: metal-mould, mould-environment, and metal-environment (ex. open riser). Since the heat transfer can be by a combination of conduction, convection and radiation, each with their own constitutive equations, most simulation programmes combine them in equivalent forms, and use an overall heat transfer coefficient.

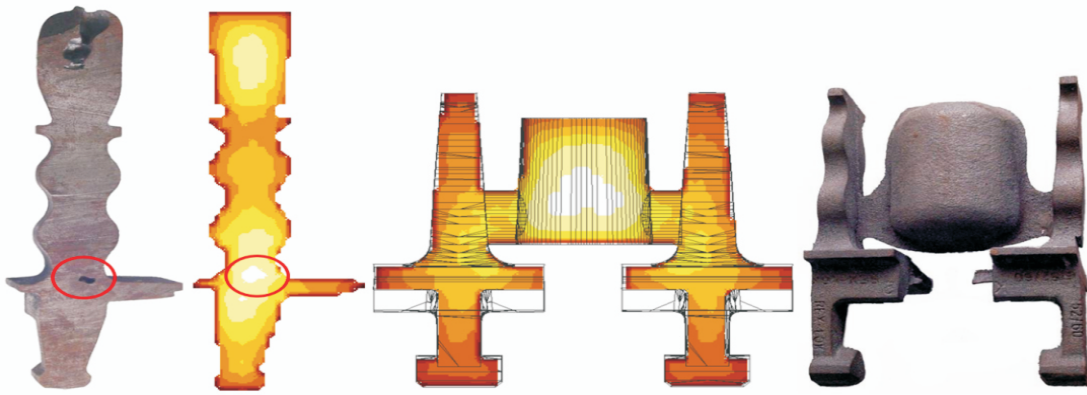


Fig. 7 : Quality and yield improvement of a ductile iron casting produced by Disamatic process

The simulation run depends on the functional module: solidification only, mould filling only, coupled filling + solidification, solidification + cooling + stress, etc, for the specific metal and process. A separate post-processing module converts the data into colour-coded values for visualization of results. Temperatures are usually coded as yellow-red for high values and blue for low values. This makes it easy for the user to interpret the results to identify defects, for example hot spots and cold shuts.

Methods optimization: This stage involves improving the methods design to eliminate defects and improve yield (*Fig. 7*). For existing castings, the simulation results are first compared with observed defects to ascertain the cause of defects (undersize feeder, oversize neck, incorrect gate, small cavity gap, etc.). Then the methods design (feeders and gating) is modified, solid modeled, imported into the simulation programme, and after necessary pre-processing, the casting is simulated again. In extreme cases, even part design may need to be changed (ex. padding) to eliminate the defects completely. Part, tooling and methods engineers can collaboratively discuss and design the casting using web-based video conferencing, saving travel time and cost.

Project closure: After finalizing the methods design, all relevant results need to be properly documented and archived. This includes generating a methods report, analysis report, images of major steps and results. A slide presentation or animation can be created for explaining to others. All input and output data, as well as the various reports are stored in a designated folder and backed up. They are communicated to the team members

for implementation. Follow-up studies include checking if the recommended methods design was implemented on the shop floor, and comparing the results of predicted and actual results. Any discrepancies must be noted in the project file for future reference and corrective action (ex. customisation of database).

5. Getting Reliable Results

Computers are characterized as GIGO: garbage in, garbage out. Colourful pictures produced by simulation can be misleading, if the inputs were incorrect. Best practices to ensure a close match between simulated results and actual casting are listed here.

- As-cast part model should be imported for simulation (*Fig. 8*). Machined part models (especially with drilled holes) will give wrong results. They need to be converted to as-cast models by filling machined features, and adding various allowances: shrinkage, machining, draft.
- The as-cast part model should be represented by a fine faceted water-tight surface. When part model file is exported in STL format, curved surfaces are approximated with a triangulated mesh. Coarse triangulation truncates and reduces the casting volume. An extremely fine triangulation can produce degenerate triangles (two edges merging with each other), later leading to errors in FEM mesh generation.
- Optimal element size should be used for mesh generation in FEM-based simulation programmes. Large elements may lead to instable computation and inaccurate results. The element size should be less than 50% of the minimum wall thickness. Also,

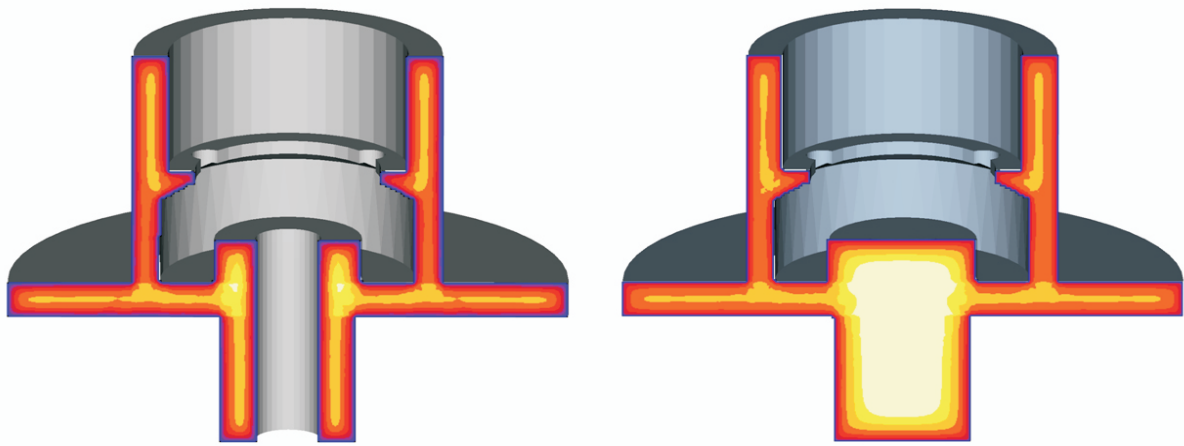


Fig. 8 : Results of casting simulation with and without drilled holes can be quite different

castings with large temperature gradients need to have a smaller mesh size for reliable results. If the casting model contains errors (such as missing faces and dangling edges), the FEM mesh cannot be generated automatically, and the errors or the mesh need to be fixed manually. Some programmes (including AutoCAST) use intelligent algorithms to fix the mesh errors automatically.

- The interfacial heat transfer coefficient is the most important source of error in FEM-based simulation programmes. Its value changes depending on the cast and mould materials (including feed-aids and coatings), instant of time (from the beginning to end of solidification and beyond), shape of casting (internal versus external corners), location (top versus side versus bottom surfaces), and process (ex. mould heating, tilt pouring, etc.). The VEM-based simulation is less sensitive to inaccurate values of interfacial heat transfer coefficient.
- Thin wall castings produced in metal moulds should be simulated using coupled filling + solidification programmes for predicting flow-related defects like cold shuts and misruns. Separate simulation of mould filling and casting solidification is much faster, but recommended only when solidification time is more than twice the filling time, as in the case of thick wall castings filled under gravity. Some programmes like AutoCAST use the results of filling simulation to

automatically modify the initial conditions of solidification simulation, giving fairly accurate results with the advantage of much faster computation than coupled simulation.

- Some elements in alloy composition can have a significant effect on casting flow and solidification characteristics. However, merely changing the alloy composition will not simulate its effect, unless the corresponding values of thermo-physical properties are also provided. This is not easy, since they need to be experimentally determined as a function of temperature. Their effect can be reverse engineered by comprehensive benchmarking (comparing simulated and observed results).
- Simulation engineers often try to eliminate every single micro-porosity by providing bigger or additional feeders and feed-aids. This is not necessary if the quality requirements are not stringent, or if the defective region is later machined with sufficient allowance.
- Finally, one must not jump to hasty conclusions if the simulated and observed results do not match. In most of such cases, what was simulated is not the same as what was produced. Even minor alterations in methods design implemented on the shop floor (for example, neck size, gate position or pouring temperature) can significantly alter the results.

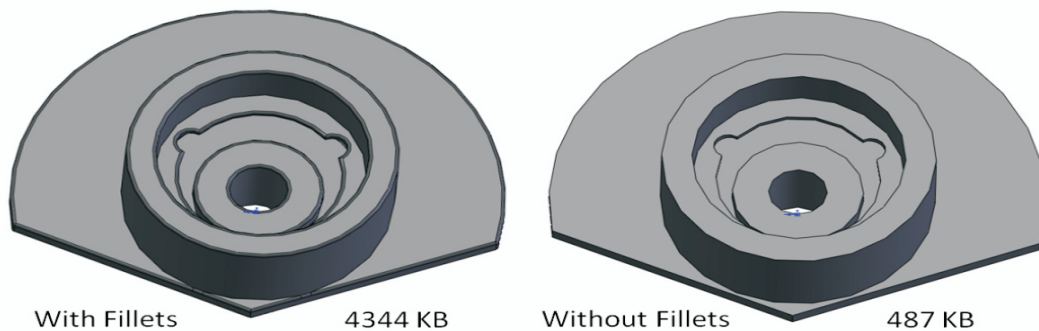


Fig. 9 : Removal of small fillets can significantly reduce the model file size by 50-90%

6. Reducing the Lead Time

Foundries using a FEM-based simulation programme often complain that it takes more time than shop-floor trials. This defeats one of the key reasons for using simulation. AutoCAST reduces the total cycle time to less than one hour by using VEM and by automating and integrating various steps. Best practices for reducing the total lead time for simulation using either FEM – or VEM-based software, without loss of accuracy of results, are presented here.

- The size of part model file (in megabytes), not its physical size (in mm), affects the computation time for mesh generation and simulation. More number of features (holes, pockets, bosses, ribs, etc.) and curved surfaces increase the model file size. Since each curved surface is approximated by a number of triangles, even a small fillet can lead to a large increase in the file size (*Fig. 9*). Hence small fillets (with radius less than 20% of the local wall thickness), and tiny features (like engraved company name) can be safely removed from CAD model, without significantly affecting the results (especially solidification).
- The computation can be speeded up by reducing the number of elements into which the casting and the mould are divided. Large element size however, carries the risk of wrong results. Small elements, which also require a corresponding smaller time step (in FDM, FVM and FEM), will lead to longer computation time. One way to reduce the total lead time is to use larger size elements for initial iterations, and a fine mesh for the final simulation to confirm the results.
- Another way to reduce the number of elements is to use the smallest mould enclosing the casting. Use of larger mould will only increase the computation time (since the mould also has to be divided into elements) without any significant increase in the accuracy of results. We have found that the temperature gradients in the mould become flat after a distance of 2-3 times the local wall thickness of a hollow casting. Hence the maximum mould size will need be casting size plus 5-6 times casting wall thickness.
- In the case of symmetric castings requiring multiple feeders, and multi-cavity moulds, considerable time may be saved by modeling, simulating and optimizing a single feeder, or a single cavity first. Then this feeder or cavity design can be duplicated to create a multi-feeder casting or multi-cavity mould. The total layout will need to be simulated and modified just once or twice before freezing the final design.
- The total lead time can be significantly reduced by fewer iterations of methods design, solid modeling of feeders and gates, simulation and interpretation of results. The secret is to start with a 'good-first' methods design, which will require only minor fine-tuning (instead of major re-design every time) to arrive at the optimal design. This can be achieved by consulting an experienced methods engineer, or by using a methods design programme before casting simulation.
- Since the gating design often depends on feeders, the feeder design should be optimized first, followed by gating, thus saving significant time.

- Simulation engineers often start with oversize feeders to reduce the number of iterations. This may lead to sub-optimal yield. One should start from an undersize feeder, and increase its size in steps until the hot spot in the casting shifts to feeder, with sufficient margin of safety. This ensures faster optimization of casting yield. Both AutoCAST and SolidCAST allow automatic optimization of feeders, saving valuable user time.

7. Ensuring Data Security

Data related to casting simulation projects is typically of three types:

- (a) Input data:** The part solid model occupies the largest space— a few megabytes to hundred megabytes or more, depending on its complexity and triangulation during export.
- (b) Output data:** The simulation results – temperature or velocity at every element, are stored in one or more files, which can occupy several hundred megabytes space.
- (c) Interpreted results and reports:** These may be generated by the programme or by the user, including screen images, animations, methods report, analysis report, and slide presentation; these may occupy only a few megabytes space (except animations).

Whether simulation is carried out by the methods engineer of a company within its premises, or by an independent consultant in a different location, data security is always a major issue of concern. This is more so, if the foundry is developing the casting for a new product and has signed non-disclosure agreements with the OEM customer. Other reasons for safe storage of casting simulation data include: its reuse for taking up similar projects in future, settling disputes in the event of defective castings, and training novice engineers in different methods design layouts. Relevant best practices are listed here.

- Hundreds of simulation projects will accumulate within a few months, and it will become difficult to distinguish between them unless the projects and their files are named properly. This is a bigger challenge for simulation consultants, who deal with different

foundries and handle a larger variety of projects. For example, many CAD programmes export their solid models with the same name (ex. PART.STL). This should be renamed appropriately (ex. Cummins-Valve110.STL) to distinguish it from other models. The project file, methods report, analysis report, and presentation slides should all be similarly named.

- The simulation computer should be equipped with a high capacity hard disk (500 GB or more). Still, if the output data per project is huge, then the hard disk may overflow within no time. In that case, the output data may be deleted, and only the input data and reports may be saved.
- Another way to reduce space is to compress (zip) all data files before archiving, which reduces its size to less than one tenth of the original. To open the project, the data files have to be unzipped, which is cumbersome if needed many times. AutoCAST automatically compresses the project into a single file during saving, and unzips it during opening. This makes it easy to store, transfer, email, and open the project any number of times.
- In case of confidential projects, the files can be encrypted or password-protected during compression, so that only the authorized user can open the files.
- If a simulation project is outsourced to an independent consultant, then it may be explicitly mentioned if the data is to be kept confidential, and for how long. If necessary, a non-disclosure agreement may be signed between the foundry and the consultant. In case of highly confidential castings, the consultant may be requested to delete all relevant files after the completion of the simulation project.
- A good anti-virus programme and firewall should be installed to protect the computer and data against malicious attacks. A major source of virus these days is from flash or pen drives. Simulation consultants should try to get the input data from their customer through e-mail or on a CD, which has lower chances of virus proliferation.
- Data can be lost from deletion by oversight or due to hard disk crash. It should be regularly backed up in a

separate (portable) hard disk, which have become quite inexpensive these days. This should be done at least once a week, preferably after every project in case of simulation consultants. The portable disk should ideally be stored in a safe place, away from the simulation computer to protect against fire or theft.

- No data storage system is completely foolproof. Hard copies of the simulation project reports should be printed out, and maintained in separate (physical) files.

8. Concluding Remarks and Future

Indian foundries have now understood the importance of casting simulation as an integral part of their operations. The penetration of casting simulation in the country is expected to rapidly rise from its current level of 5-10% (including in-house facilities and outsourced services), though it might take a decade or more to reach nearly full penetration like in Germany and USA. A large number of simulation engineers and consultants will be required to fill the gap.

The guidelines presented in this paper will help foundries properly plan and effectively implement casting simulation software in their works. The best practices will help simulation engineers and consultants to properly adapt the software depending on the requirements, and to make efficient use of the simulation facilities.

Simulation programmes are continuing to evolve, and becoming more powerful. Some of them now offer automatic optimization of methods design (like feeder size). Multi-physics simulation (coupled flow, solidification and stress), and microstructure and mechanical property prediction will become more reliable with new research being carried out.

In future, casting simulation programmes will increasingly use Internet to provide software training, upgrading, license management and technical support. Time-based licenses will keep the initial software costs down.

Further developments will make it possible to perform online casting simulation and to consult experts through a web browser at a negligible cost. Online education content will enable working foundry engineers to update, test and certify their knowledge of casting design and simulation.

As simulation technology becomes even more sophisticated in the next few years, foundries who lag behind will find it very difficult to catch up with the new world. It is important to start with small steps, and start as early as possible, to ensure a gradual and comfortable learning curve. In this context, professional bodies like the Institute of Indian Foundrymen can promote casting simulation centres in foundry clusters (such as the one in Belgaum). Leading technical institutes need to provide continuing education and critical technical support. Indian technocrats who have taken IT to the entire world now need to ensure Indian industries too benefit from advanced IT tools, including CAD and simulation, to gain a global competitive edge.

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