

Use of Flow Simulation to Develop Robust Injection and Vent Schemes that Account for Process and Material Variability in Liquid Composite Molding Process

J. Wang¹, E. Andres, P. Simacek and S.G.Advani

Abstract: In Liquid Composite Molding (LCM) processes, the process design requires an infusion and venting scheme which will saturate all the empty spaces between the fibers during mold filling resulting in a composite part without voids. However, the inherent material and process variability can change the filling patterns significantly which complicate this task. The objective of this work is to develop methodologies and tools to automate infusion process design and integrate it within the CAD design environment. The methodologies and algorithms developed examine the designed part geometry and material layups for ease of manufacturing with feasible infusion schemes by accounting for the inherent variability of the material and preform layup during the infusion processes. To accomplish this, the integrated tool has to automatically identify possible regions that are likely to introduce variability in resin flow, such as racetracking channels near corners, edges and inserts, which will cause dramatically different resin flow patterns and could result in voids. These possible scenarios are then simulated and evaluated to formulate an injection and venting scheme that is sufficiently robust to manufacture a part without any voids despite these variations. An example is presented to demonstrate the methodology of infusion design which identifies and accounts for material variability introduced due to geometric features.

Keywords: Liquid Composite Molding (LCM), simulation, race-tracking, optimization, topology, composites

1 Introduction

1.1 *Liquid composite molding process*

In Liquid Composite Molding (LCM) process, dry reinforcement – mostly woven or stitched textiles – is placed within a mold cavity, which is infused with liquid

¹Department of Mechanical Engineering and Center for Composite Materials, University of Delaware, Newark, DE 19716.

resin until it is completely saturated. Once the resin cures the part is de-molded. There are many variations of this process such as Resin Transfer Molding (RTM), which uses a rigid mold in which highly pressurized resin can be injected and Vacuum Assisted Resin Transfer Molding (VARTM) which uses one-sided mold, vacuum bag and the atmospheric pressure as the driving force. There are other techniques such as RTM Light which uses a compliant mold. LCM is widely used because it allows one to manufacture complex net-shaped parts with good structural properties and class “A” surface finish in a single step. Depending on the LCM variation in use, large parts can be produced [Advani (1994)].

The process of manufacturing a composite part with LCM initiates when the geometric design along with fiber layup and orientation needed for desired physical and mechanical properties is conceived in a Computer Aided Design (CAD) environment with widely used design software tools such as CATIA, ProEngineering, Solidworks or SimXpert. The design engineer creates the drawing needed to fabricate the mold in which the fiber preforms can be placed in desired orientations and the resin injected to manufacture the designed part. The resin injection step also known as the mold filling step plays a key role as the injected resin has to saturate all the empty regions in between the fibers to make a successful composite part.

Defects or voids result when the resin does not saturate these regions before it reaches a vent and the infusion is discontinued. This occurs because the resin flow pattern avoided these regions, or because entrapped volatiles prevented resin saturation. To prevent voids or dry spots, vents that evacuate volatiles from the mold are placed at all locations where the resin arrives last within the mold cavity. Ideally, such strategy guarantees a part without dry regions or voids. For correct vent placement, many simulation tools [Bickerton and Advani (1999); Brusckke and Advani (1994); Brusckke and Advani (1990); Kang and Lee (1999); Lin, Thomas and Huh (1998); Lin, Lee and Liou (1993); Marier, Rohaly, Advani and Fickie(1996); Mohan, Ngo and Tamma (1999); Long, Blanchard, Rudd and Smith (1998); Ruiz, Achim and Trochu (2007); Ruiz and Trochu (2007); Saad, Echchelh, Hattabi and El Ganaoui(2011); Shajaei, Ghaffarian and Karimian (2002); Trochu, Gauvin and Gao (1993); Trochu, et.al. (2006); Voller and Peng (1995); Yoo and Lee (1996)] have been developed to provide a forecast of the filling patterns after an injection gate is specified. However, the inherent material variability and the variability introduced during fabric placement in the mold due to complex curvatures, corners, edges and inserts in the geometric design will dramatically change flow patterns from one part to the next and could result in voids. Thus the flow simulation has to be able to take into account this variability to formulate an injection and venting scheme that is sufficiently robust to manufacture a part without any voids. Thus, one has to accommodate the flow pattern variability into the model. Secondly, the process

modeling should be directly connected to the part design, the same way the stress analysis is. Should the modeling results for the designed geometry suggest infusion difficulties, design changes should be considered before the mold cavity is fabricated.

1.2 Flow pattern variability and flow disturbances

In the mold filling simulation, it is assumed that the reinforcement to be saturated constitutes of continuous porous media with known material properties. Under these assumptions, once the inlet gate location and condition is specified for a designed mold geometry, the movement of the flow front can be predicted and last regions to fill identified as vent locations. This is an idealized case (we will label it as base case) in which one expects no variation of permeability in the mold from one part to the next. For this situation, only one simulation is necessary to identify the vent locations for complete filling without any dry regions or voids. However the manufacturing practice has demonstrated that the actual flow patterns vary to some degree from this idealized base case. This is due to “flow disturbances” that occur from one part to the next in the same mold cavity. While there are various causes for flow variation, such as reinforcement permeability changes [Comas-Cardona, Bickerton, Deleglise, Walbran, Binetruy and Krawczak (2008); Comas-Cardona, Le Grogneq, Binetruy and Krawczak(2007); Lomov and Verpoest (2000); Long and Rudd (1994); Long, Rudd, Blagdon Kendall and Demeri(1996a); Long, Rudd, Blagdon and Smith (1996b)], the most important factor that changes the resin flow patterns dramatically from the ideal case is race-tracking: Resin racing along gaps between mold walls and preforms, around corners and inserts as these regions offer less resistance to flow than the bulk fabric in the mold[Advani and Sozer (2003)].

Race-tracking is likely to occur along the outer edges, fabric folds, bifurcation lines (such as T-shape lines), and tapered regions of the part as shown in Fig. 1. At these edges, irregular cuts or placement of the reinforcement results in gaps or channels between the fiber preform and the mold wall. Higher permeability will result along these channels or gaps, which will make the resin go faster along the edge, changing the filling pattern and possibly leaving large unsaturated regions as the resin may have found an alternate path to the vent before saturating all the fibers within the mold cavity. Such “race-tracking” channels may not be repeatable from one part to the next during the manufacturing process, though some statistically significant patterns are usually observable.

Since our goal is to ensure that the mold will fill regardless of any disturbances in the flow, the process modeling must also address the scenarios which account for race-tracking. It is possible to add the race-tracking features to flow models [Simacek and Advani (2003)], but to actually model all possible infusion scenarios

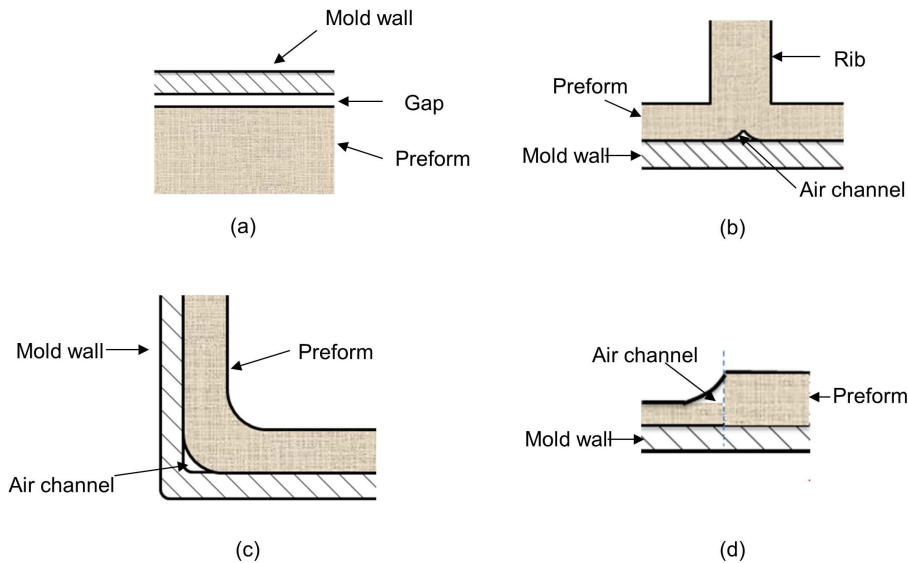


Figure 1: Potential race-tracking regions on (a) outer edge; (b) bifurcation lines; (c) sharp corners; (d) tapered regions

requires significant experience on the part of the analyst. To alleviate this constraint, one needs to develop tools that can:

- Automatically generate scenarios with various levels and permutations of racetracking along with identified geometric features such as corners and edges and assign a statistical probability to each of them. Even experienced process analyst will not be able to do this manually for a large, complexly shaped part.
- Create analysis tools to examine individual scenarios and translate the finding in a set of recommendations for robust process design. Again, manual analysis will require tedious examination of many scenarios. The resulting process design will provide the infusion and venting layout and the probability of success of such an injection scheme. If this scheme is too expensive or not possible, the design engineer is notified. Then, the designer can either explore changes in part design to facilitate ease of manufacturing, or explore better production facility that can provide tighter tolerances during manufacturing.

1.3 Coupling part design and process analysis

Accounting for the flow disturbances may not be sufficient to find injection and vent combination for successful mold filling. The outcome of such analysis may be that it is impossible – or requires too many vent locations to reliably manufacture the part by any selected process infusion and vent scheme. If the process analysis feedback is provided to the designer, it can prompt the change of part design for example, the simulation may suggest elimination of certain features (such as sharp corners or tapered inserts) that introduce unacceptable risks of racetracking and make the process less robust.

Currently, the functional design of a composite part is created separately and well in advance of the design of the manufacturing process. In the current part design practice, the designers analyze the part to ensure that the conceived design satisfies the physical and mechanical property requirement but pay no heed to the issue of manufacturability. The designed part that meets the strength and stiffness requirements is sent to the machine shop to manufacture the mold cavity or sent to the process engineer to perform mold filling simulations to determine the gate and vent locations before fabricating the mold. Two aspects are not addressed in this approach. First, the process engineer does not take into account any process variability and manufacturing issues. Second, if the manufacturing engineer cannot produce the part within limits, there is no sensible feedback that the part designer can use to introduce the required changes in the geometry to influence manufacturability.

To address manufacturability, two-way coupling between functional and manufacturing design is necessary. One must integrate process modeling directly into the design loop. By introducing manufacturing simulation tools in the design process, the designer will be able to create a composite part that can be successfully manufactured. The designer in general does not have the knowledge of the manufacturing process and can seldom use the mold filling simulation tools effectively. However, the designers are not experts in failure analysis either, yet, with the help of software tools, they check for the failure. Thus, goal of the current work is to develop a sufficiently transparent and integrated tool that will provide her or him with (a) the ability to check if the design is workable from the manufacturing standpoint and (b) provide suggestion for changes in part design if it is not manufacturable.

2 The automated process evaluation

2.1 Approach and procedure

A methodology is introduced and implemented that applies the existing process modeling and simulation tools to automate process design and evaluate part manufacturability within given manufacturing capabilities and constraints such as time to

fill the mold. The resulting output provides suggested infusion and venting schemes within the reliability requirements for the process. If the process is not possible, the methodology can suggest changes in part design.

The following steps were followed to implement the methodology.

Step 1: The part geometry and material description including laminate orientation and draping information from the design software was converted into a form suitable to simulate the resin infusion during mold filling.

Step 2: If the inlet configurations are not specified then they are created automatically before executing the resin infusion or flow simulations.

Step 3: The geometry features of the part were analyzed to identify and classify race-tracking regions in the geometry. Manufacturing data from the fabrication site can be used to assign probabilities and strengths of race-tracking to various identified race-tracking regions. The data is assumed to be available or a probability distribution for the variability can be assigned.

Step 4: Process simulations are executed for all permutations of scenarios possible based on the probability distribution of identified race-tracking edges and their strengths.

Step 5: The results record the locations of the dry spots (vents) for each scenario as well as other processing parameters such as the infusion time.

Step 6: Results are analyzed and assembled to provide suggested infusion schemes, vent locations and expected success rates.

This work will focus on describing the generation of distribution scenarios and analysis of the resulting sets (Steps 3 and 6). The implementation issues will not be discussed in detail.

2.2 Logistics and implementation

2.2.1 CAD environment and mold filling simulation tools

A composite part design is usually created using one of the many commercially available CAD software tools such as CATIA, ProEngineering, SolidWorks or SimXpert. The electronic design output format varies with the selected CAD software and often the information, such as dimensions, materials and their orientation and properties are encoded in a way that can only be read by that specific software. All CAD software is capable of creating a finite element mesh of the part which preserves the geometric dimensions and material data and orientation. Hence a tool is developed that can extract the mesh information written in Bulk Data Format (BDF) by the CAD package and re-arranged to create the data structure necessary to build various scenarios to perform mold filling simulations.

Liquid Composite Molding simulation package known as Liquid Injection Molding Simulation (LIMS)[Bruschke and Advani (1990); Bruschke and Advani (1994); Simacek, Sozer and Advani (1998)] is utilized to create the filling pattern for all permutations of race-tracking disturbances identified. To realize a seamless integration and coupling between LIMS and the composite part design process, the commercial CAE application ©MSC SimXpert was used as the CAD workbench. Its build-in python script interface enables one to execute mold filling simulation tool from its design environment. Simulation results and analysis suggestions are then transferred back and explicitly displayed into SimXpert CAD part design workbench, allowing the designer to appraise the effect of the part design on manufacturability and tweak the design based on the suggestions offered to improve the manufacturing process.

2.2.2 Creation of the base geometry

Since LCM is most commonly used to manufacture net shape shell structures, it is reasonable to mesh the part geometry with 2-D shell elements which allows one to calculate and provide the material property input of the two dimensional permeability tensor for that element, and the through thickness direction is simplified into an average thickness associated with the element.

Geometry information of the part is explicitly described in the BDF mesh file, including element and nodal information, as well as the nodal connectivity. The preform information in the BDF file is not as explicit as the geometry information, and is written in terms of PCOMP cards which describe the layup and orientation of the fabric or preform. Since preform permeability input is crucial for composite filling simulation, it is necessary to call the material library where unidirectional fiber sheet permeability data is stored, and by combining the unidirectional fiber permeability with the preform layup sequence described by the PCOMP card, the permeability for the element is averaged in the principal direction of the 2-D preform plane as in described by equations (1-4), in which $K_{xx}K_{yy}K_{xy}$ are the average 2-D permeability tensor, v_f is the average fiber volume fraction, and $K_{xxi}K_{yyi}K_{xyi}$ are the 2-D permeability tensor of the i_{th} ply, v_{fi} is the fiber volume fraction of the i_{th} ply, h_i is the thickness of the i_{th} ply.[Advani (1994); Advani and Sozer (2003); Bruschke and Advani (1990)]

$$K_{xx} = \frac{\int_{i=1}^n h_i K_{xxi}}{\int_{i=1}^n h_i} \quad (1)$$

$$K_{yy} = \frac{\int_{i=1}^n h_i K_{yyi}}{\int_{i=1}^n h_i} \quad (2)$$

$$K_{xy} = \frac{\int_{i=1}^n h_i K_{xyi}}{\int_{i=1}^n h_i} \tag{3}$$

$$V_f = \frac{\int_{i=1}^n h_i V_{fi}}{\int_{i=1}^n h_i} \tag{4}$$

Since each element in the BDF mesh file is linked to a specific PCOMP card, whose average permeability has been calculated, each element’s permeability tensor is then available and is stored as input for the filling simulation input file (Fig. 2).

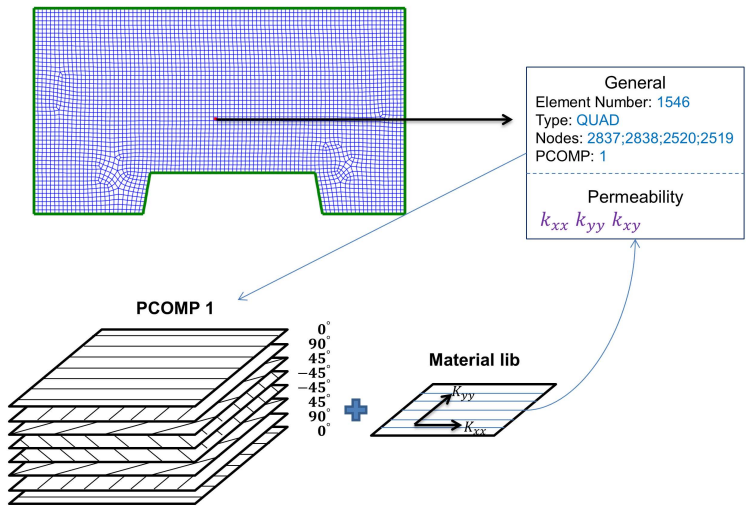


Figure 2: Preform permeability is interpreted from PCOMP card and material library information

2.3 Infusion line or injection gate plan initiation

In addition to permeability tensor input, the mold filling simulation LIMS also requires information regarding the inlet region from which the resin can enter the mold. The resin enters into a mold either through a small diameter hole known as a gate injection or through a channel which is known as a line injection. The selection of this injection location plays a key role in the simulation. The user could specify this location or one could formulate algorithms to pre-select the location and type of gate to execute the filling simulation. The gate selection will also depend on the LCM process selected. Fig. 3 shows the selection of the injection type based on the process. Currently, injection type and locations has been implemented for RTM,

VARTM and RTM-Light but can be expanded to include other gate types and LCM processes.

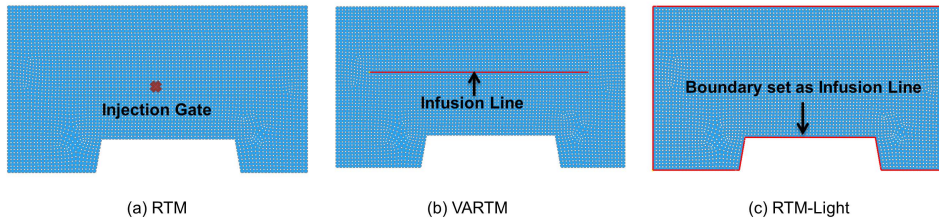


Figure 3: Automatic selection of infusion location depends on the type of process and the geometry of the part

If the process selected is RTM, the resin enters the mold cavity through a gate as shown in Fig. 3 (a). If no gate is selected by the designer, the following approach is used to select a gate: the centroid of the part is located by averaging all the nodes' coordinates weighted with the associated element volume, and the nearest node to the centroid is set as the injection gate with positive injection pressure. If VARTM is selected as the process of choice, resin enters the mold through a channel, which is also known as an infusion line as shown in Fig. 3(b). This infusion line can either be designated by the designer before the part is meshed, or the program can automatically assign a possible location for the injection line. Currently the algorithm selects an infusion line that connects the elemental edges going through the centroid and along the minor inertia. The infusion line is represented as a series of connected 1-D bar elements, whose cross-section area represents the opening size of the pipe or channel through which resin will be injected. Finally for RTM-light process, the resin is injected from the outer boundaries, which can be automatically identified using the algorithm of selecting connected element edges which are only owned by one element. If more than one boundary is detected, the longest one is selected. As with the VARTM infusion line, a series of 1-D bar elements are automatically built over the boundary, which can be denoted as the infusion line, as shown in Fig. 3(c).

2.4 Detection of disturbance regions and generation of permutation scenarios

2.4.1 Topology analysis and identification of disturbances channels

Nodal and elemental information contained in a typical mesh although sufficient for finite element analyses does not readily provide the topological information such as corners and edges of the meshed part. A new algorithm was developed

to automatically build the topology from the meshed part. By interrogating the geometric information, the elements are grouped into elemental edges, recorded as a pair of two nodes, which represent the starting and ending point of an elemental edge. Each elemental edge also contains the number of elements sharing this edge. Then all the elemental edges are placed in an array containing the elemental edges which share the same starting node for connectivity analysis. If two elemental edges have the same two nodes, but the sequence of starting and ending nodes is reversed, they are considered as the same edge. Such elemental edges are called twin edges, and each elemental edge includes the information of where its twin edge can be found.

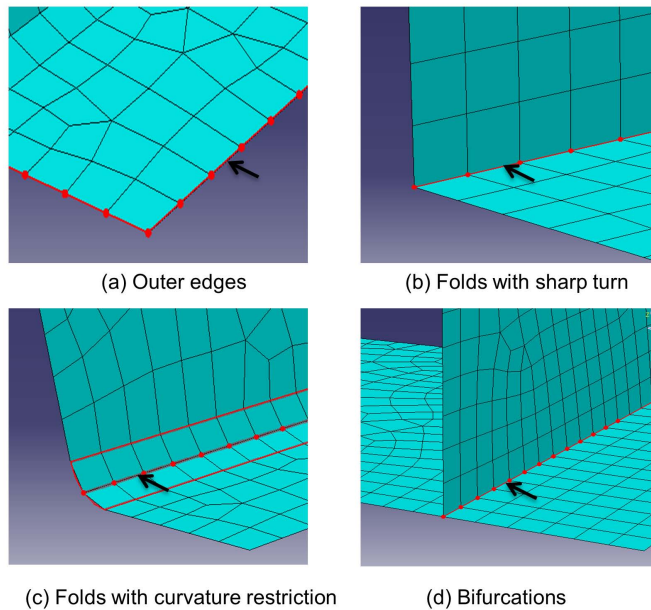


Figure 4: Automatic feature recognition of potential race-tracking channels

Together with the elemental permeability and the infusion type and location, this detailed rearranged nodes and elements map are stored into the internal data representation which is labeled as SCENARIO. Each elemental edge recorded in the SCENARIO topology map is examined to identify potential race-tracking regions. Based on the logic shown in Fig.4, one elemental edge is considered to be potential race-tracking edge if one of the following criteria is met:

- Outer edges: those element edges that belong to only one specific element,

and this information can be easily read from the data structures which are interpreted from the BDF files, as is shown in Fig. 4(a).

- **Folds:** element edges that are shared by two elements that have an angle between their normal directions. These edges are the sharp turns in the geometry that should be avoided, which is shown in Fig. 4(b). However, even if the turns are smooth, restriction should be added to the curvature as

$$\frac{h}{R} < \lambda$$

in which h is the fiber preform thickness (or element thickness in the mesh file), R is the curvature of the turning surface, and λ is the critical number which can be preset. Such edges are demonstrated in Fig. 4(c).

- **Bifurcations:** which are joints and edges that are shared by more than two elements (Fig. 4(d)).

After all the elemental edges which are potentially susceptible to race-tracking are collected in terms of a discrete set, the geometry and topology information is again interrogated, so the connectivity relations among these discrete edges are analyzed to form a series of single independent channels. However, some of the channels are too short (length smaller than in which is a preset constant based on the mesh size) to have significant effects on the flow pattern, so these channels are discarded. On the other hand, when some of the edges are parallel and sufficiently close they can be grouped together to reduce the number of permutations of the simulations to perform. Finally, some of the channels may be broken up due to irregularities in the mesh, but they are still considered.

2.4.2 Assigning race-tracking properties to the channels

Race-tracking channels permeability is assigned in terms of the channel cross-section area. The strength of the race-tracking can be obtained from the manufacturing experience and data. Thus, one can introduce a probability distribution function constructed from actual manufacturing data to define the variation in race-tracking strength from one part to the next. [Advani and Sozer (2003)]

Gokce[Gokce and Advani (2003); Gokce and Advani (2004)] used Weibull density function distribution to represent the race-tracking channel permeability, and created a discrete description of a single race-tracking channel which had two numbers associated with it: strength of race-tracking and its probability distribution. To limit the number of permutation of scenarios to be simulated, a coarse discretion is generated, by assigning probabilities for no race-tracking, low race-tracking, and

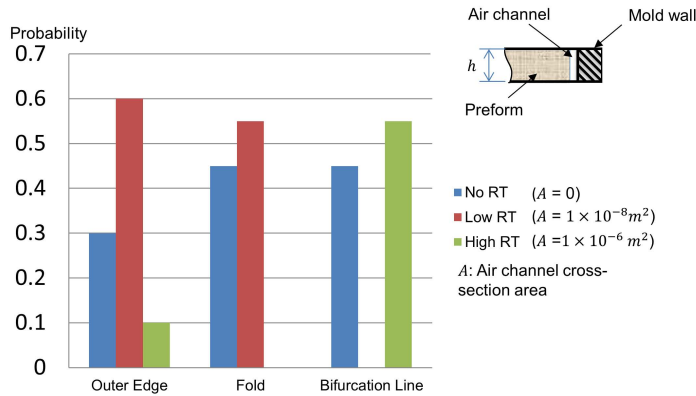


Figure 5: An example race-tracking strength with probabilities

high race-tracking rather than a continuous description (Fig. 5). It is found that the flow pattern does change significantly as one goes from no to low racetracking but not that significant as the race-tracking strength is increased. Also, edges, folds, and bifurcation lines are treated separately when specifying the likelihood of race-tracking effects, and different probability maps should be used for different manufacturing facilities.

2.4.3 Automatic generation of possible scenarios

By using the discretized race-tracking strength probability distribution and assuming each of the race-tracking channels is independent, one can build a list of scenarios in terms of permutations and combinations of all the detected race-tracking channels [Gokce and Advani (2003)]. Each scenario in the list has its own race-tracking channels configuration with associated probability.

For the example of a simple sidewall shown in Fig. 6(a), where 5 possible race-tracking edges have been identified, the race-tracking strengths and their probability provided in the table in Fig. 6(b) are assigned to the elements in these channels to describe the race-tracking behavior of the channel. Assuming that all five channels are independent and as one channel has three racetracking strengths associated with it while the other four have only two race-tracking strengths associated with them, a total number of $3 \times 2^4 = 48$ permutations of the flow scenarios are possible. Each scenario has an associated probability as shown in the scenario space generated in Fig. 6(c).

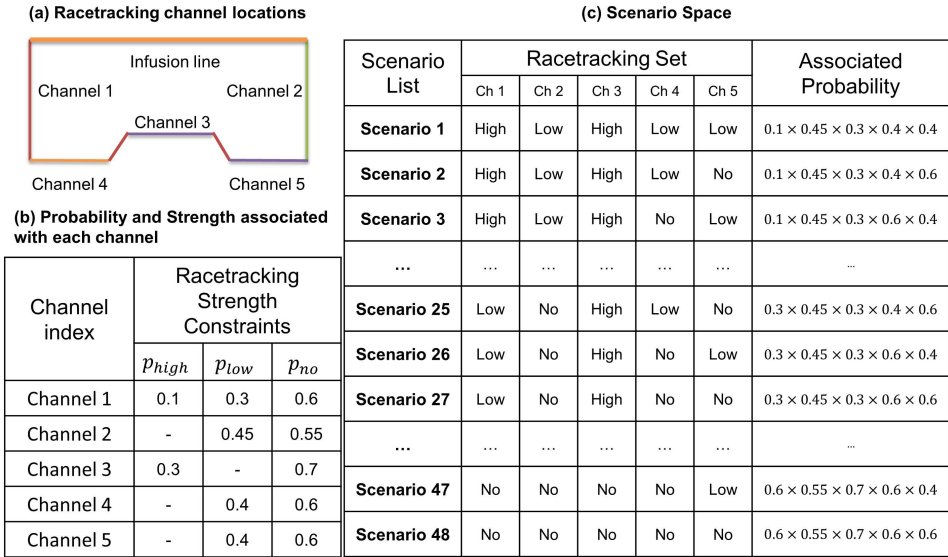


Figure 6: Scenario space generation for three potential race-tracking strengths along five edges of a simple sidewall

2.5 Mold filling simulations

Having assigned the LCM process and gate locations as explained in section 2.3 and having generated the scenario space as outlined in section 2.4, the finite element analysis software LIMS is called upon to execute a mold filling simulation for each scenario in the scenario space (Fig. 7). Simulation of each scenario is executed twice (Fig. 8). The first one assumes the mold to be under perfect vacuum (as with a membrane), such that the resin can saturate the entire preform and air is able to escape through the membrane. Filling time is easily acquired from this simulation, but potential defective areas are not obvious from these results. Therefore, it is necessary to conduct a second simulation on the same scenario, which can predict the regions in the geometry that are least likely to fill. The second simulation sets a non-zero air pressure in the mold and no vents are drilled in the mold. The air in the mold is equal to the resin pressure. All the islands of volume left unfilled are recognized as the last regions to fill requiring a placement of the vent. However, filling time results from the second simulation can be inaccurate. Hence the first simulation gives us the time to fill and the second simulation for the same scenario identifies the regions and the size of the regions that filled last. Each simulation takes only a few seconds to execute for a part with 10,000 nodes on a PC, hence

running two simulations is not a taxing overhead to obtain more accurate fill times.

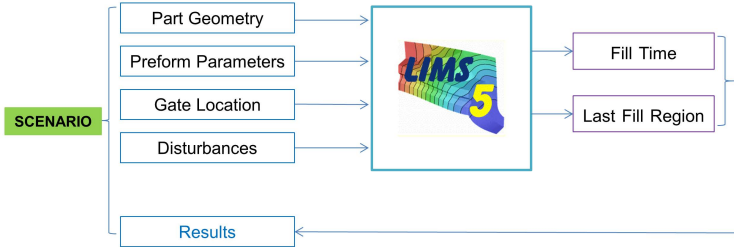


Figure 7: Each scenario filling simulation flow chart

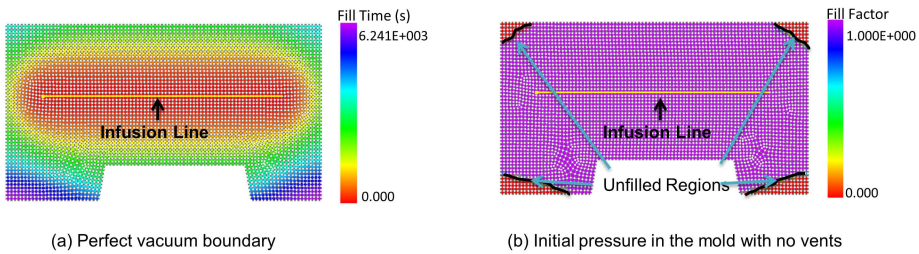


Figure 8: Each mold filling scenario is executed twice to find (a) fill time and (b) last region to fill

2.6 Analysis of simulation results

Results for each scenario in the list are generated using the mold filling simulation and recorded in the formulated data structure. The results include mold filling time, arrival times of the resin at each node, and node fill factors (all fill factors less than one are classified as unfilled regions). Combining these results with the probability of race-tracking for each scenario, a vent map is created and the success rate is forecasted.

2.6.1 Vent map generation

First, the regions that are most likely to be unfilled are identified for each scenario in the entire scenario space. Next, in each scenario all unfilled nodes are weighted with their respective scenario probabilities. These weighted node probabilities are

superimposed for the entire scenario space to produce a probability map which denotes the probability for each node to remain unfilled. All nodes with the probability higher than a preset probability value are set as possible vent locations.

Having created this unfilled region map in terms of nodal unfilled probabilities, the topology characteristics of all the nodes set as possible vent locations is examined to decide if they should be (i) listed as separate vent locations or (ii) they should be grouped together as one vent or (iii) discarded as possible vent location. The approach uses the nodal connectivity information to group all the connected nodes together as one possible vent location. Then it checks repeatedly with the topology of the part in the base data structure, until all the nodes identified as possible vent locations are classified into a group. Each group is a cluster of nodes that are connected. However, it is quite common that some of the groups may contain too few nodes. In practice, these regions are so small that even if there was some trapped air it will not cause any defects. These vents are discarded. Another situation that may occur is that two groups of nodes may be in close proximity and hence can be recognized as one vent. Thus, all the unfilled nodes above a preset probability are screened with the above approach to create the final plausible vent plan for the composite part for the selected injection location which takes into consideration material and placement variability during manufacturing. A schematic of this approach is shown in Fig. 9.

2.6.2 Success rate for a specific infusion plan

The approach used ensures that for the scenario space identified, if one places vents at all the possible locations as identified by the vent map, one would be able to fill the mold despite the disturbances caused by race-tracking. However, the vent map may suggest vents in locations that may not be possible or may be too many to be practical, in which case, it may be useful to provide the designer with a success percent as a function of number of vents. The success percent or yield is defined as the number of times the mold will fill without any voids when all the possibilities in the scenario space are executed.

To calculate the successful yield for a specific gate/vent scheme, each scenario result is compared with the vent map. Based on the nodal connectivity information, the location of the unfilled nodes in each scenario is used to identify unfilled regions. All the unfilled regions that are geometrically located in close proximity could be grouped together. A vent is placed in each group of unfilled regions in close proximity to avoid formation of voids or dry spots. On the other hand if even one unfilled region is not near any of the vents in the vent map, that scenario is labeled as unable to fill the mold successfully. After all the possible scenarios from the scenario space are executed, each scenario is weighted with its assigned

probability to calculate the successful yield for the selected gate/vent scheme.

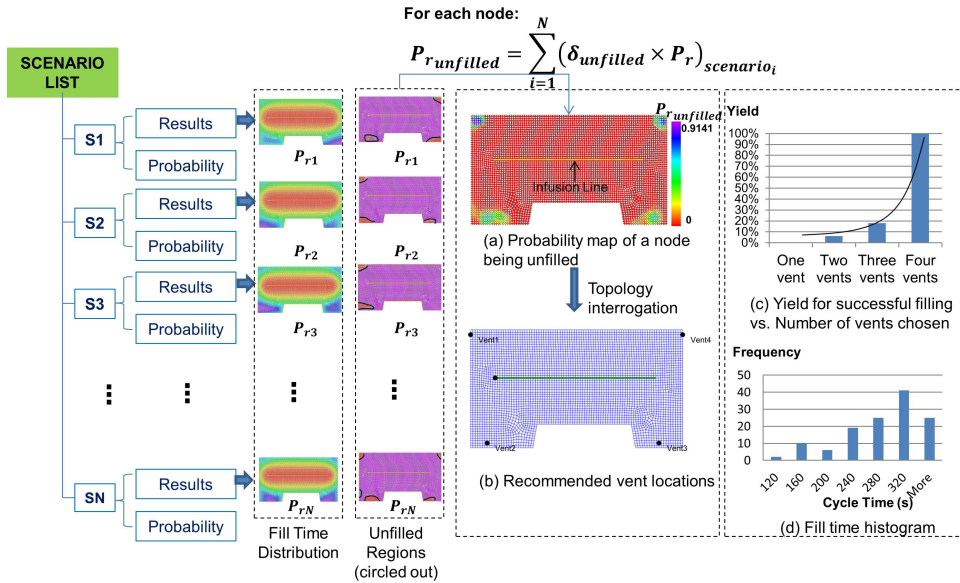


Figure 9: The mold filling results from each scenario from the scenario space are weighted with the respective probabilities to generate a vent map denoting the probability of placing a vent at that location for successful filling. In this example, four vents along the four corners ensure that one would be able to fill the mold for any scenarios from the entire scenario space.

2.6.3 Feedback to designer

The vent map, filling time and the injection location (if not selected by the designer) are returned within the designer’s environment of part design bench for evaluation. All the racetracking regions are identified, injection and vent locations marked and the fill time distribution highlighted. This information reveals to the designer regions which are most likely to have voids. Armed with this knowledge the designer may relax some of the geometric features in part design such as folds with sharp turns and corners which will help reduce the number of flow disturbance regions and hence the scenario space improving the chances of higher yield. Thus this automated evaluation process can flush out troublesome features from the mold filling viewpoint, providing the designer an opportunity to make changes to the geometry accordingly.

3 Case study of a chassis

3.1 Disturbances recognition

The CAD model is meshed in MSC SimXpert and is written into Bulk Data Format (BDF) file (Fig. 10). Based on the race-tracking channel selection criterion, ten channels are automatically detected (Fig. 11) and assumed to be independent channels, each of which is assigned with a probability of introducing race-tracking effect.

3.2 RTM-light process

To limit the number of scenarios in the scenario space, a simple discretization of race-tracking strength is used. Each race-tracking channel is described with only two possibilities (no race-tracking or race-tracking) with their respective probabilities specified. For race-tracking cases, the diameter of the race-tracking channel is assigned. Race-tracking discretization on outer edges, folds, and bifurcation lines are treated separately. For the chassis example when using RTM-light process, the outer edges serve as the infusion injection lines and hence only four independent potential race-tracking channels along the folds are likely, each of them with an assigned probability. This results in a scenario space of $2^4 = 16$ scenarios. Each scenario is assigned a probability of occurrence (for the example case, we assume equal probability for each scenario). The sum of the probability for all the scenarios in the scenario space should add up to unity.

The entire analysis for these 16 scenarios took about 632s on the computer with Intel® Core™ i7-2600 CPU @3.40GHz, with 16.0 GB RAM. Fill time and the unfilled regions for all of the sixteen scenarios are shown in Fig. 13 and Fig. 14. Using the probability analysis approach introduced in section 2.6, three vents are recommended as shown in Fig. 15 (a) so that all the scenarios can be successfully filled without voids. Fill time distribution and the relation between success yield and number of vents are also provided as shown in Fig. 16 (b) and (c).

The plan for recommended location for the vent is then compared with the mold filling simulation results in which no race-tracking or any other form of flow disturbances are taken into account. This simulation predicts one vent in the center bottom of the chassis, as is shown in Fig. 16 (b). The two regions on both sides of the chassis where void can be trapped because of the race-tracking effect in the folds will cause voids. As is shown in the Fig. 15(c), this one-vent plan will reduce the yield of successfully filling the part by 12.5%.

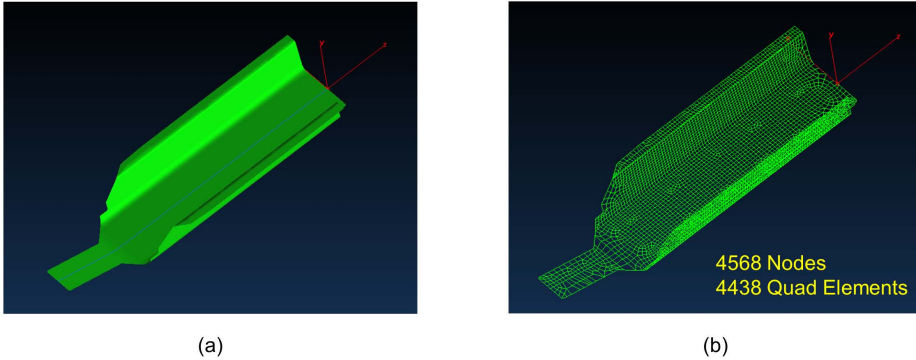


Figure 10: (a) Chassis CAD model (b) FE mesh for mold filling simulations

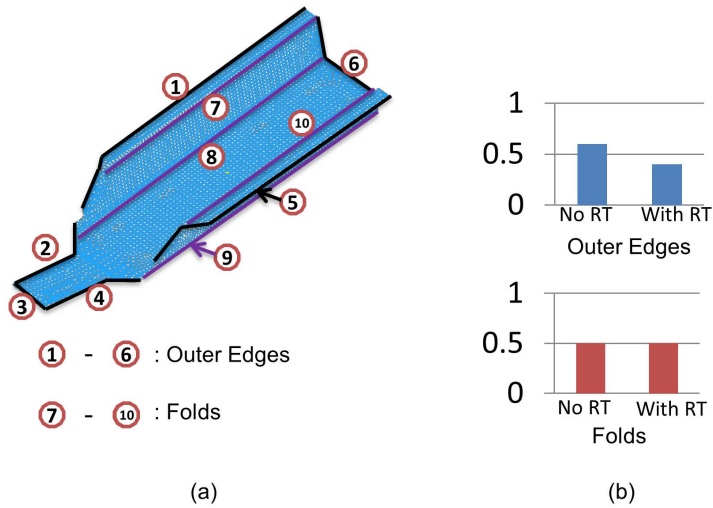


Figure 11: (a) Potential race-tracking channels identified (b) Assigned race-tracking distribution along outer edges and along folds

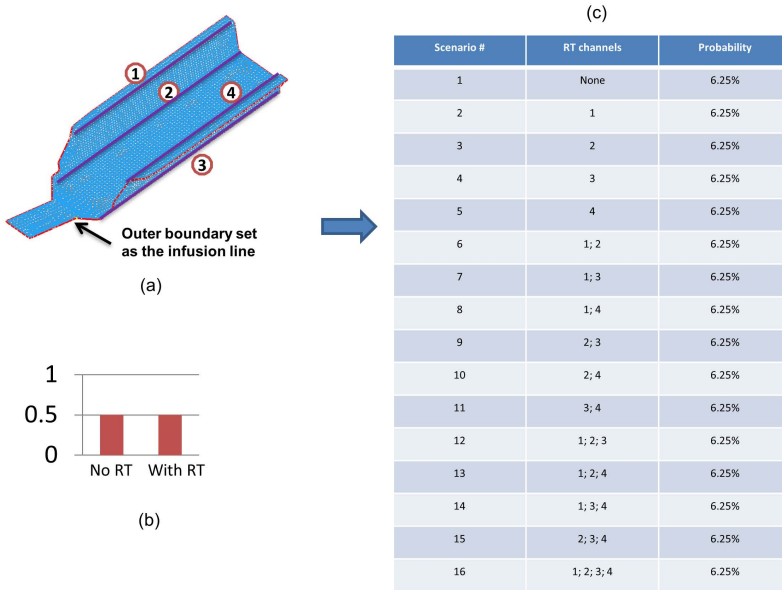


Figure 12: Scenario space generation for RTM-light process: (a) potential race-tracking channels identified; (b) race-tracking strength distribution on folds; (c) scenario space generated with equal probability for each scenario.

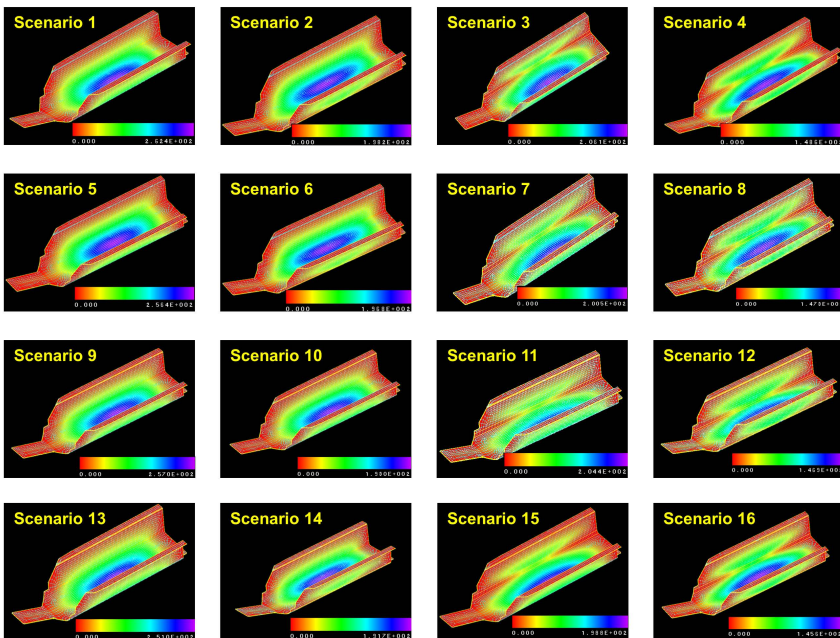


Figure 13: Resin flow contours for chassis. Injection is from outer boundaries using RTM Light process

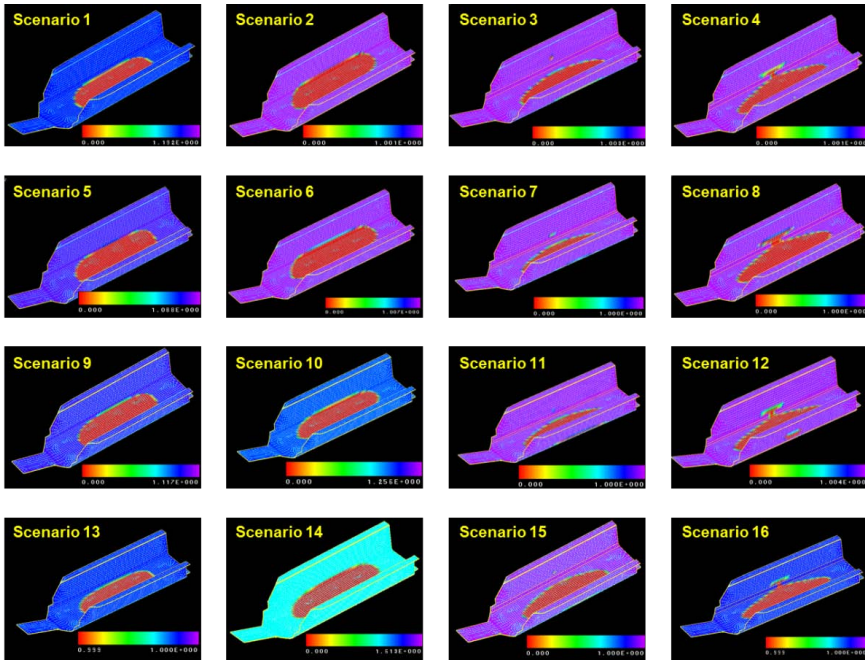


Figure 14: Unfilled regions as predicted by LIMS for all 16 scenarios with the RTM Light process

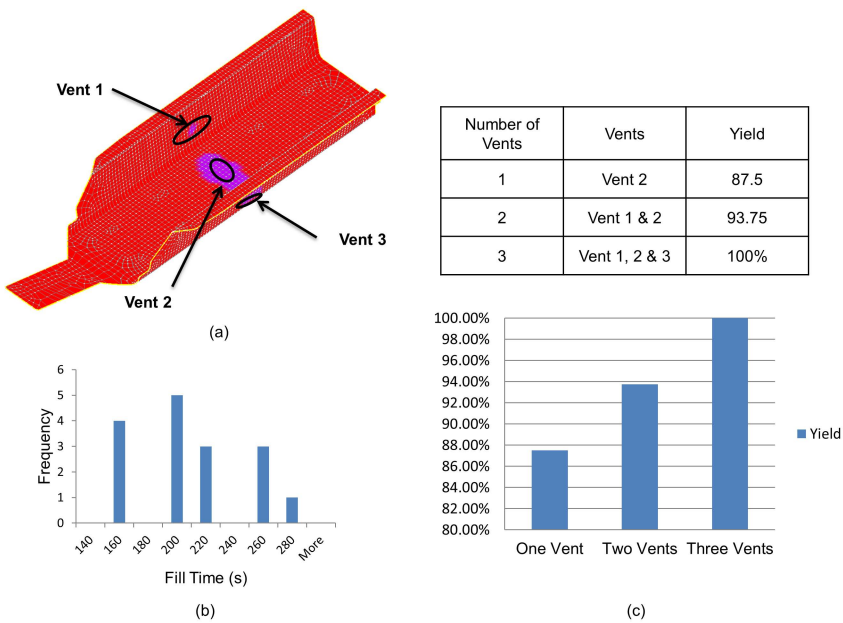


Figure 15: Feedbacks and recommendations: (a) vent locations; (b) fill time histogram; (c) successful yield vs. number of vents

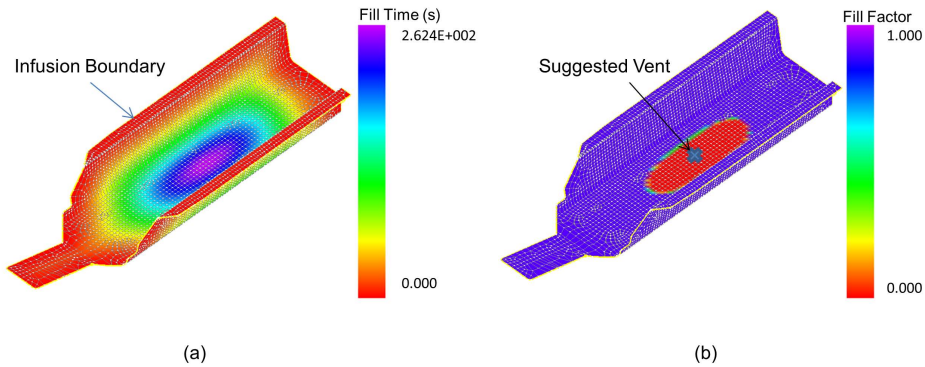


Figure 16: Simulation results for (a) Fill Pattern and (b) Fill Factor when race-tracking effect is not taken into account for RTM-light process

3.3 VARTM process

A centerline on the chassis surface is chosen as the resin infusion line for VARTM processing. The six outer edges and the four folds increase the scenario space to 1024 scenarios, as is shown in Fig. 17 (a) and (b).

Two vents are suggested by the simulation results, and the vent locations are shown in Fig. 17 (c). The suggested two vent plan is not different from the scenario in which no flow disturbances are considered as shown in Fig. 18, because the center infusion line is parallel to most of the race-tracking channels along the outer edges and folds, in which the resistance to resin flow has little effect on the flow pattern. This confirms that two vents as suggested is a robust strategy which will result in 100% yield despite the flow disturbances along 10 regions in the mold. VARTM process is usually more forgiving due to the ability to introduce line injection schemes for infusion.

3.4 RTM process

The centroid on the bottom surface of the chassis is set as injection gate with a positive injection pressure. Similar to the VARTM process, the ten independent potential race-tracking channels require 1024 scenarios to be analyzed. Six discrete vents are needed along the outer edges for 100% yield (Fig. 19), whereas if race-tracking effects are not taken into account, only two vents one on each end of the chassis will result in successful filling as shown in Fig. 20.

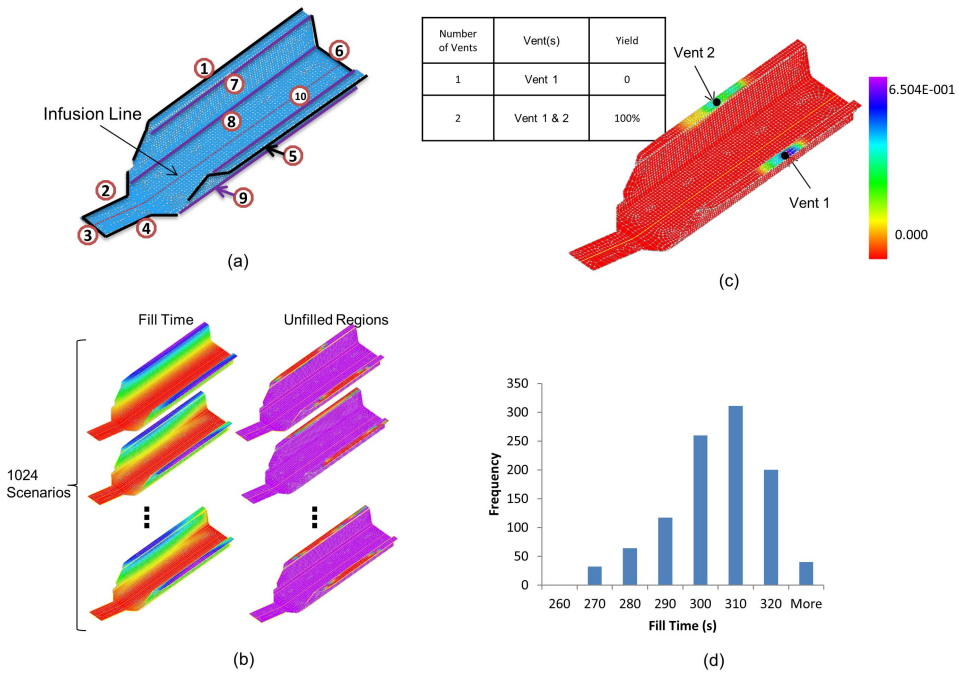


Figure 17: Simulation cycle and results for the chassis with VARTM process (a) Infusion line and potential race-tracking channels; (b) Mold filling simulation to find fill times and unfilled regions for all 1024 scenarios; (c) Vent map; (d) Fill time histogram

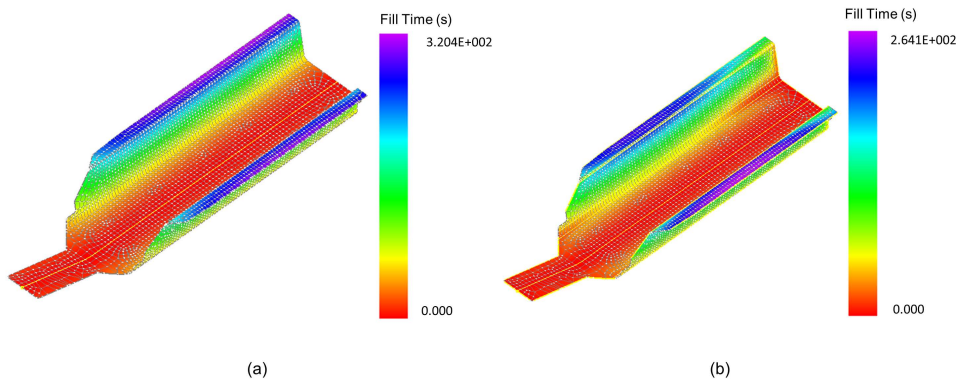


Figure 18: Flow front development comparison between the cases when (a) race-tracking effect is not present (b) race-tracking effect is introduced along all of the edges and folds

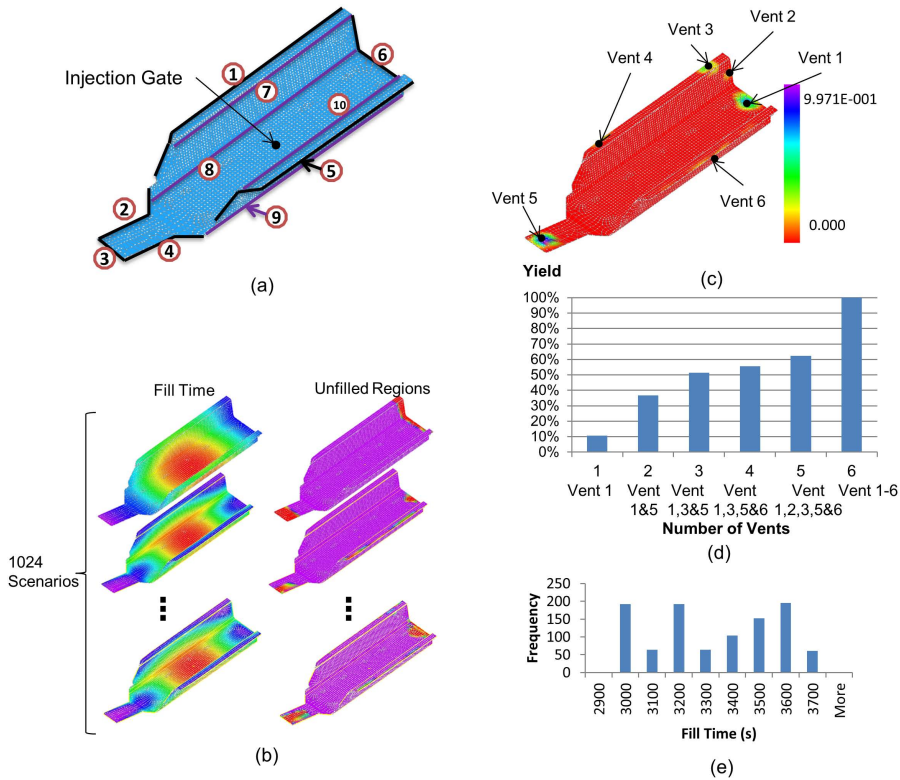


Figure 19: Mold filling simulation for the chassis using the RTM process: (a) Injection gate location and potential race-tracking channels identified; (b) Fill time and unfilled regions results for some of the scenarios in the scenario space; (c) Vent map and vent locations; (d) Successful yield vs. number of vents; (e) Fill time histogram.

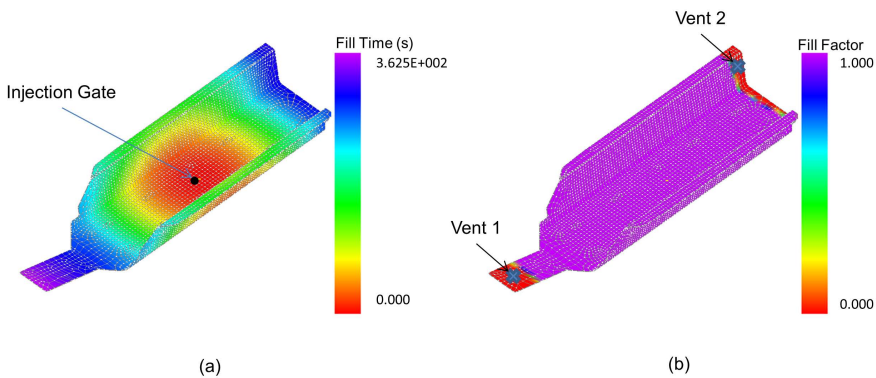


Figure 20: (a) Filling pattern and (b) Unfilled regions in the absence of racetracking when the injection gate is located in the center

4 Summary and Conclusions

A methodology is proposed by developing a seamless program that can provide information about the manufacturing of a composite part to the designer. It can identify the possible flow disturbance regions, analyze the filling patterns for all permutations possible flow disturbances, suggest vent locations and the successful yield as a function of number of vents. It can provide this information along with possible injection location and scheme for RTM-Light, VARTM and RTM process choices. The methodology is automated and does not rely on the part designer to provide any input. The automated program takes the meshed CAD file and creates a new data structure with the geometry information, material preform information, and rebuilds the topology based on the mesh file. Potential disturbances channels are automatically detected and race-tracking properties are assigned. The program can execute all the possible permutations of filling simulation and create a probability map of regions that are most likely to stay unfilled. These regions can be grouped and identified as vents to improve the yield with the infusion scheme selected. The results are returned to the designer in a readable form within the design environment.

An example case study demonstrated this for a chassis validating its usefulness to the designer as a tool to increase the manufacturability of the part by taking steps during the design phase and also providing a comparison between different LCM processes. It can be concluded that race-tracking effect along the outer edges, folds or bifurcation lines can significantly change the resin flow pattern when the mold cavity is being filled, especially when race-tracking regions are not parallel to the flow direction. Without introducing flow disturbances into the mold filling simulation model, the result may not accurately predict all the possible locations in the mold where vents should be drilled, and hence result in lower yield. With the new automated tool which identifies and addresses the race-tracking effects, one can predict the locations and number of vents more accurately. The simulation results and recommendations are provided back to the designer within the part design workbench, so that the designer can make changes to the geometric features to reduce the effect of race tracking and improve manufacturability and yield.

Acknowledgement: The financial support of this work is provided by the Defense Advanced Research Projects Agency (DARPA) under Grant FA8650-11-C-7132 for the Center for Composite Material at the University of Delaware.

Additional appreciations go to Dan Molligan, Michel Lourdemarianadin and Jason Etherington of the Center for Composite Material at the University of Delaware for making available the CAD model and the mesh data. Thanks also to Dr. Shridhar Yarlagadda of the Center for Composite Material for his suggestions.

References

- Advani, S. G.** (1994): Resin Transfer Molding: *Flow and rheology in polymer composites manufacturing*. Amsterdam, Elsevier p. 465-516.
- Advani, S. G., E.M. Sozer** (2003): *Process Modeling in Composites Manufacturing*. New York, NY, Marcel Dekker, Inc.
- Bickerton, S., S. G. Advani.** (1999): Characterization and Modeling of Race-Tracking in Liquid Composite Molding Processes. *Composites Science and Technology* 59 (15): 2215-2229.
- Bruschke, M. V., S. G. Advani.** (1990): A Finite element/control Volume Approach to Mold Filling in Anisotropic Porous Media. *Polymer Composites* 11 (6): 398-405.
- Bruschke, M. V., S. G. Advani.** (1994): A numerical approach to model non-isothermal viscous-flow through fibrous media with free surfaces. *International Journal for Numerical Methods in Fluids* 19 (7): 575-603.
- Comas-Cardona, S., S. Bickerton, M. Deleglise, WA Walbran, C. Binetruy, P. Krawczak.** (2008): Influence of Textile Architectures on the Compaction and Saturated Permeability Spatial Variations. *Recent Adv Text Compos (TexComp-9)*: 3-10.
- Comas-Cardona, S., C. Binetruy, P. Krawczak.** (2007): Unidirectional Compression of Fibre Reinforcements. Part 2: A Continuous Permeability Tensor Measurement. *Composites Science and Technology* 67 (3–4): 638-645.
- Gokce, A., S. Advani.** (2003): Combinatorial Search to Optimize Vent Locations in the Presence of Disturbances in Liquid Composite Molding Processes. *Materials and Manufacturing Processes* 18 (2): 261-285.
- Gokce, A., S. G. Advani.** (2004): Simultaneous Gate and Vent Location Optimization in Liquid Composite Molding Processes. *Composites Part A-Applied Science and Manufacturing* 35 (12): 1419-1432.
- Gokce, A., S. G. Advani.** (2004): Vent Location Optimization using Map-Based Exhaustive Search in Liquid Composite Molding Processes. *Materials and Manufacturing Processes* 19 (3): 523-548.
- Kang, Moon Koo, Woo Il Lee.** (1999): A Flow-Front Refinement Technique for the Numerical Simulation of the Resin-Transfer Molding Process. *Composites Science and Technology* 59 (11): 1663-1674.
- Lin, Mark, H. Thomas Hahn, Hoon Huh.** (1998): A Finite Element Simulation of Resin Transfer Molding Based on Partial Nodal Saturation and Implicit Time Integration. *Composites Part A: Applied Science and Manufacturing* 29 (5–6): 541-550.

- Lin, Rj, Lj Lee, MjLiou.** (1993): Mold Filling and Curing Analysis in Liquid Composite Molding. *Polymer Composites* 14 (1): 71-81.
- Lomov, S. V., I. Verpoest.** (2000): Compression of Woven Reinforcements: A Mathematical Model. *Journal of Reinforced Plastics and Composites* 19 (16): 1329-1350.
- Long, A. C., CD Rudd, M. Blagdon, KN Kendall, MY Demeri.** (1996): Simulation and Measurement of Reinforcement Deformation during Preform Manufacture. *Polymers & Polymer Composites* 4 (5): 335-341.
- Long, A. C., C. D. Rudd.** (1994): A Simulation of Reinforcement Deformation during the Production of Preforms for Liquid Moulding Processes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 208 (4): 269-278.
- Long, A. C., P. J. Blanchard, C. D. Rudd, P. Smith.** (1998): The Development of an Integrated Process Model for Liquid Composite Moulding. *Composites Part A: Applied Science and Manufacturing* 29 (7): 847-854.
- Long, A. C., C. D. Rudd, M. Blagdon, P. Smith.** (1996): Characterizing the Processing and Performance of Aligned Reinforcements during Preform Manufacture. *Composites Part A: Applied Science and Manufacturing* 27 (4): 247-253.
- Maier, RS, TF Rohaly, SG Advani, KD Fickie.** (1996): A Fast Numerical Method for Isothermal Resin Transfer Mold Filling. *International Journal for Numerical Methods in Engineering* 39 (8): 1405-1417.
- Mohan, R. V., N. D. Ngo, K. K. Tamma.** (1999): On a Pure Finite-Element-Based Methodology for Resin Transfer Molds Filling Simulations. *Polymer Engineering & Science* 39 (1): 26-43.
- Ruiz, Edu, V. Achim, F. Trochu.** (2007): Coupled Non-Conforming Finite Element and Finite Difference Approximation Based on Laminate Extrapolation to Simulate Liquid Composite Molding Processes. Part I: Isothermal Flow. *Science and Engineering of Composite Materials* 14 (2): 85-112.
- Ruiz, Edu, F. Trochu.** (2007): Coupled Non-Conforming Finite Element and Finite Difference Approximation Based on Laminate Extrapolation to Simulate Liquid Composite Molding Processes. Part II: Non-Isothermal Filling and Curing. *Science and Engineering of Composite Materials* 14 (2): 113-144.
- Saad, Aouatif, AdilEchchelh, Mohamed Hattabi, Mohammed El Ganaoui.** (2011): A Fast Computational Model to the Simulation of Non-Isothermal Mold Filling Process in Resin Transfer Molding. *Polymer Composites* 32 (6): 857-868.
- Shojaei, A., S. R. Ghaffarian, S. M. H. Karimian.** (2002): Numerical Simulation of Three-Dimensional Mold Filling Process in Resin Transfer Molding using

Quasi-Steady State and Partial Saturation Formulations. *Composites Science and Technology* 62 (6): 861-879.

Simacek, P., E. M. Sozer, S. G. Advani. (1998):textit. User Manual for DRAPE 1.1 and LIMS 4.0 Liquid Injection Molding Simulation. Technical Report UD-CCM 98-01. Newark: Center for Composite Materials.

Simacek, P., S.G. Advani. (2003): A Numerical Model to Predict Fiber Tow Saturation during Liquid Composite Molding. *Composites Science and Technology* 63 (12): 1725-1736.

Trochu, F., R. Gauvin, DMGao. (1993): Numerical-Analysis of the Resin Transfer Molding Process by the Finite-Element Method. *Advances in Polymer Technology* 12 (4): 329-342.

Trochu, François, Edu Ruiz, Vincent Achim, SofianeSoukane. (2006): Advanced Numerical Simulation of Liquid Composite Molding for Process Analysis and Optimization. *Composites Part A: Applied Science and Manufacturing* 37 (6): 890-902.

Voller, V. R., S. Peng. (1995): An Algorithm for Analysis of Polymer Filling of Molds. *Polymer Engineering & Science* 35 (22): 1758-1765.

Yoo, Yeong-Eun, Woo Il Lee. (1996): Numerical Simulation of the Resin Transfer Mold Filling Process using the Boundary Element Method. *Polymer Composites* 17 (3): 368-374.

