

Rapid tooling route selection and evaluation for sand and investment casting

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ABSTRACT: Today, a number of direct routes using RP processes (FDM, LOM, SLA, SLS, etc.), as well as indirect routes (RP coupled with secondary or soft-tooling processes like RTV vacuum casting) are available for rapid fabrication of tooling for sand and investment casting processes. Each route is unique in terms of geometric, material, quality and cost characteristics; no comprehensive database of their capabilities has been reported, especially for metal casting application. The problem of selecting the optimal RT route is a complex multi-criteria decision making problem. This paper describes a systematic approach for RT route selection and planning. A database of RT process capabilities was generated through benchmarking experiments, covering 20 different widely-used RT routes (both direct and indirect: 2 and 3-step processes) involving an impeller pattern. In this approach, RT process route selection involves translating the tooling requirements specified by the casting engineer into weighted tooling attributes using QFD-ANP, which along with part specifications is used for RT route selection by calculating the overall process compatibility indices. The routes are ranked as per the value of the overall compatibility index. Once the optimal route is selected, process planning is carried out by retrieving similar process plan using case based reasoning (CBR). The methodology has been implemented in a software program using Visual C++ programming language in Windows environment. The methodology is demonstrated and validated with an industrial example of a separator body casting. It has proved to be a robust evaluation and decision making tool for selecting appropriate tooling route for a given casting based on customer requirements.

1 INTRODUCTION

Casting industry is a vital segment of the manufacturing sector, and continues to produce intricate parts with curved surfaces, blends, internal features and varying thickness, in the widest range of size and weight, in virtually any metal or alloy, in an economical manner. A large number of casting processes are available today, with sand and investment casting accounting for over 80% of total casting production.

World over, rapid innovation cycles and the need to introduce new products 'first-to-market' are putting pressure on suppliers to reduce their lead-time for prototype parts as well as regular production parts. The conventional approach to casting development, after part design is finalized, involves part drawing interpretation, tooling design (ex. Pattern with various allowances), methoding or rigging (feeders and gating channels), tooling fabrication, process planning, casting trials, process optimization, modification of methoding and/or tooling (to achieve the desired quality and yield), and casting sample approval, leading to regular production. This

takes from typically 6 weeks for a simple casting to over 6 months for a complex casting (like an engine block).

The development time of conventional tooling (accounting for over 70% of total lead time), has become a major bottleneck in new product development, especially for intricate parts. Further, the amortised cost of tooling is high, when the order size is small as in the case of castings required for prototyping, unique products (art, medical), and replacement of broken parts (in vintage equipment). Even with CAD/CAM, tooling development for complex parts requires significant time and operator skills, owing to CNC tool path planning and verification, design of part-specific fixtures, and the number of machine tools and setups required during machining operations.

In this context, new routes for rapid fabrication of tooling, based on rapid prototyping (RP) technology, are displaying a great potential for automation and lead-time reduction, and economic advantage, especially for very intricate and small parts required one-off or in small numbers (Hilton and Jacobs, 2000). These routes are hereby referred to as 'rapid tooling'

(RT), and are the subject of the present investigation, which focuses on their application to the metal casting domain.

2 PREVIOUS AND RELATED WORKS

The most widely used RP processes include Stereolithography Apparatus (SLA), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), and 3-Dimensional Printing (3DP). The processes have been continuously improved in terms of speed, accuracy and range of materials, and used for various applications (Levy, et al., 2003). This was coupled with improvements in algorithms for part orientation, CAD model slicing: uniform and adaptive (Pandey, et al., 2004), and integration with reverse engineering (Kulkarni, et al., 2000 and Subramanian, et al. 2004).

Today, nearly 60 RP processes are available, producing parts in over 70 materials including polymer blends, paper, ceramics and metals (Grimm, 2006). Depending on the material, these parts can be directly used as patterns for sand casting, or as consumable patterns for investment casting, referred to as direct rapid tooling (Cheah, et al., 2005). Secondary processes (such as RTV silicone rubber moulding, polyurethane/epoxy casting, and investment casting) can be used to convert RP master patterns into molds (or vice-versa), yielding many more indirect rapid tooling routes for sand and investment casting (Tromans, 2001). Each RP-based tooling route is characterized by different material properties, geometry limitations, process parameters, and resulting quality (dimensional accuracy, surface finish, strength, etc.), besides fabrication time and cost (Campbell, et al., 2002). A need for evaluating RP materials and fabrication properties for integration with other manufacturing technologies has been presented by Gibson and Dongping (1997).

The suitability and economic benefits of rapid prototyping based tooling for metal casting has been established by several researchers. RP-based tooling has proven its capabilities to save time by 60-80% and reduce cost by 25% as compared to conventional tooling (Hilton and Jacobs, 2000). The major limitations were in terms of poorer surface finish augmented by staircase surfaces. (Lin, 2001), and high cost for large and simple-shaped parts (compared to conventional routes). Researchers have studied the effect of process parameters on the surface roughness of castings using Taguchi approach (Sudhir, et al., 2006), but no such work for RP-based casting tooling has been reported.

Given the large number of routes for tooling fabrication (with many being added on a continuous basis), the need for a systematic approach supported by a database of RT process capabilities for deciding

the most suitable route has been reported (Ramana and Rao, 2005). A few researchers have carried out comparative studies of a limited number of RP processes, mainly in terms of surface finish, dimensional accuracy, time and cost (Xu, *et al.*, 2000 and Arumaikkannu, *et al.*, 2005). Cost models for casting have been developed, and are useful for comparing different routes for casting production (Bidanda *et al.*, 1998; Creese and Rao, 1995), but these models need to be extended to handle RP-based routes for tooling fabrication.

In summary, RP-based routes appear to be useful for fabricating tooling for intricate castings required in small numbers, with potentially shorter lead-time and lower cost compared to conventional machining-based routes. However, any comprehensive investigation to generate a database of rapid tooling process capabilities for casting application, using a single benchmarking part, has not been reported. Further, while various approaches that have been reported for RP process selection for prototyping applications, there appears to be no methodology for generating, selecting and evaluating direct and indirect routes for rapid tooling for metal casting applications. There is also a need to analyze and incorporate tooling requirements from the casting engineer into the selection methodology.

The scope of this investigation is limited to tooling (mainly patterns) for sand and investment casting, required for one or a limited number of parts (as against mass production, for which hard tooling produced by conventional processes is preferred). The process capability database of RT routes is created by carrying out benchmarking experiments involving fabrication and inspection of patterns by direct and indirect RT routes. A QFD-ANP (quality function deployment and analytic network process) framework is employed for identifying and prioritizing tooling attributes (such as build time and layer thickness) with respect to the tooling requirements (such as low cost and good surface finish) from casting engineer to facilitate RT route selection.

3 RT PROCESS CAPABILITIES

A benchmarking exercise has been carried out by fabricating an impeller pattern (Figure 1) using 20 different RT routes. The CAD model of the pattern was obtained for this purpose by laser scanning the original wooden pattern. The results for each route included dimensional accuracy (dimensions on horizontal and vertical surfaces), geometrical accuracy (such as straightness, flatness, etc.), surface finish, build time, and cost. The process capabilities of each route were modelled using trapezoidal fuzzy membership functions. The patterns were coded to represent the process, equipment, material and build style, as

$P1(E1):M1(B1)-P2(E2):M2(B2)-P3(E3):M3(B3)$, where, P = process, E = equipment, M = material, and B = build style (S for solid, H for hollow). The processes included: SLA, FDM, LOM, TJP- Thermojet printing, SDP- Solid dimension printing, OBJ-Objet 3D printing, and VC-Vacuum casting, WIM-Wax injection moulding. Materials included: R-photo-curable resin; ABS; P-Paper; W-Wax; PVC, PC-Polycarbonate, E-Epoxy, and PU-

Polyurethane. The patterns fabricated by direct routes are listed in Tables 1–2. Similarly, patterns were fabricated by using indirect routes for sand and investment casting. Figure 2 shows one pattern fabricated by direct route (SLA) and two patterns by indirect RT routes (one for sand casting and one for investment casting). RT routes with more than three steps are not considered owing to cost, time and quality limitations involved.

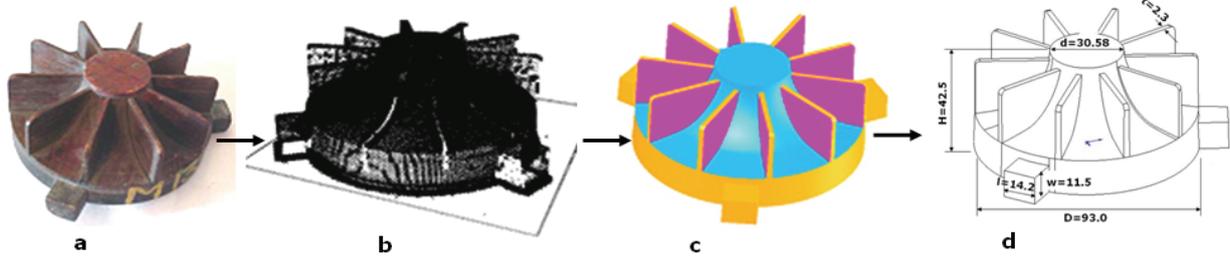


Figure 1. Impeller: (a) wooden pattern, (b) cloud of points, (c) 3D CAD model, (d) major dimensions

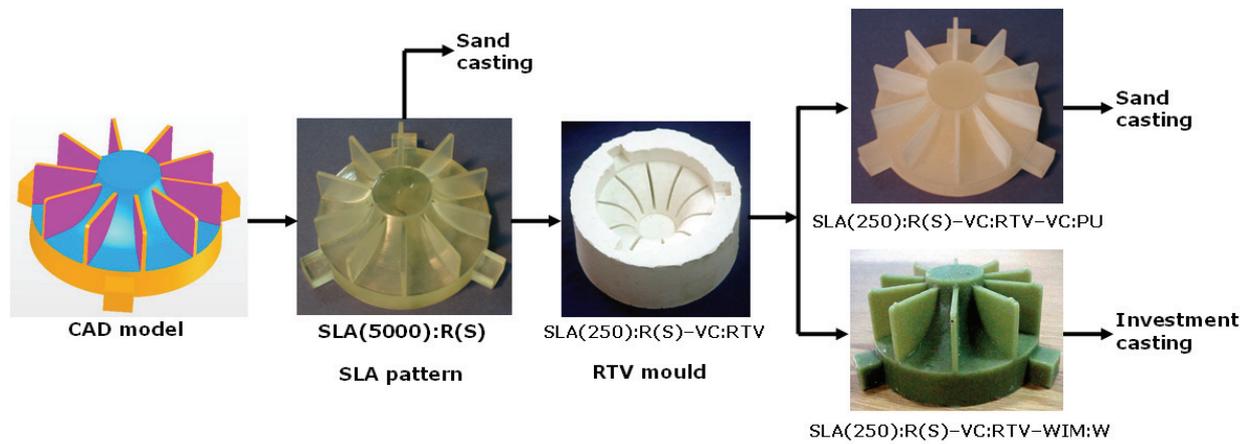


Figure 2. Patterns fabricated by direct and indirect RT routes for sand and investment casting

Table 1. Direct routes: patterns for sand casting

RP patterns	RP Machine	Manufacturer	Material	Layer thk. (mm)	Buildrate mm ³ /min
SLA(5000):R(S)	SLA 5000	3D Systems	SLA5530 epoxy	0.10	1092
SLA(250):R(S)	SLA 250		SLA5530 epoxy	0.10	6000
FDM(Titan):PC(S)	FDM Titan	Stratasys	Polycarbonate	0.25	300
FDM(1650):ABS(S)	FDM 250		ABS(P400)	0.25	300
LOM(2030):P(S)	LOM-2030H	Helisys	Paper (LPH Series)	0.20	500
SDP(300):PVC(S)	SD-300	Invision	PVC foil	0.165	4480
OBJ(260):R(S)	Objet Eden 260	Objet Geometries	Fullcure-720 resin	0.016	2250

Table 2. Direct routes: patterns for investment casting

RP patterns	RP Machine	Manufacturer	Material	Layer thk.	Build rate
SLA(5000):R(H)	SLA5000	3D Systems	SLA5530 epoxy-hollow	0.10 mm	1092 mm ³ /min
FDM(1650):ABS(H)	FDM 250	Stratasys	ABS (P400)-hollow	0.25 mm	300 mm ³ /min
TJP:W(S)	Thermojet	3D Systems	TJ88 wax	0.10 mm	6333 mm ³ /min

Dimensional accuracy: The dimensions were measured using a Carl Zeiss coordinate measuring machine and the mean values were used to calculate the relative percentage error with respect to the original CAD dimensions as follows (equation 1).

$$\bar{x} = \sum_i^n \frac{x_i}{n}, \quad (1)$$

$$Error = \left| \bar{x} - x_{CAD} \right| / x_{CAD}$$

where, i is the i^{th} dimension data obtained when the same features are measured repeatedly, n is the number of times the i^{th} dimension is measured ($n=3$ in our study), \bar{x} is the mean value of the measurement, and x_{CAD} is the original CAD dimension. Figure 3 shows the percentage error and surface roughness comparison for direct RT routes. A wide variance in dimensional accuracy is apparent. While each system is capable of delivering dimensional accuracy between 0.02 and 0.08 mm, the maximum dimensional deviation is as high as 2.31 mm. This is to be expected, especially in multi-stage rapid tooling routes.

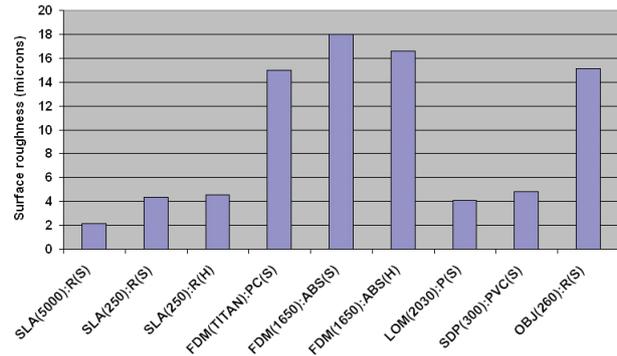
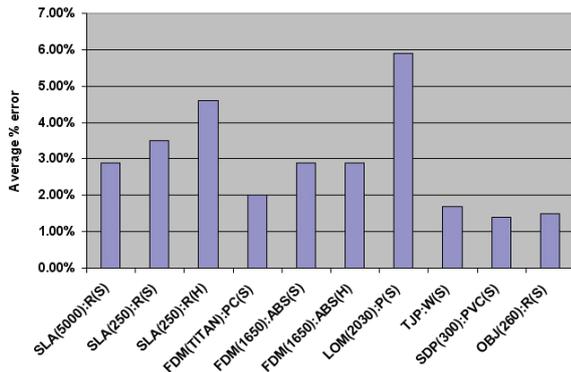


Figure 3. (a) Comparison of overall average dimensional error, and (b) surface roughness (vertical)

Defining tooling requirements and attributes: The tooling requirements (TRs) from the casting engineer include *low cost, short lead time, high accuracy, good surface finish, sufficient strength and light weight*. These can be quantified and mapped onto weighted tooling attributes (engineering characteristics of toolings) using a QFD-ANP framework for facilitating RT route selection. The tooling attributes (TAs) include *shape complexity, build time, surface roughness, dimensional accuracy, layer thickness*, and others. These are identified and grouped into three categories: *subjective, objective, and fuzzy*, which are handled in separate ways.

Assigning weights to tooling attributes: The purpose of attribute weights is to express the importance of each attribute relative to others. The difficulty in assigning relative weights for all attributes

Surface roughness: The surface roughness was measured using a surface roughness tester (Mahr Perthometer), as per DIN EN ISO 4288/ASME B461 and manufacturer's recommendations. Three measurements were taken on each surface and the average values of Ra and Rt on horizontal and vertical surfaces of each pattern were recorded (Figure 3).

4 RAPID TOOLING ROUTE SELECTION AND EVALUATION

A particular RT route may comprise of one, two or three stages. The process begins with the input of part CAD data and tooling requirements (Figure 5).

The routes are first short-listed based on part size, order quantity, and system availability. The short-listed routes are evaluated by calculating the compatibility index, and ranked. Then cost and fabrication time are estimated to facilitate a final decision by the user. The main steps are briefly explained here.

simultaneously is alleviated by pair-wise comparison in QFD-ANP framework. The QFD "house of quality" is used for representing the tooling requirements (TRs) in rows and tooling attributes (TAs) in the columns of a relationship matrix. The relative priorities between the attributes are built into the co-relationship matrix by analytic network process (ANP). The procedure for calculating the weights of tooling attributes (W_{ANP}) begins with determining the importance of TRs (w_1 matrix) assuming no interdependence, importance of TAs with respect to each TR assuming no dependence among TAs (W_2), inner dependency matrix of the TRs with respect to each TR (W_3), the inner dependency matrix of the TAs with respect to each TA (W_4), the interdependent priorities of the TRs ($W_c = W_3 \times w_1$), the interdependent priorities of the TAs ($W_A = W_4 \times W_2$), and finally the overall weights of the TAs ($W_{ANP} = W_A \times W_c$).

Short-listing of feasible RT routes: A database has been developed comprising 20 different RT routes, including direct and indirect (two or three step) routes, studied in the benchmarking experiments. The routes are short-listed based on casting type (sand or investment casting), and order quantity, specified by the casting engineer.

Compatibility evaluation to select the optimal route: The set of weighted tooling attributes are assessed for compatibility with respect to the corresponding process characteristics of the short-listed RT routes. The compatibility ranking of these routes (R1, R2, ..., Rn) for a given set of tooling requirements is obtained as follows:

- (a) Retrieve the weights of RT tooling attributes (obtained using QFD-ANP as explained earlier).
- (b) Calculate the compatibility values of the tooling attributes for each RT route capability stored in the database. The sum of weights of individual tooling attributes is normalized to one.
- (c) Calculate the process compatibility index of a feasible RT route, given by the sum of the products of weights and compatibility values of tooling attributes.
- (d) Obtain the route compatibility score by aggregating process compatibility index at each step.
- (e) Rank feasible routes by sorting them according to their route compatibility score.

The overall RT process compatibility score is determined using equation 2. Overall RT process compatibility =

$$\sum_{j=1}^n c_j \times w_j \dots \text{if } c_j > 0$$

$$= 0 \dots \dots \dots \text{if } c_j = 0 \quad (2)$$

where, c_j = compatibility value for each tooling attribute; w_j = relative weight of each tooling attribute obtained by QFD-ANP; and n = number of RT routes.

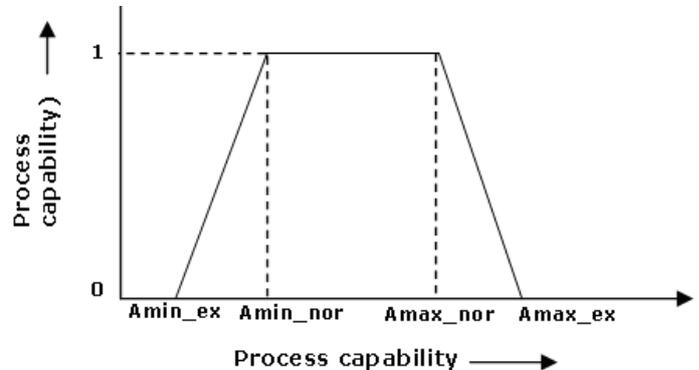
If the compatibility value for any tooling attribute c_j is zero, then the overall RT process compatibility is set to zero. An overall value of 1 indicates that the tooling and the process are fully compatible. A process compatibility value of 0 implies incompatibility (owing to one or more attributes being incompatible). Intermediate values (between 0 and 1) indicate a scope for improvement. The method of calculating the compatibility value for each category of tooling attributes is briefly explained next.

Subjective tooling attributes are generally expressed in terms of linguistic variables: for example 'process availability' can be expressed as NOT-AVAILABLE, WITHIN-REACH, CLOSELY-AVAILABLE, INHOUSE, etc. Quantification of these qualitative rating is mapped to a number between [0,1], indicating the increasing order of preference from NOT-AVAILABLE to INHOUSE availability of the process. Objective tooling attributes, which are defined without any ambiguity, are evaluated using normalization method (sum of all compatibility values in each tooling attribute is equal to one). For example, the tooling attributes 'build rate' is evaluated using this approach (minimum value being the most desired one), as per equation 3.

$$CV_p = 1/[V_p \cdot K] \quad \text{----- (3)}$$

where, CV_p = evaluated value of process p , V_p = value associated with process p , and $K = \sum_p [1/V_p]$. For example, if the build time of three processes $P1$, $P2$ and $P3$ is 54, 44 and 60 hours respectively, then $K = [1/54+1/44+1/60] = 0.0579$, and the evaluated values of $P1$, $P2$ and $P3$ will be 0.319, 0.392 and 0.287 respectively, indicating process $P2$ as the most preferred.

For fuzzy tooling attributes, the range of process capability values are mapped on a normalized scale of [0,1] such that every value in this range will represent a compatibility value between 0 and 1 (higher value indicating easier manufacturability with respect to the particular product requirement). In this work, three values: minimum, maximum and desirable (mean), have been used to represent the process capability range into trapezoidal fuzzy membership functions (Figure 4). Given the value of tooling attribute as A_{act} units, the process compatibility using the fuzzy membership function can be calculated using equation 4 as follows.



$$1 \dots \dots \dots \text{if } A_{act} \geq A_{min_nor} \text{ and } A_{act} \leq A_{max_nor}$$

$$(A_{act} - A_{min_ex}) / (A_{min_nor} - A_{min_ex}) \text{ if } A_{min_ex} < A_{act} < A_{min_nor}$$

$$(A_{max_ex} - A_{act}) / (A_{max_ex} - A_{max_nor}) \text{ if } A_{max_nor} < A_{act} < A_{max_ex}$$

$$0 \dots \dots \dots \text{otherwise} \quad (4)$$

5 COST ESTIMATION

A generic cost model for rapid tooling, applicable to a variety of processes, is given here.

$$C_T = (T_{pre} + T_{post})C_{labour} + T_{build}C_{build} + (1 + \frac{\alpha}{100})W_{part}C_{part_mat} + (1 + \frac{\alpha}{100})W_{supp}C_{supp_mat} \quad (5)$$

where, T_{pre} is the pre-processing time before building a part (hour), T_{post} is post-processing time, (such as support removal), in building a part (hour), C_{labour} is labour cost rate (INR/hour), T_{build} is build time (hour), C_{build} is machine hour rate (INR/h), W_{part} is the weight of the part material (kg), C_{part_mat} is material rate (INR/kg), W_{supp} is the weight of the support material (kg), C_{supp_mat} is the

cost of the support material (INR/kg), and α is percentage of material loss.

6 IMPLEMENTATION AND CASE STUDY

The entire methodology of rapid tooling selection and evaluation has been implemented in a software program developed using Visual C++ in Windows environment (Figure 5). It consists of five modules: (a) user input of tooling specifications, requirements, and attributes, (b) attribute weight calculation using QFD-ANP, (c) short-listing of feasible routes, (d) RT route compatibility evaluation, and (e) estimation of fabrication time and cost.

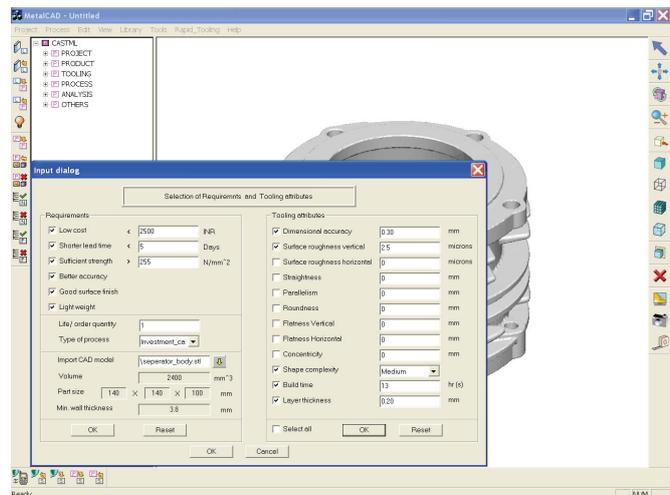
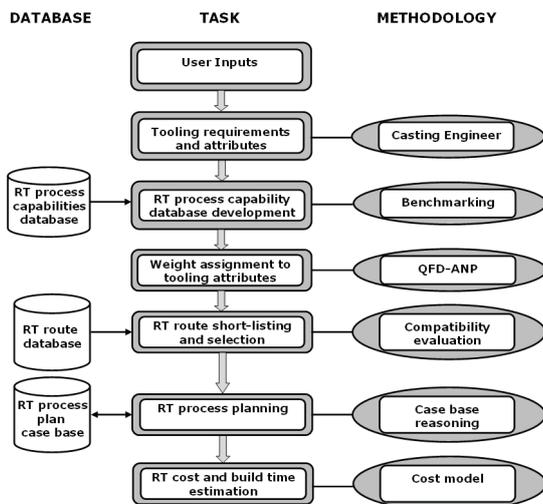


Figure 5. Steps in RT process planning and the software program

An industrial case study of an aluminium-alloy separator body casting of a hydraulic oil filter assembly belonging to army special vehicle was carried out to validate the methodology. It involved design data generation (3D scanning of part geometry, and material identification by spectrometry), selection of the most appropriate tooling for casting using QFD-ANP decision making metho-

dology, and casting process planning (Figure 6). The methodology indicated a direct route for investment casting wax pattern fabrication using Thermojet system as the best one, followed by SLA QuickCast process (Figure 7). Both patterns were fabricated accordingly, and used for making investment castings, for comparison purpose.

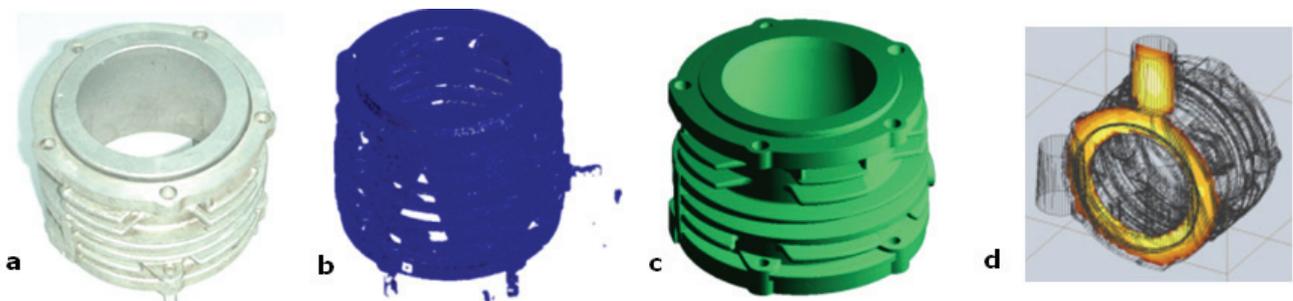


Figure 6. Reverse engineering of separator body:

(a) original part, (b) cloud of points, (c) CAD model, and (d) casting process planning

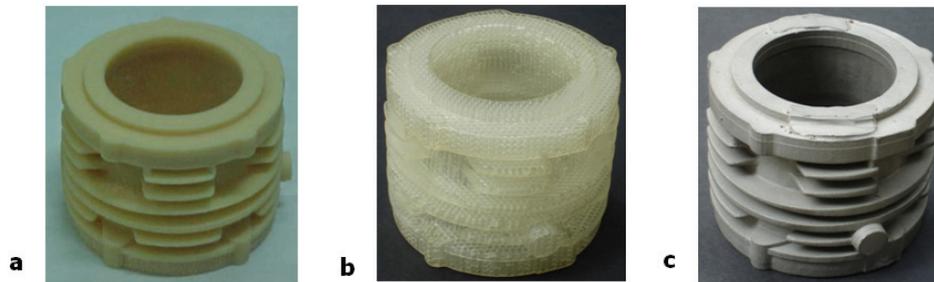


Figure 7. (a) Thermojet wax pattern, (b) SLA QC pattern, and (c) Investment cast metal part

7 CONCLUSIONS

A systematic approach for selecting the most suitable route for rapid fabrication of tooling for sand and investment casting processes. The approach involves prioritizing the tooling attributes, evaluating the compatibility, and estimating the cost of rapid tooling as well as conventional tooling, using appropriate cost models. A comprehensive database of RT process capabilities required for the purpose has been created through benchmarking experiments involving fabrication of an impeller pattern by 20 different routes. The entire methodology has been implemented in a Windows-based program and successfully demonstrated for an industrial case study of a separator body casting. To the best of our knowledge, a complete system for RT route selection driven by customer requirements and supported by a comprehensive benchmarked database of RT process capabilities has not been reported so far, especially for metal casting applications. The RT routes have already shown significant reduction in the lead-time for tooling fabrication, as well as low amortized cost of tooling for intricate parts required in small numbers. The present work is expected to facilitate better and faster decision-making in tooling process selection, leading to further reduction in lead-time and cost, while ensuring the desired quality of the tooling in line with tooling requirements. The RT process capability data base can be easily augmented with new RT routes as and when they are evolved in future. It fulfils an important gap in rapid tooling domain highlighted by previous researchers, and can lead to deeper penetration of RT technology in metal casting industry.

A major issue in rapid tooling is the accumulation of dimensional errors at each stage of the route. While this has been partially investigated in this work, there is scope for developing mathematical models for predicting the final dimensions of the tooling, and using the same to modify the original CAD model. This can be taken up in future studies.

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