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Rapid tooling route selection
for metal casting using QFD-ANP methodology

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Abstract. *An integrated methodology using quality function deployment (QFD) and analytic network process (ANP) is proposed to determine and prioritize the engineering requirements of a cast part, based on the customer needs, for selecting and evaluating an appropriate rapid prototyping (RP) based route for tooling fabrication. The QFD incorporates a planning matrix to translate the customer needs into measurable engineering requirements using a robust evaluation method based on ANP. Experimental data generated by carrying out benchmarking studies of widely used RP processes was used to facilitate assignment of relative weights in ANP. 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.*

Keywords: *Casting, Rapid prototyping; Process selection; Quality deployment function; Analytic network process.*

1. Introduction

Metal casting continues to be a widely-used process for producing a range of intricate parts. The fabrication of tooling (patterns and core-boxes) has however, become a major bottleneck, since it takes several days to weeks using either manual or CNC techniques, especially for intricate castings. In recent years, the ease and speed of tooling fabrication using rapid prototyping (RP) based techniques (hereafter referred to as rapid tooling techniques) has made a significant impact on rapid development of castings. A variety of new RP machines and materials are enabling fabrication of production grade foundry tooling within hours to days. This also facilitates comprehensive evaluation and improvement of product design earlier in its lifecycle. It has been shown that RT-enabled product development process can result in 60% reduction in overall lead time over traditional process (Hilton and Jacobs, 2000).

There are many *direct* and *indirect* rapid tooling (RT) methods for fabricating patterns for sand casting and investment casting process. Direct tooling involves use of RP models themselves as patterns and core boxes for sand casting or investment casting application. Indirect tooling makes use of RP models as intermediate masters for producing final patterns and core boxes, through soft tooling processes such as epoxy mass casting, polyurethane face casting, metal spray and silicone rubber moulding. *Semi-direct* tooling involves the use of RP systems to make dies for producing wax patterns for investment casting. The RP-based tooling routes can also be classified as single step, double step and triple step based on the number of steps required for reaching the final tooling that is used for casting (Pal *et al*, 2005).

The wide range of machines and materials available for each RP and RT process yields a large number of potential routes for fabricating a given piece of tooling. Each RT route has its own unique set of advantages, limitations and applications. The selection of the appropriate RT route must be driven by the customer requirements for the specific product. There is a need for a rational methodology for making the best choice among the available RT routes to obtain the desired cost, time and quality. For this purpose, an integrated QFD-ANP methodology has been evolved and demonstrated with an industrial example in this paper. The following section briefly reviews the related technical literature, including our previous work in this context, followed by the new approach and its results.

2. Previous and related work

Several researchers have attempted different facets of RP and RT route selection problem. This included developing analytical models for time/cost estimation, and generating experimental data by benchmarking and comparing different processes.

One of the earliest benchmarking studies carried out at Chrysler (Wohlers, 1992) compared various RP systems on the basis of total part cost. The cost elements included maintenance, material, build, pre-processing and post-processing. An object-oriented knowledge based RP process selection approach was proposed to assist designers in decision-making (Xu, *et al*, 1999). In another investigation, several decision factors influencing the tooling approach for sand casting were studied (Wang, *et al*, 1999). The factors included tooling material, tooling approach (gated, match-plate or cope-drag), tool durability, tooling cost, production volume, type of casting (prototype or production), part geometry, pattern shop capabilities, lead-time and accuracy. This study was limited to the selection of a particular RP process and material.

While there are several studies on specific applications of a particular RP and RT route and individual case studies, there is no report of a systematic approach for RP-RT route generation and evaluation, especially for casting application. The need for a systematic approach for sand casting tool development has been highlighted (Wang, *et al*, 1999a). Others also have clearly mentioned the need of a *Rapid Intelligent Tooling System* for deciding the optimal process approach (Kochan, *et al,* 1999). Kulkarni *et al* provided a detailed review of process planning techniques, concepts and the layered manufacturing process planning tasks of determining part orientation, supports, slicing and tool paths (Kulkarni *et al,* 2000*).* Dutta *et al,* highlighted the need for process planning methods with quantitative models that relate process variables to component quality characteristics for meeting product development objectives including cost, timelines, and quality in a layered manufacturing process (Dutta, *et al*, 2001).

A few researchers have successfully used AHP for material and manufacturing process selection. In casting domain, Akarte developed a web-based collaborative engineering framework, in which AHP was used as a decision model for process selection as well as evaluating potential suppliers (Akarte *et al*, 2001). Chougule and Ravi applied AHP and case based reasoning for casting process planning (Chougule and Ravi, 2003).

Two major decision-making techniques suitable for the proposed problem, that is, quality function deployment (QFD) and analytic network process (ANP) are briefly described next.

2.1 Quality deployment function (QFD)

QFD is a decision support tool, which helps manufacturers to effectively consider customer requirements in product and process development (Govers, 2001). The QFD begins with "house of quality" (HoQ) by representing the customer needs in rows and alternative attributes in the columns of a relationship matrix. The relative priorities between the attributes are built into the co-relationship matrix. Finally the decision is based on weighted sum model after normalization of relationship matrix. Many researchers have attempted quantifying the planning issues in HoQ within the past decade, mainly focusing on customer needs. Chan *et al* and Khoo and Ho employ fuzzy set theory for rating the customer needs (Chan *et al*, 1999; Khoo and Ho, 1996). Other researchers used analytic hierarchy process to determine the degree of importance of the customer needs (Armacost, 1994; Lu, *et al*, 1994). Besides establishing the relationship between customer requirements and design characteristics, QFD has also been used for many other applications as well. Martin used QFD as a quality-planning tool to transform customer requirements into product and process features (Martin and Wilhelm, 1995). Bahador used QFD in benchmarking rapid prototyping processes for evaluating their performance (Bahador and Houshyar, 1996).

2.2 Analytic network process (ANP)

The analytic network process (Saaty, 1996 and Saaty, 1999) is a more general form of the analytic hierarchy process (AHP) introduced earlier (Saaty, 1980), for choosing the most suitable alternative fulfilling the objectives in a multi-criteria decision making problem. The ANP permits more complex interrelationships (than AHP) among the decision levels and attributes (Meade and Sarkis, 1999). The relative importance of an element is measured on a ratio scale similar to AHP; it however, does not impose a strict hierarchical structure as in AHP. Figures 1a and 1b show the difference in structure between a hierarchy and network. Nodes of the network represent components, whereas loops signify inner dependence of the elements in a cluster. The ANP handles interdependence among elements by obtaining the composite weights through the development of a *super matrix*. This concept has been paralleled to the Markov chain process (Saaty, 1983).

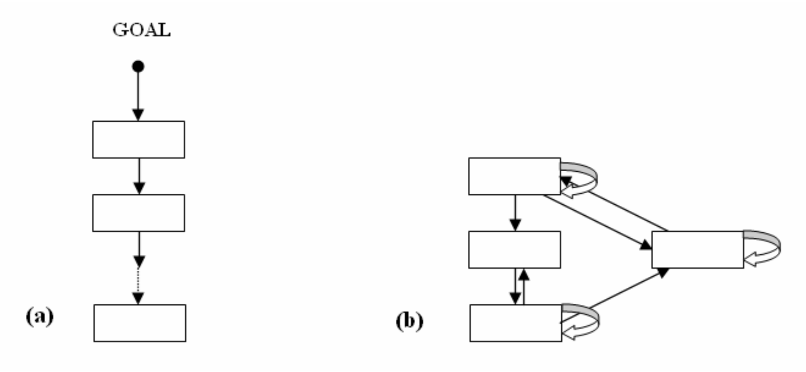


Figure 1. (a) A Hierarchy (b) A Non-linear network

In ANP, the relative importance values are determined (in a manner similar to AHP) using pair-wise comparisons using a scale of 1-9, where a score of 1 indicates equal importance between the two elements, and 9 represents extreme importance of one element compared to the other. The relations $a_{ij} = 1/a_{ji}$ (where a_{ij} denotes the importance of the i^th^ element compared to the j^th^ element), and $a_{ii} = 1$. In the aggregated pairwise comparison matrix, the value for an (i, j)-pair is in the range 1 – 9 if the influence of i^th^ element is more than that of the factor j^th^ element, while the value of that pair is in the range 1–1/9 if the influence of factor i^th^ is less than that of the factor j^th^ element. However, the value of an (i, i) pair is 1 and given the (i, j)-value, the corresponding (j, i)-value is the reciprocal. Table 1 gives the ANP scale of relative importance values.

Table 1 ANP Scale of relative importance values

Intensity	*Definition*
1	Equal
2	Equal to moderately dominant
3	Moderately dominant
4	Moderately to strongly dominant
5	Strongly dominant
6	Strongly to very strongly dominant
7	Very strongly dominant
8	Very strongly to extremely
9	Extremely dominant

After completing the pair-wise comparisons, the relative importance weight ***w*** is calculated. Saaty (Saaty, 1983) has proposed several algorithms for approximating ***w***. In our approach we are using two stage calculations that involved forming a new **n**×**n** matrix by dividing each element in a column by the sum of the column elements and, then, summing the elements in each row of the resultant matrix and dividing by the **n** elements in the row. This is referred to as the process of averaging over normalised columns, and given by:

$$w_i = \frac{\sum_{\mathrm{i}=1}^{I} \left(\frac{a_{ij}}{\sum_{j=1}^{J} a_{ij}} \right)}{J}$$

Where,

w_i = weighted priority for component i
J = index number of columns (components)
I = index number of rows (components)

In our examples, it is assumed that the pair-wise comparisons are consistent. However, Saaty has given detail explanation of inconsistencies in relationships and their calculations (Saaty, 1983).

Lee and Kim used ANP for selecting an information system project (Lee and Kim, 2000). Meade and Sarkis used ANP for selection of various project alternatives in an agile manufacturing process (Meade and Sarkis, 1999). Meade and Adrien Presley applied ANP for R&D project selection (Meade and Adrian, 2002).

3. Proposed QFD-ANP methodology for RT

The reason for choosing ANP in our methodology for RT process selection is its suitability and accuracy in offering solutions in a complex multi-criteria decision environment. Some of the *advantages* of ANP as compared to AHP are: ANP is general form of AHP with deals with dependence within a set of elements (inner dependence) and among different sets of elements (outer dependence), permits looser network structure. One of the major *disadvantages* of ANP is: ANP requires more number of pair-wise comparison matrices as compared to the AHP process; the pair-wise comparison of attributes is subjective in nature and hence the accuracy of the results depends on the user’s experience in the area concerned.

3.1 Representation of ANP in QFD

The ANP representation in QFD model is based on the structure of a hierarchy with inner dependencies within components and no feedback. Here, the customer needs

(CNs) corresponds to the alternatives, which have inner dependencies within themselves. The first step of the network representation in QFD model is the identification of the CNs and product technical requirements (PTRs). The next step consists of determining the importance of CNs (Saaty and Takizawa, 1986; Lee and Kim, 2000). The body of the house obtained by weights will be filled by comparing the PTRs with respect to each CN. Finally, the interdependent priorities of the PTRs are obtained by analyzing dependencies among the CNs and PTRs. The general representation network of QFD model is given in figure 2.

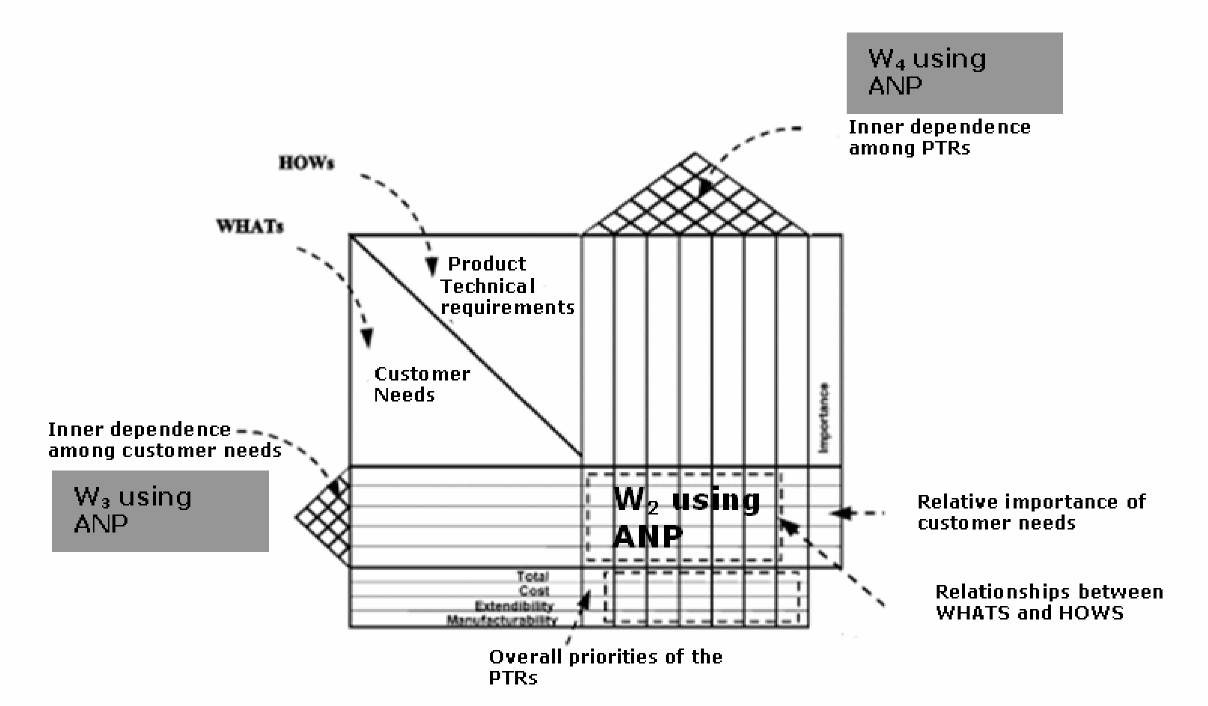


Figure 2. Representation of ANP in QFD (Karsak *et al*, 2002)

The super matrix ***W*** of the QFD model used in this work is given below.

$$W = \begin{array}{c|ccc|} & G & CN & PT \\ Goal\ (G) & 0 & 0 & 0 \\ CNs & w_1 & W_3 & 0 \\ PTRs & 0 & W_2 & W_4 \end{array}$$

Where $\boldsymbol{w_1}$ is a vector of the CNs that represents the impact of the goal, namely manufacturing a product that satisfies the customer, $\boldsymbol{W_2}$ is a matrix that denotes the impact of the CNs on each of the PTRs and $\boldsymbol{W_3}$ and $\boldsymbol{W_4}$ are the matrices that represent the inner dependencies of the CNs and the inner dependence of the PTRs, respectively.

Experimental data forms the basis of assigning relative weights in the pair-wise comparison matrices. This data was generated in a previous investigation by carrying out benchmarking studies of some of the most widely used RT processes (Pal and Ravi, *et al*, 2005). The proposed QFD-ANP approach for RT process selection involves translating the customer need into product technical requirements (PTRs) or engineering characteristics. The weighted PTRs are then used for prioritizing RP processes, as shown in figure 3.

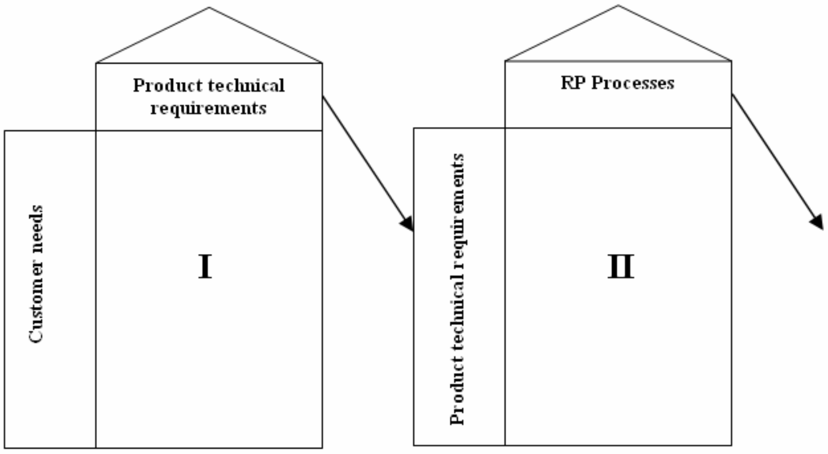


Figure 3: Voice of customer deployment in HoQ, Stage I: Prioritizing PTRs with respect to CNs, Stage II: Prioritization of RP processes with respect to PTRs

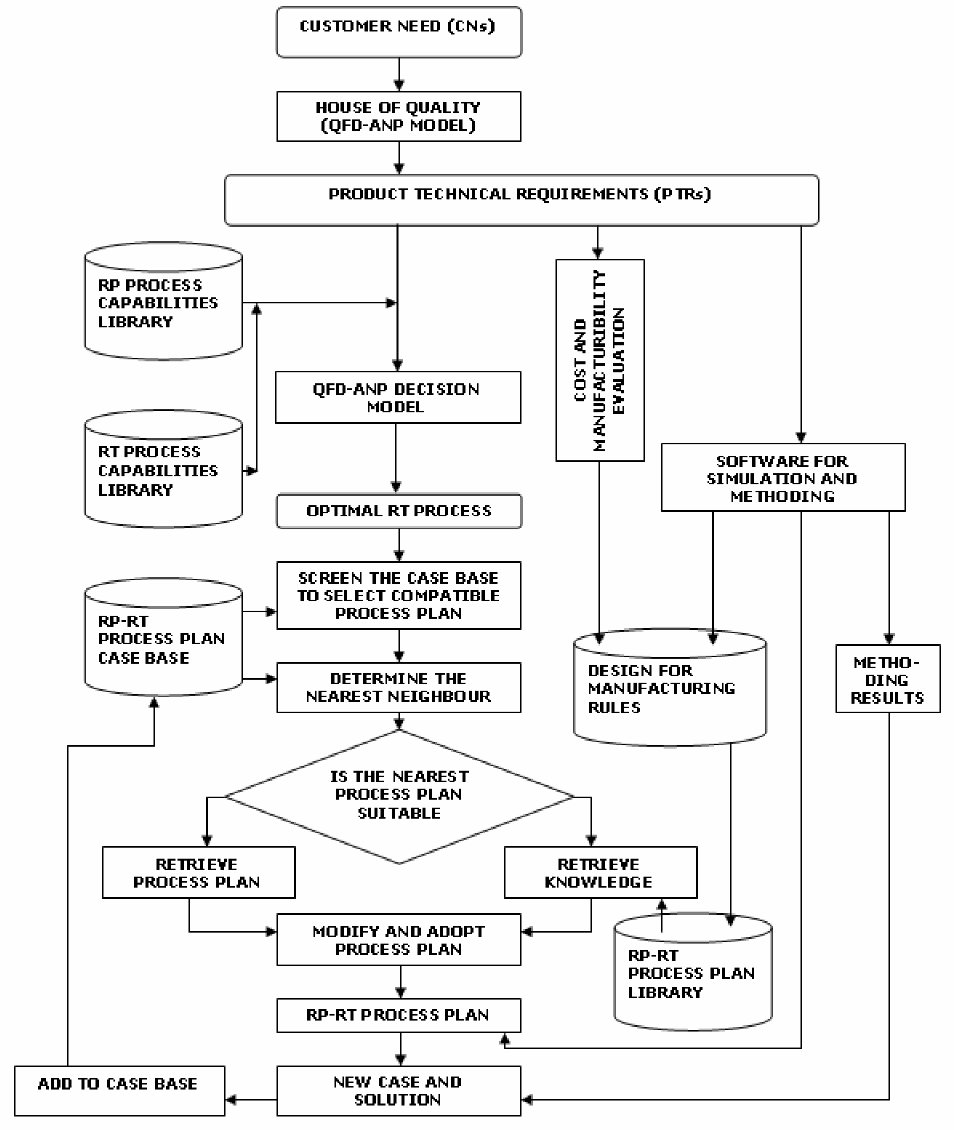


Figure 4. Framework for RP-RT process selection and process planning for rapid manufacture of intricate casting part

The methodology begins with a house of quality (HoQ), which is a planning matrix converting and prioritizing the customer needs (CNs) against a set of measurable RP product development attributes (such as product material, geometry, quality and production quantity) using QFD and ANP. This proposed approach is part of the detailed framework for RP-RT process selection and process planning for rapid manufacture of intricate casting part as shown in figure 4. The screen image of the RP process planning system is shown in figure 5.

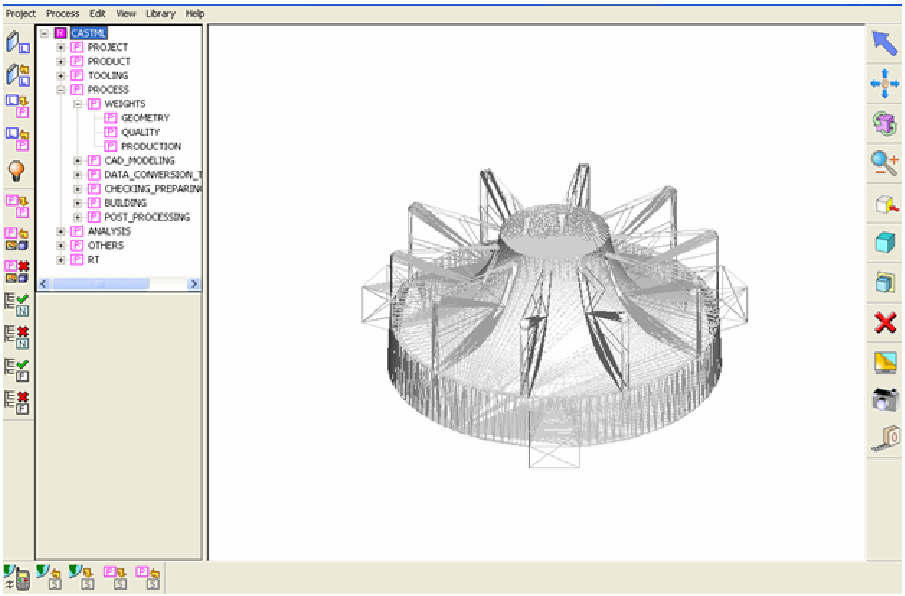


Figure 5. RP process planning system

3.2 The Decision algorithm

The decision algorithm consists of the following steps:

1. Identify the customer needs (CNs) and the product technical requirements (PTRs)

2. Determine the importance degrees of CNs by assuming that there is no dependence among the CNs *(calculation of w_1)*

3. Determine the importance degrees of PTRs with respect to each CN by assuming that there is no dependence among the PTRs *(calculation of W_2)*

4. Determine the inner dependency matrix of the CNs with respect to each CNs *(calculation of W_3)*

5. Determine the inner dependency matrix of the PTRs with respect to each PTR *(calculation of W_4)*

6. Determine the interdependent priorities of the CNs *(calculation of $Wc = W_3 \times w_1$)*

7. Determine the interdependent priorities of the PTRs *(calculation of $W_A=W_4 \times W_2$)*

8. Determining the overall priorities of the PTRs *(calculation of* $W^{ANP} = W_A \times W_c$*)*

4. Rapid tooling benchmarking studies

Experimental work was carried out by benchmarking some of the most widely used RT methods used for fabrication of direct and indirect patterns for metal casting. The experimental data and experience generated is utilized for evaluating and validating the proposed QFD-ANP framework by carrying out a case study on rapid development of a separator body metal casting part. These case studies are briefly explained in this section.

The part solid model of an industrial impeller part shown in figure 6 was used for fabricating non-expendable patterns for sand casting as well as expendable patterns for investment casting using RP techniques under *direct tooling method*. The non-expendable RP patterns were fabricated using SLA, FDM and LOM RP techniques (figure 7). The patterns FDM2 and FDM3 are made on the same machine, but the latter is made with widely spaced cross-hatching for the interior region, reducing its fabrication time. The expendable RP patterns were fabricated using SLA QuickCast and Thermojet (figure 7). Table 2 shows the summary of RP techniques and relevant parameters. Table 3 gives cost and time comparison and table 4 gives surface quality of the RP part.

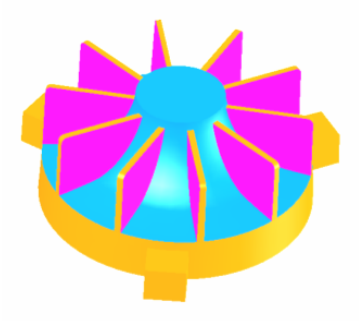


Figure 6. 3D Solid model of an impeller

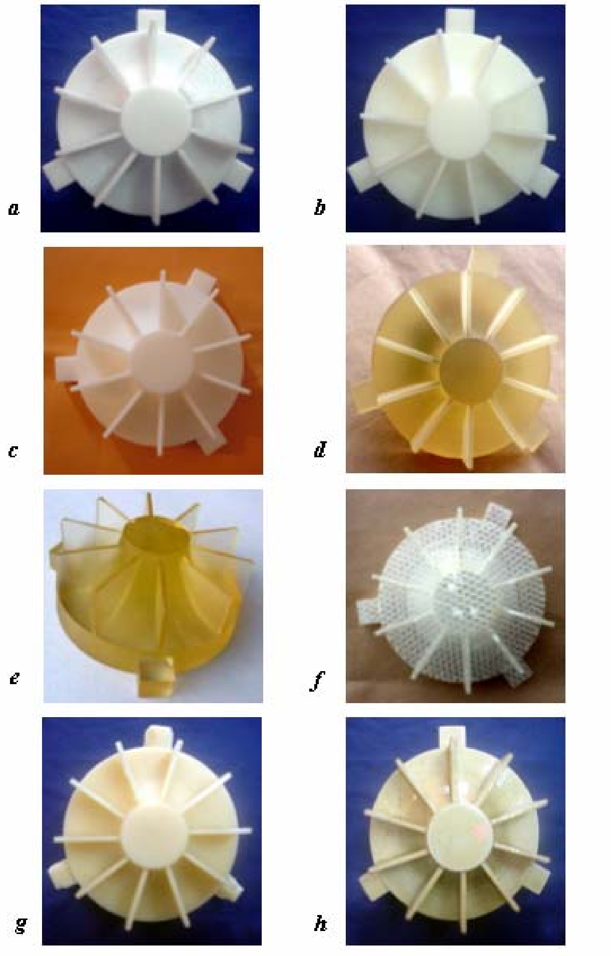


Figure 7. Fabrication of RP patterns: (a) FDM1, (b) FDM2, (c) FDM3, (d) SLA1, (e) SLA2, (f) SLAQ1, (g) TJP1 and (h) LOM1

Table 2 Summary of techniques used for producing RP patterns

	RP Machine	System Manufacturer	Material	Accuracy XY-plane (mm)	Accuracy Z-plane (mm)	Layer Thickness (mm)
FDM1	FDM Titan	Stratasys	Polycarbonate	0.15	0.13	0.25
FDM2	FDM 250		ABS(P400)	0.15	0.13	0.25
FDM3	FDM 250		ABS (P400)	0.15	0.13	0.25
SLA1	SLA 5000	3D Systems	SLA5530 epoxy rein	0.1	0.10	0.10
SLA2	SLA 250		SLA5530 epoxy resin	0.1	0.10	0.10
SLAQ1	SLA 5000		SLA5530 epoxy resin	0.1	0.10	0.10
TJP1	Thermojet		TJ88 wax	0.1	0.10	0.10
LOM1	LOM-2030H	Helisys Technologies	Paper (LPH series)	0.25	0.30	0.20

The route of *direct* and *indirect* tooling method for producing patterns for casting is shown in figure 8. In the Indirect method, the RP pattern ‘SLA1’ made by Stereolithography RP is used as a master to fabricate a silicone rubber mould. Since the impeller is flat at one end, the silicone rubber mould is made in a single piece without a parting line. The SLA1 part is placed in a cylindrical flask, and degassed silicone rubber slurry is slowly poured into the flask engulfing the master pattern, and then baked in a temperature controlled oven. The silicone rubber mould can be used for producing 40-50 wax patterns before the mould surface starts showing wear. These wax patterns are used for investment casting (figure 8).

Table 3 Cost and time comparison

	Machine cost ($1000)	Machine rate ($/hr)*	Time taken (hr)	Material rate ($/kg)	Part weight (kg)	Total cost ($)
FDM1	100	12.56	7	330	0.19	**150.62**
FDM2	55	6.90	16	300	0.09	**137.40**
FDM3	55	6.90	8	300	0.09	**82.20**
SLA1	400	50.23	2.5	250	0.21	**178.08**
SLA2	200	25.11	4	250	0.21	**152.94**
SLAQ1	400	50.23	2.5	250	0.05	**138.08**
TJP1	60	7.53	6	225	0.16	**81.18**
LOM1	120	15.07	6	20	0.17	**93.82**
Conventional wooden pattern						**200.00**
Conventional metal pattern						**450.00**

Table 4 Surface quality of RP parts

	Layer Thickness (mm)	**Condition**	**Ra (μm)**	**Rt (μm)**
FDM1	0.25	Unfinished	17.307	83.423
FDM2	0.25	Unfinished	19.847	87.140
FDM3	0.25	Unfinished	17.540	91.891
SLA1	0.10	Polished	2.578	17.596
SLA2	0.10	Polished	4.001	21.304
SLAQ1	0.10	Polished	4.469	26.221
TJP1	0.10	Unfinished	2.578	17.576
LOM1	0.20	Polished and Varnished	1.374	10.886

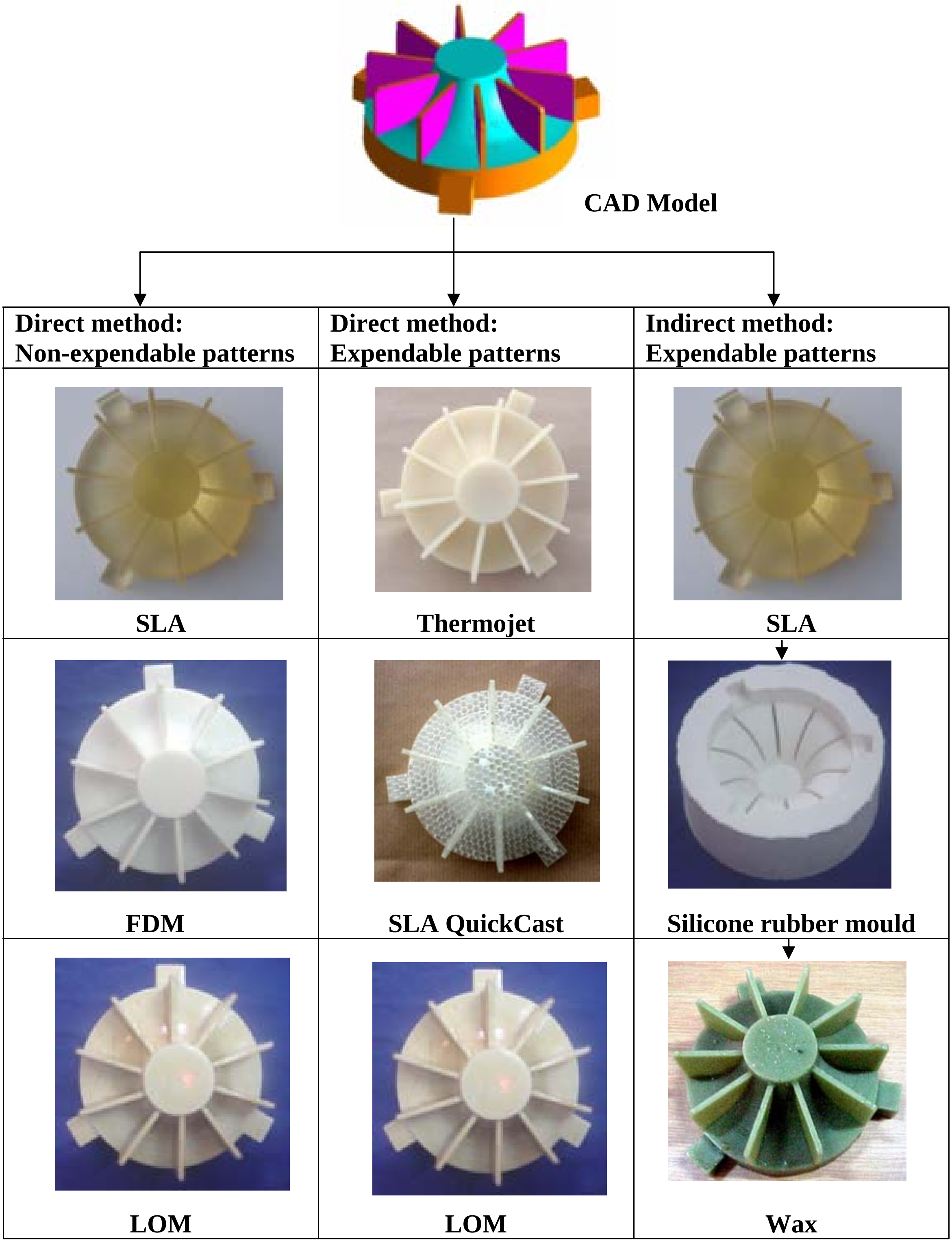


Figure 8: Some direct and indirect routes for fabricating casting patterns

5. Industrial case study

The QFD-ANP method described in earlier section is demonstrated below with an industrial part called separator body. The separator body (figure 9a) of a hydraulic oil filter assembly belonging to an army vehicle was chosen for studying the application of computer-aided technologies for rapid development of tooling for metal casting. The part had no drawings or any other data related to its manufacturing. The part was required to be developed in a short lead time with high accuracy and good surface finish. The investigation involved mainly three steps: (i) design data generation (part geometry by 3D scanning, and material identification by spectrometry), (ii) selection of the most appropriate tooling for casting using QFD-ANP decision making methodology (iii) tooling fabrication (using rapid prototyping) and investment casting (after process planning and simulation).

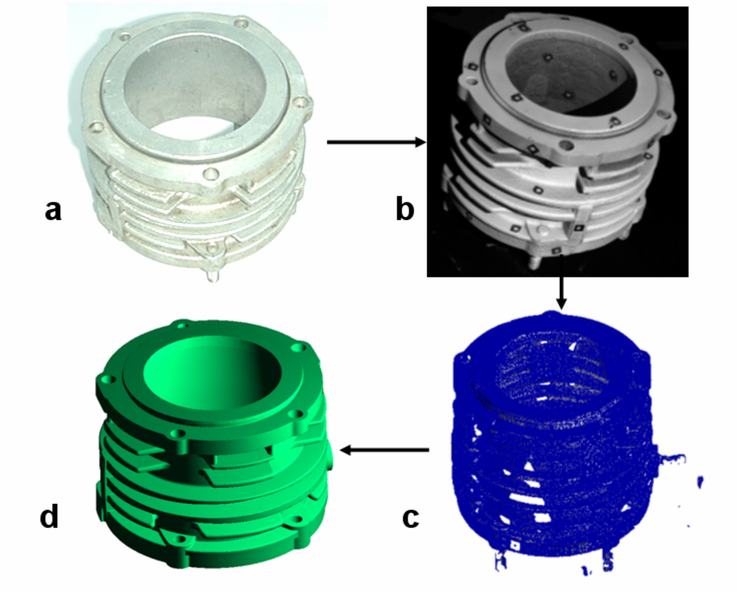


Figure 9: Reverse engineering of separator body (a) original part, (b) original part with markers (c) cloud of points, (d) CAD model

Since the part has highly intricate geometry, it is difficult to decide upon which RT process to use. Here the QFD-ANP methodology was very useful in suggesting the best RT process for tooling fabrication. The application of the methodology is demonstrated in next section.

5.1 Prioritization of product technical requirements

Step1. *Identify the customer needs (CNs) and the product technical requirements (PTRs)*

In order to understand the customer need, many discussions were held with the user of the separator body and the following six customer needs were identified: low cost, shorter lead time, better accuracy, good surface finish, sufficient strength and aesthetic quality. Having identified the customer needs and considering that the part is highly intricate, the PTRs that are likely to affect these needs are identified as shape complexity, material, surface finish, dimensional accuracy, and layer thickness. The network between the CNs and the PTRs is shown in figure 8.

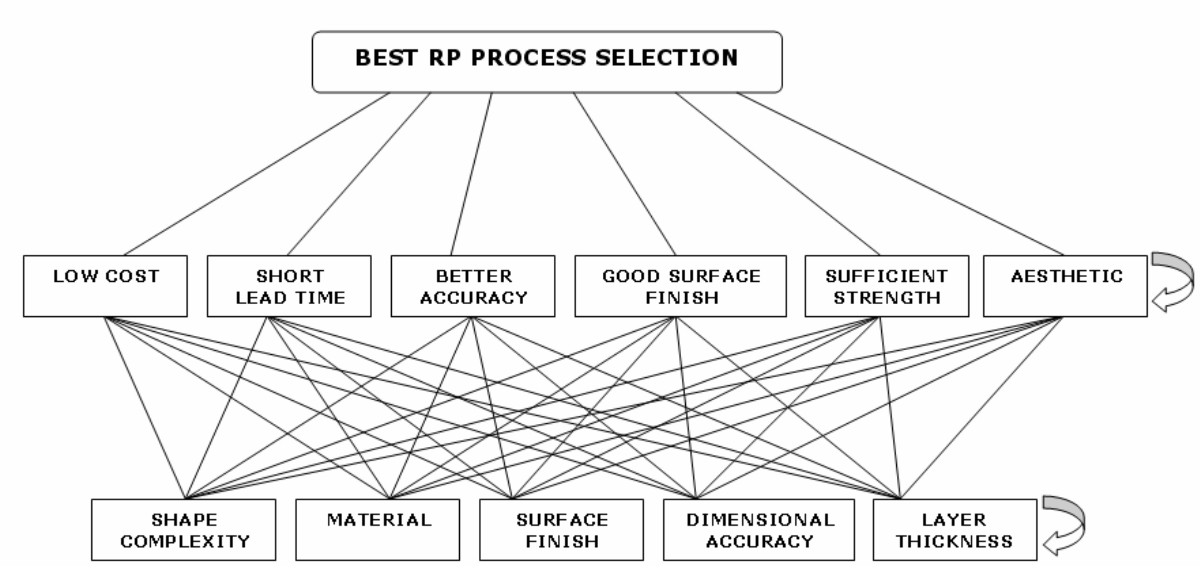


Figure 10: The ANP network for Goal, Customer need and product technical requirement

Step2. *Determine the importance degrees of CNs by assuming that there is no dependence among the CNs (calculation of* w_1*)*

Assuming that there is no dependence among the customer needs, the following eigenvector for the customer needs is obtained by performing pair wise comparisons with respect to the goal of achieving the best RP process and shown in the table 5.

Table 5 Importance degrees of CNs

User Attributes	**User Attributes**						**Relative importance weights,** w_1
	Low Cost	Shorter Lead time	Better Accuracy	Good Surface finish	Sufficient strength	Aesthetic	
Low Cost	1	5	1	3	2	1	**0.239**
Shorter Lead time	1/5	1	7	7	5	7	**0.311**
Better Accuracy	1	1/7	1	4	5	1	**0.306**
Good Surface finish	1/3	1/7	1/4	1	7	9	**0.306**
Sufficient Strength	1/2	1/5	1/5	1/7	1	5	**0.0734**
Aesthetic	1	1/7	1	1/9	1/5	1	**0.0706**

Step3. *Determine the importance degrees of PTRs with respect to each CNs by assuming that there is no dependence among the PTRs (calculation of* W_2*).*

Assuming that there is no dependence among the PTRs, they are compared with respect to each customer need yielding the column eigenvectors regarding each customer need. For example, one of the possible questions for determining the degree of relative importance of the PTRs for low cost can be as follows: "What is the relative importance of surface finish when compared to shape complexity with respect to the customer need low cost?", yielding 4 as shown in table 6. The transpose of this data shown in table 6 will be placed in the body of the HoQ. The degree of relative importance of the PTRs for the remaining customer needs are calculated in a similar way and presented in table 7.

Table 6 Importance degrees of PTRs with respect to each CN

Low cost	Shape complexity	Material	Surface finish	Accuracy	Layer thickness	Relative importance weight
Shape complexity	1	1/3	1/4	1/7	1/6	**0.046**
Material	3	1	1/3	3	1/6	**0.128**
Surface finish	4	3	1	2	1/3	**0.203**
Accuracy	7	1/3	1/2	1	1/6	**0.127**
Layer thickness	6	6	3	6	1	**0.495**

Table 7 Degree of relative importance of the PTRs with respect to customer needs

$\mathbf{W_2}$	Low cost	Shorter lead time	Better accuracy	Good surface finish	Sufficient strength	Aesthetic
Shape complexity	0.046	0.068	0.059	0.083	0.117	0.182
Material	0.128	0.041	0.046	0.050	0.300	0.059
Surface finish	0.203	0.297	0.154	0.244	0.134	0.416
Accuracy	0.127	0.200	0.318	0.266	0.082	0.082
Layer thickness	0.495	0.391	0.420	0.355	0.365	0.441

***Step4**. Determine the inner dependency matrix of the CNs with respect to each CN (calculation of W_3).*

The inner dependence among the customer needs is determined through analyzing the impact of each customer need on other customer needs by using pairwise comparisons as shown in table 8. Similarly, after completing all the pair-wise comparisons, the resulting eigen-vectors obtained from pairwise comparisons are presented in table 9.

Table 8 The inner dependence matrix of the customer needs with respect to low cost

Low cost	Low Cost	Shorter Lead time	Better Accuracy	Good Surface finish	Sufficient strength	Aesthetic	**Relative importance weights**
Low Cost	1	3	5	3	2	2	**0.332**
Shorter Lead time	1/3	1	3	3	2	5	**0.241**
Better Accuracy	1/5	1/3	1	1/3	3	2	**0.109**
Good Surface finish	1/3	1/3	3	1	3	2	**0.156**
Sufficient Strength	1/2	1/2	1/3	1/3	1	2	**0.094**
Aesthetic	1/2	1/5	1/2	1/2	1/2	1	**0.071**

Table 9 The inner dependence matrix of the customer needs

W_3	Low Cost	Shorter Lead time	Better Accuracy	Good Surface finish	Sufficient strength	Aesthetic
Low Cost	0.332	0.242	0.152	0.183	0.196	0.107
Shorter Lead time	0.241	0.401	0.100	0.182	0.216	0.061
Better Accuracy	0.109	0.118	0.348	0.147	0.358	0.178
Good Surface finish	0.156	0.121	0.239	0.402	0.131	0.220
Sufficient Strength	0.094	0.075	0.111	0.055	0.351	0.085
Aesthetic	0.071	0.030	0.047	0.030	0.044	0.345

Step5. *Determine the inner dependency matrix of the PTRs with respect to each PTR (calculation of W_4).*

The inner dependence among the PTRs is determined through analyzing the impact of each PTR on other PTR by using pairwise comparisons, typical calculation shown in table 10. The resulting eigenvectors obtained from pairwise comparisons are presented in table 11.

Table 10. The inner dependence matrix of the PTRs with respect to shape complexity

SHAPE COMPLEXITY	Shape complexity	Material	Surface finish	Accuracy	Layer thickness	**Relative importance weight**
Shape complexity	1	5	3	2	2	**0.361**
Material	1/5	1	1/3	1/5	1/7	**0.045**
Surface finish	1/3	3	1	1/2	1/3	**0.109**
Accuracy	1/2	7	3	2	1	**0.189**
Layer thickness	1/2	7	3	2	1	**0.290**

Table 11. The inner dependence matrix of the PTRs

W_4	Shape complexity	Material	Surface finish	Accuracy	Layer thickness
Shape complexity	0.361	0.081	0.088	0.103	0.182
Material	0.045	0.848	0.069	0.060	0.107
Surface finish	0.109	0.184	0.529	0.152	0.103
Accuracy	0.189	0.307	0.122	0.480	0.158
Layer thickness	0.290	0.834	0.187	0.200	0.447

Step6. *Determine the interdependent priorities of the CNs (calculation of* $W_c = W_3 \times w_1$*)*

The interdependent priorities of the CNs is given as below

$$W_c = \mathrm{W}_3 \times \mathrm{W}_1 = \begin{bmatrix} 0.278 \\ 0.291 \\ 0.252 \\ 0.296 \\ 0.128 \\ 0.077 \end{bmatrix}$$

Step7. *Determine the interdependent priorities of the PTRs (calculation of* $W_A = W_4 \times W_2$*)*

The interdependent priorities of the PTRs, are calculated as

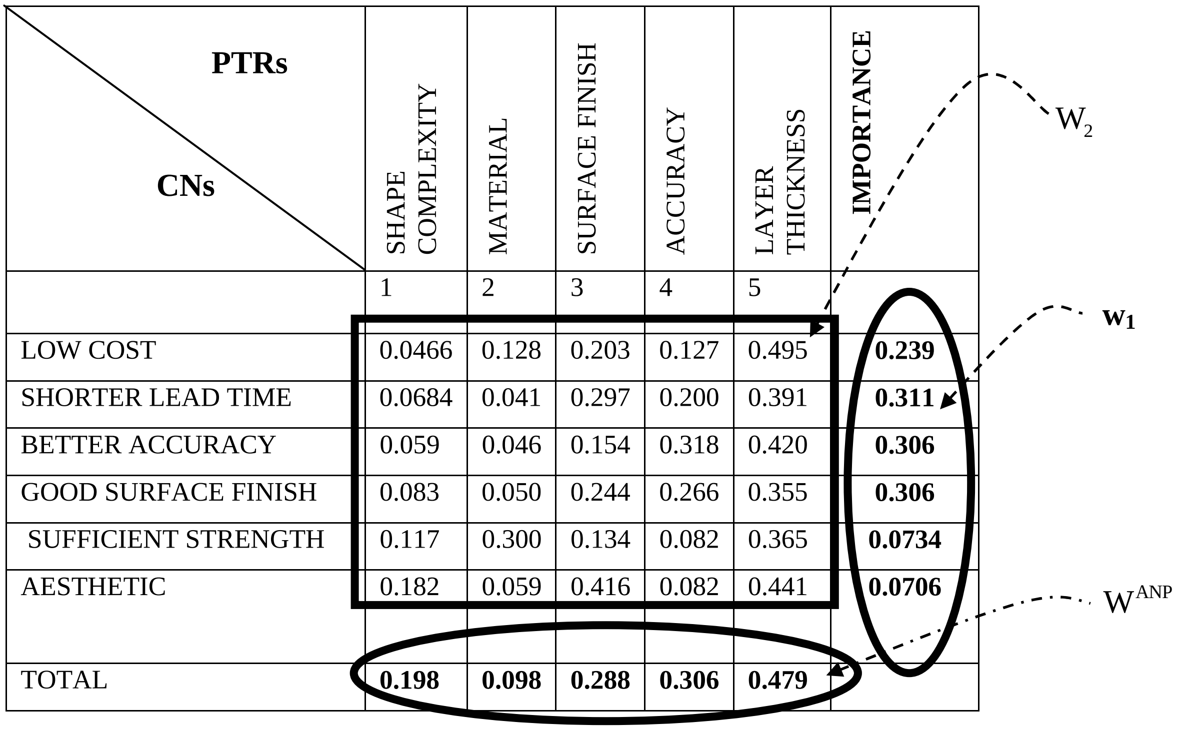
$$W_A = W_4 \times W_2 = \begin{bmatrix} 0.148 & 0.145 & 0.147 & 0.147 & 0.153 & 0.195 \\ 0.185 & 0.112 & 0.116 & 0.116 & 0.312 & 0.139 \\ 0.206 & 0.242 & 0.187 & 0.224 & 0.188 & 0.308 \\ 0.212 & 0.219 & 0.263 & 0.244 & 0.227 & 0.212 \\ 0.404 & 0.324 & 0.335 & 0.323 & 0.488 & 0.393 \end{bmatrix}$$

Step8. *Determining the overall priorities of the PTRs (calculation of* $\mathrm{W}^{\mathrm{ANP}} = \mathrm{W}_{\mathrm{A}} \times \mathrm{W}_{\mathrm{C}}$*).*

The overall priorities of the PTRs, reflecting the interrelationships within the HoQ, are obtained by

$$\mathrm{W}^{\mathrm{ANP}} = \mathrm{W}_{\mathrm{A}} \times \mathrm{W}_{\mathrm{C}} = \begin{bmatrix} 0.198 \\ 0.198 \\ 0.288 \\ 0.306 \\ 0.479 \end{bmatrix}$$

Table 12. Completely filled HoQ



PTRs / **CNs**	SHAPE COMPLEXITY	MATERIAL	SURFACE FINISH	ACCURACY	LAYER THICKNESS	**IMPORTANCE**
	1	2	3	4	5	
LOW COST	0.0466	0.128	0.203	0.127	0.495	**0.239**
SHORTER LEAD TIME	0.0684	0.041	0.297	0.200	0.391	**0.311**
BETTER ACCURACY	0.059	0.046	0.154	0.318	0.420	**0.306**
GOOD SURFACE FINISH	0.083	0.050	0.244	0.266	0.355	**0.306**
SUFFICIENT STRENGTH	0.117	0.300	0.134	0.082	0.365	**0.0734**
AESTHETIC	0.182	0.059	0.416	0.082	0.441	**0.0706**
TOTAL	**0.198**	**0.098**	**0.288**	**0.306**	**0.479**	

The ANP analysis results shows that the most important engineering parameter is the layer thickness with a relative value of 0.479, followed by dimensional accuracy, surface finish, material and shape complexity. The values filled in the HoQ are shown in table 12.

5.2 RT process selection

The QFD-ANP model is demonstrated below with an example of RP process selection by mapping the product technical requirements (PTRs) using house of quality. The Prioritized PTRs: shape complexity, material, surface finish, dimensional accuracy, and layer thickness, that is, weight vector w_1 from the previous section is used for selecting the suitable RP process among Thermojet printing (TJP), Fused deposition modeling (FDM), Laminated object modeling (LOM), Stereolithography apparatus (SLA) and Stereolithography QuickCast (SLAQ).

Step1. *Determine the importance degrees of PTRs by assuming that there is no dependence among the PTRs (calculation of w1)*

The W^{ANP} weights of the PTRs of the first stage is considered here as w_1 in the second stage.

$$\text{Therefore, } w_1 = \begin{bmatrix} \text{Shape Complexity} \\ \text{Material} \\ \text{Surface Finish} \\ \text{Accuracy} \\ \text{Layer thickness} \end{bmatrix} = \begin{bmatrix} 0.198 \\ 0.098 \\ 0.288 \\ 0.306 \\ 0.476 \end{bmatrix}$$

Step2. *Determine the importance degrees of RP processes with respect to each PTRs by assuming that there is no dependence among the RP processes (calculation of w2).*

Assuming that there is no dependence among the RP Processes, they are compared with respect to each PTR yielding the column eigenvectors regarding each PTR. For example, One of the possible questions for determining the degree of relative importance of the RP process for Accuracy can be as follows: “What is the relative importance of TJP when compared to SLA with respect to the product engineering requirement ‘Shape complexity’?”, yielding 5 as shown in table 13. The degree of relative importance of the RP processes for the remaining PTRs are calculated in a similar way and presented in table 14. The transpose of this data shown in table 13 will be placed in the body of the HoQ.

Table 13 Importance degrees of RP processes with respect to each PTR

Shape Complexity	TJP	FDM	LOM	SLA	SLAQ	**Relative importance weight**
TJP	1	5	7	7	5	**0.416**
FDM	1/5	1	3	5	7	**0.250**
LOM	1/7	1/3	1	1/3	1/5	**0.044**
SLA	1/7	1/5	3	1	1/3	**0.071**
SLAQ	1/5	1/7	5	3	1	**0.132**

Table 14 Degree of relative importance of the RP processes with respect to PTRs

$\mathbf{W_2}$	Shape complexity	Material	Surface finish	Accuracy	Feature tolerance
TJP	0.416	0.234	0.450	0.662	0.443
FDM	0.250	0.473	0.042	0.049	0.049
LOM	0.044	0.145	0.087	0.102	0.105
SLA	0.071	0.055	0.169	0.147	0.174
SLAQ	0.132	0.091	0.250	0.252	0.226

***Step3**. Determine the inner dependency matrix of the PTRs with respect to each PTRs (calculation of w3).*

The inner dependence among the PTRs **W_4** is already calculated in the first stage section, which is now used here as **W_3**. as shown in table 15.

Table 15 The inner dependence matrix of the PTRs

W_3	Shape complexity	Material	Surface finish	Accuracy	Layer thickness
Shape complexity	0.361	0.081	0.088	0.103	0.182
Material	0.045	0.848	0.069	0.060	0.107
Surface finish	0.109	0.184	0.529	0.152	0.103
Accuracy	0.189	0.307	0.122	0.480	0.158
Layer thickness	0.290	0.834	0.187	0.200	0.447

Step4. *Determine the inner dependency matrix of the RP processes with respect to each RP process (calculation of w4).*

The inner dependence among the RP processes is determined through analyzing the impact of each RP process on other RP process by using pair wise comparisons, with typical calculation shown in table 16. The resulting eigenvectors obtained from pair wise comparisons are presented in table 17.

Table 16 The inner dependence matrix of the RP processes with respect to SLA

SLA	TJP	FDM	LOM	SLA	SLAQ	**Relative importance weight**
TJP	1	5	3	3	3	**0.388**
FDM	1/5	1	1/3	1/5	1/3	**0.053**
LOM	1/3	3	1	1/3	1/5	**0.097**
SLA	1/3	5	3	1	1/5	**0.167**
SLAQ	1/3	3	5	5	1	**0.293**

Table17 The inner dependence matrix of the RP processes

W_4	TJP	FDM	LOM	SLA	SLAQ
TJP	0.388	0.414	0.314	0.417	0.469
FDM	0.053	0.053	0.047	0.217	0.076
LOM	0.097	0.106	0.093	0.100	0.055
SLA	0.167	0.207	0.178	0.227	0.157
SLAQ	0.293	0.223	0.197	0.190	0.252

Step5. *Determine the interdependent priorities of the PTRs (calculation of $w_c = W_3 \times w_1$)*

The interdependent priorities of the PTRs is given as below

$$W_c = \mathrm{W}_3 \times \mathrm{W}_1 = \begin{bmatrix} 0.222 \\ 0.181 \\ 0.287 \\ 0.324 \\ 0.466 \end{bmatrix}$$

Step6. *Determine the interdependent priorities of the RP processes (calculation of $W_A = W_4 \times W_2$)*

then, the interdependent priorities of the RP processes, are calculated as

$$W_A = \mathrm{W}_4 \times \mathrm{W}_2 = \begin{bmatrix} 0.370 & 0.397 & 0.407 & 0.488 & 0.403 \\ 0.057 & 0.076 & 0.074 & 0.088 & 0.076 \\ 0.085 & 0.096 & 0.086 & 0.107 & 0.087 \\ 0.165 & 0.189 & 0.176 & 0.211 & 0.177 \\ 0.233 & 0.235 & 0.253 & 0.316 & 0.251 \end{bmatrix}$$

Step7. *Determining the overall priorities of the PTRs (calculation of $\mathrm{W}^{\mathrm{ANP}} = \mathrm{W}_{\mathrm{A}} \times \mathrm{W}_{\mathrm{C}}$).*

The overall priorities of the RP process, reflecting the interrelationships within the HoQ, are obtained by

$$W^{ANP} = W_A \times W_C = \begin{bmatrix} 0.616 \\ 0.111 \\ 0.136 \\ 0.272 \\ 0.386 \end{bmatrix}$$

The ANP analysis results shows that the most suitable RP processes is the TJP with a relative value of 0.616, followed by SLAQ, SLA, LOM and FDM. The values filled in the HoQ are shown in table 18.

Table 18 Completely filled HoQ for RP process selection

RP Process / **PTRs**	TJP	FDM	LOM	SLA	SLAQ	**IMPORTANCE**
	1	2	3	4	5	
Shape complexity	0.416	0.234	0.450	0.662	0.443	**0.198**
Material	0.250	0.473	0.042	0.049	0.049	**0.098**
Surface finish	0.044	0.145	0.087	0.102	0.105	**0.288**
Accuracy	0.071	0.050	0.169	0.147	0.147	**0.306**
Layer thickness	0.132	0.091	0.250	0.252	0.252	**0.476**
TOTAL	**0.616**	**0.111**	**0.136**	**0.272**	**0.386**	

W_2

$\mathbf{w_1}$

W^{ANP}

5.3 Prototype Part and Casting Pattern

As per QFD-ANP decision methodology, thermojet RP process was selected as the most appropriate process. However, prototypes were also made in SLA and SLA QuickCast process for evaluation and comparision purpose. The Stereolithography (SLA) rapid prototyping process was used for fabricating the prototype (figure 11a) of the part in photo curable resin material on an SLA5000 machine. Layer thickness was set to 0.1 mm. The fabrication took 22 hours. This was followed by clearing the supports using acetone, drying in an air stream and treating with ultra violet light for two hours for improving the strength.

Two investment casting patterns were made using SLA QuickCast (figure 11b) and Thermojet RP (figure 11c) processes. A layer thickness of 0.1 mm was used in both processes. The fabrication took less than 12 hours for each pattern. The QuickCast process is a variation of the Stereolithography process giving a hollow honeycomb structure of photo curable resin material. The Thermojet material is closer to the wax used in investment casting process and is also more economical than QuickCast patterns. It was therefore chosen to fabricate the separator body by investment casting process (figure 11d).

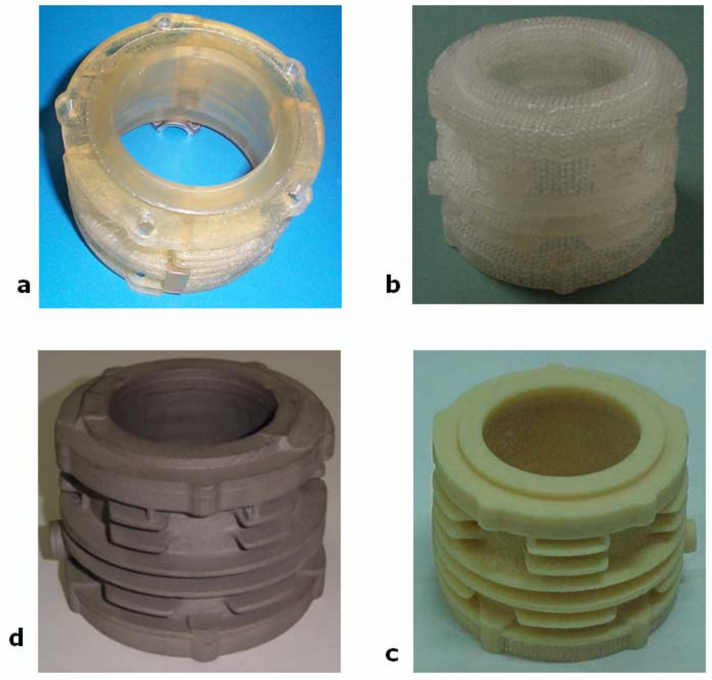


Figure 11: Rapid tooling and Investment casting (a) SLA part, (b) SLA QuickCast part, (c) Thermojet part and (d) Investment cast part

Table 19 Time details of various processes

Process	**Time taken (hours)**
3D scanning of part	4
Surface fitting	8
RP wax pattern	12
Casting simulation	4
Investment casting	80
Machining	12
Total	**120**

The separator body is considered a medium-complexity part, owing to the fins, taper on the central portion and curved geometry. Solid modeling using conventional CAD software would have taken at least a working week. In contrast, it took only four hours for 3D scanning and eight hours for surface fitting (table 19).

While metal casting is the most economical route to manufacture an intricate part, pattern development and casting trials are the major bottlenecks, consuming significant resources and taking over 60% of the total time. Manufacture of a wooden pattern for the separator body would have taken at least 3 weeks and subsequently at least 3-4 shop floor trials over 2-3 weeks would have been required to get the desired quality. In contrast, the RP wax patterns were made in less than 12 hours and the casting process was optimised in just 4 hours.

6. Conclusion

RP and RT processes offer great benefit and advantage in rapid development of one-off intricate metal casting part. However, different RP and RT systems are available in the market with unique capabilities and limitations in terms of process parameters and material. This work divided the problem of rapid prototyping process selection, into two stages: The first stage involves converting customer needs into product technical requirements using QFD-ANP approach, and prioritization of the PTRs to be considered for RP process selection. In the second stage the QFD-ANP framework is used again for prioritizing the RP processes. The RP process having the highest weight is selected as the most suitable process for that particular part. The entire approach is validated with an industrial example. The methodology enables design and manufacturing engineers to make appropriate decisions in selecting the best RP process for casting tooling application.

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