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Optimizing Cold Box Core Making in Cast Iron Foundry: A Sustainable Approach with Taguchi Technique and Desirability Function

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Abstract

Sand Casting is the most basic metal manufacturing process. The cast metals are used in almost all sectors, such as automobiles, the aviation sector, etc. Due to the restrictions in the sand mining process and to achieve sustainable manufacturing, it is important to reduce usage and the wastage of fresh sand. However, it is difficult to replace fresh sand in cold box cores due to their properties, such as grain fineness, refractoriness, etc. The present work focuses on studying the effect of a cold box core shooter machine's process parameters on producing high-quality cores with maximum core hardness and minimum gas evolution. It also aims to increase the machine's productivity by decreasing the rejection rate and reducing the cycle time needed to produce cores. For the study, four factors at three levels were selected based on the prior data and also pilot experiments. The L27 orthogonal array of the Taguchi technique was used for experimentation. The desirability function approach is used to optimize both scratch hardness (Core hardness) and gas evolution as they are conflicting in nature; for example, core hardness needs to be maximized, and gas evolution needs to be minimized. It was found that to get maximum Scratch Hardness and minimum gas evolution, resin to hardener ratio must be 0.907, Amine on timer 16 secs, LPP 21 secs, and HPP 65 secs. The present work helped reduce the rejections and also helped achieve the production target with minimum machine runs. It also reduced 200kg of sand wastage, thus moving towards sustainable manufacturing.

Keywords: Cores, Cold box core shooter machine, scratch (core) Hardness, Gas Evolution, Taguchi technique, Amine, LPP, HPP

1. Introduction

The goal of manufacturing in the mechanical industry is to produce high-quality, reliable, and cost-effective products that meet customer needs and specifications. To attain this goal requires a deep understanding of the design and engineering principles behind the product, as well as expertise in various manufacturing techniques and processes [1-2]. Among various metallic component manufacturing processes, casting is the most basic manufacturing process as it is a shaping process followed by forging, rolling, welding, machining, etc. [3]. The casting applications range from the automotive sector, aerospace [4], defense, valves, etc. Around 68% of the gray cast iron is used for these applications. India is the third largest producer of castings [5]. Foundries are classified based on the type of mould material. Sand is commonly employed as moulding material and hence termed sand casting [6]. Over 60% of all metal castings are produced through the sand-casting process [7].

There are various steps in sand casting, such as Pattern making, core making, moulding, melting and pouring, cleaning, and inspection. Moulds and cores are made up of using sand along with binders [8]. The cores are used in sand casting to form hollow intricate cavities in metal parts [9]. In the Aerospace sector, components such as Gear casings, diffusers, struts, housing, and mountings are manufactured using the sand casting process [10]. Various casting defects, such as gas evolution and sand drop, arise due to poor core quality [11-12]. Sand cores should have certain properties such as good strength and hardness, eco-friendliness, and low gas evolution [13]. Several researchers worked towards the improvement of good-quality cores. Zhang et al. investigated the gas evolution from the resin-bonded sand cores prepared by cold box, shell, and hot box techniques. During the investigation, it was found that the cold box process resulted in the highest gas evolution, followed by the shell process and then the hot box process [14]. Chang J.N. et al. emphasized the flow behaviour of sand (without binder and with varying percentages of binder) in core shooter machines. The flow behaviour is related to the quality of the cores [15]. Mateusz S. et al. worked on developing the core-making technique by reducing the pressure [16]. Martina H. et al. emphasized reducing the veining defect on ferrous castings produced using cold box cores. It was found the amount and type of ingredients in moulds, and cores cause veining [17]. Holtzer M. et al. investigated the gases released during the casting process; it was found that organic binders used for moulding and core making evolve more gasses that are dangerous and also cause pollution [18]. Stefano S. et al. emphasized the need for optimization and innovation in making eco-friendly foundries (green foundries) [19]. Hence, it is important to note that researchers have considered either the gas evolution or other properties of the core, such as hardness, but not both. The Gas evolution gives rise to blow holes in the casting. A weak core (low core hardness or scratch hardness) will break during core setting, and also sand from a weak core will fall on molten metal, causing sand drop problems during the initial stages of solidification, thus causing defects [20-22]. Hence, in the present study, an effort is made to minimize the gas evolution (so that pollution will be less and also to minimize blowholes/gas holes) and to maximize the core hardness(Scratch hardness) so that the core should not break during core setting operation and must have sufficient strength.

Conducting the experimentation in the industry is challenging as it will hamper the regular production target. Taguchi technique considers societal loss, and it also covers the output in decibels and thus considers the noise (uncontrollable factors) factors during analysis [23]. It is the most effective method to optimize any process [24]. Many researchers successfully used the Taguchi technique. It was successfully used to identify the significant factors in sand casting [25]. Rasik A.U. et al. used the Taguchi technique to reduce casting defects. The authors have considered factors such as moisture content, green compression strength, AFS (GFN) number of sand, mould hardness, permeability, pouring temperature, poring time, and pressure. There was a reduction of 2% in casting defects [26]. However, the authors have considered only a single response, and work was also done on sand moulds but not cores. Tariq S. et al. used the Taguchi technique to reduce the porosity defects in the high-pressure die-casting process used to make crankcases made of aluminum alloy [27].

Tzeng C.used the Taguchi technique to water the electrolysis process. Factors such as electrolysis time, electrode space, density, and electrolyte concentration at four levels. The obtained results helped to understand the contribution of each factor towards water electrolysis efficiency [28]. From the available literature, it was found that the Taguchi technique is the best method to conduct experiments at the least cost with minimum experimental time [29] as there are two responses viz. Gas evolution(needs to be minimized) and mould hardness(needs to be maximized) are considered for the study and are conflicting in nature, so multiple objective optimizations are required. Many researchers used the desirability function approach (DFA) for multiobjective optimization, and it yielded good results when deciding such conflicting requirements [30]. Also, the results obtained yielded better results compared to other methods [31]. Ajay R.B et al. used DFA to optimize material removal rate and surface roughness while machining Aluminium metal matrix composites. For experimentation, the author utilized the response surface methodology in the design of the experiments. The theoretical values obtained and experimental values had a maximum deviation of 3.62% [32]. Most of the authors used either conventional methods or carried out single objective optimization using DOE, and very little literature was available on the investigation of sand core properties in metal casting. Hence, the novelty of the work is to obtain optimum settings for the core shooter machine to get minimum gas evolution and maximize the core hardness for the cold box cores using the Taguchi technique and perform multiobjective optimization using the Desirability function approach to get the single optimized levels for both Gas evolution and mould hardness of the sand core. The work saved the wastage of 200kg of sand per day, along with a reduction in manufacturing costs.

2. Methodology

The flowchart of the experimentation is shown in Figure 1. The fresh silica sand with GFN 57-62 is used for experimentation (as sand sand is used for regular production as well). The binder system consists of a resin (Phenol-Formaldehyde), generally termed Part A, a hardener (Methylene Diphenyl Diisocyanate), generally termed Part B, and Amine (Tri Ethyl Amine), termed Part C. The fresh silica sand in a measured quantity is mixed with Part A and Part B in a sand muller just above the cold box core shooter machine and is mixed for a predefined time. This time depends on the room temperature. Thus, mixed sand is shot in the machine's sand magazine and made to fall into the core box. In the meantime, the amine is supplied, which helps in curing, and the quantity of amine is controlled using a timer attached to a pump on the amine tank. In order to cure the core(mixed sand) in the core box, Low-pressure purging (LPP) is carried out where amine along with compressed air(amine gas) is supplied to the sand mix to cure and harden the core uniformly. LPP also helps to reduce the usage of amine gas, thus avoiding wastage. Following this, High-pressure purging (HPP) is carried out to ensure the amine gas is supplied at all the thicknesses of the core, and it will also help in rapid curing, thus increasing productivity.HPP is always carried out after LPP as the LPP core will gain sufficient strength to withstand the high pressure of amine gas (4 bar during HPP) for further curing.

After this process, the core is separated from the core box, and then the core is cleaned and trimmed for any unwanted projections. The cores will be ready for core setting in the mould. The flow of amine, LPP, and HPP are controlled using the timer through PLC. Part A (Resin) and Hardener (Part B) are measured manually using a measuring jar and mixed with silica sand in a sand muller. After studying the existing system, it was found that higher gas evolution leads to blow holes in castings, which leads to rejection.

On the other hand, reducing the amount of resins, hardeners, and amine reduces gas evolution, but core hardness will also reduce, leading to sand drop defects. Based on the rejection report, most of the castings were rejected due to blow hole and sand drop problems. A brainstorming session was carried out, and it was found that the defects were observed near the core area. The castings that were made using cold box cores had prominent defects, and the sand wastage in manufacturing cold box cores was a concern. Hence, it was decided to target gas evolution and mould hardness, which are the root causes of blow holes and sand drops. The factors and levels for experimentation were selected based on the existing data and pilot experiments. The factors and their corresponding levels are shown in Table 1. Certain inputs, like temperature, humidity, sand temperature, etc., are beyond the control of the operator. Taguchi technique considers both Controllable (Signal) and noise (uncontrollable factors) during analysis, and the number of experimental runs is also minimal. Hence, this method was used for the study. As there are four factors, each at three levels, that need to be set, the L27 orthogonal array of the Taguchi technique is used for experimentation.

The factors and levels are selected in such a way that they will not hamper regular production (within the range) and also to avoid any sort of error due to bias, the experiments were conducted in random order, on the same machine and same operator(blocking), and repetitions are done for every experimental set(replication).

The equipment used for gas evolution testing and core hardness tester are shown in Figure 2 (a and b). The unit of gas evolution in ml/g and core hardness (scratch hardness) is given in terms of the number

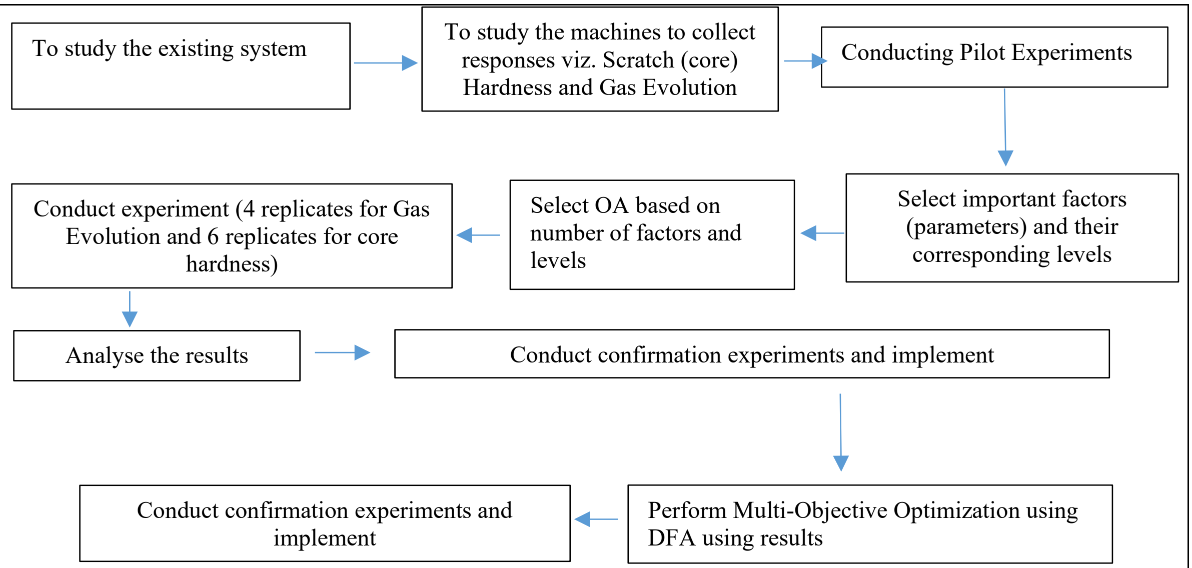

Fig. 1. Methodology of experimentation

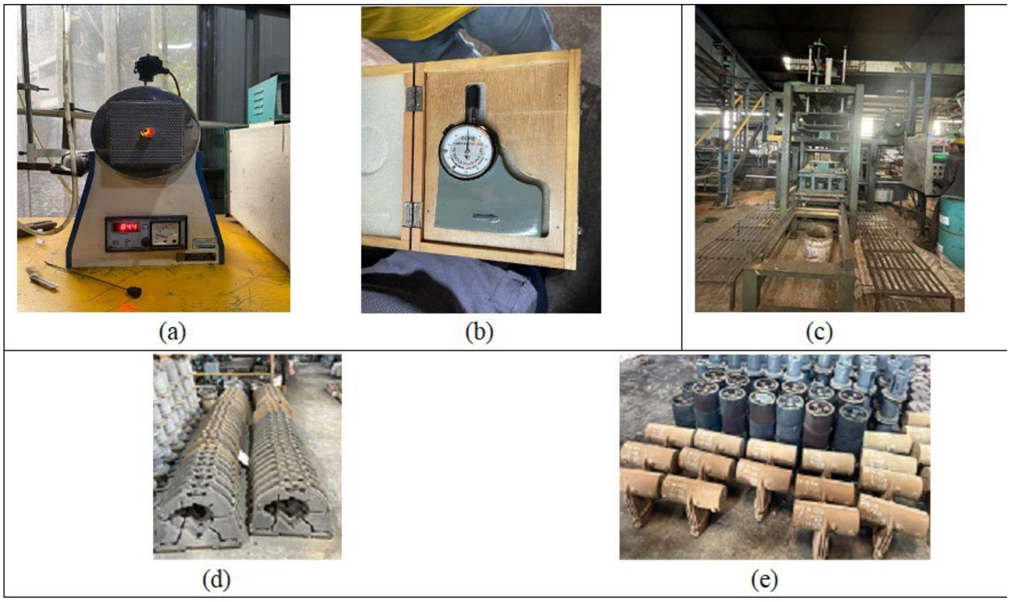

Fig. 2. (a) Gas evolution tester machine, (b) Scratch hardness tester device, (c) Cold box Core shooter machine, (d) 8 kg cold box cores, (e) 15kgs cold box cores

Table 1.
Factors and their corresponding levels

Factors	Levels		
	1	2	3
Resin to Hardener Ratio	0.8	0.9	1
Amine on timer (sec)	12	14	16
Low-pressure purging (LPP) time (sec)	17	19	21
High-pressure purging (HPP) time (sec)	35	50	65

The cold box core shooting machine is shown in fig2(c) and has a muller capacity of 100kg. Two different types of cold box cores of 8kgs(fig2(d)) and 15kgs(fig2(e)) are considered for the study.

The steps in the Taguchi technique are shown in Fig 3. The problem definition is the most important aspect of any problem-solving technique. In the present study, the problem is stated in a brainstorming session with industry personnel. The OA is selected based on the number of factors to be considered for experimentation and the number of levels.

Based on the objective function, the signal-to-noise ratio is calculated. In the present study, Core hardness needs to be maximized, and hence, better formulae are used for the same, as shown in equation 1.

$$S/_{N}\text{ larger is better} = -10\log_{10} {}^{1}/_{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \qquad (1)$$

On the other hand, gas evolution needs to be minimized, and hence, the smaller the formulae for the signal-to-noise ratio used, the better it is shown in Equation 2.

$$S/_{N}\text{ Smaller is better} = -10\log_{10} {}^{1}/_{n} \sum_{i=1}^{n} y_i^2 \qquad (2)$$

3. Results and Discussion

The experiments are conducted using the L27 orthogonal array of the Taguchi technique. The experimental design matrix and six replicates were taken for scratch hardness, and four replicates were for gas evolution. The average values of the responses are considered for analysis. The experimental matrix and the average values of responses are given in Table 2.

Table 2.
Experimental Design Matrix, responses(Average Core Hardness and Gas evolution), along with the signal-to-noise ratio of responses

Resin to Hardener ratio	Amine on timer (sec)	LPP (sec)	HPP (sec)	Average Core hardness	Average Gas Evolution	SN Ratio of core hardness (dB)	SN Ratio of Gas evolution (dB)
0.8	12	17	35	72.00000	9.100	37.1466	-19.1808
0.8	12	19	50	72.66667	9.125	37.2267	-19.2047
0.8	12	21	65	76.00000	9.125	37.6163	-19.2047
0.8	14	17	50	75.00000	9.525	37.5012	-19.5773
0.8	14	19	65	76.33333	9.450	37.6543	-19.5086
0.8	14	21	35	73.00000	9.575	37.2665	-19.6228
0.8	16	17	65	77.00000	9.725	37.7298	-19.7578
0.8	16	19	35	73.50000	9.650	37.3257	-19.6905
0.8	16	21	50	75.16667	9.600	37.5205	-19.6454
0.9	12	17	35	74.16667	9.875	37.4042	-19.8907
0.9	12	19	50	76.16667	9.975	37.6353	-19.9783
0.9	12	21	65	77.50000	9.850	37.7860	-19.8687
0.9	14	17	50	76.50000	9.950	37.6732	-19.9565
0.9	14	19	65	77.66667	9.925	37.8047	-19.9346
0.9	14	21	35	76.50000	10.025	37.6732	-20.0217
0.9	16	17	65	75.50000	10.925	37.5589	-20.7684
0.9	16	19	35	77.00000	12.225	37.7298	-21.7450
0.9	16	21	50	77.50000	12.275	37.7860	-21.7804
1	12	17	35	76.00000	13.025	37.6163	-22.2956
1	12	19	50	77.66667	13.125	37.8047	-22.3620
1	12	21	65	80.33333	13.250	38.0979	-22.4443
1	14	17	50	78.66667	13.625	37.9158	-22.6867
1	14	19	65	82.00000	13.775	38.2763	-22.7818
1	14	21	35	78.00000	13.650	37.8419	-22.7027
1	16	17	65	82.83333	14.000	38.3641	-22.9226
1	16	19	35	79.66667	13.850	38.0255	-22.8290
1	16	21	50	80.33333	14.075	38.0979	-22.9690
			Total			1018.079	-563.331

The signal-to-noise ratio is used to detect the effect of controllable and uncontrollable factors on output. Also, this will help in multiobjective optimization as it converts the units of the output(response) to decibels as logarithm is used.

The analysis is done using Minitab software. Analysis of variance (ANOVA) for Core(Scratch hardness) and Gas evolution is shown in Table 3. ANOVA is used to find the significant and insignificant factors using the Fisher test. ANOVA also helps estimate the percentage of factors contributing to the response.

Table 3.
Analysis of variance (ANOVA) table for Signal to Noise ratio of Core Hardness

Source	DF	Core Hardness(CH)					Gas Evolution (GE)				
		Sum of squares	Variance	F	P	% contribution	Sum of Squares	Variance	F	P	% contribution
Resin to Hardener ratio	2	1.4342	0.7171	54.4	0	60.79	47.893	23.947	178	0	88.8
Amine	2	0.1911	0.09553	7.25	0.01	8.1	3.4369	1.7184	12.77	0	6.37
LPP	2	0.036	0.01799	1.37	0.28	1.53	0.0942	0.0471	0.35	0.71	0.17
HPP	2	0.4605	0.23026	17.5	0	19.5	0.0589	0.0295	0.22	0.81	0.11
Residual error	18	0.2371	0.01317			10.05	2.4213	0.1345			4.49
Total	26	2.3589				100	53.905				100

The degrees of freedom refers to the number of independent comparisons that can be made among levels of the factors among experiments. As all the factors are at level 3, the degree of freedom (DF) is two and is shown in equation 3. The degrees of freedom for the entire experimental run are given by equation (4).

$$\text{DF for factors} = \text{levels} - 1 = 3 - 1 = 2 \tag{3}$$

$$\text{DFtotal} = \text{Number of experiments} - 1 = 27 -= 26 \tag{4}$$

Residual error in the ANOVA table indicates interaction among the factors, which is due to the combined effect of factors at different levels. The following equations are used to calculate different attributes of the ANOVA table.

$$SS_T = \left(\sum y_i^2\right) - \left(T^2/_N\right) \tag{5}$$

$$T = \sum y_i \tag{6}$$

$$SS_{\text{Resin to Hardener ratio}} = \left(\frac{\sum A_1^2}{n} + \frac{\sum A_2^2}{n} + \frac{\sum A_3^2}{n}\right) - CF \tag{7}$$

$$CF = \frac{T^2}{N} \tag{8}$$

$$SS_e = SS_T - SS_{\text{Resin to Hardener ratio}} - SS_{\text{Amine}} - SS_{\text{LPP}} - SS_{\text{HPP}} \tag{9}$$

Grand total, N=no.of experiments=27,n=no.of experiments conducted at that particular level, ΣA_1=sum of all responses at level 1, CF=correction factor, Yi= response. SS_T=Total sum of squares, SS_e= Sum of square of error(residual error).

$$\text{Variance} = \frac{SS}{DF} \tag{10}$$

$$\text{Fisher Value } F_{\text{Calculated}} = \frac{\text{Variance of factors}}{\text{Variance of error}} \tag{11}$$

Based on the Fisher value, one can know whether the factor is significant or insignificant by comparing the obtained value with the Fisher table value based on degrees of freedom. Instead, in software like Minitab, Design Expert, etc, one can obtain the probability value (p-value); if p value is 0 to 0.05, then it can be inferred that the factor is significant. The contribution of each factor towards the response is calculated using Equation 12[33].

$$\text{Percentage (\%) Contribution} = \frac{SS_{\text{factors}}}{SS_{\text{Total}}} \tag{12}$$

From Table 3, it can be seen that for core hardness, the amount of resin to hardener ratio (content) contributes more and is about 60.79%. It is also statistically significant at a 95% confidence level. From P-value, Amine and HPP are also statistically significant at 95%.HPP is the second highest contributor towards core hardness after resin content. It happens because resin binds the sand particles (it is a binding agent). On the other hand, High-pressure purging (HPP) helps to clear all the residues in the sand magazine and the core box, assists sand in falling with velocity, and thus improves binding strength.

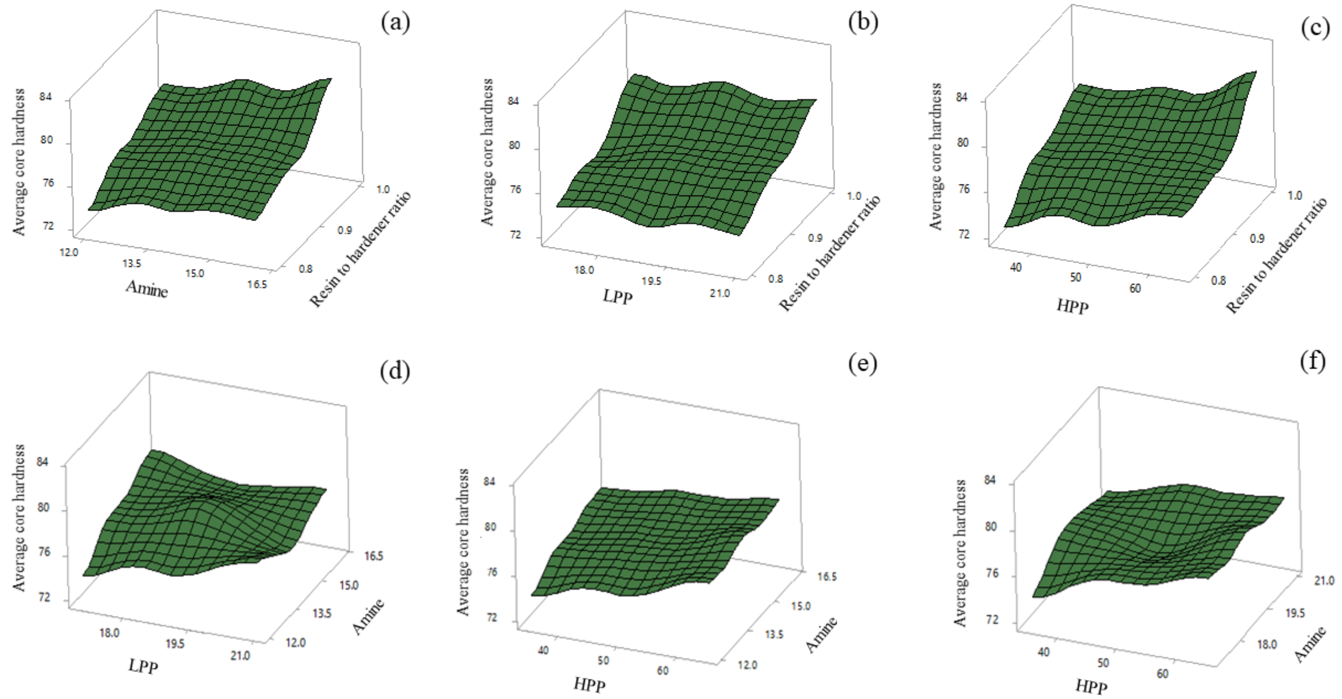

Fig. 4. 3D surface plots for core hardness v/s (a)Amine and Resin to Hardner ratio (b)LPP and Resin to hardener ratio (c)HPP and Resin to Hardener ratio (d)LPP and Amine (e)HPP and Amine (f) HPP and LPP

The 3D surface plots for Core hardness are shown in Figure 4. The 3D surface plots are plotted to understand the relationship between two factors on response at a time. The average values at all the levels were considered for plotting the graph. The interaction of resin-to-hardener ratio and amine content on core hardness is shown in Fig 4(a). The core hardness is less when the amine content is low, the resin-to-hardener ratio is also at a low level, and the core hardness is maximum when both the amine content and resin-to-hardener ratios are at a high level. From Fig 4(b), it can be seen that core hardness is lower when LPP is at a high level and the resin-to-hardener ratio is low. This is due to sand grains not getting a sufficient coating of resin and hardener, and this partial coating leads to weak bonds among sand grains. Core hardness is maximum when LPP and resin to hardener are both at high levels. The interaction effect of HPP and resin-to-hardener ratio on core hardness is shown in fig4(c). The core hardness is minimal when the HPP and resin-to-hardener ratio are at a low level and is maximum when both are at a high level. A maximum resin-to-hardener ratio (within the range) leads to uniform coating, and hence, HPP helps close the packing of sand grains. The effect of amine and LPP on core hardness is shown in Figure 4(d).

The maximum core hardness can be obtained when the amine is at a high level and LPPis at a low level. It is due to amine, which also acts as a catalyst in binding sand grains. The effect of Amine and HPP on core hardness is shown in Fig 4(e). Very little increase in core hardness can be observed when the amine content and HPP are increased. The effect of HPP and LPP on core hardness is shown in Figure 4(f). The core hardness is less when both LPP and HPP are low and increases with an increase in both factor levels. It is interesting to note that, based on the nature of graph resin to hardener ratio along with other factors. Though the effect of LPP is less, technically, this factor can not be ignored, as LPP is required to activate amine so that enough binding action can be obtained.

For gas evolution, the resin-to-hardener ratio is the important factor, contributing about 88.8%. Because resins are thermosetting plastics, and when they come in contact with molten metal or during core baking, the coating of the top layer of sand particles gets burnt and gives away the burnt gasses, thus increasing gas evolution. Amine is also chemical and gives out gasses when it comes in contact with molten metal. Both amine and resin are significant factors at a 95% confidence level and also give out greenhouse gasses, thus increasing pollution and accelerating blowholes and gas porosities on castings.

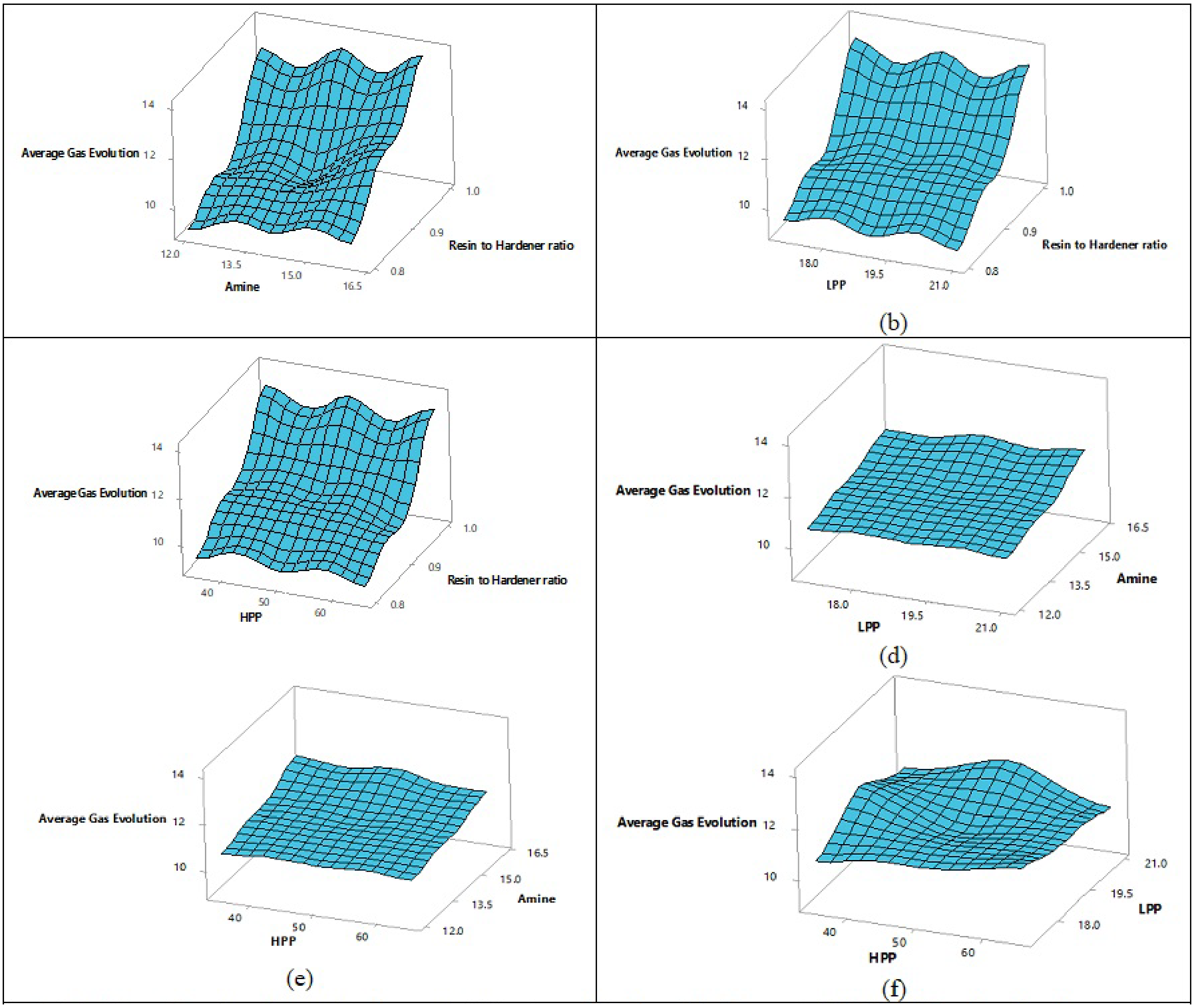

Fig. 5. 3D surface plots for core hardness v/s (a) Amine and Resin to Hardner ratio, (b) LPP and Resin to hardener ratio, (c) HPP and Resin to Hardener ratio, (d) LPP and Amine, (e) HPP and Amine, and (f) HPP and LPP

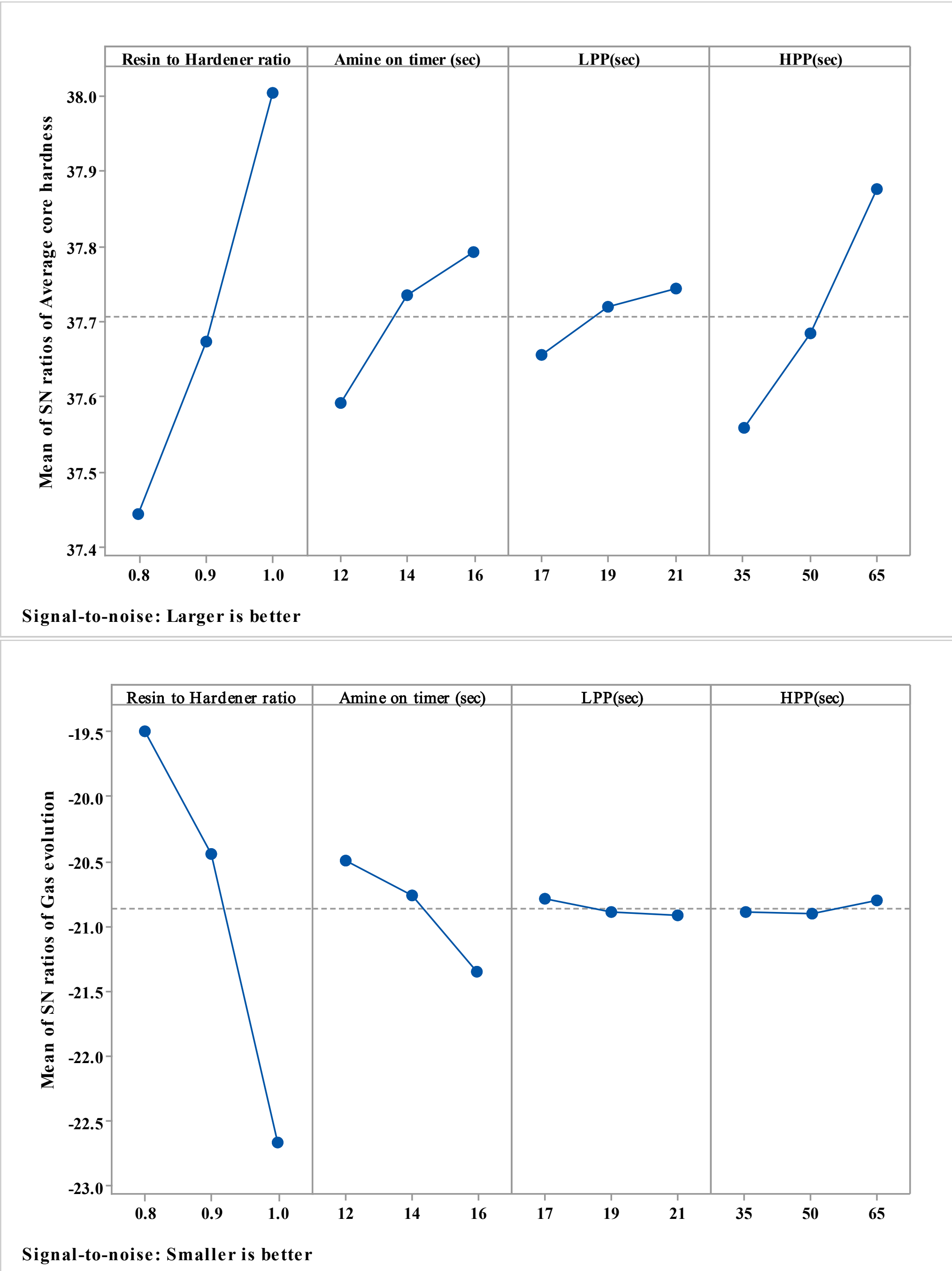

Fig. 6 (a) Factorial plots for Signal to Noise ratio (larger is better) of Core(Scratch) Hardness, (b)Factorial plots of Mean of Signal to noise ratio of Gas evolution (smaller the better)

From 6(a), it can be observed that as the resin-to-hardener ratio increases, the scratch (core) Hardness increases. Similarly, in the case of amine on a timer, LPP time, and HPP time, the scratch (core) Hardness increases with an increase in these input values. Also, the dimension of the resin-to-hardener ratio line is higher, which indicates that it is a significant factor in scratch (core) hardness. The core hardness increases with an increase in the amount of resin-to-hardener ratio as the sand particles adequately come in contact with the resin+hardener mix, and in the meantime, the high-pressure purging makes amine gas come in contact with all the sections of the core[34] and thus increasing the binding strength and also the pressure also squeezes the grains so that bonds withing grains will become stronger. As amine acts as a rapid curing agent, too much amine beyond the range will make sand

particles wet, and thus, it will weaken the core. On the other hand, if the LPP time is increased beyond the range, the core will become weak as resin and hardener starts polymerizing with time and may not further react with amine gas. The nature of the graph for the core hardness (average values at respective levels) and signal-to-noise ratio (larger the better) is the same.
The Signal-to-noise ratio is the correct way of analyzing the trend as it considers both controllable and non-controllable factors. Hence, it is considered for both Gas evolution and core hardness.
From Figure 6(b), it can be observed that as the resin-to-hardener ratio increases, the gas evolution decreases, similarly in the case of amine on timer and LPP time. However, as the value of HPP time increases, the gas evolution also increases slightly. Also, the dimension of the resin-to-hardener ratio line is higher, which indicates that it is a significant factor in gas evolution. The nature of the graph for the gas evolution values (average values at respective levels) and Signal-to-noise ratio (smaller the better) is inverse. The gas evolution increases with an increase in the resin-to-hardener ratio; it is due to the fact the more chemicals in the sand, the more gas is generated when the molten metal comes in contact as the chemical burns off, giving out gasses[35]. Amine vapors, which come in contact with mixed silica sand, also act the same as resin and hardener. Whereas LPP and HPP are the media through which amine is supplied, and hence very little influence on gas evolution can be seen in graph 6(b)
The optimized setting for Core(Scratch) hardness and Gas evolution is given in Table 4. For both responses, three confirmation tests were carried out, and the results are shown in Table 4.

Table 4.
Optimized levels for Core hardness and Gas evolution along with confirmation test results

Core Hardness				Gas Evolution			
Resin to Hardener ratio	Amine on timer (sec)	LPP (sec)	HPP (sec)	Resin to Hardener ratio	Amine	LPP	HPP
1	16	21	65	0.8	12	17	65
Confirmation Tests				Confirmation Tests			
Core hardness	82	81	82	Core hardness	77	85	72
Gas Evolution	12.2	12	13.1	Gas Evolution	11.7	13.2	11.5

From Table 4, it can be seen that for the optimized condition of Core hardness and Gas evolution, different levels of settings are required. But in both cases, the quality will be compromised, i.e., for optimized levels for core hardness, gas evolution will be more, and for optimized levels for Gas evolution, the core hardness will be less. In such conflicting requirement scenarios, multiple objective optimizations are advised.

3.1. Multiple objective optimization

In the present work, the desirability function approach is used for multiobjective optimization. The desirability function approach is flexible and easy to compute; two or more objectives can be optimized [36], weightage can be altered, and interpretation is easy [37-38] compared to Pareto optimization, weighted sum methods. Moreover, the Taguchi technique is used for experimentation, and responses are converted into signal-to-noise ratios (dB); hence, it becomes easy to perform multiobjective optimization. The steps followed in DFA are shown in Figure 4.

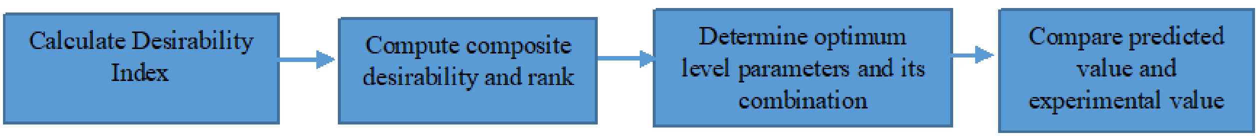

Fig. 4. Steps in the Application of the Desirability Function Approach

The units of both the responses (Core Hardness and Gas Evolution) are different; hence, both signal-to-noise ratios are considered for multiple objective optimization. In DFA, each output Y_i is converted to individual desirability function d_i, whose value lies in the range of 0 to 1 ($0 \le d_i \ge 1$). Zero dictates a completely undesirable solution, and one signifies the ideal solution [39]. The desirability index for core hardness and gas evolution is found using equation 13.

$$y_c = \left(\frac{\mathrm{CH} - \mathrm{CHmin}}{\mathrm{CHmax} - \mathrm{CHmin}}\right)^{w1} \text{ and } y_G = \left(\frac{\mathrm{GE} - \mathrm{GEmax}}{\mathrm{GEmin} - \mathrm{GEmax}}\right)^{w2} \tag{13}$$

Yc and YG are objective functions utilized for the normalization of Core Hardness and Gas Evolution, respectively. Where CHmax is the maximum core hardness value, CHmin is the minimum core hardness value, GEmax is the maximum gas evolution, and GEmin is the minimum gas evolution. The composite desirability (D_0) value is then determined using Equation 14 [40].

$$D_0 = \left((y_C^{w1} \times y_G^{w2})^{\frac{1}{Number\ of\ Objectives}} \right) \quad (14)$$

The highest D_0 value is considered the best optimal level for multiobjective optimization. The analysis is done using Minitab software. In this study, three cases with different weights are considered, as shown in Table 5. The analysis is done using Minitab software.

Table 5.
Three test cases and their associated readings

Process Variables and Core Properties	Core Conditions and Properties		
	Scenario 1: W_1= W_2 = 0.5	Scenario 2: W_1 = 0.75, W_2 = 0.25	Scenario 3: W_1 = 0.25, W_2 = 0.75
Resin to hardener ratio	0.907	0.94	0.82
Amine on timer(sec)	16	14.14	12.8
LPP(sec)	21	21	21
HPP(sec)	65	65	65
Core Hardness	77.12	79.7	76.5
Gas Evolution	9.79	11.55	9.12
Composite desirability (D_o)	0.81	0.80	0.89

From Table 5, it can be seen that for equal importance, the desirability value is 81%, and for scenario 3, it is 89%. However, both gas evolution and core hardness are equally important, and there is very little difference in input values; hence, equal importance (weightage of 0.5 to both) is considered, and a confirmation test for these settings is carried out. The obtained results were within a 5% deviation from the theoretical value. Hence, scenario 1 of equal weightage can be considered. The company used to perform trial runs before this work was carried out, and some cores were rejected because of low core hardness values or high gas evolution values. This rejection used to incur losses to the company in terms of man-hour rate, machine-hour rate, sand, resin, and hardener. The optimized values reduced these losses, reduced the consumption of sand, and reduced gas evolution (pollution), thus achieving sustainable and green manufacturing.

3.2. Cost estimation

The cost estimation is done using the Indian national rupee as it is conducted for the foundry located in India. The cost estimation for four different conditions is done as shown in Table 6. The calculations for the same are shown in this section. The production cost with respect to the material is considered as the machine-hour rate, and the man-hour rate will be the same for every shift.

Table 6.
Parameter setting at fur different conditions

	Resin to Hardener Ratio	Amine on a timer in secs (2 ml/sec)	LPP time (sec)	HPP time (sec)
Regular settings before optimization	1.1:1	20	20	65
Optimization of only Scratch (core) Hardness	1:1	16	21	65
Optimization of only Gas Evolution	0.8:1	12	17	65
Multiple-objective optimization with Equal Importance (Both Scratch (core) hardness and gas evolution)	0.907:1	16	21	65

Considering the costs associated with different particulars during the time of experimentation, the cost estimation is done.

a) Sand = Rs.4.5/Kg
b) Resin =Rs.7500 (50 litre) = Rs.150 per litre
c) Hardener =Rs.11500 (50 litre) = Rs.230 per litre
d) Amine =Rs.300/Kg

➢ Production Cost for 100 Kg of sand during initial setting (before optimization)

Sand = 100 Kg: 100 Kg * Rs.4.5 = Rs.450
Resin = 1.1 litre: 1.1 litre* Rs.150 = Rs.165
Hardener = 1 litre: 1litre * Rs.230 = Rs.230
Amine = 40 ml: $40*10^{-6}$ m^3 * 720 Kg/m^3 = 0.028 Kg * Rs.300 = Rs. 8.64

Total production cost with respect to material per 100 Kg (According to the company's initial setting) = Rs. 853.64

➢ Production Cost with respect to material for the 100 Kg of sand after the optimized parameter setting for different objectives.

1. For Core Hardness
=Sand + Resin + Hardener + Amine
$= (100 \times 4.5) + (1 \times 150) + (1 \times 230) + (32 \times 10^{-6} \times 720 \times 300) = Rs. 836.91.$

2. Gas Evolution=Sand + Resin + Hardener + Amine

$= (100 \times 4.5) + (0.8 \times 150) + (1 \times 230) + (24 \times 10^{-6} \times 720 \times 300)$ = Rs. 805.18.

3. Multiobjective Optimization (Equal Importance)=Sand + Resin + Hardener + Amine
$= (100 \times 4.5) + (0.907 \times 150) + (1 \times 230) + (32 \times 10^{-6} \times 720 \times 300) = \text{Rs.} 822.96$

- **Initial Rejection** = 200 Kg sand / Day
Considering each core of 25 Kg = 8 Cores/ Day
Production Cost for 100 Kg sand according to the company's initial setting = Rs. 853.64.
Hence, Rs. 1707.28 can be saved per day.

Table 7.
Production Cost – Estimation for 100 Kg of sand (According to the initial setting)

Resin to Hardener Ratio	Amine on a timer in sec (2 ml/sec)	LPP time sec	HPP time sec
1.1:1	20	20	65

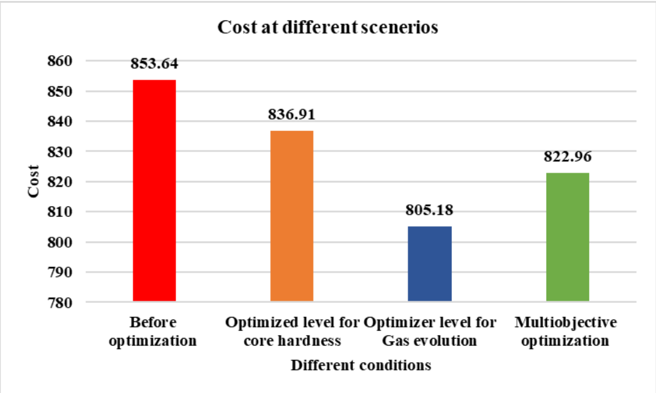

Fig 5. Cost estimation before and after optimization

The cost of manufacturing cores per 100 kg before optimization was Rs.854. After optimization, the cost came down to Rs.823. It will result in approximately 4% cost reduction. The costs associated with making cores are shown in Fig.5 in different scenarios. Also, the cores of approximately 200 kg/ day were rejected due to low core hardness and high gas evolution before optimization. After optimization, these rejections were reduced, and approximately Rs.1708 was saved. The savings are not only in monetary terms but also help to reduce the landfill problem as core sand recycling is costlier than fresh sand, and economically, it is not advisable to recycle the rejected sand cores. On the other hand, good quality sand cores come in contact with hot molten metal, and chemical burns off, thus assisting only in reconditioning sand, which can be reused as backing sand in the sand casting process.

4. Conclusion

In the present work, an attempt is made to optimize the cold box core shooter machine to get cores with maximum Scratch (core) Hardness and minimum Gas Evolution. The pilot experiments were conducted to identify the important factors that affect scratch (core) hardness and Gas Evolution. The factors such as resin-to-hardener ratio, amine on a timer, High-pressure purging (HPP), and Low-pressure purging (LPP) were considered for the study. L27 orthogonal array of the Taguchi technique is used for experiments because of its robust nature and low experimental costs, as the foundry personnel needs higher scratch (core) Hardness and lower Gas Evolution. Because of this conflicting requirement, the multiple objective optimization using the desirability function approach is carried out. The optimized setting for all three conditions is given in the table 8.
These settings increase productivity and help reduce the unnecessary wastage of raw materials, thus reducing production costs. The optimized values reduced the manufacturing cost of sand cores by 4% and also other losses associated with the rejected cores (which consume sand, resin, hardener, amine, energy, and man-hour rate) by minimizing the rejections and also reducing gas evolution (pollution) thus achieving sustainable and green manufacturing.

Table 8.
Optimized process parameter settings for cold box core-making machine

Optimization for	Resin to Hardener Ratio	Amine on a timer in secs (2 ml/sec)	LPP time (sec)	HPP time (sec)	Values of responses after optimization	
					Scratch (core) Hardness	Gas Evolution
Scratch (core) Hardness	1:1	16	21	65	82	13.1
Gas Evolution	0.8:1	12	17	65	72	11.5
Equal Importance (Both Core hardness and gas evolution)	0.907:1	16	21	65	76	12.2

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