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RESEARCH ARTICLE

Lean Implementation Framework: A Case of Performance Improvement of Casting Process

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ABSTRACT Globalization breeds increasing competition. In today's dynamic climate, lean thinking has been found a promising business continuous improvement strategy for improving quality while reducing product cost and delivery time. However, its implementation has dynamic nature of challenges that varies from industry to industry and country to country, necessitating a specific framework by taking all stakeholders onboard. This study aims to propose a lean implementation framework to reduce defects and waste to improve the performance of the metal casting industry. The structure of the framework has been divided into three phases namely the lean conception phase, lean implementation phase, and lean sustainability phase. The proposed framework integrates the six sigma DMAIC methodology with lean tools and techniques to reduce defects and achieve performance improvement. A solid cast software has been used as a computer-assisted casting simulation tool to perform the analysis of defects within the casting. Further, the proposed framework is demonstrated and validated by employing a real-time case study that was manufactured using the sand casting process. The obtained results show remarkable improvements in poured metal weight (33.3%), mold weight including gating system (40%), casting yield (24.56%, rejection rate (90%), and financial saving (24.63%). As a result of analysis of percentage improvements data, the proposed framework can provide the practitioners with a standard roadmap and motivate the casting industries to implement lean for performance improvement through organizational change. Through the effective application of the lean implementation framework, quality enhancement has been demonstrated.

INDEX TERMS Lean implementation framework, metal casting industry, six sigma-DMAIC, computer-assisted simulation.

I. INTRODUCTION

In the manufacturing sector, casting processes are used to produce almost 90% of the total products. It is due to their capability of producing near-to-net shape products in a short time and low cost. Using these methods, molten metal is poured into a mold cavity which is then solidified into a required casting shape [1]. While manufacturing the products through casting processes, the overall purpose is to fulfill the requirements of both customers and companies such as customers wanting quality products and the company trying to manufacture a defect-free part. Defective parts cause high job floor trials and rejection rates which ultimately results in profit loss for the companies. So, there is need to continuously improve the existing casting processes.

In today's dynamic environment, globalization and emerging technologies (such as rapid prototyping and tooling technology-3D printing, lost wax process, and single crystal casting through directional solidification) have facilitated much the metal casting industries to achieve continuous improvement [2]. These and other developments have dramatically affected the way product is being cast, the cost, quality, and range of products generated, and changed the basic structure of the industry. However, it needs much resources, time and cost to achieve the quality products.

Lean manufacturing (LM) refers to a philosophy and a long-term strategy of a company's management [3]. It can be described as ''doing more with less'' through the efficient use of resources available. In manufacturing organizations,

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it can be achieved by incorporating the lean culture within the organization with the ultimate objective of elimination of wastes across the departments [4] to realize the continuous improvement. For this purpose, lean manufacturing tools and techniques are the most important concepts that assist engineers and managers to sustain business competitiveness by eliminating wastes in the expanding global market. Further, lean manufacturing has provided enormous changes in the practices adopted by the practitioners in the manufacturing sector. It emphasizes the enhancement of customer satisfaction, organizational effectiveness, responsiveness to customer requirements, and efficiency [5], [6]. Therefore, lean manufacturing can be taken as a successful organizational tool to implement in manufacturing organizations for continuous improvement. However, despite many benefits of lean manufacturing, it is difficult to be applied effectively in the manufacturing sector due to (i) imperfect understanding of the lean thinking concepts and the purpose of lean practices [7], (ii) misapplications due to the use of wrong lean tools to resolve a specific problem [8], (iii) the use of a single tool to solve many problems [9], [10], and (iv) the implementation of the same set of solutions to provide the answer to each problem [11]. These limitations are needed to be tackled by top management, casting experts, lean experts, and all the employees of the organization. This would require a framework to follow for creating a lean culture within the organization. Therefore, this study aims to propose a lean implementation framework for performance improvement practices in the casting processes. The purpose of this study is to:

i. Develop a framework, called the lean implementation framework, which aims to achieve performance improvement through the creation of lean culture within the organization.
ii. Explain the developed framework and the adequate implementation phases in a practical manner to assist the organizations achieve continuous improvement.
iii. Demonstrate the potential benefits achieved to show that the proposed framework can be implemented by any business organization and can improve the company performance.

The structure of the framework has been divided into three phases namely the lean conception phase, lean implementation phase, and lean sustainability phase. The proposed framework integrates the six sigma DMAIC methodology with lean tools and techniques to reduce defects and achieve performance improvement. A solid cast software has been used as a computer-assisted casting simulation tool to perform the analysis of defects within the casting. Further, the proposed framework is demonstrated and validated by employing a real-time case study that was manufactured using the sand casting process.

II. LITERATURE REVIEW

Current literature shows various initiatives on the development of lean implementation frameworks for different purposes. Mostafa *et al.* [7] proposed a framework to identify the success factors for the implementation of lean manufacturing. To implement lean manufacturing, Nordin *et al.* [12] proposed an organizational change framework based on empirical research and validation. By considering the strengths and weaknesses of the existing lean implementation frameworks, Bhamu and Sangwan [13] proposed a lean manufacturing implementation framework for easily understanding and self-assessment of critical milestones before implementation, during implementation, and after implementation of lean manufacturing. AlManei *et al.* [14] studied the challenges, drivers, and barriers to the successful implementation of lean manufacturing frameworks. The study investigated that unsuccessful implementation of lean manufacturing frameworks may result in a high impact on organizational resources, employees, and their confidence in lean philosophy.

Using interpretive structural modeling methodology, Jadhav *et al.* [15] developed a framework for sustainable lean manufacturing implementation. The major objective of the study was to develop a phase-wise roadmap for LM implementation in the automotive industry. According to AlManei *et al.* [16], there is a need to change the organizational structure, processes, systems, and employees' behavior to successfully implement lean manufacturing. To achieve this, the author presented a conceptual framework for lean implementation on the basis of change management theory. Abu *et al.* [17] investigated the motives, barriers, challenges, and applications of lean manufacturing implementation in the wood and furniture industry of Malaysia. Similar research was also conducted by Rymaszewska [18]. Chong and Perumal [19] proposed a conceptual framework for lean implementation in small and medium enterprises (SMEs). Abu *et al.* [20] used a structural equation modeling approach to analyze the barriers to lean implementation in manufacturing industries. Abu *et al.* [21] conducted a bibliometric and systematic review to investigate pathways to implement lean manufacturing in the wood and furniture industries. Bayhan *et al.* [22] provided a set of core barriers and enablers of lean implementation in construction projects. The major purpose was to guide the construction professionals to satisfy the construction requirements of the customers.

Based on the outcomes of a case study conducted in the Indian textile industry, Prasad *et al.* [23] proposed a framework for lean implementation for achieving continuous improvement through the elimination of waste (defects). Worley and Doolen [24] demonstrated the role of communication and support by management in the implementation of a lean manufacturing framework. The study was conducted in an electronic manufacturing company in the northwestern USA. Anand and Kodali [25] developed a conceptual framework for lean manufacturing system implementation. Klochkov *et al.* [26] presented various lean performance characteristics to increase the efficiency of the manufacturing process of the casing of a water pump. In this study, only the technological aspects of the manufacturing process were covered to eliminate waste using lean manufacturing concepts such as value stream mapping, 7 wastes, and 5S under a six sigma environment. de-Albuquerque Marques and Matthé [27] employed only DMAIC six sigma methodology to improve the performance of the aluminum die-casting operation. The study recommended the use of structured methodologies to improve the product quality and efficiency of the manufacturing process. However, this research work lacks the use of the lean concept to achieve continuous improvement through the elimination of wastes during the operational activities of the manufacturing process. Similar work was conducted by Gandhi *et al.* [28]. Based on recommendations for preventive and corrective actions, the DMAIC cycle was implemented in a systematic way to counter the defects in casting units manufacturing cylinder blocks.

The above review of the literature highlights that current studies illustrate the implementation of lean manufacturing within the various business sectors. However, there is still a need to investigate the efforts that used both the lean and six sigma methodologies to improve the company's performance. Additionally, because of the issues that companies face during the implementation of lean six sigma approaches, various frameworks have been proposed to assist manufacturing organizations in this endeavor. The analysis of these frameworks has been provided in table 1.

Using the findings from the literature review, the following gaps have been identified.

i. Table 1 reveals that the majority of the frameworks have been developed by taking into the consideration only lean manufacturing concept. Two frameworks have considered the concept of six sigma. Only one framework has attempted to integrate the lean and six sigma concepts.
ii. Majority of the frameworks have been developed to assist organizations to implement these in a specific manufacturing process. There is a need for generic frameworks capable of implementation in any business sector.
iii. Majority of frameworks focused only on the investigation of causes of casting defects, hence lacking the production and economic dimensions as well.
iv. Table 1 shows that very limited frameworks were tested using the case study. There is requirement to test the frameworks through a real-time case study to encourage organizations to implement the developed frameworks practically.
v. Mostly developed frameworks for lean implementation fall under the category of conceptual model development with the basic objective to provide knowledge for lean implementation in a specific business system.

The above review of the literature highlights that significant shortcomings exist. To overcome these limitations and to promote lean six sigma within manufacturing organizations, comprehensive and simplified frameworks are compulsory. This motivates the researcher to propose a lean implementation framework for performance improvement of metal casting organizations.

This research paper is structured into the following sections: Section 1 describes the introduction of the study. Literature review on key areas including metal casting, lean manufacturing, and lean six sigma implementation framework practices has been performed in section 2. Section 3 describes the research methodology adopted for the accomplishment of this study. Overview of the organization and case study to have a deeper practical knowledge for the implementation and validation of the developed lean manufacturing framework has been given in section 4. It further leads to the analysis and discussion body of the proposed lean implementation framework and its components in section 5. Section 6 illustrates the validation of simulation results. Section 7 presents the potential benefits achieved after the implementation of the proposed framework. Lastly, the overall conclusions of the study have been illustrated in section 8.

III. RESEARCH METHODOLOGY

The methodology adopted to conduct this research is presented in figure 1.

In step 1, an introduction and literature examination was done covering large areas related to the metal casting processes, lean manufacturing, six-sigma, and lean implementation frameworks. Step 2 deals with the analysis of the case study which further leads to the discussion of the proposed framework in step 3 in the light of requirements of the collaborative company. To achieve the needed performance improvement aspect of the company, it was compulsory to take into account the process variations and waste elimination in an integrated way. Therefore, six-sigma DMAIC has been used in the current capability of the proposed framework. In step 4, achieved benefits after the implementation of the proposed framework have been presented while the conclusion of the study is discussed in step 5.

IV. OVERVIEW OF THE CASE STUDY

The organization is a well-known manufacturing group, which is dedicated to its core capabilities in providing the best quality products and services within many industries including sugar mills, cement plants, boilers, equipment for oil and gas, fertilizer, chemical plants, and OHT cranes, etc. Considering the miscellaneous nature of the business, the organization was interested in developing a lean implementation framework for enhancing the company performance through continuous improvement within the organizational culture.

This study was done based on the deliberate need of the company. A Y-chain link of a cane carrier was taken as a case study. Its CAD model was developed using solid works software and is shown in figure 2. The company was facing a continuous problem of failure of this product while transferring sugarcane from cane house to mill house in a

TABLE 1. Analysis of the frameworks, models.

Ref. No	Research Stream	Validation	Application Area	Limitations
Barot et al. [29]	Lean six sigma	No	Sand Casting	The theoretical framework has been proposed to identify the defects in casting process. The framework is developed and tested for a particular manufacturing process. It lacks the production and economic dimensions as well.
Yadav et al. [30]	Lean	Yes (case study)	Pump Manufacturing	The framework lacks six sigma concept.
Gandhi, Sachdeva, and Gupta [28]	Six sigma	Yes (case study)	Casting	The proposed framework still has room for improvement through integrating lean with the existing six sigma concept.
Bhamu, Khandelwal, and Sangwan [31]	Lean	Yes (case study)	Production line	The proposed model lacks integrated lean six sigma implementation
Kumar et al. [32]	Lean	No	Steel production	The framework is developed for steel industry. It also lacks six sigma concept.
Kukhan and Kumar [33]	Lean	No	Ethical paper production	The proposed model is developed for paper production industry. It incorporates the lean manufacturing tools which lacks the six sigma concept for process improvement.
Jasti and Sharma [34]	Lean	Yes (case study)	Auto components industry	The proposed framework lacks six sigma concept.
Seifullina et al. [35]	Lean	No	Mining Industry	The framework is developed for a particular industry. Also it lacks the integration of six sigma concept.
Bhamu and Sangwan [13]	Lean	No	Manufacturing	The framework is not validated and tested in reality environment.

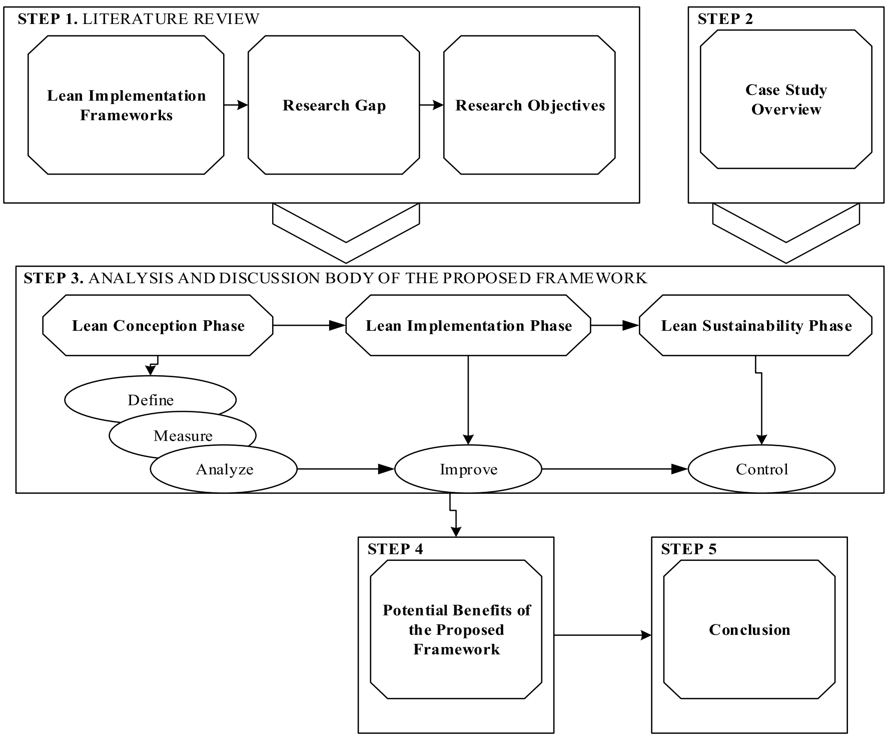

FIGURE 1. Adopted Research Methodology.

sugar mill. Based on the management need of the framework and because of the strategic focus for the industry, this study will take into account the performance improvement aspect of the industry. The purpose of using a single case study was to have deeper practical knowledge and understanding of the exploring subject of a lean implementation framework.

V. ANALYSIS AND DISCUSSION BODY OF THE PROPOSED FRAMEWORK

In today's competitive environment, lean approaches have been widely used by practitioners and academic researchers. Lean implementation rotates around lean principles namely: (i) value specification from the customer and company perspective, (ii) value stream alignment with the customer

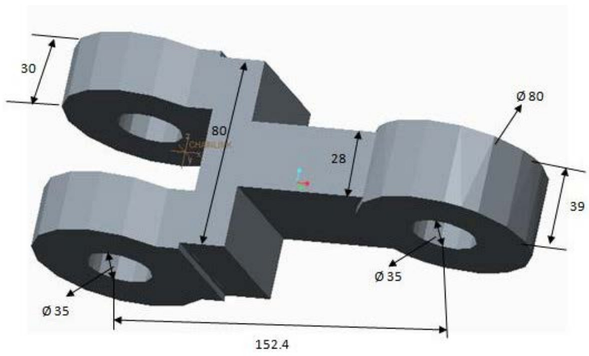

FIGURE 2. Y-Chain Link.

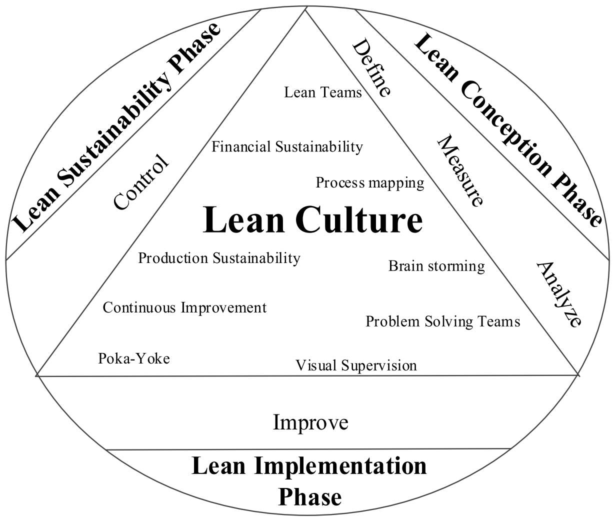

FIGURE 3. Lean Implementation Framework.

requirements, (iii) continuous flow creation in the process and entire value chain, (iv) use pull (produce exactly what customer needs in terms of production values and time) instead of push in the metal casting process, and (v) perfection achievement through continuous improvement [36]. The proposed lean implementation framework (LIF) is shown in figure 3.

It is comprised of three phases, namely: lean conception, lean implementation, and lean sustainability. The flowchart of the proposed framework for implementation is shown in figure 4.

These phases are implemented under the DMAIC approach of six sigma to simultaneously achieve the benefits of LIF. Six Sigma is a continuous improvement practice and consists of a standard five-steps (DMAIC) cycle including (i) defining the critical behaviors of required quality by the customer, (ii) measuring the problem faced by the industry, (iii) analyzing the problem, (iv) improve the process through elimination or reduction of cause, and (v) control for insuring continuous improvement [37], [38]. From the literature, it can be analyzed that most of the studies have used the DMAIC approach to implement the six sigma methodology. This approach mostly focuses on quality improvement with less focus on lean (waste reduction) which limits the capability of lean. There is a requirement for an implementation methodology that extracts the capabilities of both lean and six sigmas. Based on fact that the metal casting industry can benefit from the lean principles, the industry still lacks an intelligible and general framework to initiate the lean culture of the metal casting industry. Therefore, an integrated lean six sigma implementation approach has been proposed in this study. It will be beneficial to improve the performance of metal casting industries.

The proposed framework respites on metal casting industry culture which includes the common attitudes, expectations, and values of the people within the organization. This study takes the industry culture as the dominant tenant which will bind the LIF initiatives. A detailed discussion of each phase of LIF is provided in the following sections.

A. LEAN CONCEPTION PHASE

The lean conception phase starts with the number of initial level activities which includes the definitions of teams, tasks, and missions. It follows the Define, Measure, and Analyze steps of the DMAIC methodology as illustrated below:

1) DEFINE

According to Stephen [39], a well-defined problem would lead to a well-defined solution. The define step starts with the right mapping of the casting process flow of the Y-chain link.

a: TEAM CHARTERING

It includes the chartering of teams for lean initiation in the metal casting industry. Generally, it starts with the number of initial level activities which includes the definitions of teams, tasks, and missions.

For the proposed framework, lean teams consist of employees (from the procurement cell, technology department, maintenance of production cell, and supply chain personals) of the company and lean experts. Lean experts included academicians, consultants, and industrialists. The reason behind the addition of the company's employees was that they were aware of the company casting operations and procedures. External experts might have a deficiency of detailed information. It will ensure the presence of customer and company voices in decision-making to strengthen the process of developing a lean culture within the industry.

b: PROBLEM DEFINITION

- Failure of Y-chain link of cane carrier while transferring sugarcane from cane house to mill house of the sugar industry.
- Chain link was manufactured of carbon steel in ZG 45 steel grade using a sand casting process.

c: PROBLEM STATEMENT

The problem of failure of the Y-chain link of one of the cane carriers is being addressed in this study. After continuous

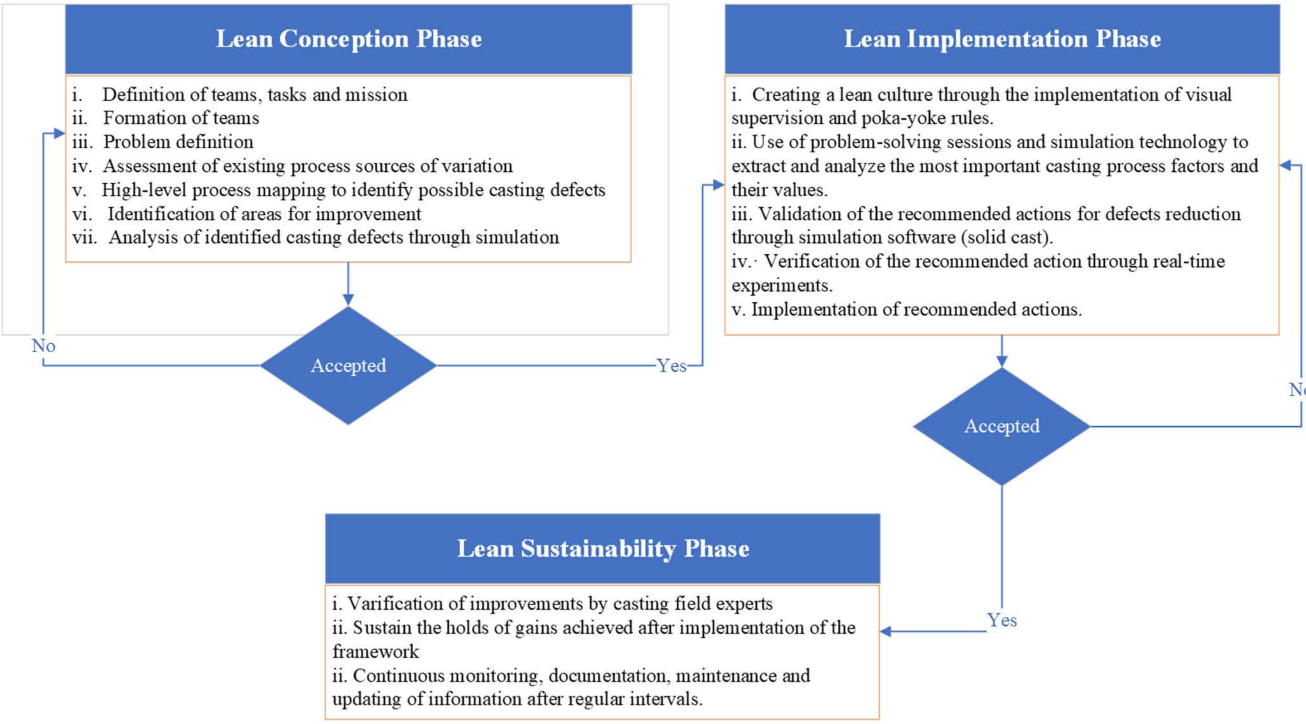

FIGURE 4. Working Flowchart of the Proposed Lean Implementation Framework.

analysis and inspection of the failed y-links through visual inspection and due to the mass production of this product, it was felt necessary to revise the casting technology so that a defect-free chain link can be cast which is critical to the quality of this project.

2) MEASURE

By following the lean principle of value stream identification, this step deals with the collection of data regarding the current performance and issues of the process or product. The overall objective of the measuring phase was to assess the existing process sources of variations and the reduction of the number of rejected parts due to these variations.

At this phase, initially, the part was manually rigged and inspected visually for porosity check. Upon examination, it was observed that there exists a sufficient amount of porosity below the riser location of the gating system of the product as shown in figure 5.

a: PROCESS MAPPING

In the measuring step, a high-level process mapping was drawn for the manufacturing of the Y-chain link through the sand casting process. For this purpose, a SIPOC table format has been used as shown below in table 2.

Further, analysis of the product and discussion with casting experts concluded that mainly defects occurred due to the application of manual methods to carry out the activities of the sand casting process.

The analysis of the casting gating design revealed the following considerations.

- Use of top gating system for metal pouring
- Ingates were kept at one side of the runner

In this way, the suspected sources of variation (SSV) are required to investigate the casting activities and their specific values. In this study, SSVs were selected through analysis of the available data and discussion with casting experts after conducting brainstorming sessions. A list of current sources of variations including the process map, activity name, sources of variation factors, and their respective dimensions are given in table 3.

The overall purpose of the measure phase was to identify the areas for improvement to:

- Reduce the casting weight
- Reduce the rejection rate
- To enhance the yield
- To reduce the total casting cost

3) ANALYZE

Today, there exist a lot of manufacturing companies that have not been able to develop themselves at the same pace as in the industrial revolution. This is because they have not invested in bringing and implementing new technologies and methodologies such as simulation and lean. In this study, to analyze the casting process, the method-through-simulation strategy was used. For this purpose, a Solid cast foundry simulation software was used.

FIGURE 5. Y-chain link with porosity.

TABLE 2. Sipoc table for process mapping of Y-link manufacturing.

Suppliers	Inputs	Process	Outputs	Customer
Technology cell	Casting length, Casting width, Casting thickness, Casting weight	3D modeling of casting design	3D model of the cast part	Casting gating design
Casting gating design supplier	Design of riser, Design of runner, Design of ingates	Casting gating design	Casting gating design	Pattern preparation,
Pattern supplier	Wooden pattern, Silica sand, Binding material	Pattern preparation	Pattern design, mold design	Melting and pouring
Foundry operation	Electric arc furnace, Steel grade Melting temperature, Pouring temperature	Melting and pouring	Solidified casting mold	Cutting and cleaning
Post casting operations	Riser cutting, Gating cutting, Grinding/cleaning	Cutting and cleaning	Cast part with a smooth surface	Checking for defects (porosity)
Quality cell	Visual inspection, Material density function Solid cast	Checking for defects (porosity)	Handle porosity	Packaging and expedition

The analysis phase starts with the 3D modeling of the cast part (chain link) using CREO 2.0 software. Further, it was used import to solid cast in STL file format. The casting material was selected and its physical properties were added as shown in figure 6. After selecting the appropriate cooling curve, the melting and solidification temperatures, the software then adds the molding material and its physical properties as shown in figure 7. It further leads to the meshing and solidification simulation of the selected product.

In this way, the manually engineered model of the measure phase was simulated and checked for porosity on material density function. A material density function is a number that can vary from 0 to 1. It is the measure of how much of the metal remains at each point in the model.

A value of 0 means that the metal has been completely drained from the cast part. A value of 1 indicates completely sound metal. The material density function, therefore, is interpreted as follows:

Value = 0, means 0% metal and 100% porosity
Value = 0.90, means 90% metal and 10% porosity
Value = 0.99, means 99% metal and 1%porosity
Value = 1, means 100% metal and 0% porosity

In solid-cast software, porosity is measured along with dimensional measurements (XYZ axis). In this study, porosity has been measured at a material density factor of 1. This step was performed under the same casting design parameters that were originally employed at the measure step the of DMAIC methodology. It can be seen from figure 8 that porosity exists at the same point (below riser) as observed in real casting at the measuring phase. It verifies the accuracy of the simulated model.

B. LEAN IMPLEMENTATION PHASE

Once the defect (porosity) has been detected, the next phase of the lean implementation framework is to implement the continuous improvement strategies including lean and manufacturing operations streamlining. In the metal casting industry, which includes the manufacturing of discrete parts, it would be best to improve the identified areas of improvement.

TABLE 3. List of current sources of variations.

Process Map	Activity Name	SSVs	Dimensions
3D Modeling of Casting Design	Modeling through solid works	Casting weight	Finish weight:4.09kg Weight after adding machining allowances: 5.5kg
Manual Method of Casting Gating Design	Modulus calculation	Modulus of casting (Mc)	1.313cm
		Modulus of the riser (Mr)	1.575cm
		The ratio for calculating Mr	1.2
	Riser design	Height to diameter ratio	1:1
		Riser geometry	Cylindrical Diameter: 78mm Height: 78mm
		Runner neck (for runner connection to casting)	Diameter: 35mm Height: 20mm
Pattern Preparation	Pattern design	Wood pattern	Top gating system with four ingates at one side of the runner
	Mold Design	Silica sand	SiO2 (96%), Fe2O3 (0.75%), impurities (1%), clay content (2%)
		Binding material	Sodium silicate (up to 2%)
Melting and Pouring	Melting and pouring	Furnace type	3-ton electric arc furnace
		Steel grade	ZG-45 (see table 4 for composition)
		Pouring temperature	1550 °C
Post-Casting Operations	Cutting	Cutting of riser and gating	Gas cutting process
	Cleaning	The smooth surface of the casting	Manual grinder

TABLE 4. Achieved composition of steel grade ZG 45.

C %	Mn %	Si %	P%	S%	Cr %	Ni %	Mo %	Cu %	Al %
0.42	0.72	0.38	0.023	0.013	0.25	0.25	0.07	0.20	0.041

In the implementation phase, the most fundamental approach was to create a lean culture within the casting industry. It was done through training and development, seminars, and workshops on the lean concept and its benefits for achieving sustainable solutions for metal casting industries. Through these activities, workers realized mental and physical empowerment to accept the new lean tools and strategies for continuous process improvement. Additionally, in this phase, technical tools such as solid cast simulation software have been used to assess the performance of the existing system and to improve the existing casting modules within the casting operations before the start of actual manufacturing. It helped in assessing the possible defects and their location within the castings which ultimately resulted in low product cost, material cost, and defects rate leading to high-quality products without any job floor trials. This phase of LIF follows the improvement step of the DMAIC methodology.

1) IMPROVE

In this study, during the lean implementation phase, the collaborative organization was committed to ensuring lean culture and communication programs across the departments to enhance teamwork and people empowerment for sustainable output. For this purpose, a diverse range of lean tools under the lean thinking concept was investigated through a literature review to improve the existing capability of the casting operations. The most feasible lean tools for the metal casting industry have been described below.

a: VISUAL SUPERVISION

In the metal casting industry, visual supervision is considered a critical lean tool to visualize and manage the casting operations. It can be useful for improving transparency in planning and control [40]. For this purpose, visual boards and 5S (sort, set in order, shine, standardize, and sustain) techniques were used for equipment location and visual management respectively. Updating visual management tools regularly was compulsory for the organization. Further, the company was also suggested to integrate the visual supervision tools with the RFID (Radio Frequency Identification) to increase the ability to manage the flow of information and parts across the departments.

b: POKA-YOKE

Poka-yoke is a lean manufacturing tool that is used to avoid the passing of defective parts. In this study, the concept of poka-yoke has been used for mistake elimination during the selection of the casting process, casting material, casting design features, and casting castability assessment. For this purpose, poka-yoke rules (if-then rules) have been developed and implemented to select the best alternative from a set of available solutions. An example of such rules is given below:

If the Casting process is sand casting AND
The casting material is steel grade ZG-45 AND
Casting weight is >5kg AND
Any other rule
Then
EAF3 is the selected furnace for melting and pouring
EAF3 is a 3-ton electric arc furnace

These rules will assist the decision-makers in selecting the right alternative on the first try which will result in reduced job floor trials and ultimately research and development costs.

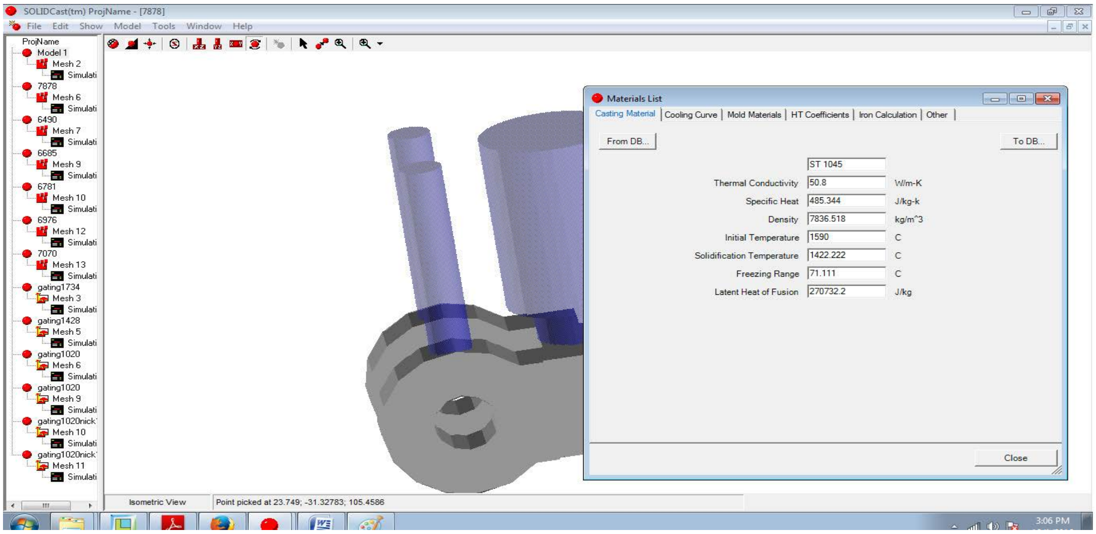

FIGURE 6. Selecting casting material and physical properties.

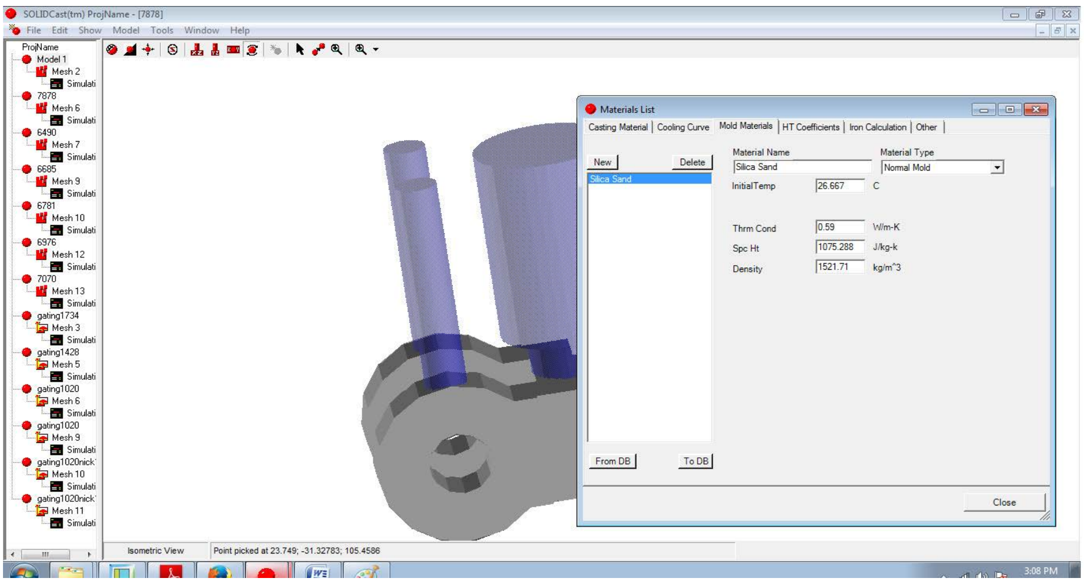

FIGURE 7. Selecting mold material and physical properties.

In this step, under the lean thinking environment, many problem-solving sessions were conducted by casting experts to recommend actions for process improvement. These sessions ultimately resulted in the following procedure to implement improve phase of the DMAIC methodology.

- Creating a lean culture through the implementation of visual supervision and poka-yoke rules.
- Use of problem-solving sessions and simulation technology to extract and analyze the most important casting process factors and their values.
- Validation of the recommended actions for defects reduction through simulation software (solid cast).
- Verification of the recommended action through real-time experiments.

Following the above-designed procedure, the recommended revised casting process features and their values are given in table 5.

Further, the recommended values (against each factor) were modeled in simulation software to check their effect on porosity. It follows the same procedure as discussed in analyzing a section of the DMAIC methodology.

After adding the material characteristics and molding material properties, a naked simulation was performed. Preliminary, casting modulus was calculated through Solid cast, and Riser was calculated using the riser design wizard feature of Solid cast as shown in figure 9 below.

During this step, the riser design wizard of solid cast software was run to specify an optimized riser with maximum

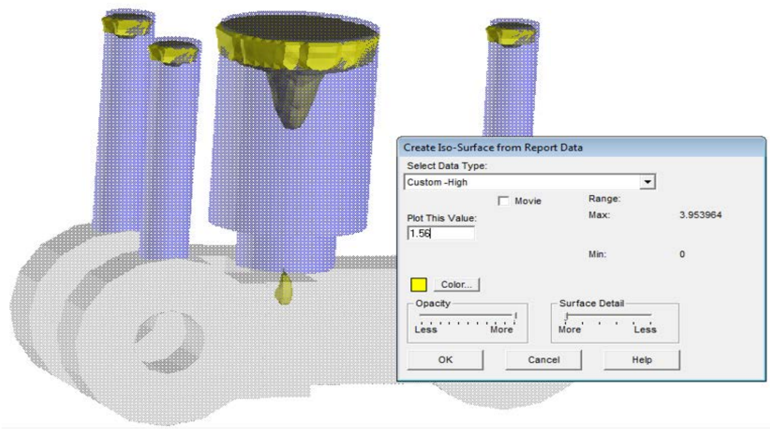

FIGURE 8. Porosity measuring.

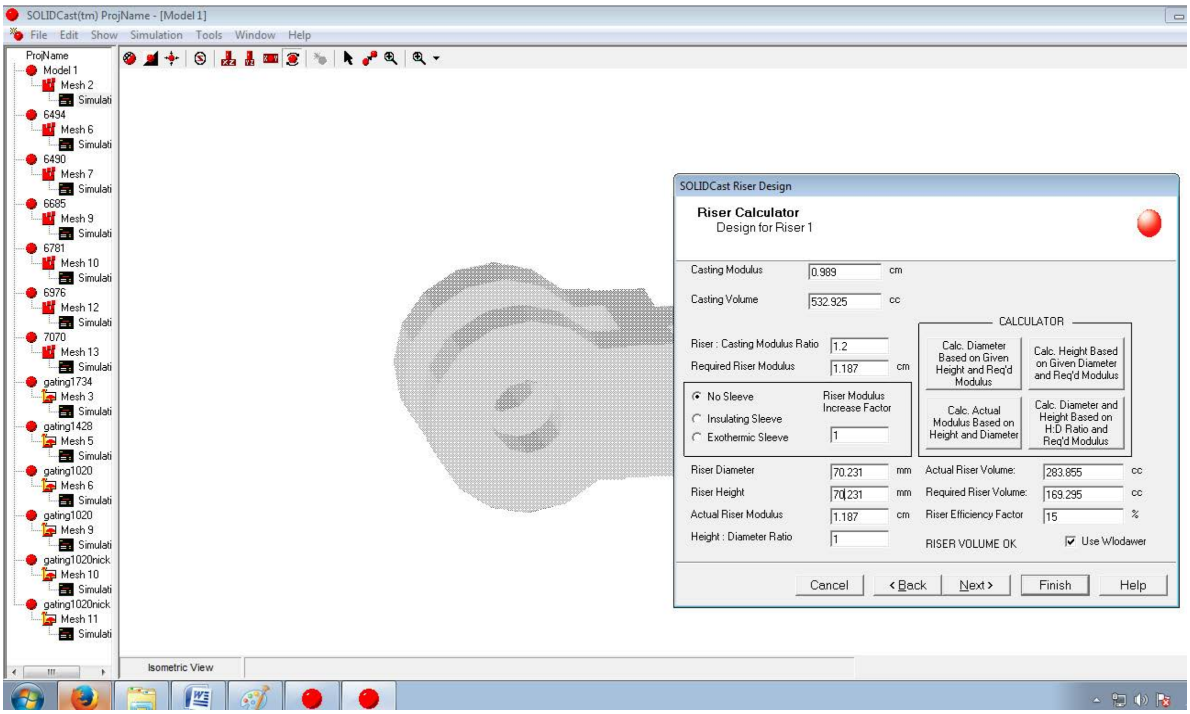

FIGURE 9. Riser design wizard.

feeding ability. In addition to this, the gating system was periodically changed to maintain the required velocity of metal flow within the mold. Overall four quantities of casting had been put in parallel in one mold to distribute the equal flow and pressure of metal in the mold as shown in figure 10 (given below).

The redesigned model was again simulated and the flow of the metal was checked using the FlowCast module of the Solid cast. After simulation, the results were checked on the material density factor for porosity check. Figure 11 (with improved gating design) reveals that there is no defect (porosity) in the redesigned simulated model. The outcomes of the improvement step are instant and counteractive.

C. LEAN SUSTAINABILITY PHASE

Although lean adoption in the metal casting industry is recent in Pakistan, its benefits have been found positive and are measured in the form of time utilization, workflow enhancement, production capacity improvement, decreasing production cost, and improvement in organization safety and working culture.

It is pertinent to mention that culture change is fundamental to achieving continuous improvement within the organization. The above-mentioned positive results have been achieved in a short period. But lean sustainability has not been reported yet in the metal casting industry. Therefore, this study recommends strongly building a

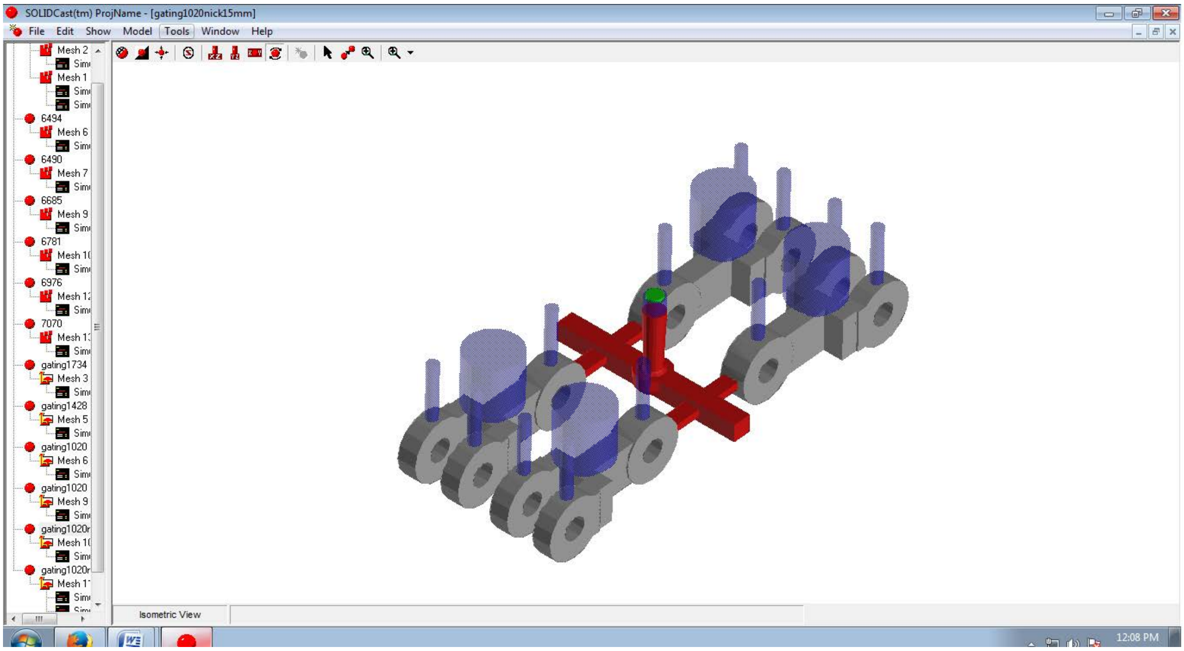

FIGURE 10. **Modified gating system with ingates attached to both sides of the runner.**

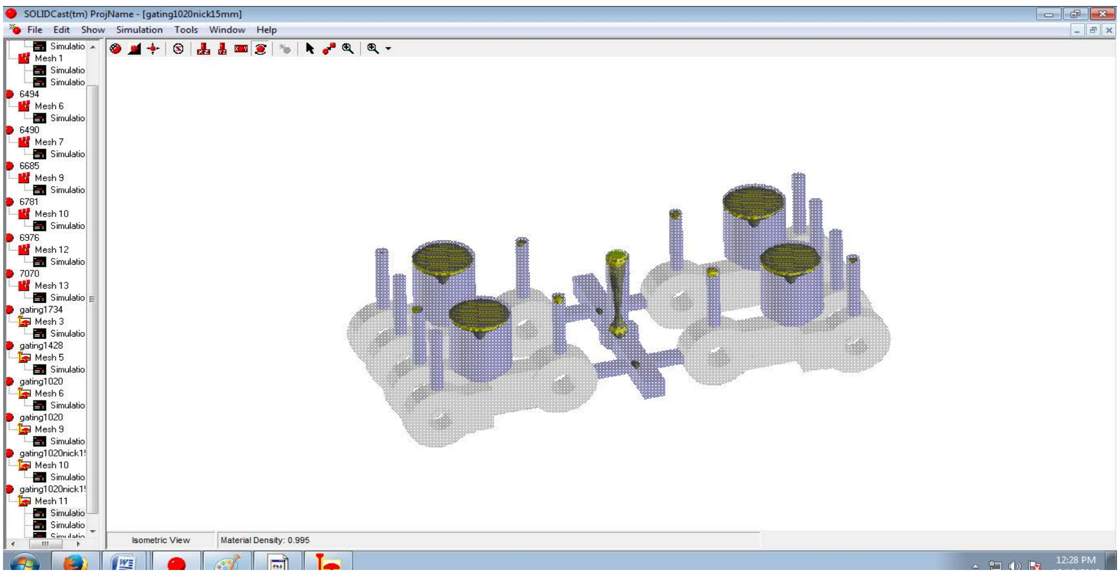

FIGURE 11. **Simulated model of the Y-chain link with improved features shows no porosity.**

continuous improvement culture through the implementation of the proposed framework. In addition to this, the outcomes of this stage show the financial (total casting cost) and production (% yield) sustainability of the proposed framework. This phase follows the control step of the DMAIC methodology as described below.

1) CONTROL

This step ensures that defects don't occur again. This is the last step of the DMAIC methodology implemented in a lean environment. The major purpose of this step was to sustain the holds of gains achieved from the improvement step in the previous phase of the lean implementation framework. In this step, the critical casting process parameters were continuously monitored, documented, maintained, and information was updated after regular intervals. For the current study, proposed (better) improvements have been provided in table 5. These improvements in process parameters were recommended, implemented, and verified by casting experts during the problem-solving meetings in the presence of lean and six sigma experts, and academicians.

TABLE 5. Revised casting features and their values for porosity reduction.

Activity Name	Revised recommendations	Values
Modeling through solid works	Casting volume	532.925cc
Modulus calculation	Modulus of casting (Mc)	0.989cm
	Modulus of the riser (Mr)	1.187cm
	The ratio for calculating Mr	1.2
Riser design	Height to diameter ratio	1:1
	Riser geometry	Cylindrical without sleeve Diameter: 70.231mm Height: 70.231mm
	Riser Volume	Actual: 283.855cc Required: 169.295cc Riser Efficiency Factor: 15%
Pattern design	Wood pattern	Bottom gating system with 2 parallel ingates at both sides of the runner
Gating System	Standard as per American Foundry Society	Gating ratio (sprue: runner: ingates): 1:2:1.5
		Revised gating system with ingates attached at both sides of the runner
Mold Design	Silica sand	SiO_2 (96%), Fe_2O_3 (0.75%), impurities (1%), clay content (2%)
	Binding material	Sodium silicate (up to 2%)
Melting and pouring	Furnace type	3-ton electric arc furnace
	Steel grade	ZG-45 (see table 2 for composition)
	Pouring temperature	1550 °C
Post-casting operations	Cutting of riser and gating	Gas cutting process
	The smooth surface of the casting	Manual grinder
Check for defects	Material density function	1

VI. VALIDATION OF SIMULATION RESULTS

In order to validate the results (porosity) obtained from the solid cast software, real-time experiments (casting of the y-chain) were performed again by implementing the recommended and modified process parameters by the experts at the improvement stage. After experimentation, the cast part was inspected visually for porosity check. After observation, it was revealed that there exists no porosity below the riser as shown in figure 12. It validates the simulated results of improve stage of DMAIC.

VII. POTENTIAL BENEFITS ACHIEVED AFTER IMPLEMENTATION OF THE PROPOSED FRAMEWORK

This section describes the potential benefits achieved after the successful implementation of the proposed framework. One assembly of bagasse ash carriers in the sugar industry mainly consists of 640 Y-chain links. One mold (casting) consists of 4 Y-chain links. It shows that a total of 160 (640/4) casting would be required for one assembly. Further, each casting took 42kg of molten metal. In this way, the total molten metal required for one assembly (160 castings) was approximately 6720kg.

TABLE 6. Tangible benefits achieved.

Real Benefits	Before	After	Percentage Improvement
Poured molten metal (kg)	6,720	4,480	33.3%
Mold weight including risers and gating design (kg)	3,200	1,920	40%
% Yield	43	57	24.56%
Rejection Rate (%)	20	2	90%
Material Cost (PKR)	244,320	173,270	29.08%
Labor Cost (PKR)	70,400	57,469	18.37%
Variable Overheads (PKR)	284,256	212,453	25.26%
Pattern Preparation Cost (PKR)	18,900	18,900	0%
Fixed Overheads (PKR)	57,792	47,177	18.36%
Total Cost (PKR)	675,668	509,269	24.63%

Before the implementation of the proposed framework, the manual gating design was following a top gating system with an unsuitable riser, runner, and ingates design. Additionally, all four cast parts were added to one side of the runner as shown below in figure 13-a. It resulted in inadequate pouring and filling of mold with molten metal. It ultimately led to porosity on the ingate-casting interface inclined towards casting or somehow within the casting near the ingate location. With this gating design, the analysis of 160 castings was performed during the measure phase and it was observed that porosity exists in a total of 32 castings. It means 128 parts (out of 640) were found defective and rejected by the quality experts. In this way, a rejection rate of 20% was observed by the company as shown in table 6. After the implementation of the proposed framework, the improved stage of the DMAIC methodology caused a reduction in the rejection rate to 2% due to the incorporation of an improved gating design (figure 13-b) recommended by casting experts. In this way, the implementation of the proposed lean implementation framework also provided many other associated tangible and non-tangible benefits to the collaborative company. The most important are given below in table 6.

In addition to tangible benefits, the implementation of the proposed framework also provided many non-tangible benefits. The detail of the cost of quality is as under:

- *Intangible cost:* including image and reputation cost of the department and organization.
- *Non-Quality Cost:* resulting from the lack of capability of the casting process in meeting the product specifications.
- *Research and development cost:* resulting from the increased job floor trials due to the rejection of the part.

The obtained results truly prove the significance of the proposed lean implementation framework. It further ensures

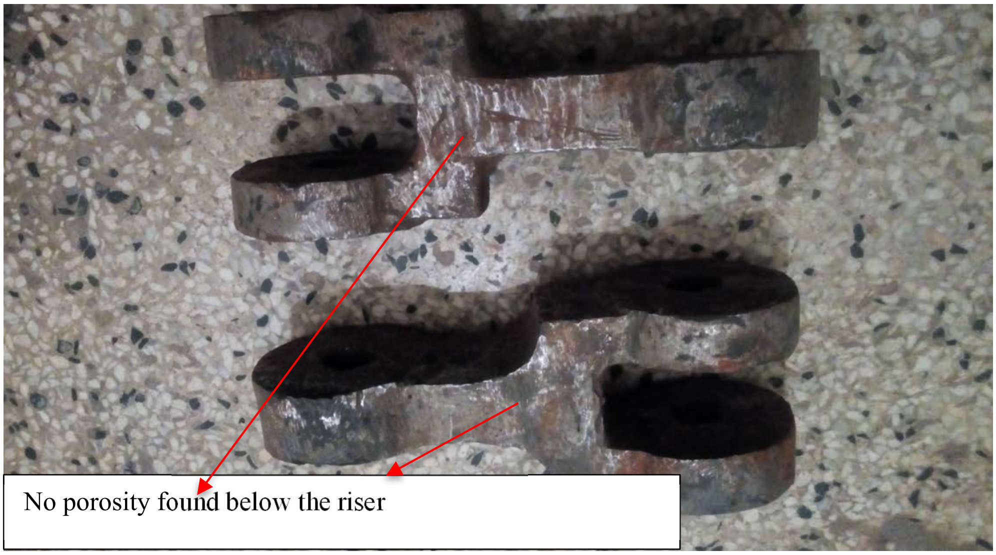

FIGURE 12. Y-chain link without porosity.

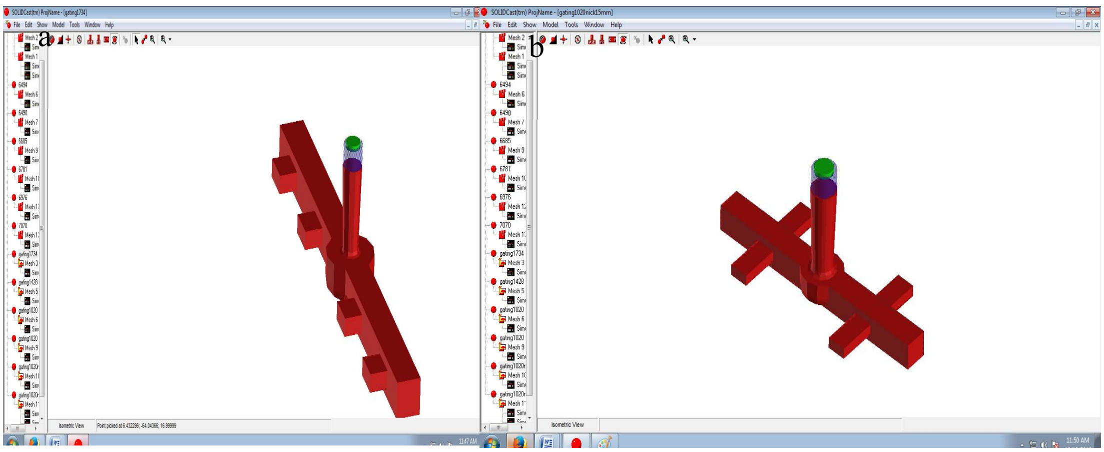

FIGURE 13. Gating design (a) existing design and (b) modified design.

the financial and yield sustainability of the sand casting process.

VIII. CONCLUSION

Lean thinking has been greatly applauded and implemented by practitioners in an enormous range of various businesses and industries. However, every sector has dynamic nature of challenges which varies among different countries thus requiring a specific framework by taking all the stakeholders on board. This study aims to propose a lean implementation framework to build a continuous improvement culture within the organization using metal casting processes for the production of parts. The proposed framework has been classified into three phases namely the lean conception phase, lean implementation phase, and lean sustainability phase. The major objective was to achieve performance improvement in the industry. Based on the results, the following conclusions have been drawn.

- This study illustrates the development and implementation of a lean implementation framework in the sand casting process of a metal casting industry.
- In this study, DMAIC (six sigma methodology) has been taken as an innovative approach to improving the performance of the process continues through simulation.
- The application of the proposed lean implementation framework recommendations decreased the weight of pouring metal from 6720kg to 4480kg with approximately 33.3% saving of pouring metal.
- Mold weight (including risers and gating system) has been reduced from 3200kg to 1920kg (∼40% improvement).
- Casting yield was increased from 43% to 57% (∼24.57% improvement).
- This study has resulted in a saving of overall casting cost of approximately 24.63% which depicts that

economic and production (casting yield) sustainability can be achieved through the implementation of LIF.

Testing of the proposed framework followed by any amendments in casting features (to achieve optimization) through other tools such as the design of experiments (DOE), Taguchi method, and response surface methodology (RSM) would greatly benefit future research in the casting industry. Application of lean implementation framework is a small step towards casting economy. Once it finds its rightful place in the cost-intensive casting industry, massive advantages can be achieved through its application in other business sectors such as service organizations.

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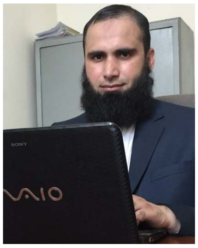

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