

REVIEW ARTICLE

A structured review of Six Sigma implementation in casting industries

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ABSTRACT

Six Sigma is an organized and systematic method for strategic process improvement that relies on statistical and scientific methods to reduce the defect rates and achieve significant quality up-gradation. Six Sigma is also a business philosophy to improve customer satisfaction, a tool for eliminating process variation and errors and a metric of world class companies allowing for process comparisons. Six Sigma is one of the most effective advanced improvement strategies which has direct impact on operational excellence of an organization. Six Sigma may also be defined as the powerful business strategies, which have helped to improve quality initiatives in many industries around the world. With the use of Six Sigma in casting industries, rejection rate is reduced, customer satisfaction is improved and financial benefits also increased. Six Sigma management uses statistical process control to relentlessly and rigorously pursue the reduction of variation in all critical processes to achieve continuous and breakthrough improvements that impact the bottom-line and/or top-line of the organization and increase customer satisfaction. In this paper author reviewed some of the significant previous published papers and focused on the general overview of publication in casting industries.

Keywords: Six Sigma; Process Improvement; Casting Defects; Customers; Innovation

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1. Introduction

Six Sigma is one of the recent quality improvement initiatives to gain popularity and acceptance in many industries across the globe. Six Sigma differs from other quality programs in its top-down drive and in its rigorous methodology that demands detailed analysis, fact-based decisions and a control plan to ensure ongoing quality control of a process. Since its initiation at Motorola in the 1980s, many companies including GE, Honeywell, Sony, Caterpillar and Johnson Controls have adopted Six Sigma and obtained substantial benefits. It can help industries and service sector to reduce cost, increase profits, keep current customers and create new customers. It is a business philosophy to improve customer satisfaction, a tool for eliminating process variation and errors and a metric of world class companies allowing for process comparisons. A Six Sigma philosophy generates top box customer satisfaction and repeat customers by reducing the cost of products because it is based on the principle, "Do right the first time". Six Sigma is a level of performance that reflects significantly reduced defects in products and services, a statistical measurement of process capabilities as well as a bench-mark for comparison. It is a set of statistical tools to help companies to measure, analyze, improve and control processes. It is also a commitment to all customers and consumers of products and services

that an organization continually works on improving its products and processes to reduce the defects.

Six Sigma may also be defined as the powerful business strategies, which have helped to improve quality initiatives in many industries around the world. Six Sigma administration uses statistical process control to persistently and austere pursue the diminution of variation in all critical processes to achieve continuous and breakthrough improvements that impact the bottom-line and/or top-line of the organization and increase customer satisfaction. It is a company-wide systematic approach to achieve continuous process improvements.

The name Six Sigma also refers to the capability of the process to deliver products within the specified limits. The Greek letter σ or ‘sigma’, corresponding to ‘s’, also is a notation of variation sense of standard deviation. For a stable process, the distance from the process mean to the nearest tolerance limit according to the Six Sigma approach, be at least six times the standard deviation σ of the process output. However, the target process

mean is also allowed to vary somewhat over time. If the process mean varies up to a 1.5σ from the target value, then on average at most 3.4 Defective Per Million Opportunities (DPMO) will occur if the output is normally distributed. Six Sigma is based on the normal distribution theorem introduced by Carl-Friedrich Gauss as given below:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}$$

Where:

x = quality characteristic and

σ = standard deviation of quality characteristic

The above Equation describes a normal distribution curve whose form is defined by two parameters, the mean average value and the standard deviation “sigma”. Six Sigma is the tool used to help in designing highly capable parts that meet the set specifications. These specifications are +/- six times standard deviations from the process mean i.e. from the center line. **Figure 1** shows the normal distribution of a quality characteristic (x).

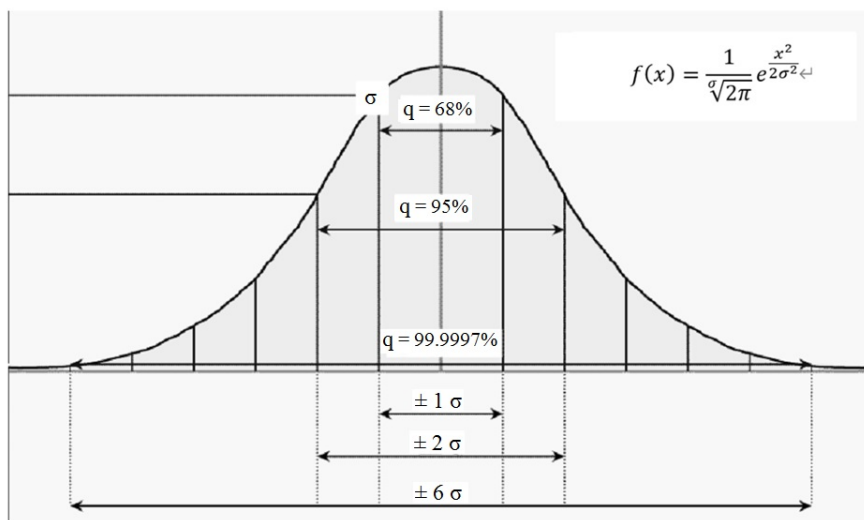


Figure 1. Normal distribution curve.

Figure 1 shows that 99.9997% of observations are lying within $\pm 6\sigma$ limits. It can never reach to 100% that means that there will always be some room for improvement. Motorola Company modified the statistical meaning of Six Sigma. The definition can allow the sample mean shifts from the center of the population, and the observed process or product would out lie the Six Sigma limits only 3.4 times per million operations under the original specifications. In addition, the Sigma performance

can also be expressed by “Defect Per Million Opportunities” (DPMO) as shown in **Table 1**.

Table 1. Defects per million opportunities

| Percentile Yield | DPMO | Shift from Mean | Popular Age |
|------------------|---------|-----------------|----------------|
| 6.68% | 933,200 | $\pm 0 \sigma$ | Prior to 1970s |
| 30.9% | 690,000 | $\pm 1 \sigma$ | Prior to 1970s |
| 69.2% | 308,000 | $\pm 2 \sigma$ | 1970s |
| 93.3% | 66,800 | $\pm 3 \sigma$ | 1980s |
| 99.4% | 6,210 | $\pm 4 \sigma$ | Early 1990s |
| 99.98% | 320 | $\pm 5 \sigma$ | Mid 1990s |
| 99.9997% | 3.4 | $\pm 6 \sigma$ | 2000s |

2. Six Sigma methodology and used tools

There are mainly five Phases in DMAIC Six Sigma methodology e.g. Define, Measure, Analyze, Improve and Control.

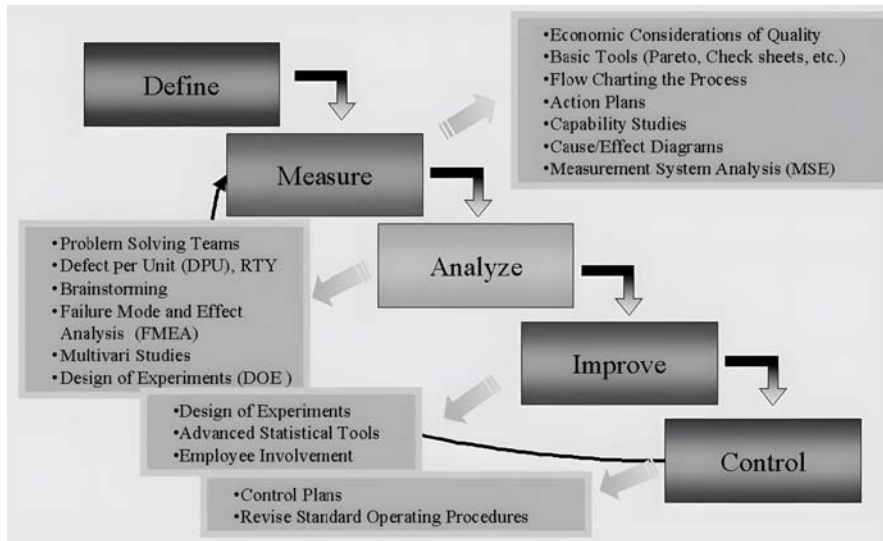


Figure 2. DMAIC process.

(1) Define phase. This is one of the most critical phases of DMAIC methodology. Therefore, maximum time and efforts should be allocated to this phase. In this phase organization define the requirements and expectations of the customer, define the project boundaries and define the process by mapping the business flow. Tools used in Define phase are project Charter, Pareto Diagram, Flow Chart, CTQ Tree, Process Map, and Supplier-Input-Process-Output-Customer (SIPOC) Diagram etc.

(2) Measure phase. This is basically a data collection phase, wherein present situation data are collected and then current Sigma level is calculated for the process in consideration. In this phase measure the process to satisfy customer's needs, develop a data collection plan, collect and compare data to determine issues and shortfalls. Tools used in Measure Phase are Pareto Diagram, Data Collection Form, Control Charts, Gauge R & R, and detailed Process Map, Process Capability Analysis etc.

(3) Analyze phase. This is investigation phase, wherein analyze the causes of defects and sources of variation, determine the variations in the process and prioritize opportunities for future improvement. Course of action is formed to reduce the gap between present scenario and after to meet improvement goals. All root causes are investigated and analyzed and then the most critical ones are selected

for improvements. Tools used in Analyze phase are Histogram, Run Chart, Control Charts, Scatter Chart, Cause and Effect Diagram, Analysis of Variance (ANOVA), Design of Experiment (DOE), Failure Mode and Effect Analysis (FMEA), Regression Analysis, Hypothesis Testing, Multivariate Chart, Interrelations Diagram etc.

(4) Improve phase. This phase involves application of scientific tools and techniques for making substantial improvements in quality and productivity of product. Improve the process to eliminate variations, develop creative alternatives and implement enhanced plan. In this phase, processes and product performance characteristics are improved for achieving desired outcome. Firstly, Six Sigma drive is applied to set targets, which would result from the improved measures. Accordingly, target Sigma levels are calculated. Tools used in Improve phase are Brainstorming, Affinity Diagram, Multi Voting, Suitability Matrix, DOE etc.

(5) Control phase. The basic objectives of this phase are to ensure that processes stay in control after the improvement solution has been implemented. Control process variations to meet customer requirements, develop a strategy to monitor and control the improved process and put into practice the improvements of systems and process. Swiftly detect out un-control state and determine the associated causes and sources of variation, so that ac-

tions might be taken to control the problem before non-conformances are produced. Tools used in Control phase are Related Activity Chart, Standard Operating Procedure (SOP), and Control Plan etc. **Figure 2** shows a DMAIC process.

3. (1.5 Sigma) Shift explanation

It can be seen that Six Sigma actually translates about 2 defects per billion opportunities and 3.4 defects per million opportunities, which we normally define as Six Sigma, really corresponds to a Sigma value of 4.5, without considering the shift of 1.5 Sigma both the side from mean. If the process mean varies at most 1.5σ from the target value, then on average at most 3.4 Defects Per Million

Opportunities (DPMO) will occur. **Table 2** shows relation between σ and DPMO.

In practice, we desire that the process mean to be kept at the target value. However, the process mean during one time period is usually different from that of another time period for various reasons. This means that the process mean constantly shifts around the target value. To address typical maximum shifts of the process mean, Motorola added the shift value of $\pm 1.5\sigma$ to the process mean. This shift of the mean is used when computing a process Sigma level as shown in **Figure 3**. This figure shows the 6σ (Six Sigma) quality level corresponds to a 3.4 part per million (ppm) rate.

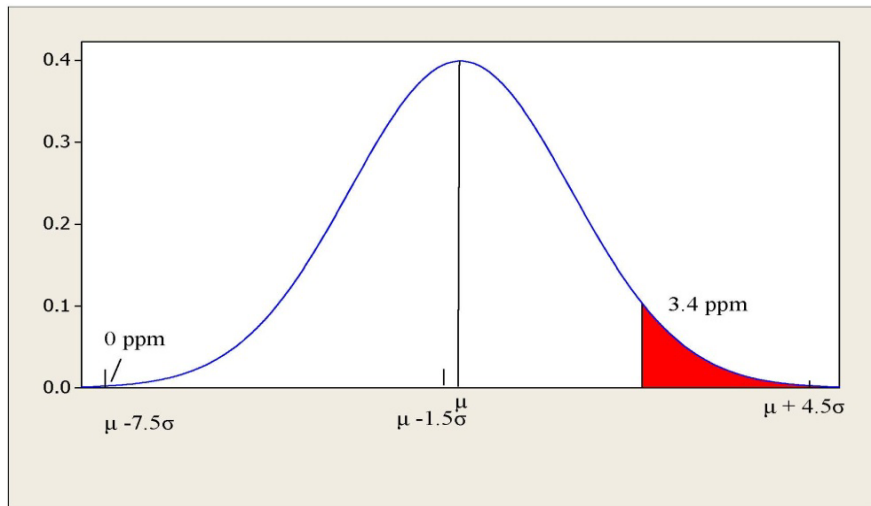


Figure 3. Effect of 1.5σ shift of process mean when 6σ quality levels is achieved.

Table 2. Relation between σ and DPMO

| Quality level | DPMO (without σ shift) |
|---------------|-------------------------------|
| 3 Sigma | 2,700.000 |
| 4 Sigma | 63.000 |
| 5 Sigma | 0.570 |
| 6 Sigma | 0.002 |

4. Implementation of Six Sigma techniques in casting industries

Casting is one of the most economical routes to produce metallic components in which the liquid metal is directly poured into the mould cavity of required size and shape. Over 70% of all metal castings are produced via a green sand casting process. The major drawback of casting processes is the formation of casting defects such as porosity, segregation, hot tears etc. A large number of experimental investigations linking green sand casting

parameters with casting quality have been carried out by researchers and foundry engineers over the past few decades. Various researches have also worked in the area of implementation of Six Sigma in the casting industries which is summarized below.

Swift *et al.*^[1] concluded that insufficient amount of feed metal available at early stages of the solidification aggravates the pull-down defect. Juran *et al.*^[2] stated that control factors are the selected independent variables of the experiment, which have different effects on the response variables when adjusted to different levels. They can be subdivided into quantitative control factors and qualitative control factors. Enright and Prince^[3] developed a simple mathematical model to study effects of

liquid metal flow, transient heat transfer and foam degradation during casting process. Byrne^[4] recognized that green sand casting parameters design are one of the key elements in casting quality. The casting process has a large number of parameters that may affect the quality of castings. Some of these parameters affecting quality are controllable, while others are noise factors. QIT-Fer et Titane Inc.^[5] stated that the feeding system can be designed and dimensioned, once the optimal pouring temperature has been established. In green sand moulds, expansion of mould due to soft ramming leads to melt shop defects. Sufficient mould hardness should be maintained to overcome melt shop defects caused by soft ramming. Melt shop defects may also occur if casting has some parts with lower modulus that solidify quickly and causes a pressure that tends to separate the mould halves. Such separating pressure can be controlled by sufficient clamping of boxes.

Johnston^[6] claimed that there are many sources of stochastic variation in a foundry. Common sources include processing, loading and unloading times, commencement and duration of manual tasks etc. Author stated that fluctuations can also occur in vessel capacities due to slag build up and lining erosion, load volumes, melt composition and upstream metal demand. Taguchi^[7] have introduced several new statistical tools and concepts of quality improvement that depend heavily on the statistical theory of experimental design.

Lipinski *et al.*^[8] presented the numerical basis of Magmasoft, a commercial finite difference solver for the simulation of casting. Minaie *et al.*^[9] studied the flow patterns and associated solidification phenomena during the die casting process by considering continuity, transport of momentum and energy. The model created for the analysis in the flow field was able to provide useful information for the position of the gates and overflows by predicting the order in which different areas of the die cavity are filled. Papai and Mobley^[10] presented detailed temperature measurements in die casting dies, from which the values of parameters like the heat transfer coefficient at the interface casting-die are calculated. Sulaiman and Gethin^[11] used a network for metal flow analysis in the pressure die casting process to

predict the metal flow characteristics in the filling system by simplifying the complex Navier-Stokes equation.

Blundell and Dhanju^[12] stated that casting is a complex process and involves the interactions of many interdependent casting process variables. Designing cast components and determining the correct casting process requires extensive knowledge of various casting processes and their practical capabilities and limitations. The quality of castings depends on a great amount of factors, which in their turn could have varying interactions with others. Defective castings lead to tremendous loss of productivity. Frayce *et al.*^[13] described the difficulties in performing numerical simulation of the die casting process and introduced Prometheus-3D for the prediction of filling patterns during casting. According to Taguchi^[7] the parameters which exert a great deal of influence on the die casting process can be adjusted to varying levels of intensity so that some settings can result in robustness of the manufacturing process. Taguchi has introduced several new statistical tools and concepts of quality improvement that depend heavily on the statistical theory of experimental design.

Venkatesan *et al.*^[14] modeled the three-dimensional fill of an experimental cavity. Authors utilized water analog reports to fine tune their models. Rao and Prasad^[15] developed a three-layer back propagation neural network to extract the complex relationship, involved in hot-deformation process modeling. By developing the network, it helped greatly not only in reducing the number of experiments required to characterize a material's behavior but also reduced the problems associated with empirical, semi-empirical constitutive models that involve the evaluation of a large number of constants. Barua *et al.*^[16] used the Taguchi's method to optimize the mechanical properties of the Vacuum (V) casting process. Their prime focus was on minimizing the casting defects, developed in components manufactured by the green sand casting process. The gradient search method, the Finite Element Method (FEM), neural network method and the Taguchi method are some prominent methods, generally used for casting system design.

Hahn^[17] stated that in order to maintain market

position, foundries have to adapt the constantly increasing demands with regard to the quality and functioning of their products. Campbell *et al.*^[18] reported that there are several guidelines for the design of green sand casting parameters. The variations in casting parameters chosen by different researchers have led to significant variations in these empirical guidelines. Jolly *et al.*^[19] analyzed numerical simulators based on Frequency Division Multiplexing (FDM) and FEM, provided powerful means of analyzing various phenomena occurring during the casting process.

Antony and Banuelas^[20] described that the casting process has a large number of parameters that may affect the quality of castings. Some of these parameters are controllable factors, while others are noise factors. Authors also indicated that linking Six Sigma to business strategy and customer needs is critical for successful implementation. Arita and McCann^[21] stated that many foundries are interested to implement Six Sigma to improve the quality of their products. Indeed, the implementation of Six Sigma methodology into foundry has become globally popular. Masters *et al.*^[22] described a robust design method for reducing cost and improving to determine the optimum configuration of design parameters for performance, quality and cost. Shaji and Radhakrishnan^[23] performed an analysis of the process parameters in surface grinding with graphite as the lubricant, using Taguchi method. Authors analyzed the process parameters such as speed, feed and mode of dressing as influential factors on the force components and surface finish developed, using Taguchi's experimental design methods. Sillen^[24] described that to minimize the volume contraction in liquid state, an optimum pouring temperature must be chosen. Higher amount of primary austenite caused by low carbon equivalent induces melt shop defects. Syrcos^[25] analyzed various significant process parameters of the die casting of aluminium alloy. Author tried to obtain optimal settings of the die casting parameters while achieving the optimum casting density of the aluminium alloy castings.

Treichler *et al.*^[26] introduced his approach in using experimental design for: (1) designing and developing products/processes so as to be robust to

component variation; (2) designing products/processes so as to be robust to environmental conditions; (3) minimizing variation around a target value.

Alagarsamy^[27] stated that employing a disciplined approach to understand nature of the defect and mechanism of defect formation and controlling key process factors, rejections can be reduced. Muzammil *et al.*^[28] optimized a gear blank casting process by using Taguchi's robust design technique. In their study, they demonstrated that the casting process involves a large number of parameters affecting the various casting quality features of the product. The reduction in the weight of casting compared to the target weight was taken proportional to the casting defects. Ghani *et al.*^[29] stated that Taguchi's method of experimental design is a viable methodology, which not only provides the maximum amount of information with the minimum number of trials but also establishes functional relationships between the input and output variables.

Vijayaram *et al.*^[30] stated that it is necessary to improve the quality of castings without increase in price. The price is influenced by the cost of production, which in turn is influenced by rework or rejection. Attention to quality assurance can reduce wasteful rework. Thus, quality production results in foundry's growth and profit. Timely implementation of modified techniques based on the quality control research is necessary to avoid defects in products. Shen *et al.*^[31] also proposed a combining artificial neural network and genetic algorithm method to optimize the injection moulding process. Karunakar and Datta^[32] conducted experiments with varying grain fineness number, clay percentage, moisture percentage, mulled time and hardness with an objective to formulate the green sand mixture optimally.

Sarkar^[33] applied Define, Measure, Analyze, Improve, and Control (DMAIC) methodology of Six Sigma for process improvement considering Overall Equipment Effectiveness (OEE) as a parameter for a 0.5 Ton induction furnace. The application of statistical data analysis was performed with the help of standard statistical software packages.

Parappagoudar *et al.*^[34] tackled the problems related to both the forward as well as reverse mappings in green sand mould system by using a back-propagation neural network (BPNN) and a genetic-neural network (GA-NN).

Prabhushankar *et al.*^[35] evaluated critically the various definitions that exist in the literature and a new holistic definition has been proposed. Also, there is a lot of ambiguity in the literature with respect to the origin of Six Sigma. An effort is made to eliminate such confusion by tracking the origin and growth of Six Sigma.

Behera *et al.*^[36] constructed a benchmark model to study the solidification behavior of green sand aluminium alloy castings (LM6) and detection of hot spots in castings with the help of Finite Element Method (FEM). Denkena *et al.*^[37] introduced a novel method for generating and analyzing computer-aided design (CAD) models of mould cavities to compute the tool accessibility. Singh and Mishra^[38] stated that reduction in a small percentage rejection, can save lot of energy in a foundry and can make it competitive in the global market. Kumar *et al.*^[39] proposed an optimization technique for process parameters of green sand casting of a cast iron differential housing cover based on the Taguchi parameter design approach. Kumar *et al.*^[40] stated that Six Sigma is an organized & systematic method for strategic process improvement that relies on statistical & scientific methods to reduce the defect rates and achieve significant quality up-gradation.

Franchetti and Yanik^[41] proposed the DMAIC Six Sigma approach with an emphasis on value stream analysis to reduce costs and increase capacity for a local manufacturing company in Northwest Ohio, USA. The DMAIC approach and case study demonstrated a broad application and how an organization can significantly reduce costs.

Sambhe and Dalu^[42] discussed the implementation of Six Sigma methodology in reducing rejection and rework in a honing process in an automobile part manufacturing company. The Six Sigma DMAIC (define–measure–analyze–improve–control) approach has been used to achieve this result. This article explains the step-by-step approach of Six Sigma implementation in a manufacturing process for improving quality level.

Singh and Khanduja^[43] validated the concept of Six Sigma successfully by unveiling a tested DMAIC methodology, especially for foundry SMEs. The present Indian foundry scenario has been reviewed in terms of types of foundries, their production trend and geographical clusterification. The concept of Six Sigma has been defined and further surveyed deeply with respect to more frequently used themes.

Desai^[44] explained phase with application of define–measure–analyze–improve–control methodology and ultimately showed how breakthrough improvement could be brought in quality and productivity in a foundry industry.

Kumar *et al.*^[45] stated that Defects in castings lead to non-conformities and reduce the productivity of various industries. Authors studied several factors contribute to casting defects in melt shop. Kumar *et al.*^[46] explored Six Sigma practice in a casting industry. That could improve the green sand casting process of a foundry by reducing the casting defects. The goal was to determine which variables influenced this evolution and the relative weight of critical success factors as the methodology developed.

Gijo *et al.*^[47] identified the root causes for the problem of rejection and rework through data-based analysis at different stages for a project in foundry shop using the Six Sigma Define–Measure–Analyze–Improve–Control (DMAIC) approach and its application in improving the leaf spring manufacturing process. The process parameters were optimized and measures for sustainability of the results were incorporated in the process. As a result of this study, the overall rejection was reduced from 48.33 to 0.79 per cent, which was a remarkable achievement for this small-scale industry.

Misra and Chauhan^[48] tried to shed some light on how Six Sigma methods are helpful in reducing the cost and improving the process output. A cast component (bypass flap housing) was observed to be prone to a high rejection rate owing to defects in casting process. Being the major source of economic losses, the goal of the study was to discern and rectify the cause of rejection so that economic savings can be made.

Sachin and Dileplal^[49] applied six sigma

methodology based on DMAIC approach to a foundry industry. The scope of the study is limited to automated high-pressure green sand moulding line. The root causes of different casting defects are identified and various actions are recommended to improve the production process. Vendrame Takao *et al.*^[50] described the application of the Six Sigma methodology in a small and medium-sized enterprise of North American plumbing products. In this study, authors used the Six Sigma tools and methodology to reduce cycle time and increase sales. The integration of quality tools with the Six Sigma methodology is fundamentally important in this process. This article describes the application of the Six Sigma methodology in a small and medium-sized enterprise of North American plumbing products. Sambhe^[51] converged on impeding factors while implementing SS drive and also pinpoints the gains achieved through successful implementation. The result of this study suggests some operational guidelines for effective implementation of Six Sigma from evidences acquired through research questionnaire and interviews with industrial professionals, apportioned to assort auto sector mid-sized enterprises (MSEs) in India.

Contribution of researchers is shown in **Table 3** below.

5. Conclusions and future research

Six Sigma is the most fervent managerial methodology not only in manufacturing area but also in the services industry. The activities for Six Sigma are not limited to process or operation levels, but extended to all the levels of an enterprise to reduce cost and produce high quality products. Many researchers have indicated that Six Sigma can increase organization's competitive capability and enhance the quality of products or services by conducting the projects.

The review of the available literature on application of Six Sigma in casting industries is presented in this paper, to monitor the quality of casting. Various Six Sigma approaches/techniques on casting processes suggested by various researchers are discussed.

From the review of the literature, it is clear that Six Sigma methodology has been applied in indus-

tries for over two decade and Foundry is the main source of production in the manufacturing industries, particularly automotive industry, which is power intensive also. Therefore, it is a potential manufacturing industry, for implementing Six Sigma methodology.

Researchers and practitioners are trying to integrate Six Sigma with other existing innovative management practices that have been around to make Six Sigma methods even more attractive to different organizations that might have not started or fully implemented the Six Sigma method.

The review has observed that Six Sigma research is pragmatic in nature which reinforces the use of real-world data. Apparently theoretical development is critical to the development of Six Sigma studies in casting Industry. Based on the literature review presented in this paper, Authors identify below a number of research implications and directions for future research in casting Industry as follows:

It is obvious that Six Sigma research will grow rapidly in future covering various disciplines and domains in casting Industry. Consequently, there is a need to construct and clearly present the application of Six Sigma within each domain in a proposed structure.

It is not surprising that a large portion of the reviewed articles in this study were related to Six Sigma tools, techniques, and methodologies in casting Industry. Still detailed analysis of these tools and methodologies within casting Industry is required.

More research may be conducted on user experiences reflecting Six Sigma pros and cons in casting Industry.

Researchers must try to develop new Six Sigma applications in casting Industry and at the same time the capabilities of user infrastructure need to be considered.

More theory based empirical research in casting Industry is needed to improve the creation of Six Sigma hypothesis.

Since the collective use of analytical and pragmatic research techniques has the prospective to offer greater perceptivity into research, it is desirable to see more research papers on application

of Six Sigma methodology in casting Industry.

Table 3. Contribution of researchers

| Sr. No. | Name of Researcher | Year | Area covered/Contribution |
|---------|-----------------------------|------|---|
| 1 | Enright and Prince | 1983 | Developed a simple mathematical model to study effects of liquid metal flow, transient heat transfer and foam degradation during casting process. |
| 2 | Byrne | 1987 | Analysed that green sand casting parameters design is one of the key elements in casting quality. |
| 3 | QIT-Fer et Titane Inc. | 1987 | Stated that the feeding system can be designed and dimensioned, once the optimal pouring temperature has been established. |
| 4 | Johnston | 1989 | Analysed the sources of stochastic variation in a foundry. |
| 5 | Lipinski <i>et al.</i> | 1991 | Investigated numerical basis of Magmasoft, a commercial finite difference solver for the simulation of casting. |
| 6 | Minale <i>et al.</i> | 1991 | Studied the flow patterns and associated solidification phenomena during the die casting process by considering continuity, transport of momentum and energy. |
| 7 | Papai and Mobley | 1991 | Investigated the temperature measurements in die casting dies. |
| 8 | Sulaiman and Gethin | 1992 | Studied the network for metal flow analysis in the pressure die casting process. |
| 9 | Frayce <i>et al.</i> | 1993 | Investigated the difficulties in performing numerical simulation of the die casting process. |
| 10 | Taguchi | 1993 | Studied the parameters which exert a great deal of influence on the die casting process for robustness. |
| 11 | Venkatesan and Shivpuri | 1993 | Modelled the three-dimensional fill of an experimental cavity |
| 12 | Blundell and Dhanju | 1994 | Studied the interactions of many interdependent casting process variables in casting. |
| 13 | Rao and Prasad | 1995 | Developed a three-layer back propagation neural network to extract the complex relationship, involved in hot-deformation process modelling. |
| 14 | Barua <i>et al.</i> | 1997 | Studied the Taguchi's method to optimize the mechanical properties of the Vacuum casting process. |
| 15 | Hahn | 1999 | Stated that foundries have to adapt the constantly increasing demands with regard to the quality and functioning of their products in order to maintain market position. |
| 16 | Campbell <i>et al.</i> | 2000 | Explained the guidelines for the design of green sand casting parameters. |
| 17 | Jolly <i>et al.</i> | 2000 | Analysed numerical simulators based on Frequency Division Multiplexing. |
| 18 | Antony and Banuelas | 2002 | Investigated the casting process parameters that may affect the quality of castings. |
| 19 | Syracos | 2002 | Analysed various significant process parameters of the die casting of aluminium alloy. |
| 20 | Arita and McCann | 2002 | Stated that implementation of Six Sigma methodology into foundry has become globally popular. |
| 21 | Masters <i>et al.</i> | 2002 | Investigated the robust design method for reducing cost and to determine the optimum configuration of design parameters for performance. |
| 22 | Shaji and Radhakrishnan | 2002 | Performed an analysis of the process parameters in surface grinding with graphite as the lubricant. |
| 23 | Sillen | 2002 | Analysed the optimum pouring temperature to minimize the volume contraction in liquid state. |
| 24 | Treichler <i>et al.</i> | 2002 | Introduced his approach in using experimental design for designing and developing products/processes so as to be robust to component variation. |
| 25 | Alagarsamy | 2003 | Analysed the nature of the defect and mechanism of defect formation. |
| 26 | Muzammil <i>et al.</i> | 2003 | Optimized a gear blank casting process by using Taguchi's robust design technique. |
| 27 | Ghani <i>et al.</i> | 2004 | Studied the Taguchi's method of experimental design to establishes functional relationships between the input and output variables. |
| 28 | Vijayaram <i>et al.</i> | 2006 | Explained how to improve the quality of castings without increase in price. |
| 29 | Shen <i>et al.</i> | 2007 | Proposed a combining artificial neural network and genetic algorithm method to optimize the injection moulding process. |
| 30 | Karunakar and Datta | 2007 | Conducted experiments to formulate the green sand mixture optimally. |
| 31 | Sarkar | 2007 | Applied Define, Measure, Analyse, Improve, and Control (DMAIC) methodology of Six Sigma for process improvement considering Overall Equipment Effectiveness (OEE) as a parameter for a 0.5 Ton induction furnace. |
| 32 | Parappagoudar <i>et al.</i> | 2008 | Analysed the problems related to both the forward as well as reverse mappings in green sand mould system by using a back-propagation neural network (BPNN) and a genetic-neural network (GA-NN). |
| 33 | Prabhushankar <i>et al.</i> | 2008 | Evaluated critically the various definitions that exist in the literature and a new holistic definition has been proposed. Also, there is a lot of ambiguity in the literature with respect to the origin of Six Sigma. |

Table 3 (Continued.)

| Sr. No. | Name of Researcher | Year | Area covered/Contribution |
|---------|------------------------------|------|---|
| 34 | Behera <i>et al.</i> | 2011 | Suggested a model to detect hot spots in castings with the help of Finite Element Method (FEM). |
| 35 | Denkena <i>et al.</i> | 2011 | Investigated the models of mould cavities to compute the tool accessibility. |
| 36 | Franchetti and Yanik | 2011 | Proposed the DMAIC Six Sigma approach with an emphasis on value stream analysis to reduce costs and increase capacity for a local manufacturing company in Northwest Ohio, USA. |
| 37 | Kumar <i>et al.</i> | 2011 | Proposed an optimization technique for process parameters of green sand casting of a cast iron differential housing cover based on the Taguchi parameter design approach. |
| 38 | Kumar <i>et al.</i> | 2011 | Stated that Six Sigma is an organized & systematic method for strategic process improvement that relies on statistical & scientific methods to reduce the defect rates and achieve significant quality up-gradation. |
| 39 | Kumar <i>et al.</i> | 2011 | Studied that Taguchi method is an efficient and effective Six Sigma tool, for achieving the optimum set of operating parameters for a particular product quality characteristic. For many casting industries, Sigma quality level is a measure of the process defect rate and thus can be used to measure the quality of the casting process. |
| 40 | Kumar <i>et al.</i> | 2011 | Explained that the efficiency and performance level of the green sand casting can be improved by adopting a Six Sigma approach. Using the Six Sigma tools, a significant reduction in casting defects can be obtained and hence the product quality is improved. |
| 41 | Sambhe and Dalu | 2011 | Discussed the implementation of Six Sigma methodology in reducing rejection and rework in a honing process in an automobile part manufacturing company. |
| 42 | Singh and Mishra | 2011 | Proposed that reduction in a small percentage rejection, can save lot of energy in a foundry and can make it competitive in the global market. |
| 43 | Desai | 2012 | Explained phase with application of Define–Measure–Analyse–Improve–Control methodology and ultimately showed how breakthrough improvement could be brought in quality and productivity in a foundry industry. |
| 44 | Singh and Khanduja | 2012 | Validated the concept of Six Sigma successfully by unveiling a tested DMAIC methodology, especially for foundry SMEs. |
| 45 | Kumar <i>et al.</i> | 2013 | Explored Six Sigma practices in a casting industry that could improve the green sand casting process in a foundry by reducing the casting defects. |
| 46 | Kumar <i>et al.</i> | 2013 | Stated that Defects in castings lead to non-conformities and reduce the productivity of various industries. Authors studied several factors contribute to casting defects in melt shop. |
| 47 | Gijo <i>et al.</i> | 2014 | Identified the root causes for the problem of rejection and rework through data–based analysis at different stages for a project in foundry shop using the Six Sigma Define–Measure–Analyse–Improve–Control (DMAIC) approach and its application in improving the leaf spring manufacturing process. |
| 48 | Misra, and Chauhan | 2015 | Tried to shed some light on how Six Sigma methods are helpful in reducing the cost and improving the process output. A cast component (bypass flap housing) was observed to be prone to a high rejection rate owing to defects in casting process. |
| 49 | Sambhe | 2016 | Converged on impeding factors while implementing SS drive and also pinpoints the gains achieved through successful implementation. The result of this study suggests some operational guidelines for effective implementation of Six Sigma from evidences acquired through research questionnaire and interviews with industrial professionals, apportioned to assort auto sector mid-sized enterprises (MSEs) in India. |
| 50 | Sachin and Dileplal | 2017 | Applied six sigma methodology based on DMAIC approach to a foundry industry. The scope of the study is limited to automated high-pressure green sand moulding line. The root causes of different casting defects are identified and various actions are recommended to improve the production process. |
| 51 | Vendrame Takao <i>et al.</i> | 2017 | Described the application of the Six Sigma methodology in a small and medium-sized enterprise of North American plumbing products. In this study, authors used the Six Sigma tools and methodology to reduce cycle time and increase sales. The integration of quality tools with the Six Sigma methodology is fundamentally important in this process. This article describes the application of the Six Sigma methodology in a small and medium-sized enterprise of North American plumbing products. |

Conflict of interest

The authors declare that they have no conflict of interest.

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