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Project selection through fuzzy analytic hierarchy process and a case study on Six Sigma implementation in an automotive industry

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Six Sigma is viewed as a systematic, scientific, statistical and smarter approach for management of innovation and focuses on establishing world class business performance. The main identifiers and supreme features of Six Sigma amongst other improvement techniques are: its rich ground which covers many customer oriented and problem solving techniques and its scientific methodology which is based on statistics. One of the most important factors of achieving success is selection of the right Six Sigma projects. This article presents a case study in which both Six Sigma project is selected and Six Sigma methodology is adopted to reduce the energy cost by the optimisation of material transferring heat loss in an automotive supplier industry. To cope with ambiguity and vagueness in the Six Sigma project selection problem, the Fuzzy Analytic Hierarchy Process has been used. This article also describes how various tools and techniques are employed in the different phases within the Six Sigma methodology and how the improvement actions are implemented. In conclusion, the key benefits and experience gained from this project are emphasised.

Keywords: Six Sigma; DMAIC; project selection; fuzzy analytic hierarchy process (FAHP); Taguchi method

1. Introduction

Under the pressure of the competitive conditions of modern economics, only the firms those ensure the correct way of doing business in its all processes stand in the market. Corporations who can minimise the waste and errors, and own a management philosophy that can convert mistakes to success by giving life to learning from the past, will be the ones to survive in the market making profits and keeping an efficient business. The Six Sigma method is a project-driven management approach to improve the organisation's products, services and processes by continually reducing defects in the organisation. It is a business strategy that focuses on improving customer requirements understanding, business systems, productivity and financial performance (Kwak and Anbari 2006).

Six Sigma is considered to provide a structured methodology, often referred to as define, measure, analyse, improve and control (abbreviated as DMAIC). DMAIC method, in addition to experience, with a predominantly data-based, systematic and disciplined approach helps to analyse the problems and find the root reasons. Thus, it would be able to solve the problem at the lowest cost and optimum point that provides highest return.

As Six Sigma is a project-driven methodology, it is essential to prioritise projects which provide maximum financial benefits to the organisation. Generating and prioritising the critical Six Sigma projects, however, are real challenges in practice. Although there is a substantial amount of literature on Six Sigma, this literature lacks comprehensive in-depth case study displaying how Six Sigma projects are selected and implemented in detail.

The objective of this article is twofold. First, the most beneficial Six Sigma project is selected by using Fuzzy Analytic Hierarchy Process (FAHP) technique. Second, a case study is presented based on the methodology of using Six Sigma quality tools to reduce the energy cost by optimisation of material transferring heat loss in an automotive supplier industry. The remainder of this article is organised as follows. In the next section a survey of related literature on Six Sigma approach is given. Section 3 describes both how the most beneficial project is selected *via* FAHP and the different phases of the

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DMAIC methodology and the tools and techniques employed within the case study. Conclusions and future research opportunities are addressed in the final section.

2. Literature review

The literature review is presented in two sections. It starts with a description of Six Sigma project selection and its key practices. This is followed by a section discussing Six Sigma applications.

2.1. *Literature on Six Sigma project selection*

One of the most difficult aspects of Six Sigma is the selection of the improvement projects. Project selection is very important decision because of the fact that these projects require different resources (capital, labour, etc.). Project selection is the one of the most critical success factors for the effective deployment of a Six Sigma program (Breyfogle *et al.* 2001). Recently, literature on Six Sigma project selection has received increasing attention. Banuelas *et al.* (2006) use survey as a method of investigation, respondents were asked what criteria are considered to select projects and how potential projects are identified, prioritised, selected and evaluated. Kumar *et al.* (2007a, b) provide the identification of important inputs and outputs for Six Sigma projects that are then analysed using data envelopment analysis (DEA) to identify projects, which result in maximum benefit. Su and Chou (2008) develop a novel approach to create critical Six Sigma projects and identify the priority of these projects. First, the projects are created from two aspects, namely, organisation's business strategic policies and voice of customer (VOC). Second, an analytic hierarchy process (AHP) model is implemented to evaluate the benefits of each project and; a hierarchical failure mode effects analysis (FMEA) is also developed to evaluate the risk of each project; and from which the priority of Six Sigma projects can be determined. Kumar *et al.* (2009) propose a hybrid methodology combining AHP with project desirability matrix (PDM) for Six Sigma project selection. This article demonstrates the efficiency of the proposed methodology by its application in a small and medium enterprise manufacturing die-casting unit. Tkác and Lyócsa (2009) outline Six Sigma project characteristics and present a new model for evaluating Six Sigma projects. To design a Six Sigma project evaluation model, they utilised mathematical optimisation modelling techniques and real options theory. Yang and Hsieh (2009) present a study that proposes to adopt national quality award criteria as the Six Sigma project selection criteria, and proposes a hierarchical criteria evaluation process. The strategic criteria are evaluated by the management team using a Delphi fuzzy multiple criteria decision making (MCDM) method. More recently, Büyüközkan and Öztürkcan (2010) develop a novel approach based on a combined analytic network process (ANP) and decision making trial and evaluation laboratory (DEMATEL) technique to help companies determine critical Six Sigma projects and identify the priority of these projects, especially in logistics companies. Table 1 displays the reviewed literature on Six Sigma project selection. Although, selecting the right Six Sigma project is one of the most sensitive elements in the deployment of Six Sigma, the literature on Six Sigma project evaluation and project selection is rare (Yang and Hsieh 2009). Previous literature on Six Sigma project selection focuses on deterministic MCDM techniques. In this study, to cope with ambiguity and vagueness in the Six Sigma project selection problem, the FAHP has been used.

2.2. *Literature on Six Sigma applications*

The benefits of implementing Six Sigma programs have been extensively reported in the literature and range from the simple reduction in the number of manufacturing defects to the improvement of the market share and the competitive advantage of a company (Kwak and Anbari 2006). In the academic literature, integrated Six Sigma research has been subject of many studies during the last decade. In this study, we focus on the Six Sigma literature including case study applications in the manufacturing industry and published after 2005. For a complete review of Six Sigma, the reader is referred to Brady and Allen (2006), Schroeder *et al.* (2008) and Aboelmaged (2010).

Tsou and Chen (2005) develop a quality improvement model based on the structure of classical economic production quantity model. The asymmetrical truncated loss function is used to evaluate the cost of poor quality (COPQ) in a production system. A practical quality improvement case which follows the Six Sigma DMAIC method in a car seat assembly line is discussed to verify the proposed model. Banuelas *et al.* (2005) present a case study illustrating the effective use of Six Sigma to reduce waste in a coating process. They state that this literature fails to demonstrate an in-depth case study showing how Six Sigma projects are carried out in organisations. Recently, however, attention has increasingly been placed on case studies in which various techniques of Six Sigma methodology are applied. Kumar *et al.* (2006) propose

Table 1. Literature review on Six Sigma project selection.

Author	Approach	Application area
Kumar *et al*. (2007a, b)	DEA	Locomotive starter motor battery
Su and Chou (2008)	FMEA–AHP	Semiconductor foundry
Tkác and Lyócsa (2009)	Real options theory	R&D project
Yang and Hsieh (2009)	Delphi FMCDM	Automotive supplier
Kumar *et al*. (2009)	FAHP–PDM	Automative industry
Büyüközkan and Öztürkcan (2010)	ANP–DEMATEL	Logistics industry

a lean sigma framework to reduce the defect occurring in the final product (automobile accessories) manufactured by a die-casting process. In another study (Kumar *et al*. 2007a, b), they present an extensive literature review based on the experiences of both academics and practitioners on Six Sigma, followed by the application of the DMAIC problem-solving methodology to identify the parameters causing casting defects and to control these parameters. Anand *et al*. (2007) deal with an application of Six Sigma methodology to improve the yield of deep drawing operations. The fuzzy-rule-based system and response surface methodology is implemented to improve the performance of the process. Yang *et al*. (2007) introduce a unique Six Sigma-based methodology for the supply chain management domain which has been developed and applied in a leading global manufacturing. Tang *et al*. (2007) stress the importance of the needs for operations research/management science (OR/MS) techniques to enhance Six Sigma deployment in operational and transactional environments and propose a new training roadmap for core Six Sigma professionals. They also give an illustration of how the Six Sigma framework is implemented to reduce the waiting times in a hospital retail pharmacy through more efficient manpower allocation strategies. This case study is discussed with particular emphasis on the application of queuing techniques in the 'Analyze' and 'Improve' phases. Bunce *et al*. (2008) integrate Six Sigma concepts and industrial engineering tools within a quality framework, which are used to improve damaged can claim on a crateless retort production system. Johnston *et al*. (2008) aim to investigate the integration of business improvement methodologies with intelligent techniques for the improvement of manufacturing efficiency. In another study, Johnston *et al*. (2009) report on the application of intelligent system techniques to improve the downstream performance prediction within the manufacturing environment. The application is guided by a Six Sigma methodology to obtain improved performance. Aksoy and Orbak (2009) give an application of Six Sigma methodology for reducing the quantity of rework parts for robotic arc welding process. El Haouzi *et al*. (2009) propose an approach to design a product-driven system and validate its feasibility and efficiency using a real industrial case. Their approach is based on Six Sigma and discrete event simulation. Lo *et al*. (2009) present a case study to improve the quality of injection-moulded lenses with the implementation of DMAIC procedures based on the Six Sigma approach. Using a successful Six Sigma program in a network technology company, Chakravorty (2009) develops an effective implementation model which consists of six steps. Chen *et al*. (2009) present the application of the Taguchi method to optimise the roundness of the holes cut by an aging plasma-cutting machine. Jou *et al*. (2010) propose a model to evaluate and improve the performance of new product development procedures by following the systemic procedure of Six Sigma and applying criteria defined by the application of performance matrix, factor analysis and theory of constraints. More recently, Lee and Wei (2010) present a case study at a printed circuit board company illustrating how the company effectively applied a Lean Six Sigma project. In another study, Wei *et al*. (2010) propose a Six Sigma project to improve the replenishment process in a logistics centre.

Table 2 classifies the literature and relation of the proposed research with the existing literature. Most of the research is tended to focus on either Six Sigma project selection or the Six Sigma applications in different industries. This literature lacks comprehensive in-depth case study displaying both how the most beneficial Six Sigma project is selected and how sigma projects are implemented within organisations. In this study, the most beneficial Six Sigma project was also selected *via* FAHP technique in the define phase, prior to Six Sigma implementation. Then, in-depth case study in an automotive supplier industry is presented. The phases of Six Sigma and their results are indicated in detail. Furthermore, it is also shown how various techniques of Six Sigma methodology are applied to achieve financial benefits.

Table 2. Summary of the literature and proposed research.

	Define					Measure				Analyse								Improve	Control			
Reviewed literature	Project charter	Financial analysis	VOC	SIPOC	Process chart/map	Value stream mapping	Pareto analysis	Quality function deployment	Data collection plan	Box plot	Failure mode and effect analysis	Root cause/cause and effect	Design of experiments	Analysis of variance	Taguchi based design	OR/MS tools	AI based methodology	Hypothesis tests	Statistical process control	I-Charts	Project selection tools	Other techniques
Banuelas *et al*. (2005)	+	+					+			+		+		+					+		+	
Kumar *et al*. (2006)	+	+			+		+					+	+		+				+			L
Kumar *et al*. (2007a, b)	+				+		+					+	+						+			RA
Anand *et al*. (2007)								+				+	+	+	+	+	+					
Bunce *et al*. (2008)				+	+							+	+					+	+			
Johnston *et al*. (2008)				+													GA					
Aksoy and Orbak (2009)	+				+							+			+				+			
Chakrovorty (2009)													+						+			
Chen *et al*. (2009)	+	+									+	+	+		+							
El Haouzi *et al*. (2009)			+	+								+				+[a]						K
Johnston *et al*., (2009)												+		+			NN					RA
Lo *et al*. (2009)												+	+	+	+				+			
Jou *et al*. (2010)					+																	TOC
Lee and Wei (2010)	+													+				+	+			
Wei *et al*. (2010)	+	+									+	+		+								
Proposed research	+	+		+	+				+	+	+		+		+	+[b]		+		+	+	

Notes: GA, genetic algorithm; RA, regression analysis; K, Kano Model; L, Lean Six Sigma; NN, neural networks; TOC, Theory of Constraints.
[a]Discrete event simulation.
[b]FAHP.

3. Six Sigma implementation

This section describes both how the most beneficial project is selected *via* FAHP and the different phases of the DMAIC methodology and the tools and techniques employed within the case study. The case study was conducted in a leading automotive supplier industry in Turkey.

3.1. *Six Sigma project selection*

Six Sigma is a project-driven approach and by which the organisation can achieve the strategic goal through effectively accomplishing projects. Notably, project generation and priority performs the most critical parts while carrying out Six Sigma initiations. Six Sigma is a tactical tool of significant value in achieving operational excellence. The project selection decision, under a resource constraint, is the early stage of implementation for a Six Sigma intervention.

The Six Sigma project selection problem falls within MCDM. For many MCDM methods, it is not easy to express all criteria quantitatively or using linguistic terms. It is more appropriate to use the fuzzy set theory in dealing with uncertainty. In this study FAHP is used for the Six Sigma project selection. In the FAHP method, the pair-wise comparisons in the judgment matrix are fuzzy numbers and use fuzzy arithmetic and fuzzy aggregation operators, the procedure calculates a sequence of weight vectors that will be used to choose main attribute. This approach can not only adequately handle the inherent uncertainty and imprecision of the human decision making process but can also provide the robustness and flexibility needed for the decision maker to understand the decision problem (Chan and Kumar 2007). There are many FAHP methods proposed by various authors. These methods are systematic approaches to the alternative selection and justification problem by using the concepts of fuzzy set theory and hierarchical structure analysis. This study proposes to adopt Chang's (1996) extent analysis method to select the most beneficial Six Sigma project, since the steps of this approach are relatively easier than the other FAHP approaches and similar to the conventional AHP. The outlines of the extent analysis method on FAHP are given in the following paragraphs.

3.1.1. *Chang's extent analysis method*

Chang (1996) uses triangular fuzzy numbers (TFN) for the bilateral comparison scale of AHP. Chang's approach is less time taking and less computational expense than many other FAHP approaches, besides it can overcome the deficiencies of traditional AHP.

Let $X = \{x_1, x_2, \ldots, x_n\}$ be an object set and $U = \{u_1, u_2, \ldots, u_m\}$ be a goal set. Chang (1996) identified that each goal, g_i, is performed, according to extent analysis. For each object, m extent analysis values can be obtained. These extent analysis values are showed with the following signs:

$$M_{gi}^1, M_{gi}^2, \ldots, M_{gi}^m \quad i = 1, 2, 3, \ldots, n$$

All the $M_{gi}^j\,(j = 1, 2, \ldots, m)$ are TFN.

The steps of Chang's (1996) extent analysis can be given as in the following:

Step 1: The fuzzy synthetic extent with respect to ith object is defined as:

$$S_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1} \tag{1}$$

to obtain $\sum_{j=1}^{m} M_{gi}^j$, the fuzzy addition operation of m extent analysis values for a particular matrix is performed such that

$$\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{2}$$

and to obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1}$ the fuzzy addition operator of M_{gi}^j values is performed such that

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j = \left(\sum_{i=1}^{m} l_i, \sum_{i=1}^{m} m_i, \sum_{i=1}^{m} u_i \right) \tag{3}$$

And then, the inverse of the vector above is computed, such that

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right) \tag{4}$$

Step 2: The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ can be defined as

$$V(M_2 \geq M_1) = \sup_{y \geq x} \left[\min\left(\mu_{M_1}(x), \mu_{M_2}(y) \right) \right] \tag{5}$$

Equation (5) can be expressed as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1, & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \tag{6}$$

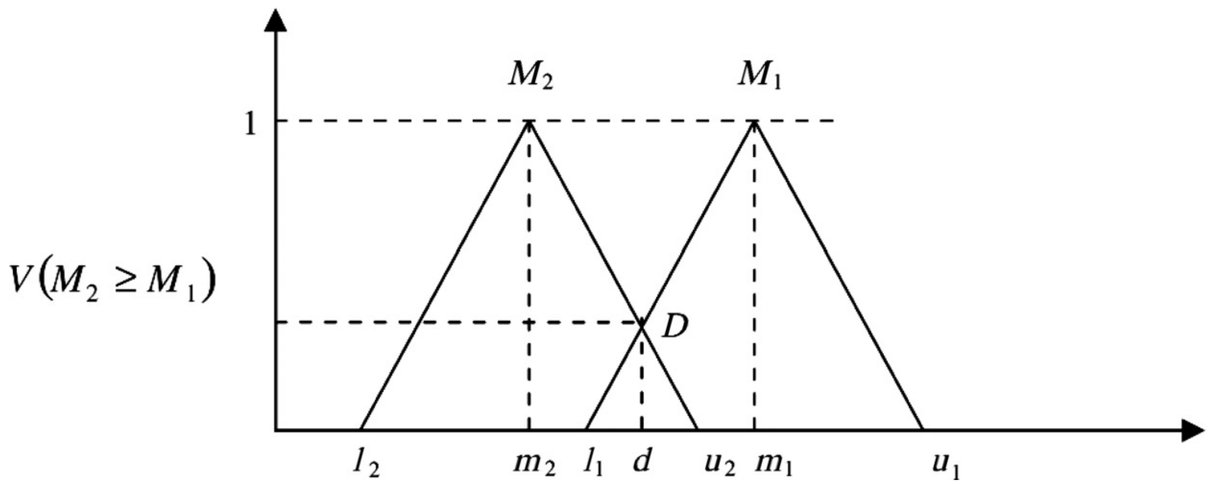

Figure 1. The intersection between M_1 and M_2.

Equally, we can express $V(M_2 \geq M_1)$ as seen in Figure 1, where d is the ordinate of highest intersection point D between μ_{M_1} and μ_{M_2}.

Step 3: The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i = (i = 1, 2, \ldots, k)$ can be defined by

$$\begin{aligned} &V(M \geq M_1, M_2, \ldots, M_k) \\ &\quad = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and } \ldots \text{ and } (M \geq M_k)] \\ &\quad = \min V(M \geq M_i), \quad i = 1, 2, \ldots, k, \end{aligned} \tag{7}$$

$$\text{Assume that } d'(A_i) = \min V(S_i \geq S_k) \tag{8}$$

For $k = 1, 2, \ldots, n$; $k \neq i$, weight vector is given by Equation (9)

$$W' = \left(d'(A_1), d'\left(A_2'\right), \ldots, d'(A_n)\right)^T \tag{9}$$

where $A_i (i = 1, 2, \ldots, n)$ are n elements.

Step 4: After normalisation, the normalised weight vectors are

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \tag{10}$$

where W is a non-fuzzy number.

3.1.2. *Application of FAHP for Six Sigma project selection*

In this study, we evaluate three Six Sigma project alternatives named as project A (balance rework decrease), project B (optimisation of material transferring heat loss) and project C (shortening heat treatment process time). The whole hierarchy of selection of best beneficial Six Sigma project can be easily visualised from Figure 2.

The triangular fuzzy conversion scale given in Table 3 is used in the evaluation model of this article. In this article, we propose to use FAHP for determining the weights of the main and sub-criteria.

First, the fuzzy evaluation matrix of the criteria is constructed by the pair-wise comparison of the different criterion relevant to the overall objective using TFN, which is shown in Table 4.

The weight vector from Table 4 is calculated as

$$W_{\text{goal}} = (0.30, 0.57, 0.13)^{\mathrm{T}}$$

The values of fuzzy synthetic extents with respect to the three different criteria denoted by S_{r}, S_{b} and S_{e}, respectively, are calculated as follows:

$$\begin{aligned} S_{\mathrm{r}} &= (3.17, 4, 5) \otimes (0.06, 0.08, 0.10) \\ &= (0.20, 0.31, 0.48) \\ S_{\mathrm{b}} &= (5, 6, 7) \otimes (0.06, 0.08, 0.10) \\ &= (0.31, 0.46, 0.67) \\ S_{\mathrm{e}} &= (2.33, 3, 4) \otimes (0.06, 0.08, 0.10) \\ &= (0.15, 0.23, 0.38) \end{aligned}$$

The degree of possibility is calculated by the use of (6);

$V(S_{\mathrm{r}} \geq S_{\mathrm{b}}) = 0.52$ was calculated using the equation,
$V(S_{\mathrm{r}} \geq S_{\mathrm{b}}) = 0.52$, $V(S_{\mathrm{r}} \geq S_{\mathrm{e}}) = 1$,
$V(S_{\mathrm{b}} \geq S_{\mathrm{r}}) = 1$, $V(S_{\mathrm{b}} \geq S_{\mathrm{e}}) = 1$, $V(S_{\mathrm{e}} \geq S_{\mathrm{r}}) = 0.61$,
$V(S_{\mathrm{e}} \geq S_{\mathrm{b}}) = 0.23$

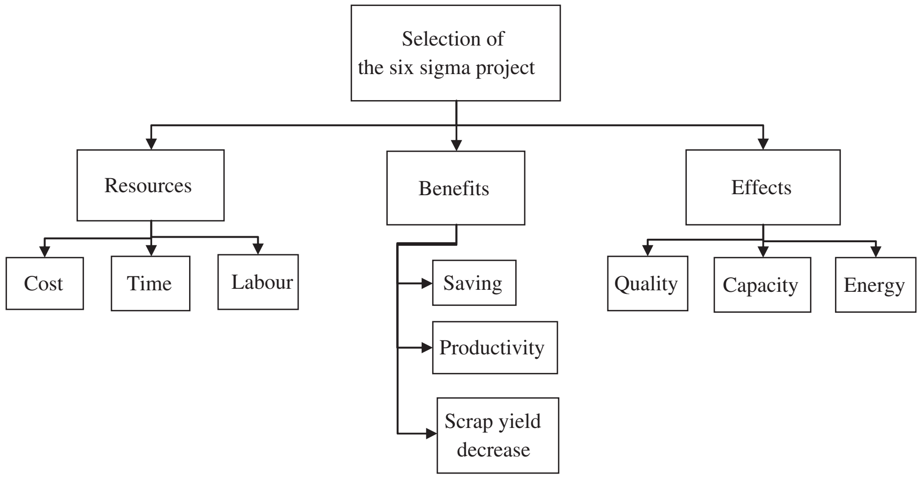

Figure 2. Criteria and sub-criteria for the project selection.

Table 3. TFN scale (Chang 1996).

Statement	TFN
Absolute	(7/2, 4, 9/2)
Very strong	(5/2, 3, 7/2)
Fairly strong	(3/2, 2, 5/2)
Weak	(2/3, 1, 3/2)
Equal	(1, 1, 1)

Table 4. Evaluation of the criteria with respect to goal.

Evaluation of the sub-criteria with respect to goal			
	Resources	Benefits	Effects
Resources	(1, 1, 1)	(0.67, 1, 1.5)	(1.5, 2, 2.5)
Benefits	(1.5, 2, 2.5)	(1, 1, 1)	(2.5, 3, 3.5)
Effects	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1, 1, 1)

For each pair-wise comparison, the minimum of the degrees of possibility is found as follows:

$$W' = ((\min(V(S_r \geq S_b), V(S_r \geq S_e)), \times \min(V(S_b \geq S_r), \ V(S_b \geq S_e)), \times \min(V(S_e \geq S_r))$$

Therefore the weight vector is given as $W' = (0.52, 1, 0.23)^T$ and after the normalisation process, the weight vector with respect to decision criteria can be presented as follows:

$$W_{goal} = (0.30, 0.57, 0.13)^T$$

Now, the different sub-criteria are compared under each of the criterion separately by following the same procedure as discussed above. The fuzzy evaluation matrices of sub-criteria with respect to each main criterion and the weight vectors of each criterion are shown in Tables 5–7.

Table 5. The fuzzy evaluation sub-criteria with respect to resources.

Evaluation of the sub-criteria with respect to resources				
	Cost	Time	Labour	W_R
Cost	(1, 1, 1)	(3.5, 4, 4.5)	(1.5, 2, 2.5)	0.78
Time	(0.67, 1, 1.5)	(1, 1, 1)	(0.67, 1, 1.5)	0
Labour	(0.67, 1, 1.5)	(1.5, 2, 2.5)	(1, 1, 1)	0.22

Similarly, the fuzzy evaluation matrices of decision alternatives and corresponding weight vector of each alternative with respect to corresponding criteria are determined. Evaluations of the projects with respect to sub-criteria are shown in Table 8.

Table 9 shows all the priority weights driven from the calculations explained above. Finally, the priority weights of each Six Sigma project can be calculated by weights per project multiplied by weights of the corresponding criterion. With respect to the results, project B 'optimization of material transferring heat loss' was selected as the most effective Six Sigma project alternative.

3.2. *Case study*

The selected project involves the minimisation of the unnecessary use (waste) and optimisation of the use of electricity and natural gas by analysing and focusing on the transfer process and moulding process.

Table 6. The fuzzy evaluation sub-criteria with respect to benefits.

Evaluation of the sub-criteria with respect to benefits				
	Saving	Productivity	Scrap yield decrease	W_B
Saving	(1, 1, 1)	(2.5, 3, 3.5)	(3.5, 4, 4.5)	0.96
Productivity	(0.67, 1, 1.5)	(1, 1, 1)	(1.5, 2, 2.5)	0.04
Scrap yield decrease	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1, 1, 1)	0

Table 7. The fuzzy evaluation sub-criteria with respect to effects.

Evaluation of the sub-criteria with respect to effects				
	Quality	Capacity	Energy	W_E
Quality	(1, 1, 1)	(1.5, 2, 2.5)	(0.67, 1, 1.5)	0.30
Capacity	(0.67, 1, 1.5)	(1, 1, 1)	(0.67, 1, 1.5)	0.13
Energy	(2.5, 3, 3.5)	(1.5, 2, 2.5)	(1, 1, 1)	0.57

Project encloses from melting area to casting area (until melted alloy is loaded to casting machine). The main objective of this study is to reduce the energy cost by optimisation of material transferring heat loss with the implementation of DMAIC procedures based on the Six Sigma approach. Water consumption is not included in the project. The DMAIC procedures are adopted in this article for reducing the energy cost in an automobile supplier industry. Figure 3 shows the flowchart for the DMAIC steps.

3.2.1. *DMAIC cycle*

3.2.1.1. *Define phase*. The aim of this phase is to define the scope and goals of the project. Project charter is used as a main tool for define phase. Project scope, boundaries and limitations and financial gains are expressed in the project charter. Table 10 presents the targets of the project.

It is important to determine critical to quality (CTQ) factors of the project. CTQ factors are the important measurable characteristics of products or processes for which performance standards or specification limits must be satisfied. A number of brainstorming sessions of team members were conducted to identify CTQ characteristics based on the VOC input. The goal of the team members was to identify the root cause of problem. A tree diagram was developed by team members, so parameters that would be monitored were modified. In this study there were two CTQs: natural gas consumption and electricity consumption (Figure 4).

Using tree diagram wider aspect of the target was divided into more detailed levels. CTQs of the project were determined with tree diagram and these would be used as 'Output' in the supplier, input, process, output, cost (SIPOC) diagram. SIPOC diagram is a tool that helps project team to see all elements of the process. It is a macro level process map. SIPOC diagram is given in Figure 5.

Detailed process map was developed by team members after completing SIPOC. Generally detailed process map consists of $1+7$ steps:

Step 0: Supplier list and customer expectations will be specified.

Step 1: Define important outputs considering general inputs and customer expectations.

Step 2: Define process steps.

Step 3: Define steps that have no impact on the output quality (non-added value steps).

Step 4: Define basic outputs for every process step.

Step 5: Define basic inputs for every process step.

Step 6: Categorise basic inputs for every process step.

Step 7: Define controllable specifications for basic inputs.

Figure 6 shows the detailed process map. Process outputs and basic inputs were defined and categorised by team members. Three categories are used:

- *Noise inputs:* They have effects on outputs but it is not easy or possible to control these variables (ambient temperature, humidity, etc.).
- *Process parameters:* These have effects on outputs (pressure, temperature, etc.).
- *Procedures:* Standard procedures. (e.g. work instructions).

Basic inputs are used in prioritisation matrix to establish relations with process outputs.

Table 8. Evaluation of the projects with respect to each sub-criteria.

	Project A	Project B	Project C		Project A	Project B	Project C		Project A	Project B	Project C
Cost				*Savings*				*Quality*			
Project A	(1, 1, 1)	(0.67, 1, 1.5)	(1.5, 2, 2.5)	Project A	(1, 1, 1)	(0.67, 1, 1.5)	(1.5, 2, 2.5)	Project A	(1, 1, 1)	(2.5, 3, 3.5)	(3.5, 4, 4.5)
Project B	(2.5, 3, 3.5)	(1, 1, 1)	(3.5, 4, 4.5)	Project B	(2.5, 3, 3.5)	(1, 1, 1)	(3.5, 4, 4.5)	Project B	(0.67, 1, 1.5)	(1, 1, 1)	(1.5, 2, 2.5)
Project C	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1, 1, 1)	Project C	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1, 1, 1)	Project C	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1, 1, 1)
Time				*Productivity*				*Capacity*			
Project A	(1, 1, 1)	(0.67, 1, 1.5)	(0.67, 1, 1.5	Project A	(1, 1, 1)	(1.5, 2, 2.5)	(1.5, 2, 2.5)	Project A	(1, 1, 1)	(0.67, 1, 1.5)	(0.67, 1, 1.5)
Project B	(2.5, 3, 3.5)	(1, 1, 1)	(1.5, 2, 2.5)	Project B	(0.67, 1, 1.5)	(1, 1, 1)	(0.67, 1, 1.5)	Project B	(2.5, 3, 3.5)	(1, 1, 1)	(1.5, 2, 2.5)
Project C	(1.5, 2, 2.5)	(0.67, 1, 1.5)	(1, 1, 1)	Project C	(0.67, 1, 1.5)	(1.5, 2, 2.5)	(1, 1, 1)	Project C	(1.5, 2, 2.5)	(0.67, 1, 1.5)	(1, 1, 1)
Labour				*Scrap yield decrease*				*Energy*			
Project A	(1, 1, 1)	(0.67, 1, 1.5)	(0.67, 1, 1.5	Project A	(1, 1, 1)	(2.5, 3, 3.5)	(3.5, 4, 4.5)	Project A	(1, 1, 1)	(0.67, 1, 1.5)	(0.67, 1, 1.5)
Project B	(2.5, 3, 3.5)	(1, 1, 1)	(1.5, 2, 2.5)	Project B	(0.67, 1, 1.5)	(1, 1, 1)	(1.5, 2, 2.5)	Project B	(3.5, 4, 4.5)	(1, 1, 1)	(2.5, 3, 3.5)
Project C	(1.5, 2, 2.5)	(0.67, 1, 1.5)	(1, 1, 1)	Project C	(0.67, 1, 1.5)	(0.67, 1, 1.5)	(1, 1, 1)	Project C	(2.5, 3, 3.5)	(0.67, 1, 1.5)	(1, 1, 1)

Table 9. Priority weights of main and sub-criteria.

	Sub-attributes of resources			
	Costs	Time	Labour	Priority weight
Weight	0.78	0	0.22	
Project A	0.3	0.13	0.13	0.26
Project B	0.13	0.57	0.57	0.23
Project C	0.57	0.3	0.3	0.51
	Sub-attributes of benefits			
	Saving	Productivity	Scrap yield decrease	Priority weight
Weight	0.96	0.04	0	
Project A	0.04	0.45	0.96	0.06
Project B	0.96	0.21	0.04	0.93
Project C	0	0.34	0	0.01
	Sub-attributes of effects			
	Quality	Capacity	Energy	Priority weight
Weight	0.3	0.13	0.57	
Project A	0.96	0.13	0.13	0.38
Project B	0.04	0.57	0.57	0.41
Project C	0	0.3	0.3	0.21
	Main attributes			
	Resources	Benefits	Effects	Priority weight
Weight	0.3	0.57	0.13	
Project A	0.26	0.06	0.38	0.1616
Project B	0.23	0.93	0.41	0.6524
Project C	0.51	0.01	0.21	0.186

Prioritisation for CTQs is done and relations between CTQs and process inputs are graded. Determining which process inputs will be focal point to meet the requirements of CTQs is the important result of prioritisation matrix. Thus, which process input has an effect on which process output is identified. In this study, CTQs were graded in the scale of 1–10 related to customer prioritisation. Scoring was done according to this scale: 0 = no relationship, 1 = very weak relationship, 3 = medium level relationship, 5 = strong relationship, 9 = very strong relationship. Table 11 shows the prioritisation matrix.

Inputs that have big impact on natural gas and electricity consumption were identified as follows:

(1) Waiting time in front of casting bench
(2) Waiting time in degassing
(3) Transfer time
(4) Oven set value (melting)
(5) Temperature of the pot
(6) Isolation of the pot.

3.2.1.2. *Measure phase*. The goal of the measure phase of the Six Sigma strategy is to gather information about the current situation, to obtain baseline data on the current process performance and to identify the problem areas. By define phase it was determined which data would be collected. So, data gathering plan and data collecting forms would be composed. Project team continued to collect data for 2 months and gathered 50 samples. While collecting data, it was a chance to analyse process steps and discover the non-value added works.

As an outcome of the measure phase, the Six Sigma team narrowed its focus on distinct groups of project issues and opportunities. Project team collected the following data:

- Durations of every work step during the material transfer process
- Material temperature at every work step
- Consumed natural gas and electricity in casting and melting area

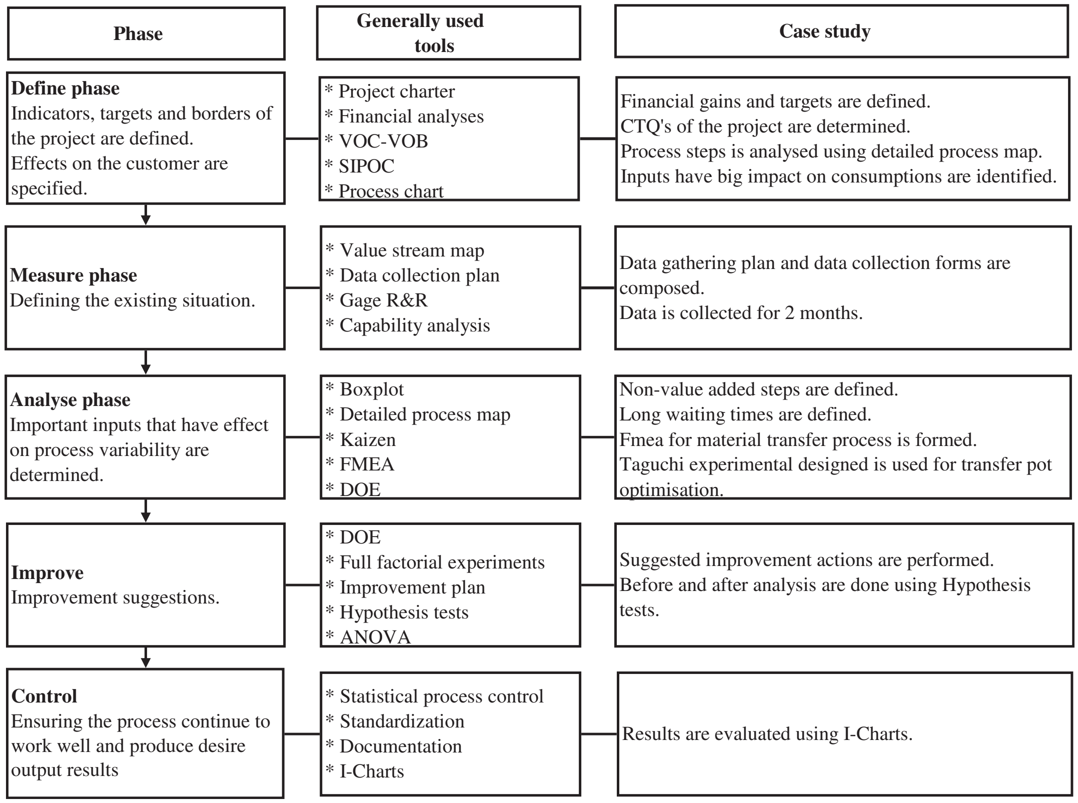

Figure 3. DMAIC cycle.

Table 10. Targets of the project.

Measure of values	Initial	Target
Electricity consumption (kWh/kg)	Melting: 0.003 kWh/kg Casting heater: 0.10 kWh/kg	Melting: 0.0028 kWh/kg Casting heater: 0.097 kWh/kg
Natural gas consumption (sm^3/kg)	0.11 m^3/kg	0.105 (4%)

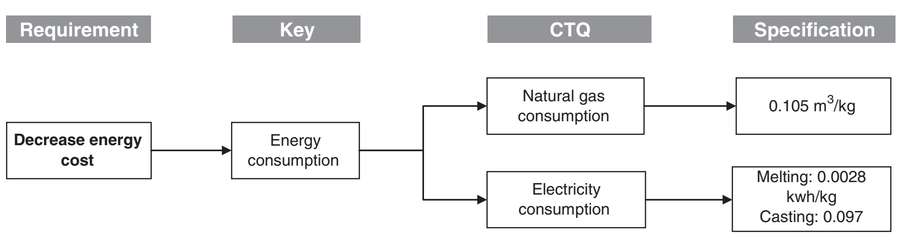

Figure 4. Tree diagram.

- Set temperatures, production quantities, pot temperatures, etc.

3.2.1.3. *Analyse phase*. The goal of the analyse phase is to study the data using graphical/statistical analysis tools to identify and isolate the root cause(s) of quality problems. The data collected from the measure phase served as an input for the analyse phase. Because the data collection was carried out for a relatively long period of time, it allowed the process to reveal its full-range variation on a long-term basis. In this phase, data are analysed and the causes of any problems are discovered. The following are some of the tools used in analysing the data.

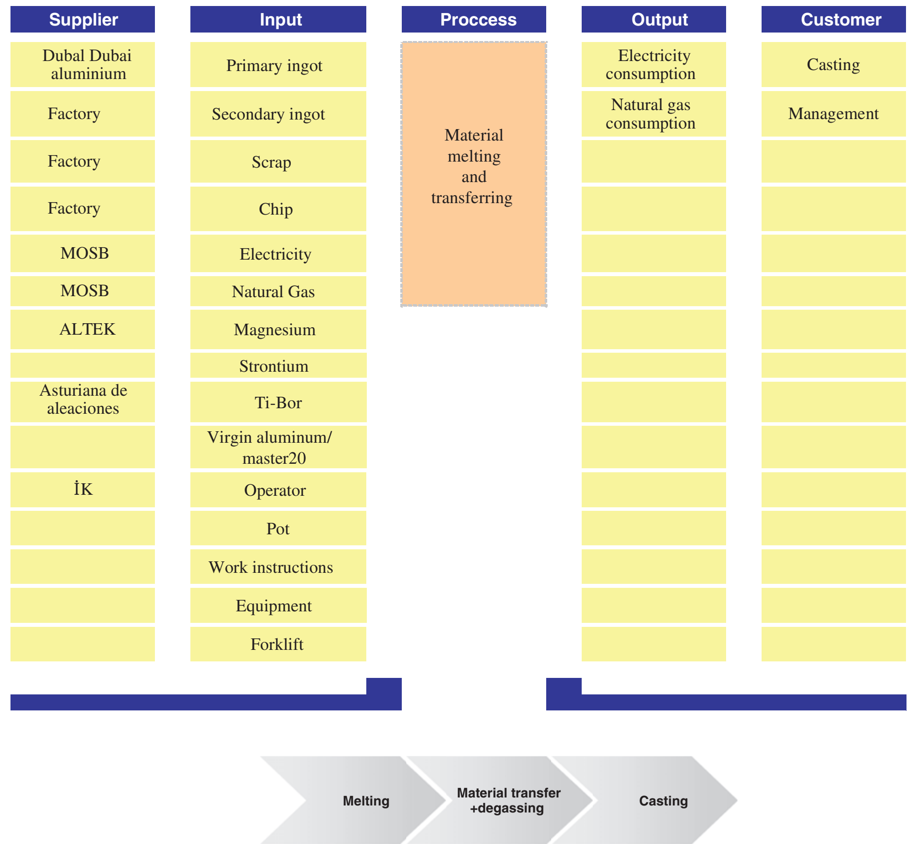

Figure 5. SIPOC diagram.

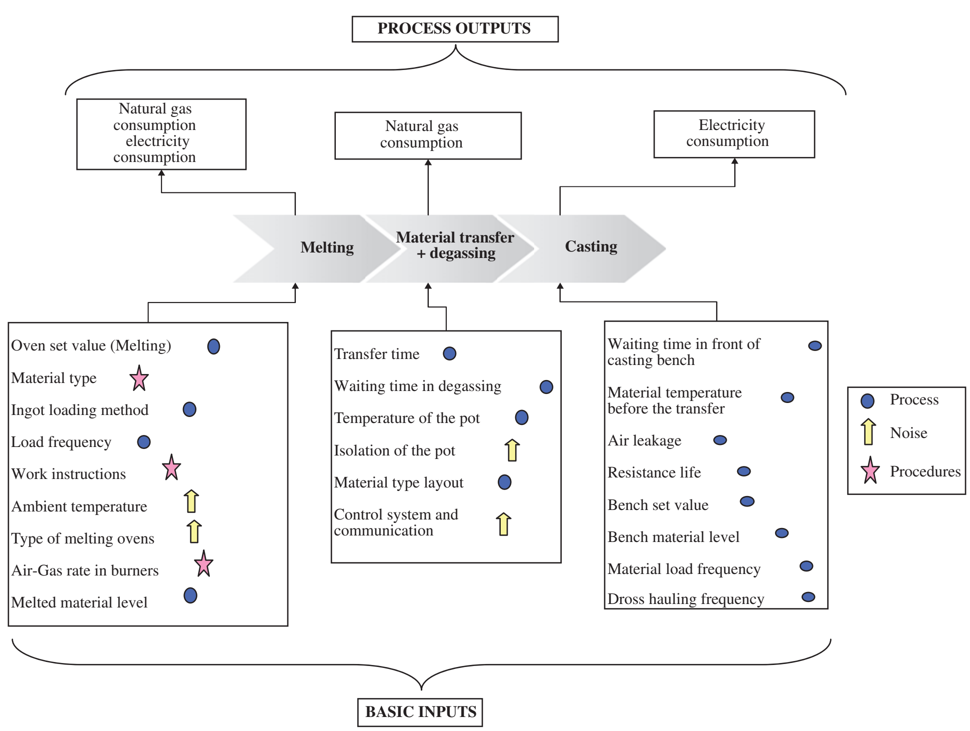

Figure 6. Detailed process map.

Table 11. Prioritisation matrix.

Inputs	Outputs		
	Natural gas consumption	Electricity consumption	Degree of importance
	10	8	
	77	138	Total
Melting[a]			
Oven set value (melting)	9	3	204
Material type	1	1	28
Ingot loading method	3	2	46
Load frequency	9	3	114
Work instructions	5	3	104
Ambient temperature	1	1	68
Type of melting ovens	3	1	48
Melted material level	5	3	74
Air-gas rate in burners	7	1	108
MET. TR-DEG[a]			
Temperature of the pot	8	9	152
Isolation of the pot	8	8	144
Material type layout	7	8	134
Control system and communication	1	8	74
Transfer time	1	9	235
Waiting time in degassing	1	8	317
Casting[a]			
Waiting time in front of casting bench	1	2	325
Material temperature before the transfer	1	9	262
Air leakage	1	2	82
Resistance life	1	8	74
Bench set value	1	9	82
Bench material level	1	9	82
Material load frequency	1	9	82
Dross hauling frequency	1	8	74

Note: [a]Process step.

3.2.1.3.1. Box plot. First durations of every step were analysed. Figure 7 shows that the box plot of every work step durations.

When the box plot was analysed, three important points were realised:

(1) Degassing time was very long. Material temperature was decreasing approximately 30° at the end of this step.
(2) 'Waiting time in degassing' was a non-value added work step. This step must have been analysed.
(3) Waiting time in casting was very long and its variance was too high.

A meeting was done with the production engineers regarding the possibility of decreasing degassing operation time. After sample casting production was done, it is understood that decreasing degassing time was not possible because it would cause increase in 'casting hole' scraps.

Project team used fitted line plot to evaluate the amplitude of temperature decrease. An equation showed the relationship between time and temperature was shown in Figure 8. This means that temperature is decreasing 5° in every single minute.

3.2.1.3.2. Failure mode and effect analysis. In the analyse phase, it is a good way to use FMEA to understand relationships between risks and process steps. FMEA helps to prioritise improvement actions. The risk priority number (RPN) is determined by three risk parameters which are: Severity (S), Occurrence (O) and Detection (D). The multiplication of (S), (O) and (D) values leads to what is known as the RPN. RPN is calculated as follows: $\text{RPN} = (S) \times (O) \times (D)$. These parameters are defined on the same scale level, such as the 10-point system, to identify the various levels of risk situation.

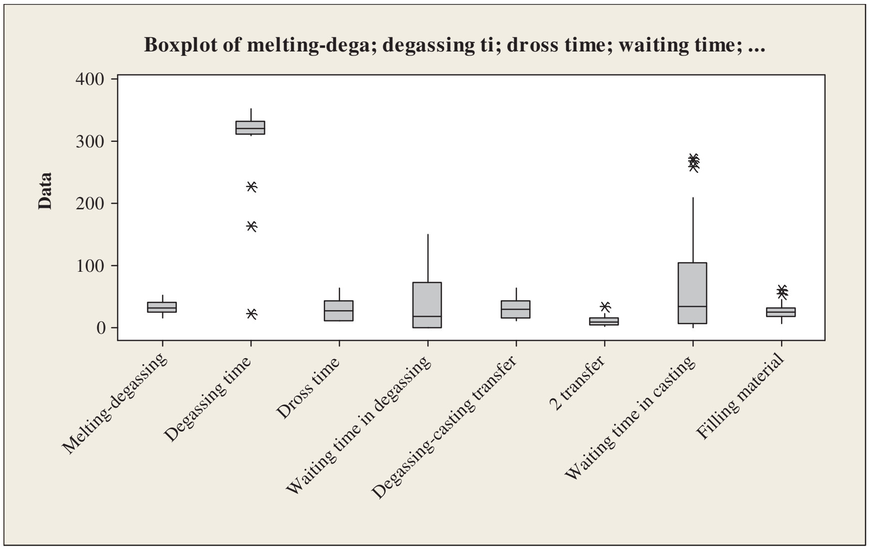

Figure 7. Box plot of work step durations.

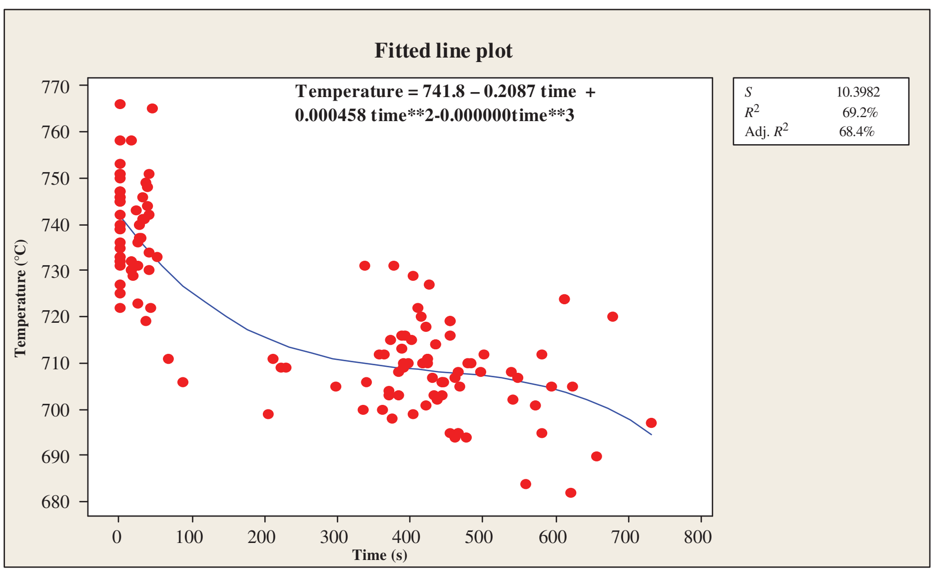

Figure 8. Fitted line plot.

For concerns with a relatively high RPN, the engineering team must make efforts to take corrective actions. According to FMEA in Table 12, project team focused on 'waiting time in front of bench', since its RPN value is the highest. A casting bench is able to get material when its inside pressure is equal to zero. If it is not equal to zero, material transfer operator must wait until the pressure is equal to zero. This waiting time can be 1–300 s and it causes temperature loss in melted material in the transfer pot. The current system did not show any sign that the casting bench was ready to get material. Material transfer operators were giving melted material to casting benches in a row. If the casting bench was not ready, they would wait and these would cause energy loss. Project team decided to establish a warning system between casting bench and material transfer operators. It will be expressed in detail in the improve phase.

3.2.1.3.3. Taguchi experimental design. Materials were transferred by using transfer pots. Project team has decided to make an analysis regarding the transfer pots. These pots did not have isolations and covered on

Table 12. FMEA for material transfer process.

Process function requirements	Potential failure mode	Potential effects of failure	*S*	Potential causes/ mechanisms of failure	*O*	Current process controls	*D*	RPN	Recommended actions	Responsibility and target completion dates
Material transfer	Waiting time infront of casting bench	Temperature of material is lower than set temperature – energy loss	8	There is not any sign that casting bench is available for material transfer	8	–	9	576	Establishing a warning system	Maintenance
	Material transfer with wrong type of material	Production loss	7	Lack of attention	2	–	3	42	Material type labels	Casting
	Delay in material filling in casting bench	Low quality casting production loss	9	There is not any indicator that shows material level	5	Operator loading form	3	135	Indicators that show material level	Maintenance

Table 13. L9 array for transfer pot measurements.

Pot temperature (°C)	Isolation status	Production status	Pot cover status	$\Delta T1$	$\Delta T2$	$\Delta T3$	$\Delta T4$
130	Isolated	On production	With cover	72	72	70	74
130	Non-isolated	Empty	No cover	80	85	79	102
130	Isolated	On production	With cover	70	70	71	69
320	Isolated	Empty	With cover	40	40	41	40
320	Non-isolated	On production	With cover	59	61	58	67
320	Isolated	On production	No cover	45	46	46	47
570	Isolated	On production	No cover	28	28	28	27
570	Non-isolated	On production	With cover	31	31	31	32
570	Isolated	Empty	With cover	27	26	27	27

the top. They were heated up before transferring operations but there was no specific temperature for them. Four parameters affecting the transferring pots have been identified in the analyse step. Since full-scale experiments are too cumbersome and time-consuming to be executed, the Taguchi-based design of experiments is employed for identifying the most significant parameters with the corresponding optimal combinations. Taguchi method is a robust parameter design method based upon improving the quality of a product by minimising the effect of causes of variation. This research uses two major tools of Taguchi method – orthogonal array (OA) and the signal-to-noise ratio. An OA can be defined as a fractional factorial matrix which is used for determining the combinations of parameter levels to use for each experimental run while ensuring a balanced comparison of levels of any parameter or interaction of parameters. The design of OA comprises of rows and columns where rows represent the level of parameters for a particular experimentation while column represents a particular parameter that can be changed in each run. In the Taguchi method, S/N ratio is used for representation of the ratio of meaningful signals to background errors. Therefore, a larger S/N ratio indicates better quality characteristics for the transfer pots. In this study, the transfer pot is a quality characteristic with nominal-to-best attribute. As stated earlier, there are four parameters regarding the transfer pots:

(1) Pot temperature (130°C, 320°C and 570°C).
(2) Isolation status (isolated–non isolated).
(3) Production status (on production–empty).
(4) Pot cover status (with cover–no cover).

- Pot temperature: Three temperature levels were chosen (130°C, 320°C and 570°C).
- Isolation status: Measurements were done with both isolated and non-isolated pots to see if isolation status had an effect on temperature decrease.
- Production status: On production or empty.
- Pot cover status: A sample pot with cover was designed and used for measurements.

There were 24 different combinations to use all levels of parameters: $2^3 \times 3^1 = 24$ (three parameters with two levels, one parameter with three levels). Taguchi OAs were used to decide experiments. L9 Standards Array was proper for this case (Table 13). For every experiment four measurements were done. Pots were heated up to three different temperatures (130°C, 320°C and 570°C). After heating, pots were filled up with material (beginning temperature was 740°C for material). During 20 min project, team collected the decrease of material temperature data (ΔT). Using Equations (11) and (12), S/N ratios and means were obtained. Table 14 shows S/N ratios and means.

$$\bar{y} = \frac{\sum_j y_j}{n} \quad \sigma = \sqrt{\frac{\sum_{\forall j} (y_j - \bar{y})^2}{n-1}} \tag{11}$$

$$S/N = \eta = 10 \times \log\left[\frac{\bar{y}^2}{\sigma^2}\right] \tag{12}$$

After these calculations, output tables for S/N and means were composed using Equations (13)–(15). Output tables for S/N ratios and means can be seen in Tables 15 and 16.

$$A_1 = (S/N1 + S/N_2 + S/N_3)/3 \text{ (for } S/N \text{ ratio table)} \tag{13}$$

$$A_1 = (\mu_1 + \mu_2 + \mu_3)/3 \text{ (for } \mu \text{ table)} \tag{14}$$

$$B_2 = (S/N_2 + S/N_5 + S/N_8)/3 \text{ (for } S/N \text{ ratio table)}$$
$$B_2 = (\mu_2 + \mu_5 + \mu_8)/3 \text{ (for } \mu \text{ table)}$$
$$\Delta_C = \max\{C_1, C_2, C_3\} - \min\{C_1, C_2, C_3\} \tag{15}$$

Table 14. S/N ratios and means.

$\Delta T1$	$\Delta T2$	$\Delta T3$	$\Delta T4$	σ	Mean	S/N
72	72	70	74	1.632993	72	32.887
80	85	79	102	10.66146	86.5	18.184
70	70	71	69	0.816497	70	38.663
40	40	41	40	0.5	40.25	38.116
59	61	58	67	4.031129	61.25	23.634
45	46	46	47	0.816497	46	35.016
28	28	28	27	0.5	27.75	34.886
31	31	31	32	0.5	31.25	35.918
27	26	27	27	0.5	26.75	34.567

Table 15. Output table for S/N.

	Output table for S/N			
Level	A	B	C	D
1	29.911	35.296	34.607	30.363
2	32.255	25.912	30.289	29.362
3	35.124	36.082	32.394	37.565
Δ	5.2122	10.17	4.3179	8.2035

Table 16. Output table for means.

	Output table for means			
Level	A	B	C	D
1	76.167	46.667	49.75	53.333
2	49.167	59.667	51.167	53.417
3	28.583	47.583	53	47.167
Δ	47.583	13	3.25	6.25

As an example:

Value of B for Level 1

$$= B_1 = (S/N_1 + S/N_4 + S/N_7)/3$$

$$= (32.887 + 38.116 + 34.886)/3 = 35.296$$

Value of A for Level 2

$$= A_2 = (S/N_4 + S/N_5 + S/N_6)/3$$

$$= (38.116 + 23.633 + 35.016)/3 = 32.255$$

The average values of the S/N ratios for each parameter at different levels for all the trials are plotted in Figures 9 and 10. The optimum settings of three parameters were decided according to the graph of S/N ratios in Figure 9. S/N ratios with the highest level were chosen for optimum combination.

Optimum settings of process parameters are as follows: Pot temperature: 570°C; production status: on production, pot cover status: with cover.

Isolation status parameter was decided according to the graph of means in Figure 10. For isolated pots, it can be seen that ΔT is lower. Isolation status: isolated. Values of these four parameters were determined for optimum solution.

3.2.1.3.4. Scatter plot. Change in material temperature *versus* time can be seen in Figure 11. Within 20 min it was understood that pots that were heated up to 570°C before the beginning of material transfer showed least heat loss (around 30°C). Generally, casting set temperatures differ from 680°C to 710°C. Material is taken from melting ovens at 760°C or 740°C. The objective is to support material to casting ovens in the range of 680–710°C.

3.2.1.4. *Improve phase*. The goal of the improve phase is to implement solutions that address the problems (root causes) identified during the previous (analyse) phase. Following the analyse phase, improvement studies began to determine the actions to be taken to eliminate current problems. The focus of this section is on the possible improvement proposals that were structured in the light of findings from analyse phase. A number of improvement actions were implemented in the following paragraphs.

3.2.1.4.1. Degassing time. Findings from analyse phase show that the longer operation time causes need of longer time for decrease in metal temperature. Attempts with less degassing time point out a negative result regarding the loss of casting quality and observed defects of holes in casting. For this reason, no changes were made to degassing time.

3.2.1.4.2. Waiting time after degassing. It was understood that operations after degassing station was undefined and non-value added actions. After observation of this fact, meetings were held with the operators and waiting time was eliminated in most case and minimised for the rest.

The duration of the degassing time is approximately 5 min. During the degassing operation, an operator is interested in other jobs (e.g., loading the material for melting operation). During this time, if degassing time ends, the material is waiting and so there will be an energy loss. To prevent the energy lost, a countdown indicator was installed. When degassing operation begins, countdown indicator starts to work.

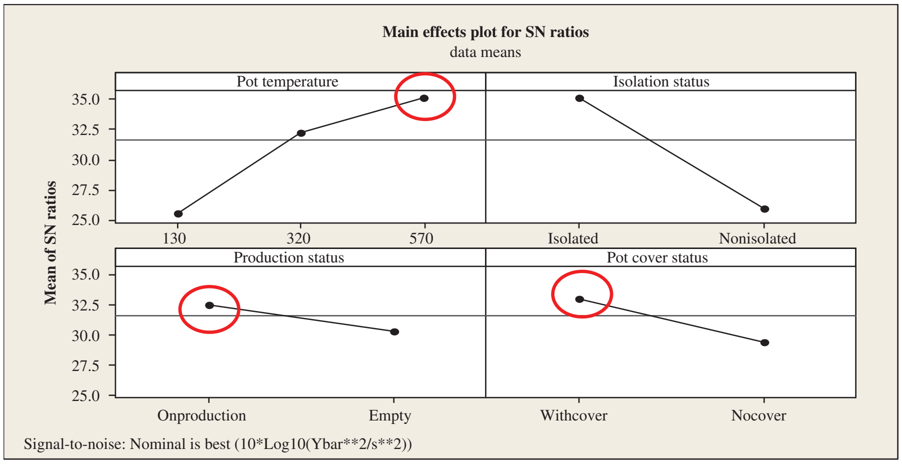

Figure 9. Main effects plot for S/N ratios.

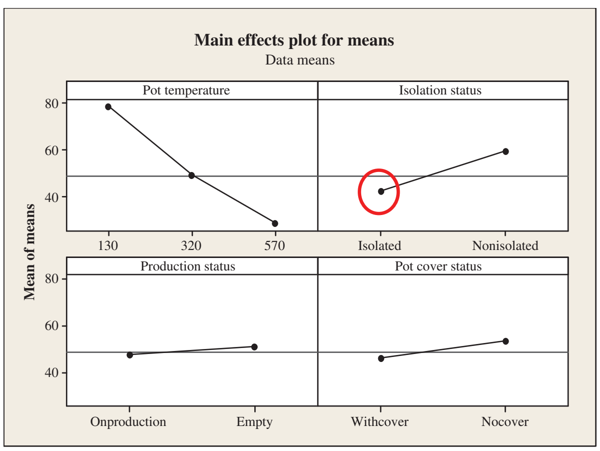

Figure 10. Main effects plot for means.

The operator goes to take the material when the degassing time ends. So, there is no waiting time or at most 4 s as an average (in some cases when the operator could not interrupt his job to go to take the material).

3.2.1.4.3. Waiting before casting bench. This problem had the biggest role in the loss of metal temperature during transfers. Metal was fed to the casting benches by the operators without knowing the availability of the bench and this was causing a waiting period of up to 4–5 min. In order to clear the availability situation, an informative system was designed. If the metal has to be fed to the casting bench, then previous casting cycle has to be completed and pressure inside the oven has to be zero. But as the operators did not know the point of process in this cycle, they were starting the feed and this was resulting in unwanted standbys. To clarify the availability of the ovens, lights were implemented to the ovens which were set-up to show green when the inside pressure decreases to zero. So, whenever an operator arrives to the casting benches, he was able to understand the availability of bench to start the feeding. After revising the related procedures and short trainings to the operators, this process has become a standard. Besides availability lights, a three-degree lightning system was also set-up to show the metal level inside the bench in order to let the operator to know the amount of metal inside. After this implementation, operator was able to know which bench to choose according to availability, how much and in what sequence he should start feeding metal to the possible selections regarding the amount of metal in the bench (i.e. start feeding the bench which has the lowest level of metal).

A 3-grade was represented by different colours:

- Green light: metal level is sufficient.
- Yellow light: available to be fed.
- Red light: metal level is very low.

After the above improvements, measurement and time studies were repeated. Based on the new data, hypothesis test was used to understand the difference between previous and new statuses if there was any. The *t*-test is used to evaluate whether the means of two groups are statistically different from each other. Considering the average values were going to be compared, '*t*-test' was selected as the appropriate method. First check point was the variances. As seen in Figure 12, the variances between new states are different from each other.

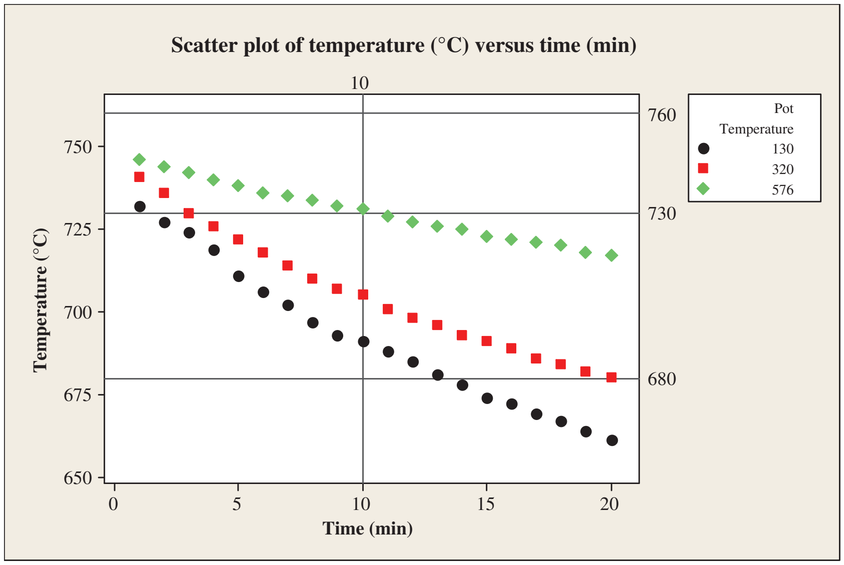

Figure 11. Scatter plot of material temperature *vs.* time.

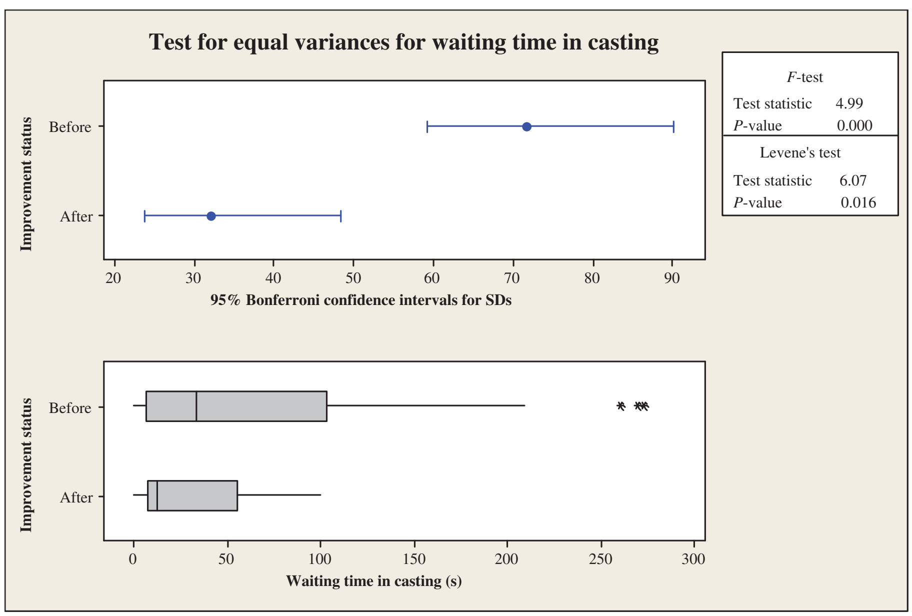

Figure 12. Test of variances.

According to the results of *t*-test, average waiting time in casting has changed before and after the improvements (Table 17).

H_0: $\mu A = \mu B$ (average waiting time before improvement and after improvement average waiting time is equal)
Ha: $\mu A \neq \mu B$
$\alpha = 0.05$

Before–after analysis is used to calculate the ratio of the improvement level. Results of this analysis not

Table 17. Test for equal variances waiting time in casting.

Two-sample *t*-test	*N*	Mean	SD	SE mean
Waiting time in casting-before	59	61.3	71.5	9.3
Waiting time in casting-after	22	27	32	6.8

Notes: Difference = $\mu_{(\text{waiting time incasting before})} - \mu_{(\text{waiting time}_{\text{incasting after}})}$.
Estimate for difference = 34.3; 95% confidence interval for difference: (11.3, 57.3); *t*-test of difference = 0 (*versus* not =): *t*-value = 2.97, *p*-value = 0.004, DF = 76.

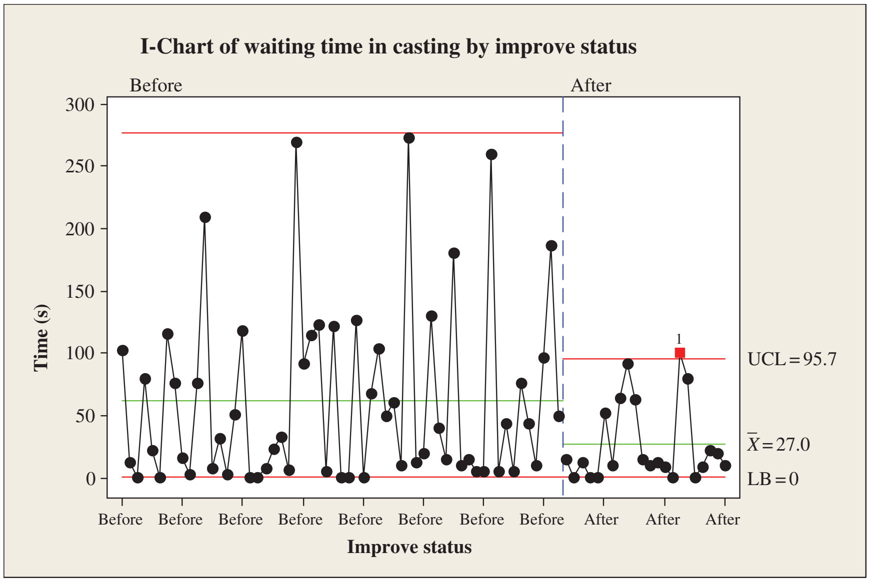

Figure 13. I-Chart for waiting time in casting by improvement status.

only showed the decrease in average value but also in the variance figure. Average of waiting time in casting was decreased from 62 to 27 s after the improvements (Figure 13).

3.2.1.4.4. Improvements of transfer pots. As a result of the Taguchi OAs study, it was decided to standardise all transfer pots. All transfer pots were isolated. Proposal was collected from supplier to design a cover on the top of pots. As a standard, it was decided to heat the transfer pots up to 570°C.

3.2.1.4.5. Other things to do. Slope difference between melting and degassing was causing time loss while transferring metal with forklift. Forklifts had to slow down while passing over this area not to overflow material to the outside. There was also a risk for job security. When the required resource is provided, it is planned to remove this slope.

3.2.1.5. *Control phase*. Control phase is obviously the most important stage of Six Sigma methodology. At this stage all the activities that are accomplished in the other four stages are investigated so that their permanence should be sustained. The goal of the control phase is to put ongoing measures in place to monitor both the process output and the factors that influence output variation, thus ensuring that results achieved in the previous phase are sustained. In this phase, project team ensures that the processes continue to work well, produce desired output results and preserve quality levels.

Three monitored parameter in the project:

(1) Natural gas consumption in melting ovens (target: 0.105 kWh/kg).
(2) Electricity consumption in casting benches (target: 0.097 kWh/kg).
(3) Electricity consumption in melting ovens (target: 0.0028 kWh/kg).

After improvement actions, measurements continued periodically. Project team evaluated the results by using I-Charts. I-Chart displays individual values of each measurement of the process and mean of these values. After improvements, natural gas consumption value decreased to 0.10079 sm^3/kg (Figure 14). Electricity consumption in casting benches fell down from 0.100 to 0.08976 kWh/kg (Figure 15). Figure 16 shows that new average value of electricity consumption in melting ovens is 0.002789 kWh/kg.

After achieving the optimal condition and proving that a sustained improvement had been achieved, the team analysed the financial impact of the project. As a summary, Table 18 shows the target and realised values of project criteria. This table indicates an average improvement for the two criteria which are greater than the project target.

In the control phase, another important point is standardisation. Standardisation makes sure that important elements of a process are performed consistently in the most effective manner.

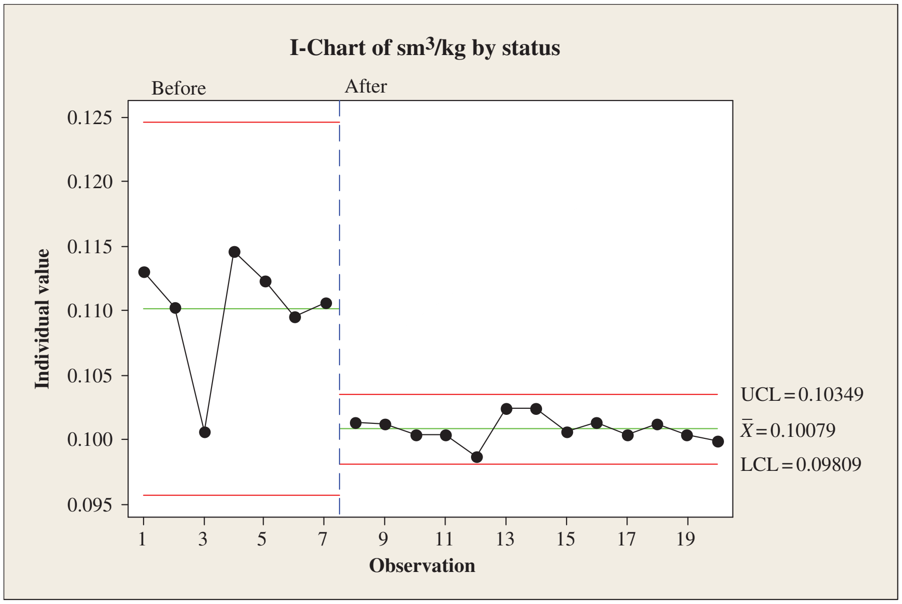

Figure 14. I-Chart of natural gas consumption in melting ovens.

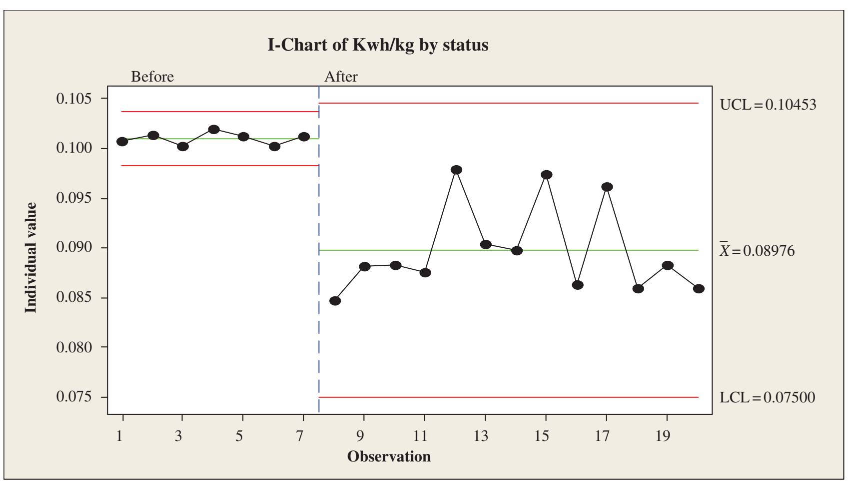

Figure 15. I-Chart of electricity consumption in casting benches.

After improvement actions, required procedures were prepared for material transfer operation according to new conditions.

4. Conclusion and future research

Six Sigma is a systematic methodology that utilises information and statistical analysis to measure and improve a company's operational performance and systems by identifying and preventing defects in manufacturing and service-related processes in order to exceed expectations of customers. Six Sigma is a quality management philosophy which sets very high standards for itself. Its program predicts that increase in number of sigma will decrease the differences from set targets. In this approach, product and service performance of the company is measured by sigma level. Sigma level will continue to increase as the company determines and corrects the reasons which cause the deviations in business processes. This progress means decrease in the number of errors and failures in business and production processes. The main target of Six Sigma is reaching products and

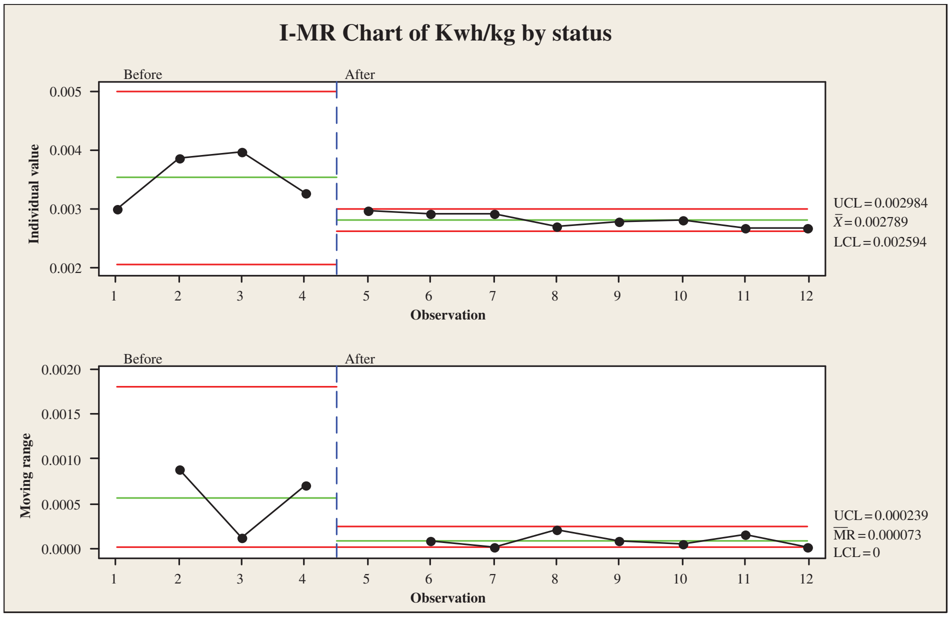

Figure 16. I-MR Chart of electricity consumption in melting ovens.

Table 18. Comparison before and after improvement for the two criteria.

Criteria	Initial	Realized	Target
Natural gas consumption (sm^3/kg)	0.11 m^3/kg	0.101 m^3/kg	0.105 (4%)
Electricity consumption (kWh/kg)	Melting: 0.003	Melting: 0.0027	Melting: 0.0028
	Casting heater: 0.10	Casting heater: 0.089	Casting heater: 0.097

processes which perfectly satisfy requirements and expectations, minimising variation and deviation to zero.

This article presents a real case study illustrating the effective use of Six Sigma methodology to reduce the energy costs. It illustrates in detail how the Six Sigma project is selected and how to define, measure, analyse, improve and control phases of the Six Sigma DMAIC methodology that are carried out. Many qualitative or quantitative tools (FAHP, Taguchi design, FMEA, hypothesis tests and box plot analysis) are employed. In conclusion, expected values of project criteria are reached. Expected gain was €25,990 /year at the beginning of the project. After realisations around €29,000 for the 6-month period was gained.

Six Sigma is being a popular icon of statistics and management, a trademark and a cult all over the globe. Companies that implement Six Sigma are not only saving millions of dollars but also are having significant increases in productivity, efficiency, quality and customer satisfaction levels. Other benefits of Six Sigma are reduction in in-process defect levels, and maintenance inspection time, improving capacity cycle time, and inventory on-time delivery, increasing savings in capital expenditures and profitability, reduction of operational costs, cycle time and customer complaints, reduction in the COPQ, improved sales and reduced inspection (Kwak and Anbari 2006, Aboelmaged 2010).

Many techniques in the possession of OR/MS practitioner could and should be integrated into Six Sigma applications to complement the existing standard Six Sigma tools. New tools and techniques based on OR/MS, artificial intelligence, information systems technologies could be added to the existing framework as part of further research into the area of study (Tang *et al*. 2007).

As a future research detailed analysis of Six Sigma tools that could not be mentioned in this study can be investigated. Six Sigma theory and how does it integrate with other improvement strategies should be a potential future work. Additionally, managing Six Sigma risks and crises must be researched.

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