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Comprehensive Six Sigma application: a case study

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Six Sigma as a framework for eliminating defects at the project level and improving performance and customer satisfaction at the corporate level has been generally recognised. This case-oriented paper reports an important Six Sigma management case study at the world's largest cold rolling mill situated in China. The descriptions of measures taken at the company level, as well as that of the exemplary application experience of this company, would constitute a most comprehensive account of the impact brought about by Six Sigma to the company. A Black Belt project was conducted to improve the cold rolling capability to meet the thickness requirements using the Six Sigma methodology – DMAIC (define, measure, analyse, improve and control) principle. The implementation of Six Sigma methodology led to a significant financial impact on the profitability of the company. Seven key factors were also found to be instrumental to the successful Six Sigma management implementation in the company.

Keywords: Six Sigma; DMAIC; quality management; quality improvement; metallurgy; China

1. Introduction

Six Sigma is a systematic methodology aimed at operational excellence through continuous process improvements. As we know, although Six Sigma originated from Motorola in 1986 arising from the need to improve product quality and customer satisfaction in the face of fierce competition from Japan, some of the basic approaches and tools of Six Sigma originated from the widespread application of statistical methods in the American military industry since the Second World War (Deming 1993). The procedures to obtain variation reduction systematically by statistical means or methods were given by Shewhart and Deming. The essential nature of 'Six Sigma' is 'confidence building', which in turn makes it easier for a company to direct (modify, maintain and prevent) the behaviour of 'people' (customers, vendors, employees, etc.) in a manner that sustains the survival or growth of the company (Christiansen 2011).

It is noteworthy that Aboelmaged (2010) pointed out that case study is the most dominant research method in Six Sigma articles (55.4% in 231 articles). There have been reports on gains in financial benefits and competitive advantages arising from Six Sigma applications from various countries and districts (e.g. Bañuelas, Antony, and Brace 2005; Desai 2006; Kumar et al. 2006; Anand et al. 2007; Su and Chou 2008; Aksoy and Orbak 2009; Chakravorty 2009; Chen and Lyu 2009; El Haouzi, Petin, and Thomas 2009; Lo, Tsai, and Hsieh 2009; Yang and Hsieh 2009; Chen et al. 2010; Jou et al. 2010; Zu, Robbins, and Fredendall 2010; Gijo, Scaria, and Antony 2011; Li et al. 2011; Antony, Gijo, and Childe 2012; Bilgen and Sen 2012; Tanik and Sen 2012; Ghosh and Maiti 2012; Lin et al. 2013). Although Six Sigma was introduced to China soon after its inception in America in the 1980s and an increasing number of Chinese companies are implementing or planning to deploy Six Sigma, research and case studies of Six Sigma implementation in Chinese companies have seldom been reported until now. In this paper, we present a case of comprehensive Six Sigma application in a large stainless steel company, through the illustration of an overall Six Sigma implementation strategy and a successful project, to furnish an insight into the potential impact of Six Sigma in the industrial sector of the world's second largest economy.

The paper is organised as follows. Section 2 presents the overall Six Sigma implementation strategy of Company T. Section 3 illustrates how DMAIC (define, measure, analyse, improve and control) is used to solve an important problem in what is referred to as Company T. Section 4 presents the economic benefits of this Black Belt project. Section 5 consists of a discussion of the key factors of successful Six Sigma management implementation; the last section presents the major conclusion of the paper.

2. Company-level Six Sigma implementation at 'Company T'

2.1. *Six Sigma start-up*

The case study is related to quality management in a stainless steel cold rolling mill, which for the purpose of

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this presentation is referred to as 'Company T'. The company's Six Sigma promotion approach is first introduced, and then a Black Belt project related to the thickness of stainless steel cold rolling sheet is described along with the economic benefits.

Company T, founded in 1934, is a 'mega' enterprise in iron and steel encompassing iron mining, production, machining, distribution and trading. It is also the largest stainless steel enterprise in the world with advanced technologies and equipments, complete product types and specifications. Its annual production capability is about 10 million tons of steel, including 3 million tons of stainless steel.

As a conventional state-owned enterprise, Company T has been in constant search for effective quality management methods. For example, quality control circles have a history of more than two decades; in early 1990s, the company began to implement ISO9000 and was certified. These efforts have played an important role in motivating the staff and solving on-site quality problems. With the rapid development of the company and the need for continuous improvement in quality, statistical process control theory and methods have been deployed to enhance quality performance. Various quality management techniques, such as 5S, TPM and JIT, have been implemented as well, in efforts to improve site management, elevate operational efficiency of equipment and facilitate on-time production.

At the turn of the century, it was determined that to build a globally competitive stainless steel enterprise, it takes a breakthrough from management by experience to management by scientific tools. Thus, QC circles were found to be inadequate in handling inter-process, inter-departmental quality issues, while teams with responsibilities in quality improvement would face a lack of systematic improvement procedures and effective analytical tools. And the deployments of QC circles, TPM, 5S and other initiatives belong to different departments, and collaborations among them were less common. Thus, the potential of these initiatives is not fully utilised. The reported successful experience of domestic as foreign companies such as Posco of Korea led to the strategic decision, in 2004, by the leadership of Company T to turn to Six Sigma management, which made the company one of the earliest among steel enterprises in China to embrace Six Sigma.

With high-level management commitment, the company drew up the 2006–2010 Five-Year Plan for Six Sigma management. The entire company senior management team attended the introductory training. And with the five-year plan, the company chairman took the lead for its implementation, set up a company Six Sigma office, with additional rewards to those promoting Six Sigma. The company CEO initiated the corresponding human resource incentives, attended meetings for Six Sigma promotion and project selection, and secured various needed resources. As Six Sigma champion, the chief engineer took the lead for formulating annual Six Sigma promotion plans, identifying improvement projects, conducting project reviews and promoting the presence of a Six Sigma culture in general.

2.2. *Integration of Six Sigma and other initiatives*

Like many other Chinese state-owned enterprises, Company T faced some problems raised by some employees. Typical questions were: What are the differences between Six Sigma and other management initiatives? and How can we balance the resources required by Six Sigma and other methods such as TQM, Lean Production and TPM? With the help from outside consultants, Company T realised that the core values of Six Sigma and other management initiatives are basically the same. The advantages of Six Sigma are: (1) Six Sigma provides a systematic infrastructure and mechanism for continuous improvement through strong top-down management commitment; (2) Though Six Sigma does not bring about any new tools, and actually Six Sigma tools and methods existed before the name Six Sigma was coined, Six Sigma provides a clear and easy-to-implement DMAIC roadmap for business process improvement, with DMADV (Define, Measure, Analyse, Design and Verify) or IDDOV (Identify, Define, Develop, Optimise and Verify) and other roadmap of design for Six Sigma for product/process design and innovation; (3) The effective project management and rigorous problems-solving tools of Six Sigma provides a general framework for problem identification, problem analysis and problem-solving. Thus, Six Sigma project can reach accountable business results; and (4) The systematic action-learning-type training of Black Belts, Green Belts and Yellow Belts provides an effective and efficient talent cultivation system. Thus, Six Sigma can be integrated with Lean Production, TPM and other management initiatives. And there are many successful stories of Six Sigma integration. Thus Company T builds a big Six Sigma umbrella at corporate level, which includes QCC (Company T puts it as Quick Six Sigma projects), TPM and Lean Production, etc.

2.3. *Organisation for implementation*

The Six Sigma management style in Company T focuses on the full participation of all employees, with fast and continuous improvements. The strategy and main thrusts are as follows.

2.3.1. *Full participation*

All employees are required to learn the basic principles and contents of Six Sigma management through various familiarisation programs and training. Every employee is expected to be able to make good use of Six Sigma ideas appropriate to their work responsibilities.

2.3.2. *Multi-level and systematic organisation structure*

The first level encompasses quality-related teams or projects, related to complete processes, systems and long-term activities; members comprise all related staff and the main management and technical personnel.

The second level comprises 'contract' project teams aiming at solving specific quality problems and optimisation of management processes; team members consist of technical and management specialists and experts.

The third level are 'Quick Six Sigma' (QSS) teams with projects focusing on existing problems and quick improvements: depending on the depth and breadth of the study, projects are categorised into those for Black Belts (BB), Green Belts (GB) and Yellow Belts; team members are made up of engineers, managers and operators directly related to the specific processes in question.

The fourth level is based on Lean Six Sigma projects, addressing work standardisation as well as operations quantification and control; the bulk of the team members are related operators.

2.3.3. *Quick and continuous improvement*

The multi-level structure of Six Sigma implementation teams is formed to solve business problems of strategic level and operational level. And this structure helps Company T form the critical mass of Six Sigma. Thus, Company T builds up a continuous improvement model based on Six Sigma. On one hand, the ready formation of different level Six Sigma teams to address critical business issues as well as operational situations ensures timely concentration of resources for problem-solving. On the other hand, it is recognised that there is no finishing line for quality improvement; thus, persistent Six Sigma improvement efforts are essential: as soon as the targets of one stage are reached, new ones are set for further gains in quality performance.

3. Black Belt project: sheet thickness improvement

A significant Black Belt project in the context of the above company-wide Six Sigma improvement effort will now be presented. The project is about improving the capability to meet the thickness requirements of stainless steel cold rolling sheets.

3.1. *Background of project*

Stainless steel cold rolling sheet is the most competitive product in Company T. The thickness of the cold rolling sheet is recognised as the key quality characteristic. Thickness variation control not only reflects product quality, but also has a close relationship with the economic benefits that can be derived by the customers. However, from market surveys and customers' responses, the thickness variation of cold rolling sheet produced in Company T has been too large. Through benchmarking with its competitor Company P, Company T found that the means of its cold rolling sheet thickness are about 0.01–0.04 mm larger than the corresponding values in Company P, and the variation is quite larger than its competitor's. Thus, the managers in the cold rolling mill made the decision to have a Six Sigma project aimed at decreasing the variation of thickness and improving the thickness compliance of stainless steel cold-rolled sheets to enhance the market competitiveness of their products. The team members were trained to use Minitab software to do statistical analysis. In this paper, all statistical analysis outputs are based on Minitab.

3.2. *Definitions*

3.2.1. *Definition of non-conforming product*

Based on quality inspection standards, the thickness of steel rolls is measured as the vertical diameter of steel sheet. If the thickness of a roll is within the upper and lower specifications, then the roll is regarded as a conforming product, otherwise it is non-conforming.

3.2.2. *Definition of yield*

Total inspection is used here. The number of wholly tested rolls is the denominator and the number of conforming rolls is the numerator. Thus, this ratio is taken as the yield of the production line.

3.2.3. *Goal of the Black Belt project*

The thickness yield in Company T is only 68.9% now. However, it is 85.2% in Company P. Through team work analysis using SMART (specific, measurable, attainable, relevant and time-bound) rule, the goal of this Black Belt project is to increase the yield in Company T to 90%.

3.2.4. *Team members*

The chief engineer in Company T acts as the project champion. Through Supplier, Input, Process, Output, Customer and project stakeholder analysis, we found that several departments are involved in this project including the technical department (product and process design), testing, equipment maintenance, etc. A cross-functional team is formed including team members from each department. Also, some experienced front line workers are invited to be extended team members. A Black Belt from technical department works as the team leader. The team makes a detailed project plan and reaches consensus on the conduct of behaviour for the project activities.

3.3. *Measure*

3.3.1. *Measurement system analysis*

The cold rolling sheet thickness leads to continuous data. The measurement system is analysed based on the thickness data measured by micrometre and four testers. The measurement system analysis is shown in Table 1. It can be seen that the variance of total gauge R&R% is only 1.49% of the total variance, and the number of distinct categories is 94. Thus, the capability of this measurement system is reliable.

Table 1. Measurement system analysis of stainless steel cold rolling sheet thickness.

Source	Study var. Std. dev. (SD)	% study (6 × SD)	Var. (% SV)
Total gauge R&R	0.010973	0.06584	1.49
Repeatability	0.010452	0.06271	1.42
Reproducibility	0.003340	0.02004	0.45
Operator	0.003340	0.02004	0.45
Part-to-part	0.737699	4.42620	99.99
Total variation	0.737781	4.42669	100.00

Note: Number of distinct categories = 94.

3.3.2. *Process flow analysis and key process input variables identification*

In cold rolling mill, the key process is the rolling process, for which the flow chart is shown in Figure 1. For each process step in rolling, we identified the possible factors that may impact the thickness of the stainless steel plate. The cause and effect diagram as shown in Figure 2 is then used to find the main factors that might influence the large sheet thickness variation from considerations of human, machine, materials and method elements, aided by the brainstorming process. Eventually 32 potential factors are identified.

3.4. *Analyse*

3.4.1. *Factors selected*

In this project, the defect is thickness of out specification including large thickness variation and extra thickness. Here, a cause-and-effect matrix is used to show the relationship of these 32 factors and the defects. The importance of defects is set up by its weighted score in Table 2. Nineteen factors (bold type in Table 2) with total score larger than 50 are selected as key factors related to the main defects. Next, a failure mode and effect analysis (FMEA) is carried out for these factors, as shown in Table 3.

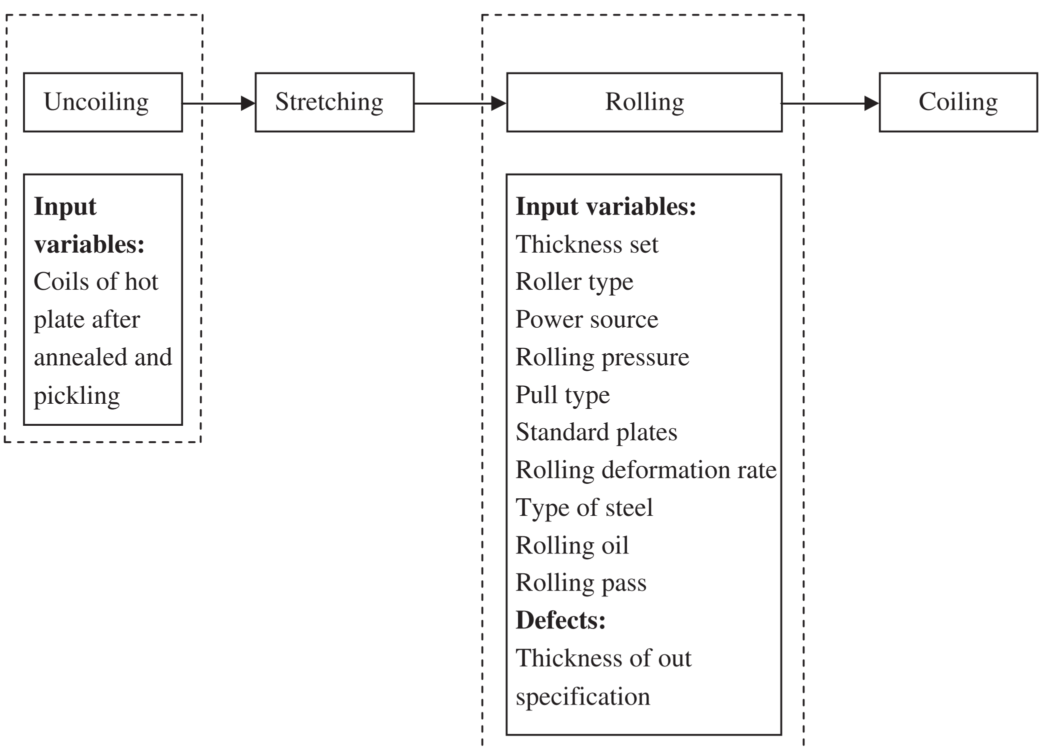

Figure 1. The flow chart of cold rolling process.

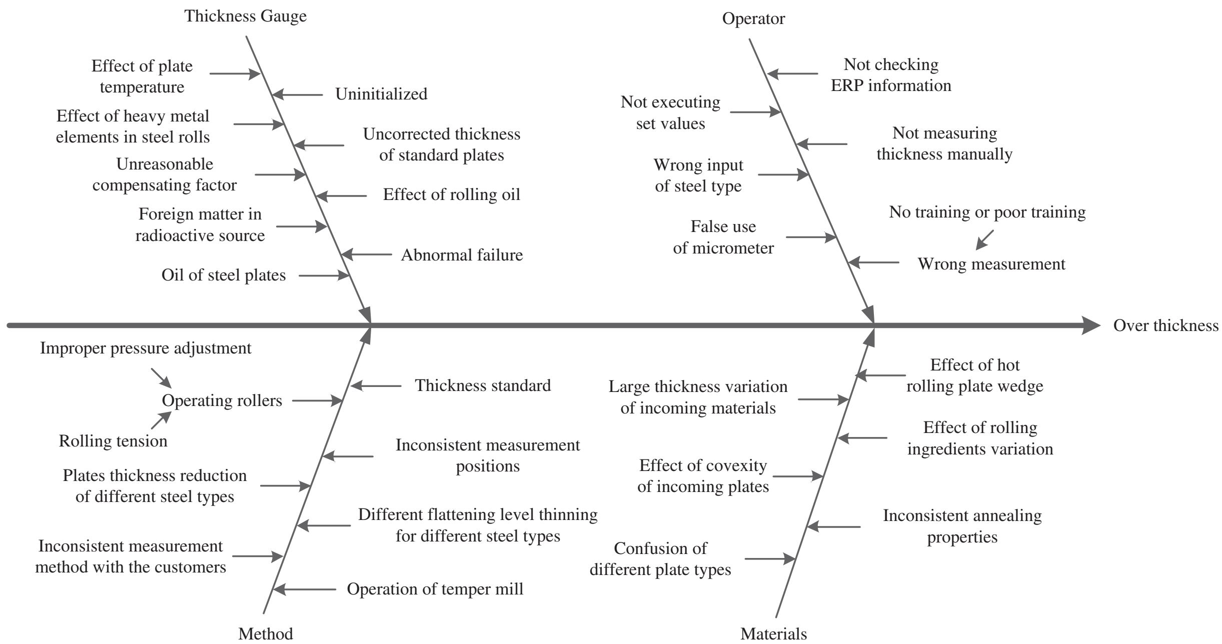

Figure 2. The cause and effect diagram of over thickness.

Table 2. C&E matrix of cold rolling plate thickness.

Rating of importance (1–10)		5	9	
	Key requirements	Large variance	Extra thickness	
	Process step	Rating: 0–10		Total
1	**Thickness standard**	**8**	**5**	**85**
2	Order	3	1	24
3	**Rolling parameters**	**3**	**9**	**96**
4	**Stretching force**	**3**	**9**	**96**
5	Plate temperature	3	3	42
6	**Compensating factor of thickness gauge**	**3**	**9**	**96**
7	**Standard plates**	**1**	**9**	**86**
8	Rolling oil	**3**	**3**	**42**
9	**Power source**	**3**	**9**	**96**
10	Oil residue on plate surface	**3**	**3**	**42**
11	**Measure position**	**6**	**2**	**58**
12	**Thickness reference revision**	**2**	**9**	**91**
13	**Thickness reference filled**	2	2	28
14	**Contract requirement**	**5**	**3**	**52**
15	**Wedge-shaped raw material**	**9**	**3**	**72**
16	Plate crown of raw material	4	3	47
17	Thickness of raw material	3	1	24
18	**Ingredient Ni of raw material**	**9**	**1**	**54**
19	**Ingredient Cu of raw material**	**9**	**3**	**72**
20	**Ingredient Mo of raw material**	**9**	**3**	**72**
21	**Ingredient Cr of raw material**	**3**	**4**	**51**
22	**Ingredient Al of raw material**	3	1	24
23	Inspectors	3	3	42
24	Raw materials annealed	3	1	24
25	**Flattening passes**	**9**	**3**	**72**
26	Rolling passes	3	3	42
27	**Rolling strain of final product pass**	**5**	**4**	**61**
28	Rolling tension	1	3	32
29	**Manual thickness measurement**	**3**	**9**	**96**
30	**Difference of rolling shift teams**	**6**	**3**	**57**
31	**Difference of rollers**	**6**	**3**	**57**
32	Total rolling strain	3	4	24

Table 3. FMEA of cold rolling plates.

Item	Potential failure mode	Potential effects of failure	S (Severity rating)	Potential causes	O (Occurrence rating)	Current controls	D (Detection rating)	RPN
Wedge-shaped raw material	**Large variance**	**Large variation of thickness**	**7**	**Incorrect wedge control of hot rolling raw material**	**4**	**N**	**4**	**112**
Ingredient Cr of raw material	**Inaccurate thickness gauge measurement**	**Thickness of out specification**	**6**	**Melting control**	**4**	**N**	**4**	**96**
Ingredient Ni of raw material	**Inaccurate thickness gauge measurement**	**Thickness of out specification**	**6**	**Melting control**	**4**	**N**	**4**	**96**
Ingredient Mo of raw material	**Inaccurate thickness gauge measurement**	**Thickness of out specification**	**6**	**Melting control**	**4**	**N**	**4**	**96**
Ingredient Cu of raw material	**Inaccurate thickness gauge measurement**	**Thickness of out specification**	**6**	**Melting control**	**4**	**N**	**4**	**96**
Rolling parameters	Disunity	Large variation of thickness	8	Failure to obey design	6		3	144
	Unreasonable values	Extra thickness	9	Design parameters insufficiency	4	Temporarily set up references	3	108
Rolling strain	Non-standard	Bad rolling performance	5	Lack of quality consciousness	6	Process periodical inspection	3	90
Rolling strain of final product pass	**Disunity**	**Final product thickness of out specification**	**3**	**Steel ingredient, annealing and process**	**7**	**N**	**6**	**126**
Compensating factor of thickness gauge	**Not able to find the best value**	**Final product thickness of out specification**	**7**	**Variance of ingredients or system error of thickness gauge**	**3**	**N**	**6**	**126**
Manual thickness measurement	Inaccurate measurement	Inaccurate actual thickness measurement	7	Incorrect micrometre calipers	5	Training	2	70
Power source	Abnormal work	Not scheduled for maintenance or abnormal	9	Abnormal problems such as equipment failure	1	Temporary treatment	8	72
Rolling shift teams	**Different operation process**	**Poor thickness unity**	**4**	**N**	**6**	**N**	**4**	**96**
Rollers	**Different system**	**Poor thickness unity**	**4**	**N**	**6**	**N**	**5**	**120**
Standard plates	Incorrect size	Incorrect roller thickness control	10	Abnormal when calibrating	1	N	9	90
Flattening passes	Non-standard	Incorrect thinning level	6	Strong arbitrariness	5	Wide flow for various plate types	3	90
Stretching force	Disunity	Different thinning level	6	Different raw plate shape level	4	Focus on improving plate shape	2	48

(*Continued*)

Table 3. (*Continued*).

Item	Potential failure mode	Potential effects of failure	S (Severity rating)	Potential causes	O (Occurrence rating)	Current controls	D (Detection rating)	RPN
Thickness standard	Many personalised standards	Poor process control, order, inspection and judge	7	No standards provided to customers or little standards	8	N	2	112
Measure position	Incorrect measurement thickness	Not conforming with thickness measured by customer	5	Thickness inconsistency between the middle and edge of plate	4	C100 position required	2	40
Thickness reference revision	Non-conformity to the standard	Poor reference thickness	6	Did not grasp the points of thickness revision	5	Training and check	3	90
Contract requirement	Did not distribute the products according to the raw orders	Inconsistent thickness	6	Handle non-scheduled products	3	Strengthen equipment inspection	2	36

There are 16 factors whose risk priority number (RPN) is larger than or equal to 90. The cause of nine factors, marked by bold type in Table 3, will be analysed and improved by the statistical tools in the following section. Another seven factors can be immediately corrected through a simple and quick improvement scheme. Then, a second FMEA of these seven factors is analysed. Except that thickness standards need to be coordinated with the design department, the RPN values of the other six factors are all below 90, which are shown in Table 4.

3.4.2. *Analysis schemes*

In this section, the effects of wedge-shaped raw material, chemical ingredients, rolling shift teams and roller unit

Table 4. The improved FMEA of cold rolling process.

Items	Failure mode	Current status	Prior RPN	Measures taken	S	O	D	RPN
Rolling parameters	Disunity Unreasonable	Thickness specification is not consistent with customer requirements. Rolling parameters are not fully carried out in practice	144 108	Parameters are redesigned. New thickness standards and process needs are well trained	8 9	2 2	3 3	48 54
Thickness standard	**Many personalised standards**	**There are 1379 types of thickness requirements and is no unified standard**	**112**	**Based on customer requirements, current standards and experience in the industry, new thickness standards are set down**	**7**	**7**	**2**	**98**
Rolling strain	Non-standard	The relationship between raw materials and finished products is lack of standardisation	90	Based on the steel characteristics and real production conditions, such relationship is standardised	5	3	3	30
Standard plates	Incorrect size	In practice standard thicknesses of some standard plates are not precise	90	Each standard plate has to be manually inspected to make sure thickness is ok	10	0	9	0
Flattening passes	Non-standard	Thickness reduction amount is not clear enough after flattening process	90	After thorough learning of thickness reduction amount of each process, thickness unity is provided according to steel types, thickness specification and process requirements	6	2	3	36
Thickness reference revision	Non-conformity to the standard	Thickness revision concept is misunderstood and not executed consistently	90	Thickness reference is classified and revised. Each inspector is well trained	6	2	3	36

on thickness yield control are analysed. Different tools are used for different data types.

3.4.2.1. *Effect of wedge-shaped raw materials.* The effect of wedge value of hot rolling plates on the thickness of cold rolling plates is investigated here. Wedge is a measure of the thickness at one plate edge as opposed to the other edge. It may be expressed as absolute measurements or as relative measurements. Here, absolute measurements are used. In a hot rolling process, wedge may be caused by rigidity of rolling mill, work piece deviation, raw material wedge or uneven temperature. Ten coils with target cold rolling plate thickness of 2.0 mm were randomly assigned to each nominal wedge values of 0.01, 0.04 and 0.07 mm. The thickness values of cold rolling plates are shown in Table 5.

In the analysis, the hypothesis tested is as follows. H_0: there is no statistically significant thickness difference for different wedge values. H_1: there is statistically significant thickness difference for different wedge values. One-way ANOVA is used and the results are shown in Figure 3. Boxplots of thickness by wedge value are shown in Figure 4. Because the resulting p value is virtually zero, the null hypothesis is rejected, i.e. there are statistically significant differences in the thickness for different wedge values. Besides, when the wedge value is 0.01 mm, the mean thickness is 1.85 mm, which is the closest to target thickness 2.00 mm and the thickness standard deviation is also the smallest. Therefore, the wedge value of hot rolling plates should be 0.01 mm in order to control the thickness variation of cold rolling plates with target thickness 2.0 mm.

3.4.2.2. *Effect of chemical ingredients Cr, Ni, Mo and Cu.* The addition of chemical ingredients makes the stainless steel respond well to heat treatment, resulting in different mechanical strengths, such as hardness and corrosion resistance. However, there is variation in the chemical ingredients due to measurement positions and the smelting processes. In this project, one type of stainless steel with target thickness 2.00 mm contains 17–19% chromium (Cr), 12–16% nickel (Ni), 1.2–2.5% copper (Cu) and 1.5–2.5% molybdenum (Mo). The thickness is measured with the use of X-ray thickness gauge for 100 coils where 10 positions are chosen in each coil. Regression analysis between thickness and chemical ingredients is shown in Figure 5. It can be seen from Figure 5 that the standard error is 0.0128 mm. The thickness variation due to the ingredients can be controlled within $\pm 3 \times 0.0128$ mm, that is 0.0768 mm.

Table 5. Values of thickness with different wedges (unit: mm).

Wedge values	0.01	0.04	0.07
Thickness	1.850	1.840	1.830
	1.852	1.842	1.828
	1.851	1.843	1.830
	1.852	1.841	1.826
	1.850	1.844	1.824
	1.849	1.838	1.828
	1.851	1.839	1.831
	1.849	1.837	1.832
	1.848	1.836	1.829
	1.850	1.840	1.832

One-way ANOVA: thickness versus Wedge

```
Source  DF   SS          MS          F       P
Wedge    2   0.0022483   0.0011241   223.83  0.000
Error   27   0.0001356   0.0000050
Total   29   0.0023839

S = 0.002241   R-Sq = 94.31%   R-Sq(adj) = 93.89%

Individual 95% CIs For Mean Based on Pooled StDev
Level  N   Mean     StDev    ---------+---------+---------+---------+
0.01   10  1.85020  0.00132                              (-*-)
0.04   10  1.84000  0.00258                  (--*-)
0.07   10  1.82900  0.00258  (-*-)
---------+---------+---------+---------+
1.8340    1.8410    1.8480    1.8550

Pooled StDev = 0.00224
```

Figure 3. Results of one-way ANOVA.

Moreover, the p values of ingredients Ni and Cr are 0.624 and 0.491, respectively, which are much larger than 0.05. Thus, ingredients Ni and Cr do not significantly affect the thickness. On the other hand, the p values of ingredients Cu and Mo are 0.015 and 0.004, respectively, both being smaller than 0.05. Thus, there is significant relationship between thickness and ingredients Cu and Mo. The scatter plots of thickness adjusted for Cu vs. Mo adjusted for Cu are shown in Figure 6. Those of thickness adjusted for Mo vs. Cu adjusted for Mo are shown in Figure 7. Next, ingredients Ni and Cr are deleted from the regression analysis. The regression results are shown in Figure 8. The p values of ingredients Cu and Mo are 0.007 and 0.003, respectively, which are smaller than 0.05. Thus, there is significant relationship between thickness and ingredients Cu and Mo. In practice, high-quality copper and molybdenum wires are first mixed into the smelting furnace based on their lower or middle specifications. The proportions of Cu and Mo are measured at regular times. More wires may be used in the smelting process.

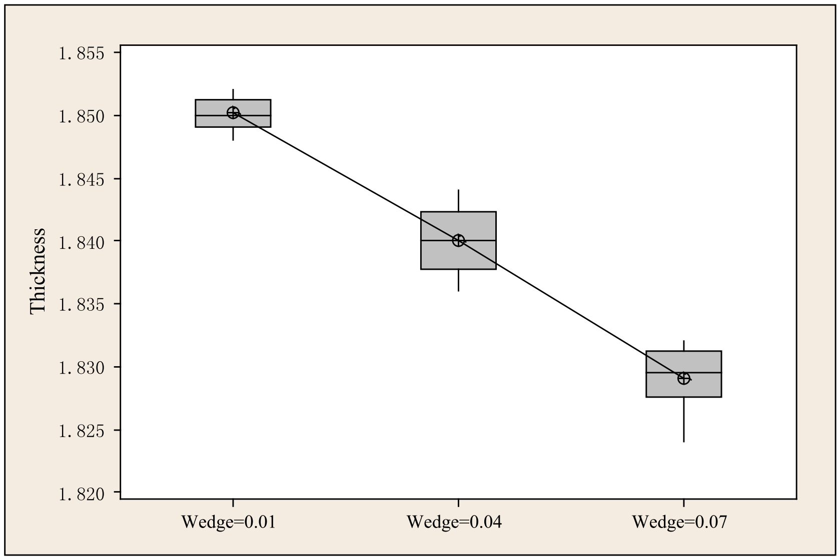

Figure 4. Boxplots of thickness by wedge value.

Regression Analysis: Thickness versus Cr, Ni, Mo, and Cu

The regression equation is

Thicknesses = 2.04 - 0.0111 Ni -0.00526 Cr – 0.0408 Cu – 0.197 Mo

Predictor	Coef	SE Coef	T	P
Constant	2.03570	0.18250	11.15	0.000
Ni	-0.01112	0.02259	-0.49	0.624
Cr	-0.00526	0.00759	-0.69	0.491
Cu	-0.04083	0.01643	-2.49	0.015
Mo	-0.19693	0.06560	-3.00	0.004

S = 0.0127556 R-Sq = 80.9% R-Sq(adj) = 88.2%

Figure 5. Regression analysis between thickness and chemical ingredients of Cr, Ni, Mo and Cu.

3.4.2.3. *Effect of rolling shift teams and roller unit.* Multi-vari analysis is used to analyse the effect of rolling shift teams and roller unit on thickness. We chose three rollers numbered 1#, 2# and 3# which are randomly operated by four shifts named A, B, C and D. The thicknesses of ten coils are randomly measured for each shift operating one roller. The thicknesses are shown in Figure 9. It can be seen that the thickness variation is mainly caused by different shifts for each roller. However, the variation between different rollers is relatively small. Thus, the front line workers should be well trained according to operation instruction to guarantee production consistency.

3.5. *Improve*

The main task in this step is to further analyse the effect of rolling strain, compensating coefficient and rolling parameter on the cold rolling plate thickness with the use of design of experiments (DOE) (Box, Hunter, and Hunter 2009). A full factorial design with three factors at two levels (i.e. a 2^3 factorial design) with three centre points is adopted. For confidential reason, the level selection for each input variable and the raw data of experimental design are not provided. The analysis is shown in Figure 10. It can be seen from Figure 10 that the three main effects and the interaction between strain and compensating coefficients are significant. After deleting the insignificant interactions in the model, the reduced model is shown in Figure 11. There is no curvature and lack of fit of the model. Residual analysis validates the appropriateness of the model. As the curvature coefficient measures the sum of the quadratic effects or strain and rolling parameter, it is probably appropriate to add some star points in the design in future investigations.

Optimisation is also used to find the best values of strain, compensating coefficient and rolling parameter. Based on the optimised values of these parameters, 20 coils of hot rolling plates with the target of thickness 2.0 mm are tested to observe if the actual thickness is within the thickness specification limits. The thickness of experimental coils falls in the confidence interval range, which shows that the conclusions from the DOE analysis are correct. The process parameters can be used in production.

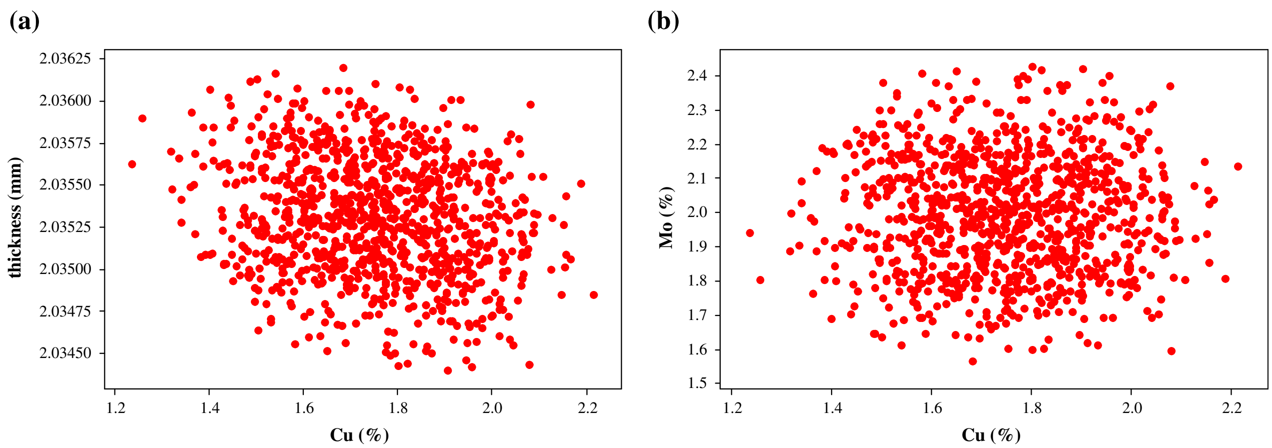

Figure 6. (a) Thickness adjusted for Cu and (b) Mo adjusted for Cu.

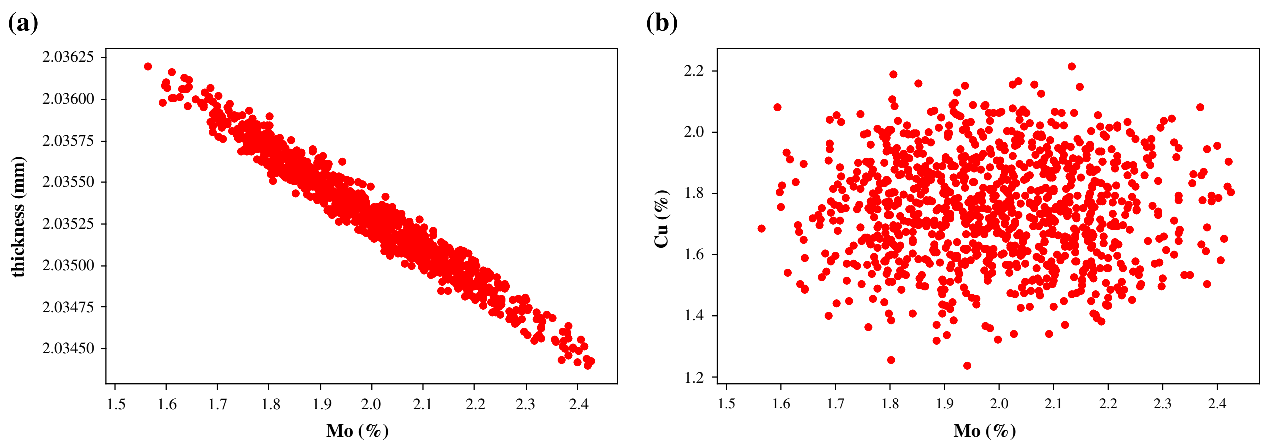

Figure 7. (a) Thickness adjusted for Mo and (b) Cu adjusted for Mo.

Regression Analysis: Thickness versus Cu and Mo

The regression equation is

Thicknesses = 1.85 - 0.0443 Cu – 0.181 Mo

Predictor	Coef	SE Coef	T	P
Constant	1.85281	0.00212	875.77	0.000
Cu	-0.04429	0.01592	-2.78	0.007
Mo	-0.18053	0.05922	-3.05	0.003

S = 0.0126807 R-Sq = 80.1% R-Sq(adj) = 88.8%

Figure 8. Regression analysis between thickness and chemical ingredients of Cu and Mo.

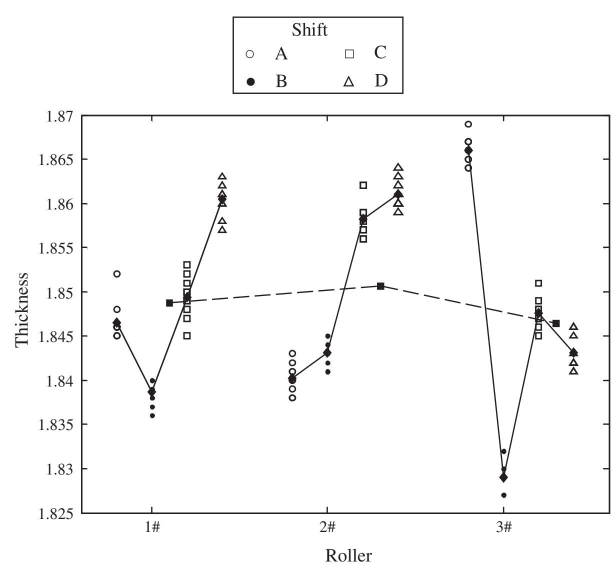

Figure 9. Multi-vari chart of rollers and shifts.

Factorial Fit: Thickness versus Strain, Compensation coefficient , Rolling parameter

Estimated Effects and Coefficients for Thickness (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		1.84088	0.001061	1735.59	0.000
Strain	0.01125	0.00563	0.001061	5.30	0.034
Compensating coefficient	0.01575	0.00788	0.001061	7.42	0.018
Rolling parameter	0.01375	0.00687	0.001061	6.48	0.023
Strain*Compensating coefficient	-0.00475	-0.00238	0.001061	-2.24	0.155
Strain*Rolling parameter	0.01125	0.00562	0.001061	5.30	0.034
Compensating coefficient* Rolling parameter	-0.00325	-0.00162	0.001061	-1.53	0.265
Curvature		-0.00488	0.002031	-2.40	0.138

S = 0.003   R-Sq = 99.66%   R-Sq(adj) = 95.43%

Analysis of Variance for Thickness (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00112738	0.00112738	0.00037579	41.75	0.023
2-Way Interactions	3	0.00031937	0.00031937	0.00010646	11.83	0.079
3-Way Interactions	1	0.00000613	0.00000613	0.00000613	0.68	0.496
Curvature	1	0.00005185	0.00005185	0.00005185	5.76	0.138
Residual Error	2	0.00001800	0.00001800	0.00000900		
Pure Error	2	0.00001800	0.00001800	0.00000900		
Total	10	0.00152273				

Figure 10. Full factorial design analysis (full model).

3.6. *Control*

The significant key factors found in the measurement, analysis and experiment steps are controlled through control plans to sustain the effectiveness achieved through the project. The aim is to keep the current thickness level and prevent any quality deterioration. Such actions are shown in Table 6.

The cold rolling coils are inspected periodically to monitor the improved results. Here, an individual moving range control chart is used. The chart shows that the thickness is in control.

The original thickness yield is only 68.90%. However, it reaches to 95.82% after the improvement of the Six Sigma project. There is a significant increase in thickness yield. Furthermore, the thickness yield is also over the target value, that is 90%.

4. Economic benefit analysis

There were about 40 cold rolling coils with over-large thickness per month before this project was carried out. However, such number decreases to 5 coils per month after improvement project. The cost of rolling and pickling processes is 651RMB per ton, the cost reduction in these two processes is 296,000RMB every month. Then the cost reduction each year is 3552,000RMB. At the same time, the loss due to quality rejections is 125,000RMB in 2009. Such loss after this project can be reduced by about 72,000RMB each year. It is noted that the application cost during this project mainly includes the salaries of Black Belts and various team members, amounting to about 10,000RMB. Thus, the economic benefit is 3520,000RMB ($550,000) per year.

Factorial Fit: Thickness versus Strain, Compensation coefficient , Rolling parameter

Estimated Effects and Coefficients for Thickness (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		1.83955	0.001468	1253.12	0.000
Strain	0.01125	0.00563	0.001721	3.27	0.017
Compensating coefficient	0.01575	0.00788	0.001721	4.57	0.004
Rolling parameter	0.01375	0.00688	0.001721	3.99	0.007
Strain*Rolling parameter	0.01125	0.00562	0.001721	3.27	0.017

S = 0.00286873 R-Sq = 98.82% R-Sq(adj) = 94.09%

Analysis of Variance for Thickness (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00112738	0.00112738	0.00037579	15.85	0.003
2-Way Interactions	1	0.00025312	0.00025312	0.00025312	10.68	0.017
Residual Error	6	0.00014223	0.00014223	0.00002370		
Curvature	1	0.00005185	0.00005185	0.00005185	2.87	0.151
Lack of fit	3	0.00007238	0.00007238	0.00002413	2.68	0.283
Pure Error	2	0.00001800	0.00001800	0.00000900		
Total	10	0.00152273				

Figure 11. Factorial design analysis after optimisation (reduced model).

Table 6. The control plan of key factors.

No.	Key factors	Control style	Relative unit
1	Process implementation of rolling process	Check the implementation everyday	Rolling
2	Implementation of thickness inspection correctness	Check the thickness correctness everyday	Inspection
3	Procedure of abnormal thickness quality information	Thickness curve of abnormal coils has to be printed and recorded	Rolling
4	Check and feedback of raw material thickness control	Ten coils are sampled each month. The values of wedge and plate crown are measured and fed back to the former process and management	Technique
5	Calibration of roller thickness gauge	The compensating coefficient of thickness gauge for all kinds of steels has to be calibrated each month	Electric
6	Thickness standard plates	Based on the average level of steel ingredients, thickness standard plates are calibrated in automated company	Technique
7	Rolling strain	The corresponding specification between the final product thickness and raw material is planned. The requirement for raw materials is reported each month according to the contracts	Production

5. Discussion

The above project is just one example of the Black Belt and Green Belt projects finished in Company T. From 2009 to 2011, Company T successfully conducted 475 projects which yielded 600 million RMB ($100,000,000) hard savings. Twenty-one projects were selected as national excellent Six Sigma projects by the China Association for Quality (CAQ). And Company T was awarded as Excellent Company for Six Sigma Implementation by CAQ.

For a typical Chinese state-owned enterprise, Company T gained competitive advantages through Six Sigma deployment in terms of quality improvement, cost reduction and service enhancement. Through our investigation into Company T, we found the following key success factors for its Six Sigma implementation. All these factors are almost the same as the research findings of the previous literature (Coronado and Antony 2002; Linderman et al. 2003; Kwak and Anbari 2006; Pandey 2007; Schroeder et al. 2008; Zu, Fredendall, and Douglas 2008; Kumar, Antony, and Cho 2009; Büyüközkan and Öztürkcan 2010; Zu, Robbins, and Fredendall 2010; Brun 2011; Nair, Malhotra, and Ahire 2011; Parast 2011; Manville et al. 2012).

5.1. *Strong support and involvement of top management*

Because Six Sigma is a top-down management activity, commitment of top management becomes a key successful factor of Six Sigma implementation. Commitment does not only mean strong support by providing visible resources for Six Sigma, but also means personal involvement or participation in Six Sigma projects. In Company T, top leaders act as the champions of Six Sigma projects, which can make sure that each project links to the company strategy and guarantees resources input in the improvement process.

5.2. *Career plan of belt employees*

Six Sigma will never succeed without active participation of Black Belts, Green Belts and Yellow Belts. To motivate these belts employees, Company T designed a career plan for them besides a monetary reward based on the hard savings of the successful projects they finished. Some managers are selected from the Black Belt or Master Black Belt employees. Thus, Six Sigma management can be carried out by the managers of each level in the organisation, and become their daily work. The continuous improvement mechanism and culture are formed through continuously finding projects, defining projects, managing projects and reviewing project results.

5.3. *Six Sigma infrastructure*

Six Sigma infrastructure is one of the key elements to maintain sustainable implementation of Six Sigma. In Company T, a well-established infrastructure was established at the very beginning when Six Sigma was announced. A Six Sigma office was formed to be responsible for Six Sigma project management. The head of the office directly reported to the CEO. A five-year Six Sigma implementation plan was drafted with specific goals and tasks for each year. Also, a set of documents was set up for Six Sigma project selection, project review and financial results assessment.

5.4. *Well-established action-learning training system*

The uniqueness of Six Sigma training is based on problem-solving. Projects were selected before project team members received Six Sigma training. Six Sigma training is divided into different phases such as DMAIC or DMADV and the training is in parallel with project execution. The belts employees are required to utilise what they learned in the classroom to their projects with the help of consultants. And Company T established a hierarchy of training system targeted at champions, Black Belts, Green Belts, Yellow Belts, staff members and front line workers.

5.5. *Information system*

Information system can also be regarded as an important element of infrastructure for Six Sigma companies. Successful Six Sigma implementation needs reliable data collection and analysis, which were poor before Six Sigma was introduced into Company T. Along with Six Sigma deployment, Company T also introduced MES and ERP systems and upgraded its intranet system. The well-established information system provides online data collections. And Six Sigma office also developed its project management system and put it on the website for instant monitoring of project progress. Six Sigma project success story sharing is also realised via intranet.

5.6. *Six Sigma culture*

For managers at each level, such idea as making use of Six Sigma to promote operation performance and increase company competition is sent out to each management area. All the managers know very well the core of Six Sigma management and provide support and resources to Six Sigma implementation. For engineers and quality management employees, such idea as making good use of data in Six Sigma implementation to achieve quality management innovation is popularised. All of them consciously use the theory and tools of Six Sigma to raise the efficiency and quality management level of

Company T. For the basic level employees, such idea as using Six Sigma to reduce poor quality cost and increase economic value added is practicable. Six Sigma management becomes an essential part of their daily work.

5.7. *Integration with other management methods*

Other management methods such as Lean Production, TPM, QC, ISO90001 and performance excellence model were also introduced into Company T before Six Sigma management. As mentioned above, Company T builds a big Six Sigma umbrella at the corporate level which includes Lean Production, TPM and others, since the core value of these initiatives is continuous improvement. The integration avoids the separations of continuous improvement programmes with different names and affiliated with different departments. And the integration combines Six Sigma's top-down strategy and the bottom-up culture of lean to form critical mass for continuous improvement.

6. Conclusions

It is well reported that many of the Top 500 corporations in the world have implemented Six Sigma management to improve their product and service quality. Systematic and sustained applications of Six Sigma in China are, however, not as widely known. This paper has outlined the initiatives in the promotion of Six Sigma in one famous steel organisation, namely Company T. A significant Black Belt project at this company is also presented.

It can be appreciated from the accounts given here that Six Sigma has become a prime mover in a company's drive for global competitiveness, and the aligned statistical tools in Six Sigma offer unprecedented opportunities for non-statisticians to integrate analytical tools with technical problem-solving. What follows is a changing company culture that results from the behaviour of employees and managers alike, ultimately realising the goal of a learning organisation. Business leaders with organisational capability, project management techniques and habits of statistical diagnosis have emerged along with Six Sigma management. In fact, they are the ones that planted the seeds for reform and increased competitiveness of the company – this has certainly more significant and far-reaching implications than what many have routinely seen in the DMAIC roadmap.

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