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Implementation of FMEA for Process Improvement in Machine Woven Carpet Production

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ABSTRACT

In this study, Failure Mode and Effect Analysis (FMEA) is applied in a carpet production facility, with the aim of enhancing productivity through the elimination of the most critical failures. A comprehensive analysis was conducted to investigate the most frequent faults encountered over a six-month period, whereby the frequency of occurrence for each type of failure was documented. The Risk Priority Numbers (RPN) for each failure mode were subsequently assigned by the FMEA team. Then, a thorough root cause analysis was conducted, leading to the implementation of targeted preventative measures. After implementation of preventive measures, analysis revealed a significant reduction in predetermined failures when compared to former situation. Specifically, a remarkable 75% decline in scrape failures, a 28.57% reduction in abrage failures, and a 59.82% decrease in corner burning failures were determined.

Dokuma Makine Halısı Üretiminde Proses İyileştirme için HTEA Uygulanması

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Anahtar Kelimeler
Halı üretimi
Hata türü
Hata etkisi
Risk öncelik sayısı

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ÖZ

Bu çalışmada, bir halı üretim tesisinde Hata Türü ve Etkileri Analizi (HTEA) yöntemi kullanılarak, en kritik hataların ortadan kaldırılması yoluyla üretkenliğin artırılması amaçlanmıştır. Altı aylık bir dönem boyunca karşılaşılan hataları belirlemek üzere kapsamlı bir analiz gerçekleştirilmiş ve her bir hata türünün meydana gelme sıklığı kayıt altına alınmıştır. Ardından, her bir hata türü için Risk Öncelik Sayıları (RÖS) HTEA ekibi tarafından belirlenmiştir. Sonrasında ayrıntılı bir kök-neden analizi yapılmış ve hedefe yönelik önleyici tedbirler uygulanmıştır. Önleyici faaliyetlerin uygulanmasının ardından yapılan analizler, önceki duruma kıyasla belirlenen hatalarda önemli ölçüde azalma olduğunu ortaya koymuştur. Özellikle, kazıma hatasında %75, abraj hatasında %28,57 ve köşe yakma hatasında %59,82 oranında azalma tespit edilmiştir.

1. INTRODUCTION

Failure Mode and Effect Analysis (FMEA) is a systematic engineering methodology aimed at identifying, evaluating, and eliminating existing or potential failures, problems, and faults in systems, designs, processes, and services before they adversely affect customers. This analytical technique identifies known or potential problems in a process or product to formulate the preventive strategies [1]. In the textile industry, which encompasses a wide range of production systems designed to create a diverse array of textile products, the implications of customer dissatisfaction can be substantial, leading to increased production costs and compromised product quality. Consequently, many researchers have explored the application of FMEA as a means to enhance the overall quality of textile products and the production systems. FMEA can be classified into four distinct categories: system FMEA, design FMEA, process FMEA, and service FMEA. FMEA serves as a critical tool in proactively addressing potential failures through a comprehensive analysis of failure modes, their impacts, causes, and existing control measures, thereby contributing to improved quality in the textile sector.

The assessment of failure priorities in FMEA is grounded in three key components: occurrence, severity, and detectability. Occurrence (O) refers to the likelihood of a failure happening, rated on a scale from 1 to 10, where a higher score indicates a greater potential for occurrence. Severity (S) measures the impact of the failure mode, also rated from 1 to 10, with increased ratings corresponding to more critical risks associated with the failure. Detectability (D) is the ease with which a failure can be identified before it reaches the customer, on a scale of 1 to 10, where a higher score signifies a lower capability to detect the failure. The prioritization of identified problems is represented through Risk Priority Numbers (RPN). This numerical value is computed as the product of occurrence, severity, and detectability. The RPN itself serves primarily to rank the relative concerns associated with various systems, designs, products, processes, and services. It is important to note that the RPN should be interpreted within the context of prioritizing failure modes; it does not hold intrinsic significance beyond this ranking. Calculating the RPN (Eq. 1) involves multiplying the values assigned for severity, occurrence, and detectability [2,3].

$$RPN = S \times O \times D \tag{1}$$

If RPN <40, No need for preventive activity
If 40 <RPN<100, preventive activity is profitable.
If RPN>100, preventive activity must be implemented.

Several studies in the literature based on the application of Failure Modes and Effects Analysis (FMEA) in textile manufacturing processes. Yücel applied the FMEA method in a garment manufacturing company with the aim of minimizing sewing-related defects. During a four-week production period, defects observed in sewn products were identified and corresponding preventive actions were developed. Following the implementation, the defect rate in the jeans production line was reduced from 11.5% to 7.4%, while the defect rate in the shirt production line decreased from 12.9% to 7.7%. In addition, the average monthly time spent on reworking defective products was reduced from 2660.7 minutes to 1694.4 minutes [4]. Özyazgan and Engin conducted a FMEA-based analysis for a three-months period in a knitting factory to calculate the risk priority numbers (RPNs) of various failures. The findings indicated that the most critical failures were primarily associated with knitting machines. To mitigate these issues, the authors suggested improving workplace conditions, providing employee training, and reviewing machine maintenance procedures, settings, and software systems [5]. Similarly, Kaewsom and Rojanarowan utilized the FMEA technique in filament yarn production and decreased the defect rate from 3.35% to 1.76% [6]. In another study, Özyazgan applied FMEA to identify and eliminate failures occurring in woven fabric production. The results revealed that the major sources of defects were related to insufficiently trained weaving machine operators. Therefore, the study emphasized the importance of enhancing personnel training as a key preventive measure [7]. Sabır and Bebekli carried out a case study in a selected textile dyeing and finishing plant using the FMEA approach. Various types of defects occurring in the dyeing process were identified, and the most critical ones were selected based on their RPN values. For each critical defect, the root causes and necessary preventive actions were determined. Consequently, several improvement recommendations were proposed [8]. Küçük et al. examined the application of FMEA in a ready-to-wear manufacturing facility, focusing on spreading and cutting processes. Risk priority numbers were calculated for 18 different failures, and eight failure types with RPN values exceeding 100 were selected for further analysis. Preventive actions were then developed for these critical failures, leading to recommendations aimed at

improving process performance [9]. Nguyen et al. conducted a case study in a nonwoven manufacturing facility using an enhanced FMEA approach that incorporated quality cost factors and the detection capability of failure identification systems to determine the priority of each failure mode. The authors introduced an analytical model instead of conventional FMEA framework, The results obtained from this model highlighted the importance of routine inspection and maintenance of machine components as key preventive measures. According to the findings, the defect rate of 2.41% was reduced to 1.13% using the proposed method [10]. Ünal and Acar applied the FMEA method to examine defects occurring in the quality control department of a denim outerwear manufacturing plant. Risk Priority Numbers were calculated for the identified failure modes, and preventive actions were defined with the aim of lowering the RPN values and improving overall quality performance [11]. In another study, Pazireh et al. utilized FMEA to develop and implement a quality control system for T-shirt production lines. The method was used to identify and rank potential defects and to provide appropriate operational guidelines for quality control stations. RPN values were calculated for each station, and production lines were monitored based on these values as a preventive strategy. The efficiency of the system before and after FMEA implementation was evaluated through simulation software. In the optimization model, inspection rates at each station and the overall defect percentage were defined as decision variables and objective functions. The results indicated that FMEA significantly improved the allocation of inspection activities across stations and led to a substantial decrease in defective products [12]. Beyene et al. focused on minimizing excessive machine downtime in a weaving factory by analyzing its root causes and their impact on production losses. The application of FMEA in the weaving process revealed that daily downtime could be reduced by approximately 299.04 hours for a total of 178 looms through appropriate corrective and preventive measures [13]. Temel et al. investigated failures in a textile dyeing plant using the FMEA technique and determined the RPN values of the identified failure modes. Their analysis showed that the most critical failures occurred in HT fabric dyeing, centrifuge, and drying units. As a result, improved machine maintenance practices were recommended as the primary preventive action [14]. Mutlu and Altuntaş proposed an integrated methodology combining FMEA and Fault Tree Analysis (FTA) to evaluate failures in a ring spinning production system. The analysis classified 22.80% of failures as unacceptable, 15.78% as high risk, 28.07% as moderate, and 37.35% as acceptable. Based on these findings, the authors recommended the implementation of productive maintenance strategies to eliminate machine-related failures in ring-spun yarn production [15]. Similarly, Fithri et al. applied FMEA to reduce defect levels in woven fabric manufacturing. Failure modes were assessed using RPN values, and several preventive actions were suggested, including the development of Standard Operating Procedures (SOP), the use of machine inspection forms for maintenance activities, operator training programs, and improved coordination with the spinning department regarding raw material quality [16]. Eren and Pamuk examined the application of FMEA in a ready-to-wear apparel manufacturing facility. The study identified that the highest RPN values were associated with insufficient technical expertise among customer service personnel, poor interdepartmental communication, and incomplete information flow. Following the implementation of corrective measures, the RPN values for 12 out of 13 identified failure factors were reduced to below 40 [17]. Cardiel-Ortega and Baeza-Serrato applied the FMEA method in a knitting factory producing children's garments to identify fault types and their effects. RPN values were calculated for six predefined failure modes, and the analysis resulted in a comprehensive report that supported the development of preventive action plans for knitting machines, corrective actions for high-priority failures, and a structured implementation strategy [18].

It can be seen from the literature that, the studies generally focused on FMEA technique to merely determine the most severe failures. Additionally, some of them provided suggestions for preventive activities. Among the textile focused FMEA implementation studies only a few of them compares the situation after application of preventive activities. So, in the literature there is a lack of information about the real time effects of FMEA application on in textile production lines. Additionally, visible carpet failures are generally disturbing, cannot be tolerated and the disposal of the low-quality carpet is an important problem due to high mass. In this study, current failures in carpet production were detected and the most severe failures were determined. For this aim, occurrence, severity, detectability and PRN values of the current failures were obtained by using FMEA technique. The effects of failures were assessed and the causes of these failures were reviewed. By this way, possible preventive activities were emerged and the proper preventive activities were initiated for the carpet production mill. Then, preventive activities were implemented. Differently from the previous studies, after implementation of preventive activities, RPN values were reassessed to determine the real time effects of FMEA. Also, real time reduction of failure carpet product was determined for each failure type by using the production rates of the carpet production mill.

2. MATERIAL AND METHOD

This study focuses on identifying the most critical failure modes in a carpet manufacturing facility through the application of the Failure Modes and Effects Analysis (FMEA) method and on developing actions to minimize these failures. To achieve this objective, a multidisciplinary team was established to carry out the FMEA procedure. The team systematically identified the failure modes across the carpet production process and evaluated their possible effects and root causes. For each failure mode, severity, occurrence, and detection scores were assigned, and the corresponding Risk Priority Numbers (RPN) were calculated based on the product of these factors. Preventive measures were formulated and implemented for failure modes with RPN values exceeding 100. Following the implementation, the effectiveness of these measures was assessed through a three-month monitoring period, after which the RPN values were recalculated to evaluate improvements. FMEA process flow chart is given in Figure 1.

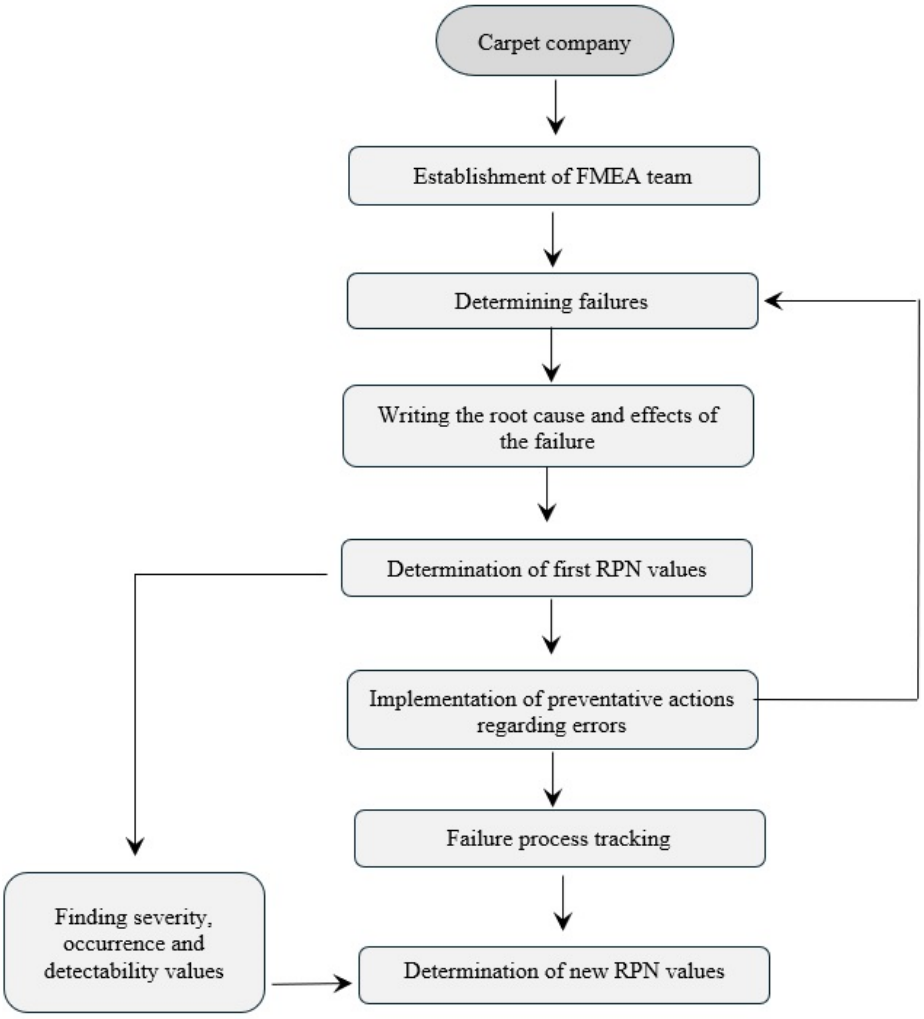

Figure 1. FMEA flow diagram

Studies have been carried out to reduce the most common faults in the carpet company. Using the failure modes and effects analysis, occurrence, severity, detectability rankings for every failure type are determined by the FMEA team. Then, the RPN value was obtained by multiplying occurrence (O), severity (S), detectability (D) values. The FMEA team consists of 5 people. The FMEA team members are the employees who have experience about production. FMEA Team Members are assistant production manager, machinist, garment master, quality control manager, textile engineer. Based on quality control records and previous experience, a list of failures that occur in the carpet company was created. The values mentioned are given in Table 1. According to this list, preventive actions should be determined for faults with a risk priority number of 100 and higher.

Table 1. FMEA failure RPN chart of case study [19]

Failure Modes	Severity	Occurrence	Detectability	RPN
Scrape	9	8	5	360
Abrage	8	7	2	112
Pile space	6	5	3	90
Excessive yarn on carpet back	5	6	3	90
Cross-line pile creation of all colors	8	3	4	96
The rippling of the carpet	8	5	2	80
Knife burn	8	5	2	80
Knife mark	8	5	2	80
Platin mark	7	3	3	63
Imbalance pile	3	4	5	60
Transverse gap on carpet back	6	5	2	60
Ground breakage	8	2	3	48
Foaming	6	4	2	48
Improper Corner Burning	7	8	4	224
Unacceptable repair	6	5	3	90
Yarn residue	6	5	3	90
Crossness	6	5	3	90
Improper winding	5	2	7	70
Damaged packaging	8	4	3	96
Curvature in length cutting	7	6	2	84
Glue leakage	9	3	2	54
Design failure	7	4	3	84
Sending missing carpet	6	5	3	90
Sending wrong order	9	2	3	54
Inappropriate yarn on the loom	7	3	4	84

After the RPN values had been calculated, the FMEA team selected the failure modes with RPN values exceeding 100 for further analysis. Among these, the most critical failure was identified as scrape, with an RPN of 360. This was followed by corner burning and abrage, which had RPN values of 224 and 112, respectively. Because of these three failure modes exhibited the highest risk levels, the implementation study was concentrated on the determined failures. The FMEA methodology was then applied to reduce the occurrence and impact of these failures. Through structured brainstorming sessions, the FMEA team examined the effects and root causes of each determined failure mode. Based on this analysis, appropriate preventive measures and corrective actions were developed and implemented. Analysis for the determined failure modes are illustrated in Table 2.

Table 2. Effects, root-cause, severity, occurrence, detectability and RPN values of the selected failures [19]

Failure modes	Effects of the failure	S	Root-cause (Potential causes of the failure)	O	Current controls	D	RPN
Scrape	The collapse of the carpet backing and imbalanced stretch of pile yarns on carpet surface resulting in irregular pile texture.	9	Entanglement of pile yarns coming from the creel, Improper setting of the distance between faceto face carpets due to lack of lancets, Careless weaving operators, High rate of creel loading, Feeding the pile yarn from the creel as improper bundle form	8	Weaving quality control form / Visual	5	360
Corner Burning	Customer dissatisfaction and complaints due to unraveling of the carpet edges.	7	Improper secure of the sewing threads as a result of not burning the excess threads in the corners after sewing. Inability to make small sizes due to increased workload.	8	Finished product control form	4	224
Abrage	Color differences on the carpet surface	8	Using the same color of pile yarns with different lot numbers which have different color intensity Irregular tension between the pile yarn bobbins and within the yarn on the bobbin itself	7	Pile yarn input control form Creel change form	2	112

Following the detailed evaluation of failure modes, their effects, and root causes by the FMEA team, appropriate preventive actions were systematically identified for each failure type.

Preventive Actions for Scrape Failure

- Periodic inspection of the creel. In addition, particular attention should be given to the drawing-in operation, which involves threading warp yarns through the heald eyes and reed dents in accordance with predefined rules.
- Installation of lancets on weaving machines to improve operational stability.
- Implementation of targeted training programs for weaving loom operators.
- Minimization of the bobbin splitting process in polyester yarn production to reduce defect formation.

Preventive Actions for Corner Burning Failure

- Providing regular training sessions to enhance employee awareness and skill levels.
- Positioning visual instruction boards near machines, illustrating acceptable and unacceptable tip burning conditions to support correct practices.
- Applying job rotation strategies, particularly for small batch production orders, to reduce operator-related errors.

Preventive Actions for Abrage Failure

- Conducting comprehensive inspections of incoming yarns from suppliers using light cabinets and testing equipment for strength, elongation, and twist in the yarn laboratory. All test results should be documented using a pile yarn input control form, and only yarns approved by the laboratory supervisor should be forwarded to the weaving department.
- Verifying the label information inside bobbins mounted on the creel, with inspections carried out jointly by weaving operators and quality control personnel.
- Ensuring that creel change forms are properly completed and that creel inspections are consistently performed by both the weaving operators and the quality control unit [19].

3. THE RESEARCH FINDINGS

3.1. Scrape Failure

Scrape is a failure characterized by the collapse of the carpet backing and the stretching of pile yarns onto the carpet surface, as illustrated in Figure 2.

Figure 2. Photographic view of scrape failure [19]

This failure was primarily observed in three-rapier looms that lacked lancet equipment. In such cases, the narrowing gap between two adjacent carpets caused the cutting knife to penetrate the fabric, leading to the formation of the scrape defect. To prevent this issue, a modification was carried out on the carpet weaving machines by converting the looms from a three-rapier configuration to a two-rapier system. This preventive activity was not applied the entire facility. In order to detect the effect of this preventive activity specifically, only three weaving looms were modified. Table 3 presents a comparison of scrape defect quantities recorded before and after the implementation of this FMEA-based preventive action.

Table 3. Amounts defective products due to scrape failure before and after the preventive actions

	Before preventive actions	After preventive actions
Amount of total defective production in total production	5.07 %	0.49 %
Amount of scrape defective production to total defective production	43.90 %	40.23 %

As indicated in Table 3, prior to the implementation of preventive actions, defective products accounted for 5.07% of the total output of the carpet manufacturing plant. Following the application of preventive actions targeting three major failure modes, this proportion decreased significantly to 0.49%. This improvement is attributed to the substantial reduction in scrape-related defects, which had previously been identified as the most critical failure type. Before the FMEA implementation, scrape defects constituted 43.90% of all recorded failures, while after the preventive actions this amount decreased to 40.23%. This slight decrease can be explained by the fact that machine modifications had not yet been completed across the entire facility. Therefore, it was concluded that further revisions of carpet weaving looms should be considered essential for achieving sustained improvements in overall product quality and for effectively addressing scrape failures. It is anticipated that once the planned weaving loom upgrades are fully implemented, the occurrence of scrape defects in total production will become negligible [19].

3.2. Corner Burning Failure

Corner burning refers to the operation in which loose yarns at the edges of carpets are secured using a controlled flame. When this process is performed incorrectly, the carpet edges may begin to unravel during use, leading to customer dissatisfaction and subsequent complaints. A corner burning defect photographic view is illustrated in Figure 3.

Figure 3. Photographic view of corner burning failure [19]

As a preventive action, a training program was introduced to improve employee understanding of proper corner burning practices. Employee awareness was further reinforced by placing visual panels on the machines that displayed examples of acceptable and unacceptable applications. Table 4 presents a comparison of corner burning defect quantities recorded before and after the implementation of these FMEA-based preventive actions.

Table 4. Amounts defective products due to corner burning failure before and after the preventive actions

	Before preventive actions	After preventive actions
Amount of total defective production in total production	5.07 %	0.49 %
Amount of corner burning defective production to total defective production	9.90 %	3.15 %

The results indicate that the occurrence of this defect was reduced by approximately 66% compared to the initial level, which can be regarded as a significant improvement.

3.3. Abrage Failure

Abrage failure arise from uneven yarn tension, which leads to visible color variations in the carpet surface. A representative photographic image of this defect is given in Figure 4.

Figure 4. Photographic view of abrage failure

To address this issue, additional testing equipment was acquired for the yarn laboratory as part of the preventive actions. Incoming yarns are now subjected to systematic inspection and testing, and all measurement results are documented. Only yarns that receive laboratory approval are released to the weaving department. Furthermore, during creel replacement procedures, the quality control unit verifies and records the accuracy of bobbin placement and creel sequence to prevent mismatches. Table 5 is given for comparison of abrage failure defective product amounts observed before and after the implementation of FMEA-based preventive actions.

Table 5. Amounts defective products due to Abrage failure before and after the preventive actions

	Before preventive actions	After preventive actions
Amount of total defective production in total production	5.07 %	0.49 %
Amount of abrage defective production to total defective production	14.78 %	13.70 %

The findings indicate that abrage-related defects decreased by approximately 8%, suggesting that further or alternative preventive strategies may be required to achieve more substantial improvement.

3.4. Changes in RPN Values of Selected Failures

Table 6 provides a comparative understanding for severity, occurrence, detectability and RPN values before and after implementation of preventive actions for each predetermined failure mode.

Table 6. RPN values for selected failures before and after preventive actions

Failure mode	Before preventive actions				After preventive actions				Change in RPN, %
	S	O	D	RPN	S	O	D	RPN	
Scrape	9	8	5	360	9	5	2	90	75
Corner burning	7	8	4	224	7	5	3	90	59.82
Abrage	8	7	2	112	8	5	2	80	28.57

Prior to the implementation of the FMEA study, the RPN for the scrape defect was calculated as 360. Following loom modifications, particularly the installation of lancets, a notable reduction in scrape-related failure was achieved. As a result, the RPN value declined to 90, corresponding to a 75% improvement. In the case of corner burning failure, the RPN value was reduced from 224 to 90, indicating a success rate of approximately 59.82%. For the abrage defect, the initial RPN was determined to be 112, which decreased to 80 after the application of FMEA-based preventive actions, yielding a reduction of 28.57%. Based on the outcomes observed in the weaving and post-weaving processes, it can be inferred that the primary contributors to these failures are related to existing loom configurations and insufficient employee awareness.

4. RESULTS

Failure Modes and Effects Analysis (FMEA) is a widely used quantitative method aimed at enhancing product quality and improving customer satisfaction by identifying and eliminating potential failures before they occur. In this study, FMEA was applied in a carpet manufacturing company to systematically analyze existing defects and their root causes through structured discussions conducted by a dedicated FMEA team. For this purpose, the production system was examined across the yarn laboratory, weaving, and finished product departments, and the root causes of the observed failures were identified.

The analysis focused on three core production departments where manufacturing activities are concentrated. Within these departments, failure modes with the highest RPN were identified in collaboration with the FMEA team, and targeted preventive actions were implemented accordingly. Examination of the failure sources revealed that issues such as loom configuration and insufficient operator awareness were among the primary contributors to defects. To address scrape-related failures, loom adjustments were carried out by installing lancets and converting three of carpet weaving looms from a three-rapier system to a two-rapier configuration in line with the established revision plan. To mitigate abrage defects, incoming yarns supplied to the facility were subjected to systematic testing and documentation using a pile yarn input control form, and only approved yarns were released to the weaving department. Additionally, creel arrangements were monitored through creel change forms to ensure correct yarn placement.

For corner burning defects, employee training and awareness initiatives were strengthened by installing visual instruction boards near the machines, illustrating correct and incorrect burning practices. As a result of the FMEA-based improvements, reductions of 75% in scrape defects, 28.57% in abrage defects, and 59.82% in corner burning defects were achieved. These improvements are expected to enhance the company's competitive position and reputation by lowering defect rates, improving product quality, reducing operational costs, ensuring timely and problem-free product delivery, and ultimately increasing customer satisfaction [19].

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