Effectiveness of Failure Mode and Effect Analysis (FMEA) Method: An Application in a Mattress Factory

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Industrial Engineering

Eastern Mediterranean University
February 2022
Gazimağusa, North Cyprus

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ABSTRACT

In today's competitive environment companies use a variety of quality control methods to increase product quality and transparency, but selecting methods that are consistent with their principles may put additional power for sustainable development and profit.

FMEA is one of the easiest and effective risk assessment method that aims to eliminate or prevent the errors and failures which may occur in the future. This method can be very effective when combining with different efficiency measurement methods.

In this research FMEA is implemented to Bonnell-spring orthopedic mattress production factory to identify potential failure modes and find recommended solutions to increase customer satisfaction and construct a better workplace. Numerous calculations applied in order to arrange different failure modes and calculate their efficiencies using Data Envelopment Analysis (DEA) method. It has been found that the FMEA itself can be insufficient as using aggregated FMEA and calculating the efficiency by DEA changed the importance of some failures. DEA based FMEA was the first corresponding research related to mattress production industry.

Keywords: FMEA, DEA, DEA based FMEA

ÖZ

Günümüz rekabet ortamında şirketler ürün kalitesini ve şeffaflığını artırmak için çeşitli kalite kontrol yöntemleri kullanır, ancak ilkeleriyle tutarlı yöntemlerin seçilmesi, sürdürülebilir kalkınma ve kâr için ek güç sağlayabilir.

Hata Türleri ve Etkileri Analizi, mevcut durumda göze rahatlıkla çarpmayan ancak gelecekte oluşabilecek hataları ortadan kaldırmayı amaçlayan bir kalite kontrol yöntemidir. Bu yöntem, farklı verimlilik ölçüm yöntemleri ile birleştirildiğinde çok etkili olabilir.

Bu araştırmada, olası arıza türlerini belirlemek ve müşteri memnuniyetini artırmak ve daha iyi bir işyeri inşa etmek ve önerilen çözümler bulmak için bir bonel yaylı ortopedik yatak üretim fabrikasında HTEA uygulanmıştır. Veri Zarflama Analizi (VZA) kullanılarak farklı hata türlerinin verimliliklerini hesaplamakla beraber uygulama içerisinde çok sayıda hesaplama yapılmıştır. Çalışma sonucunda HTEA-nın tekbaşına yeterli olmadığı ve VZA uygulamasının hataların verimliliğini değiştirdiği saptanmıştır. VZA bazlı HTEA, yatak üretim endüstrisi ile alakalı ilk araştırmadır.

Anahtar Kelimeler: FMEA, DEA, DEA based FMEA

ACKNOWLEDGEMENT

I would like to thank my supervisor Assoc. Prof. Dr. Sahand Daneshvar, who did not hesitate to support me during the execution of this study with his soft explanations helped me to not stress myself throughout the study.

Thanks to Birol Turhan for the excellent working environment provided for me whenever I wanted and all the BRT CLASS workers for showing patience and enduring me during my hard work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AGD	Aggregated Detection
AGO	Aggregated Occurrence
AGRPN	Aggregated Risk Priority Number
AGS	Aggregated Severity
CRS	Constant Returns to Scale
DMU	Decision Making Unit
DRS	Decreasing Returns to Scale
e_c	Input vector
IRS	Increasing Returns to Scale
MIL-P	Military Specification for Planned Maintenance
NASA	National Aeronautics and Space Administration
OECD	Organization for Economic Co-operation and Development
P	Priority
P_e	Efficiency Priority
PPS	Production Possibility Set
P_r	Risk Priority
RTS	Returns to Scale
SFM	Sub Failure Mode
VRS	Variable Returns to Scale
z_d	Output vector

Chapter 1

INTRODUCTION

1.1 Initial information

Products used in the world today result from human labor after a certain production process. Since the products result from human labor, they may have various defects or shortcomings, which may cause dissatisfaction of the customer who buys the product. This is one of the serious problems of today, which leads to the unreliability of the enterprise. Therefore, businesses need to consider customer satisfaction to both improve and increase production. Of course, they must add the risks that may occur during production to the major problems, but still, all the risks can lead to untimely delivery of the product to the buyer. Therefore, enterprises use various qualitative and quantitative methods to further improve the production process.

The mattress industry is one of the rapidly growing industries in the world. As people's health comes to the fore, so does the production of mattresses is being more attention requiring by manufacturers to stabilize their business. A mattress is a large pad for supporting a lying person. It is designed to be used as a bed with or without a bed frame. Mattresses consist of a quilted case, usually of heavy fabric, containing materials such as wadding, buckram, foam rubber, or a framework of metal springs.

Figure 1: Layers of Orthopedic Innerspring Mattress

1.2 Problem definition

Mattress production involves mixed processes, even if it looks very ordinary for most people. Mattress manufacturers encounter various problems during production. There may be different internal and external reasons for customer dissatisfactions or process failures that can seriously reduce the quality of work. For example, if the memory foam will be too soft, it can cause to loss of correct spinal alignment by sinking into the mattress. This does not mean that the situation is better when the foam is hard, but an additional problem arises, which is the lack of thermal conductivity of the mattress preventing comfortable sleep. To overcome such problems, it is necessary to identify the types of failures in mattress production and find suitable solutions.

There are countless studies in the literature about mattresses. Most of them are related to the optimization of the mattress production line and ergonomic assessments of orthopedic mattresses. Other studies were interested in the effect of firmness of mattress on back pain, also consisting researches related to the impact of the carbon footprint that mattresses cause(Colditz, Joy, & Dunster, 2002). The cost-oriented

FMEA method was also used for improvement in cost management, reducing costs occurring because of failures(Meril Baby, 2014).

In this study, the failures of mattress production in an orthopedic mattress factory were discovered, comprehensively addressing all risky processes, including failures of the facility plan. Potential sources and the effects of each of these failures laid out in addition with help of individual expert opinions to calculate and rank the RPNs.

DEA method was applied to measure the effectiveness of the FMEA method, which was shown which failure mode should be considered more seriously.

1.3 Significance of study

Advantages of this study:

- ❖ Satisfying expert knowledge about the issue
- ❖ Average severity, occurrence and detection ratings of each failure mode
- ❖ Taking advantage of operator experience
- ❖ Suggesting recommended risk reduction activities for a better RPN

Disadvantages of this study:

- ❖ Requires serious attention on rating (FMEA doesn’t like mistakes)
- ❖ Missed failure modes
- ❖ Disinformation

1.4 Thesis design

This thesis will be disunited into five different chapters, the first chapter will cover general information and the importance of the research, the second chapter will consist of information about FMEA and DEA methods and past corresponding researches, the third section will cover research methodology including information about conducting

FMEA and DEA for the recent study, the fourth section will include analyzed research results consisting FMEA and DEA tables and the last chapter will be conclusion part including discussion and future study.

The scheme of this study is shown below:

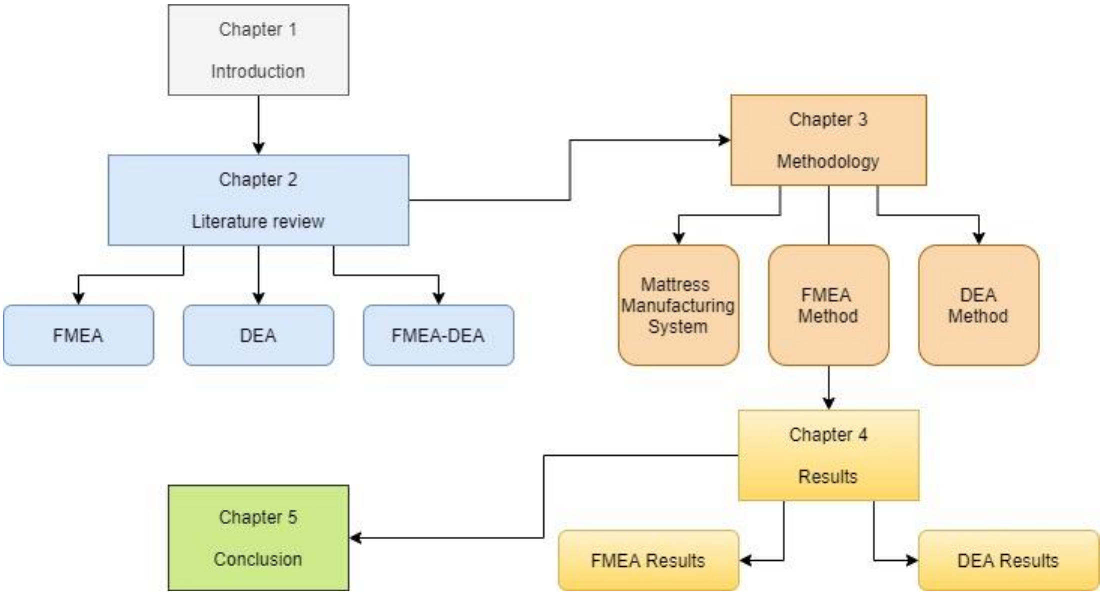

Figure 2: Thesis scheme

Chapter 2

LITERATURE REVIEW

2.1 Review of FMEA

FMEA is a systematic, proactive process assessment method for determining where and how it might fail, and for assessing the relative impact of different failures to identify the parts of the process that most need change.

FMEA method implemented in different areas, such as construction projects, safety ship operations, mine facilities, automotive industry, hospitals, pharmaceutical logistics industry, textile industry, including manufacturing sectors, and so on.

Many types of research focused on implementing FMEA to different sectors, pairing it with additional tools while some of them put new theories about improving the efficiency of the method.

A table was constructed consisting of a group of papers and publications related to FMEA and its implementation in different areas:

Table 1: Review of FMEA

	Publication Year	Topic	Author	Summary
1	2000	Software FMEA techniques(Goddard, 2000)	P.L. Goddard	Software FMEA is used for embedded automotive platforms to minimize the cost of critical designs(Goddard, 2000)
2	2001	"Failure mode and effects analysis using grey theory"(C. L. Chang, Liu, & Wei, 2001)	Ching-Liang Chang, Ping-Hung Liu, Chiu-Chi Wei	Grey theory applied to FMEA, and it successfully detected several undetected failures in process steps(C. L. Chang et al., 2001)
3	2002	"Fuzzy assessment of FMEA for engine systems"(Xu, Tang, Xie, Ho, & Zhu, 2002)	K Xu, LC Tang, M Xie, SL Ho, ML Zhu	The fuzzy expert assessment was implemented to solve sharing of wrong information among experts from various sectors (Xu et al., 2002)
4	2002	"FMEA methodology design, implementation, and integration with HACCP system in a food company"(Scipioni, Saccarola, Centazzo, & Arena, 2002)	Antonio Scipioni, Giovanni Saccarola, Angela Centazzo, Francesca Arena	FMEA integrated with the HACCP system for improving the production cycle in a food company and the generated data can be useful. (Scipioni et al., 2002)
5	2003	"Using failure mode and effects analysis to improve patient safety"(Spath, 2003)	Patrice L. Spath	FMEA is used with a multiple-choice questionnaire to improve patient safety. Patient feedbacks helped to construct a systematic approach. (Spath, 2003)
6	2006	"Implementing FMEA in a collaborative supply chain environment"(Teng, Ho, Shumar, & Liu, 2006)	S. Gary Teng, S. Michael Ho, Debra Shumar, Paul C. Liu	Research has been done in a collaborative environment. This research will help companies to conduct FMEA in a collaborative supply chain environment. (Teng et al., 2006)
7	2008	"Development of a fuzzy FMEA based product design system"(Chin, Chan, & Yang, 2008)	Kwai-Sang Chin, Allen Chan, Jian-Bo Yang	A framework of a fuzzy FMEA helped to enhance the robustness of the production scheme by helping inexperienced users to perform quality improvements. (Chin et al., 2008)
8	2008	Failure mode and effects analysis (FMEA) in the context of risk management in new product development: A case study in an automotive company(Segismundo & Miguel, 2008)	André Segismundo, Paulo Augusto Cauchick Miguel	This study seeks to propose a systematization of risk management using the FMEA method to optimize the decision-making process in new product development (NPD). (Segismundo & Miguel, 2008)

	Publication Year	Topic	Author	Summary
9	2009	"An alternative evaluation of FMEA: Fuzzy ART algorithm"(Keskin & Özkan, 2009)	Gülşen Aydın Keskin, Coşkun Özkan	FMEA method is used to make the correct decision based on the fuzzy Adaptive Resonance Theory (ART) algorithm to improve the correctness of clustering problems in artificial neural networks. (Keskin & Özkan, 2009)
10	2009	"FMEA: A model for reducing medical errors"(Chiozza & Ponzetti, 2009)	Maria Laura Chiozzaa, Clemente Ponzettib	FMEA technique applied in laboratory medicine. Acceptable reduction of the risk priority number (RPN) was obtained after applying FMEA to various testing procedures.(Chiozza & Ponzetti, 2009)
11	2011	"Risk analysis method: FMEA/FMECA in the organizations"(Lipol & Haq, 2011)	Lefayet Sultan Lipol, Jahirul Haq	Each method implemented and measured their efficiency to help companies to select the right production plan.(Lipol & Haq, 2011)
12	2011	"Application and improvement study on FMEA in the process of military equipment maintenance"(Li, Kang, Ma, & Li, 2011)	Yanliang Li, Rui Kang, Lin Ma, Lei Li	Analyzes equipment maintenance and investigates faults of military equipment. Research explores MP-FMEA to verify the sensitiveness of the method. (Li et al., 2011)
13	2012	"Applying of Method FMEA (Failure Mode and Effects Analysis) in the Logistics Process"(Šolc, 2012)	Marek Šolc	This research aims to develop a production process by solving low storage flexibility and unbalanced material handling. (Šolc, 2012)
14	2013	"Fuzzy FMEA application to improve purchasing process in a public hospital"(Kumru & Kumru, 2013)	Mesut Kumru, Pınar Yıldız Kumru	The fuzzy logic approach preferred to remove inaccurate numbering to improve purchasing system. (Kumru & Kumru, 2013)
15	2014	"A Case Study: A Process FMEA Tool to Enhance Quality and Efficiency of Manufacturing Industry"(Parsana & Patel, 2014)	Tejaskumar S. Parsana and Mihir T. Patel	FMEA method used to manage risks while manufacturing cylinder heads. (Parsana & Patel, 2014)
16	2015	"An application of failure mode and effect analysis (FMEA) to assess risks in the petrochemical industry in Iran"(Kangavari, Salimi, Nourian, & Askarian, 2015)	Mehdi Kangavari, Sajad Salimi, Rohallah Nourian, Leila omidi, Alireza Askarian	FMEA method combined with brainstorming techniques to plan correct failures in the welding process. Aggregated RPN for the welding process decreased from 120 to 96 after necessary acts. (Kangavari et al., 2015)

	Publication Year	Topic	Author	Summary
17	2016	“Applying UGF Concept to Enhance the Assessment Capability of FMEA”(Akbarzade Khorshidi, Gunawan, & Ibrahim, 2016)	Hadi Akbarzade Khorshidi, Indra Gunawan, M. Yousef Ibrahim	Universal Generating Function (UGF) technique used to improve the efficiency of grading FMEA scores. (Akbarzade Khorshidi et al., 2016)
18	2017	“An extension to Fuzzy Developed Failure Mode and Effects Analysis (FDFMEA) application for aircraft landing system”(Yazdi, Daneshvar, & Setareh, 2017)	Mohammad Yazdi, Sahand Daneshvar, Hashem Setareh	Contributed to aircraft landing system to concentrate on its risks and to take necessary actions. Traditional and Fuzzy Developed FMEA techniques used and compared to achieve an effective result. (Yazdi et al., 2017)
19	2017	“Comprehensive risk management using fuzzy FMEA and MCDA techniques in highway construction projects”(Ahmadi, Behzadian, Ardeshir, & Kapelan, 2017)	Mohsen Ahmadi, Kourosh Behzadian, Abdollah Ardeshir, Zoran Kapelan	SED index combined with FMEA for a better result to successfully cope with risky events with minimal deviation. (Ahmadi et al., 2017)
20	2019	“Improving failure mode and effect analysis (FMEA) with consideration of uncertainty handling as an interactive approach”(Yazdi, 2019)	Mohammad Yazdi	Sensitivity analysis applied to analyze the effectiveness of RPN scores. Interactive fuzzy AHP and entropy methods are used to achieve better results. (Yazdi, 2019)
21	2020	“Automotive leaf spring design and manufacturing process improvement using failure mode and effects analysis (FMEA)”(Aized et al., 2020)	Tauseef Aized, Muhammad Ahmad, Muhammad Haris Jamal, Asif Mahmood, Syed Ubaid ur Rehman, Jagjit Singh Srai	Potential failures of automotive leaf spring manufacturing were found out using FMEA. Necessary computations were made for decreasing RPN numbers. (Aized et al., 2020)
22	2020	“Failure Mode and Effects Analysis (FMEA) for Immunogenicity of Therapeutic Proteins”(Chirmule, Khare, Khandekar, & Jawa, 2020)	Narendra Chirmule, Ravindra Khare, Atul Khandekar, Vibha Jawab	The multi-dimensional approach is used to verify potential risks of immunogenicity. FMEA is used for accurate measurements of drug development. (Chirmule et al., 2020)
23	2021	“Using QFD and FMEA to Improve Maintenance Effectiveness in a Petroleum Refinery”(Rahman, Said, Hassan, Yusoff, & Atmadyaya, 2021)	Fauzan Rahman, Mohamad Sazali Said, Azmi Hassan Mohd, Shahrizan Yusoff, Surya Atmadyaya	Quality Function Deployment (QFD) combined with FMEA to decrease maintenance and repair time. (Rahman et al., 2021)

2.2 Review of DEA

DEA is the main data analysis technique used to evaluate inter-unit activities. Researchers carry out different measurements to evaluate the performance of units in different fields, such as health, management, finance, manufacturing sectors.

Data Envelopment Analysis is mostly effective by combining it with other decision-making techniques. This is the reason researchers focus on applying different methods to construct a better system to evaluate correct measurements. They enhanced and expanded types of DEA using distinct approaches, and collaborate DEA with other techniques.

The table below contains a list of articles in the literature using the DEA method:

Table 2: Review of DEA

	Publication Year	Topic	Author	Summary
1	2002	"On the Origins of Data Envelopment Analysis"(Førsund & Sarafoglou, 2002)	Finn R. Førsund, Nikias Sarafoglou	This research aims to provide forgotten development stages of DEA to the readers. Unexplored research ideas emphasized. (Førsund & Sarafoglou, 2002)
2	2003	"The efficiency of Australian universities: a data envelopment analysis"(Abbott & Doucouliagos, 2003)	Abbott, Malcolm, Chris Doucouliagos	Technical efficiency was analyzed in Australian universities using non-parametric techniques. Inputs and outputs mixed and found that there is balanced efficiency concerning the DEA model. (Abbott & Doucouliagos, 2003)

	Publication Year	Topic	Author	Summary
3	2004	“Measuring the economic inefficiency of Nepalese rice farms using data envelopment analysis”(Dhungana, Nuthall, & Nartea, 2004)	Basanta R. Dhungana, Peter L. Nuthall, Gilbert V. Nartea	Nepalese rice farmers work inefficiency calculated using the DEA method. It has been found that inefficiency is mostly related to their ages and genders. (Dhungana et al., 2004)
4	2005	“Interval efficiency assessment using data envelopment analysis”(Wang, Greatbanks, & Yang, 2005)	Ying-Ming Wang, Richard Greatbanks, Jian-Bo Yang	This research aims to conduct an interval efficiency assessment using DEA in a fuzzy input-output-oriented base. A minimax regret-based approach (MRA) is introduced to compare and rank the efficiency intervals of DMU(Wang et al., 2005)
5	2006	“Data envelopment analysis for weight derivation and aggregation in the analytic hierarchy process”(Ramanathan, 2006)	Ramakrishnan Ramanathan	AHP method is considered a key success for DEA in this research and the new method is called DEAHP, which does not suffer from various alternatives. (Ramanathan, 2006)
6	2011	“Improving weak efficiency frontiers in the fuzzy data envelopment analysis models”(Khoshfetrat & Daneshvar, 2011)	Sahar Khoshfetrat, Sahand Daneshvar	A new method was conducted to improve weak efficiency scores of DMUs by applying the fuzzy CCR model. (Khoshfetrat & Daneshvar, 2011)
7	2012	“Fuzzy data envelopment analysis: A discrete approach”(Emrouznejad & Mustafa, 2012)	Emrouznejad, Ali, Adli Mustafa	"local α-level" was introduced to develop new multi-aim programming to assess the efficiency of DMUs under uncertainty from the intervals of the α-cut approach. (Emrouznejad & Mustafa, 2012)
8	2013	“A Review of Ranking Models in Data Envelopment Analysis”(Hosseinzadeh Lotfi et al., 2013)	F. Hosseinzadeh Lotfi, G. R. Jahanshahloo, M. Khodabakhshi, M. Rostamy-Malkhlifeh, Z. Moghaddas, M. Vaez-Ghasemi	Applied different ranking methods and divided them into seven groups. The effectiveness of each ranking method is analyzed by putting them into an application.(Hosseinzadeh Lotfi et al., 2013)
9	2014	“A three-stage Data Envelopment Analysis model with application to the banking industry”(Ebrahimnejad, Tavana, Lotfi, Shahverdi, & Yousefpour, 2014)	Ali Ebrahimnejad, Madjid Tavana, Farhad Hosseinzadeh Lotfi, Reza Shahverdi, Mohamad Yousefpour	DEA model proposed with three stages. The first two stages are calculated parallel to pass into the third stage. Applicability was measured with a case study done in the banking industry to improve efficiency. (Ebrahimnejad et al., 2014)
10	2014	“COMPUTING THE BIENNIAL MALMQUIST INDEX USING MODIFIED VARIABLE RETURNS TO SCALE DEA MODEL” (DANESHVAR & IZBIRAK, 2014)	Sahand Daneshvar, Gokhan Izbirak	Malmquist productivity index calculated concerning output-oriented BCC and CCR models. Comparisons showed the model helped to stabilize the value of the Malmquist index after modifying the VRS frontier. (DANESHVAR & IZBIRAK, 2014)

	Publication Year	Topic	Author	Summary
11	2015	"A Data Envelopment Analysis Application for Measuring Efficiency of University Departments"(Gökşen, Doğan, & Özkarabacak, 2015)	Yılmaz Gökşen, Onur Doğan, Bilge Özkarabacak	DEA input-output-oriented models applied to solve inefficiency problems in the departments of Dokuz Eylul University. (Gökşen et al., 2015)
12	2016	"Evaluating and ranking sustainable suppliers by robust dynamic data envelopment analysis"(Yousefi, Shabanpour, Fisher, & Saen, 2016)	Saeed Yousefi, Hadi Shabanpour, Ron Fisher, Reza Farzipoor Saen	Dynamic decision-making unit (DIDMU) approach was introduced to rank sustainable suppliers. Dynamic DMU helped to overcome shortcomings. (Yousefi et al., 2016)
13	2016	"Enhanced data envelopment analysis for sustainability assessment: A novel methodology and application to electricity technologies"(Galán-Martín, Guillén-Gosálbez, Stamford, & Azapagic, 2016)	Ángel Galán Martín, Gonzalo Guillén Gosálbez, Laurence Stamford, Adisa Azapagic	Alternatives ranked according to sustainability reasons. Inefficient alternatives become more accurate after applying the method. (Galán-Martín et al., 2016)
14	2017	"A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency"(Mardani, Zavadskas, Streimikiene, Jusoh, & Khoshnoudi, 2017)	Abbas Mardani, Edmundas Kazimieras Zavadskasb, Dalia Streimikienec, Ahmad Jusoha, Masoumeh Khoshnoudia	This research aimed to review DEA techniques concerning differences in energy efficiencies. The results showed DEA helps to solve efficiency issues in most sectors. (Mardani et al., 2017)
15	2018	"Efficiency Analysis of Healthcare System in Lebanon Using Modified Data Envelopment Analysis"(Mustapha D Ibrahim & Daneshvar, 2018)	Mustapha D. Ibrahim, Sahand Daneshvar	Modified DEA model developed to check the efficiency of the healthcare system in Lebanon. Researchers found that there is a significant improvement in efficiency and the recent improvement will continue if the healthcare system reform will be maintained. (Mustapha D Ibrahim & Daneshvar, 2018)
16	2019	"An Estimation of the Efficiency and Productivity of Healthcare Systems in Sub Saharan Africa: Health Centred Millennium Development Goal-Based Evidence"(Mustapha D Ibrahim, Daneshvar, Hocaoğlu, & Oluseye, 2019)	Mustapha D. Ibrahim, Sahand Daneshvar, Mevhibe B. Hocaoğlu, Olasehinde Williams, G. Oluseye	The efficiency of the healthcare systems of SSA was calculated with DEA concerning data from 2010 to 2015. Variations in the efficiency of SSA healthcare systems were observed via implementing DEA methodology and it has been found that the healthcare system has inefficient measurements concerning corrupted governments. (Mustapha D Ibrahim, Daneshvar, et al., 2019)
17	2018	"Modified variable return to scale back-propagation neural network robust parameter optimization procedure for multi-quality processes model"(Daneshvar & Adesina, 2018)	Sahand Daneshvar, Kehinde Adewale Adesina	A modified VRS-BPNN robust optimization framework was proposed for optimizing multi-quality response systems. Optimum parameters settings were achieved effectively. The largest anticipated improvement is set up with the proposed model.(Daneshvar & Adesina, 2018)

	Publication Year	Topic	Author	Summary
18	2019	"Evaluating the sustainability of national logistics performance using Data Envelopment Analysis"(Rashidi & Cullinane, 2019)	Kamran Rashidi, Kevin Cullinane	Operational logistics performance of OECD nations evaluated using DEA approach, and a comparison made by Logistics Performance Index (LPI) measurement. (Rashidi & Cullinane, 2019)
19	2019	"Cost and Time Management Efficiency Assessment for Large Road Projects Using Data Envelopment Analysis"(Ahbab, Daneshvar, & Celik, 2019)	Changiz AHBAB, Sahand DANESHVAR, Tahir ÇELIK	This research filled the gap in the literature by conducting the DEA method referencing time and cost management issues in large construction projects and applying sensitivity analysis to examine causes of the poor management. (Ahbab et al., 2019)
20	2019	"Transnational resource generativity: Efficiency analysis and target setting of water, energy, land, and food nexus for OECD countries"(Mustapha D Ibrahim, Ferreira, Daneshvar, & Marques, 2019)	Mustapha D. Ibrahim, Diogo Cunha Ferreira, Sahand Daneshvar, Rui Cunha Marques	The corresponding research aims to analyze the efficiency of Water-Energy-Land-Food (WELF-Nexus) relief in OECD countries to check the reserves for the current and next generation. It has been found that correct policies will extend the WELF-Nexus sustainability. (Mustapha D Ibrahim, Ferreira, et al., 2019)
21	2020	"The origins, development, and future directions of the data envelopment analysis approach in transportation systems"(Mahmoudi, Emrouznejad, Shetab-Boushehri, & Hejazi, 2020)	Reza Mahmoudi, Ali Emrouznejad, Seyyed-Nader, Shetab-Boushehri, Seyed Reza Hejazia	Transportation systems applications are measured and classified using the DEA method. It has been found that DEA can help decision-makers to apply better transportation rules in a sustainable environment. (Mahmoudi et al., 2020)
22	2021	"Dual Efficiency and Productivity Analysis of Renewable Energy Alternatives of OECD Countries"(Kara, Ibrahim, & Daneshvar, 2021)	Sedef E Kara, Mustapha D Ibrahim, Sahand Daneshvar	The efficiency dimension of Renewable Energy was analyzed via the DEA method. Bioenergy, Hydro energy, and Wind energy had higher efficiencies than other energy sources. (Kara et al., 2021)
23	2020	"Target setting in data envelopment analysis: efficiency improvement models with predefined inputs/outputs"(Mustapha Daruwana Ibrahim, Daneshvar, Güden, & Vizvari, 2020)	Mustapha Daruwana Ibrahim, Sahand Daneshvar, Hüseyin Güden, Bela Vizvari	The efficiency of target setting measurements was analyzed by conducting CCR based DEA. Target setting helps managers to check the possibility of their desires.(Mustapha Daruwana Ibrahim et al., 2020)

2.3 Review of the FMEA-DEA synthesis

In this part, the techniques where the DEA approach was synthesized with the FMEA technique and several techniques was explored, like Grey Incidence Analysis, fuzzy FTA, exponential RPN, bounded approach; aircraft systems, manufacturing processes, and others. The table below contains research papers consisting combination of FMEA-DEA methods:

Table 3: Review of combination FMEA-DEA

	Publication Year	Topic	Author	Summary
1	2005	"A FUZZY DATA ENVELOPMENT ANALYSIS APPROACH FOR FMEA"(Garcia & Schirru, 2005)	P. A. A. GARCIA, R. SCHIRRU & P. F. FRUTUOSO E MELO	Some inference rules were bypassed. This study applied to PWR auxiliary feedwater system. DEA-APGF (profiling of severity efficiency) approach was implemented to compare the results.(Garcia & Schirru, 2005)
2	2007	"Application of FMEA-DEA (Failure Modes and Effect Analysis - Data Envelopment Analysis) to the air conditioning system of the control room of a nuclear power plant"(Barbosa & Gilberto, 2007)	Barbosa Junior, Gilberto Varanda	FMEA-DEA analysis applied to the nuclear power plant. The criticality of the failure modes analyzed with implementing DEA helping operators to manage efficient failure modes. (Barbosa & Gilberto, 2007)
3	2009	"Applying DEA to enhance assessment capability of FMEA"(D. S. Chang & Sun, 2009)	Dong-Shang Chang, Kuo-Lung Paul Sun	DEA applied to enhance the assessment capability of FMEA by exclusively investigating S, O, D levels to improve scale levels. (D. S. Chang & Sun, 2009)
4	2011	"Using Integrated FMEA-DEA Approach to Classify Purchasing Items Based on Kraljic's Model"(Arabzad & Ghorbani, 2011)	S. Mohammad Arabzad, Mazaher Ghorbani	This study was implemented in an aircraft manufacturing company to manage the supply environment using a combined FMEA-DEA approach. Supply bottleneck reduced and manufacturing power planned to be improved. (Arabzad & Ghorbani, 2011)

	Publication Year	Topic	Author	Summary
5	2012	“Failure Mode and Effects Analysis Using Data Envelopment Analysis”(HADI, Hejazi, Forghani, & Hejazi, 2012)	A. Hadi-Vencheh, S. Hejazi, A. Forghani, S. N. Hejazi	The bounded DEA model was proposed to measure the overall risk of the failure modes. (HADI et al., 2012)
6	2013	“Safety Risk Assessment in Mass Housing Projects Using Combination of Fuzzy FMEA, Fuzzy FTA, and AHP-DEA”(Ardeshir, Amiri, & Mohajeri, 2013)	A Ardeshir , M Amiri, M Mohajeri	This research was conducted in the construction industry to apply a safety risk assessment. It is approved that the methodology used in this research can help safety operators to identify and control the risks associated with the construction sector. (Ardeshir et al., 2013)
7	2014	“Developing a Method for Risk Analysis in Tile and Ceramic Industry Using Failure Mode and Effects Analysis by Data Envelopment Analysis”(Mirghafouri, Asadian Ardakani, & Azizi, 2014)	Seyyed Habibollah Mirghafouri, Faezeh Asadian Ardakani, Fatemeh Azizi	The fuzzy set theory was executed to evaluate S, O, D elements. The recommended suggestion was given to the company managers to execute necessary tasks. (Mirghafouri et al., 2014)
8	2016	“Integrated FMEA Approach for Supplier Selection Problem: The Case on Steel Manufacturing Company”(Parvez, Rakib, & Islam, 2016)	Nokib Parvez, Md. Golam Rakib, Sayed Islam	Analytic Hierarchy Process (AHP) and Fuzzy AHP are used effectively with the FMEA technique. The best supplier is selected from the supply chain sector. (Parvez et al., 2016)
9	2016	“Risk measurement and prioritization of auto parts manufacturing processes based on process failure analysis, interval data envelopment analysis, and grey relational analysis” (Baghery, Yousefi, & Rezaee, 2018)	Majid Bagheri, Samuel Yousefi, Mustafa Jahangoshai Rezaee	Failure modes of manufacturing auto parts delivered with PFMEA technique. Interval based DEA and GRA combined to extract the criticality ratio (Baghery et al., 2018)
10	2020	“Fuzzy smart failure modes and effects analysis to improve the safety performance of the system: A case study of an aircraft landing system”(Daneshvar, Yazdi, & Adesina, 2020)	Sahand Daneshvar, Mohammad Yazdi, Kehinde A. Adesina	A case study was conducted by retrieving information on aircraft landing system accidents reported by Iranian airlines. Multi-expert opinions were adopted to apply into AHP weighted model to evaluate the efficiency by using the DEA method. (Daneshvar et al., 2020)
11	2019	“Stock Evaluation under Mixed Uncertainties Using Robust DEA Model”(Peykani, Mohammadi, & Seyed Esmaeili, 2019)	Pejman Peykani, Emran Mohammadi, Fatemeh Sadat Seyed Esmaeili	Stock efficiency measurement made by applying DEA models without CRS and VRS with information gathered from Tehran Stock Exchange (TSE). It has been found that this methodology can be applied to the banking and finance sector. (Peykani et al., 2019)
12	2020	“Failure Modes and Effects Analysis (FMEA) Method Based on Data Envelopment Analysis (DEA) Approach for the Efficiency Measurement of Radio Frequency Identification (RFID)”(Chnina, 2020)	Khaoula Chnina	Failure modes of RFID system assessed by experts' knowledges. Weighted AHP technique and CCR based DEA method was implemented to verify the effectiveness of the failures. (Chnina, 2020)

Many papers reviewed so far related to implementing FMEA and DEA conducted in different areas or systems. Concerning the rich information database, a lot of potentially sufficient data has been retrieved to perform an FMEA assessment on our case study related to mattress production. According to our research it has been found that the FMEA technique was not used comprehensively to find and inspect the cause and effects of the mattress production process. In this study, failures of the mattress production system and environment was found mostly concerning the failures causing customer dissatisfactions.

The FMEA method was harmonized with other techniques to boost its accuracy, like DEA. In conclusion, our FMEA approach with averaged O, S, D values and implementing the DEA method will be the first corresponding research related to the mattress industry, and the DEA technique will measure the efficiency of the findings.

Chapter 3

METHODOLOGY

3.1 FMEA

3.1.1 A brief history of the FMEA

The first proper use of FMEAs was by the United States Military at the end of the 1940s. They reduced variation of the sources and corresponding potential mistakes in the production of munitions by developing this technique (MIL-P-1929) and it proved a highly desirable tool. NASA accepted the FMEA as an important project planning technique, as it was validated that failure of manufacturing risk was reduced by the use of FMEA. It is proven that FMEA brought engineers to the success of the Apollo (1963) mission, as NASA accredited the success of moon landings to the use of FMEA. NASA used FMEA to identify single-point failures on the Apollo (1963) mission. After a while, it was erupted by Aerospace (1965) and Nuclear (1975) industries.

Figure 3: Review of main FMEA history

In the 1970s, the Ford automobile company implemented FMEA in their auto design process to eliminate potential manufacturing errors. In February 1993, an alternative approach was formalized for FMEA by the American Society for Quality Control (ASQC) and the Automotive Industry Action Group (AIAG). They explained it as: The FMEA is a comprehensive technique to point out the possible failures and mark them before they arise, intending to eliminate them or minimize the coherent risks. Some frequently used FMEA standards include ARP5580(non-automobile applications), SAE J1739(design assessment for manufacturing and assembly processes), AIAG (automotive supply chain processes), and Military-Standard-1629A. FMEA has become the main requirement in the QS9000 standard in the automotive sector(En.wikipedia.org, 2019). The FMEA is a qualitative risk analysis tool used in many branches of industry and it can be implemented in almost any process and system to manage and correct risky actions.

3.1.2 Definition of FMEA

FMEA is a technique used to find and eliminate root causes based on potential errors that may occur before, after, and during the assembly, design, or manufacturing phase of any product or process. It improves operational performance and reduces the resulting risk level by analyzing all potential errors of the applied system. Now, FMEA is widely used not only in advanced technology fields such as nuclear energy, aviation, electronics, and automotive but also in many service sectors, such as health and tourism, as well as the production sector, software/hardware sector. FMEA is group work, and it needs expert knowledge to apply the methodological rules correctly.

FMEA can be memorized as a brainstorming risk assessment technique.

3.1.3 Types of FMEA

• System FMEA

The System FMEA concerns the whole system. It can also contain associated interaction failures between sub-systems, including interaction with the environment.

• Process FMEA (PFMEA)

The Process FMEA focuses on the failures associated with the manufacturing and assembly processes.

• Design FMEA (DFMEA)

In Design FMEA, the focus is on sub-system and component failures. It has also an interaction between components and sub-systems, additionally failures which consent interaction with the environment.

• Service FMEA

Service FMEA helps to eliminate wrong installation and operation of the process.

• Software FMEA

Software FMEA helps to improve the quality of the software products.

• Failure modes, effects, and criticality analysis (FMECA)

The only difference of FMECA is a calculation of RPN with exception of detection value, which can assess the criticality of the failure modes, respectively. In our research, the main associated design, process, and system failures of the mattress production were mostly concerned.

3.1.4 Sequence of FMEA

Before conducting an FMEA assessment, the corresponding process or system must be learned to apply the method in the right way. The FMEA method has 5 consecutive steps shown below:

1. Getting ready for failure analysis.

A. appointing the team members, discussing the detail of the analysis.

B. learning the functionality of the system and process, learning what can break down the system.

C. learning O, S, D scales.

D. constructing the FMEA table.

2. Analysis of failures of the system.

E. collective brainstorming and putting for all the failure modes of the components.

F. generating the causes of each failure mode.

G. defining the effects of failures.

3. Evaluation of the failures.

H. allocating occurrence rankings of each failure mode.

I. allocating severity rankings of failure modes.

J. allocating detection rankings of each failure.

K. calculation of RPN based on O, S, D points.

L. ranking all failures by an appropriate arrangement of the RPN marks.

M. showing RPN in matrix scheme.

N. checking the RPN value if it is below or more than the allowed value.

4. Finding necessary actions to optimize the risks.

O. recommending preventive, softener actions to decrease the potential risk value as much as possible considering each O, S, D value.

5. Executing and tracking recommended actions.

P. implementing the necessary action.

Q. monitoring and calculating the failure process for any improvements.

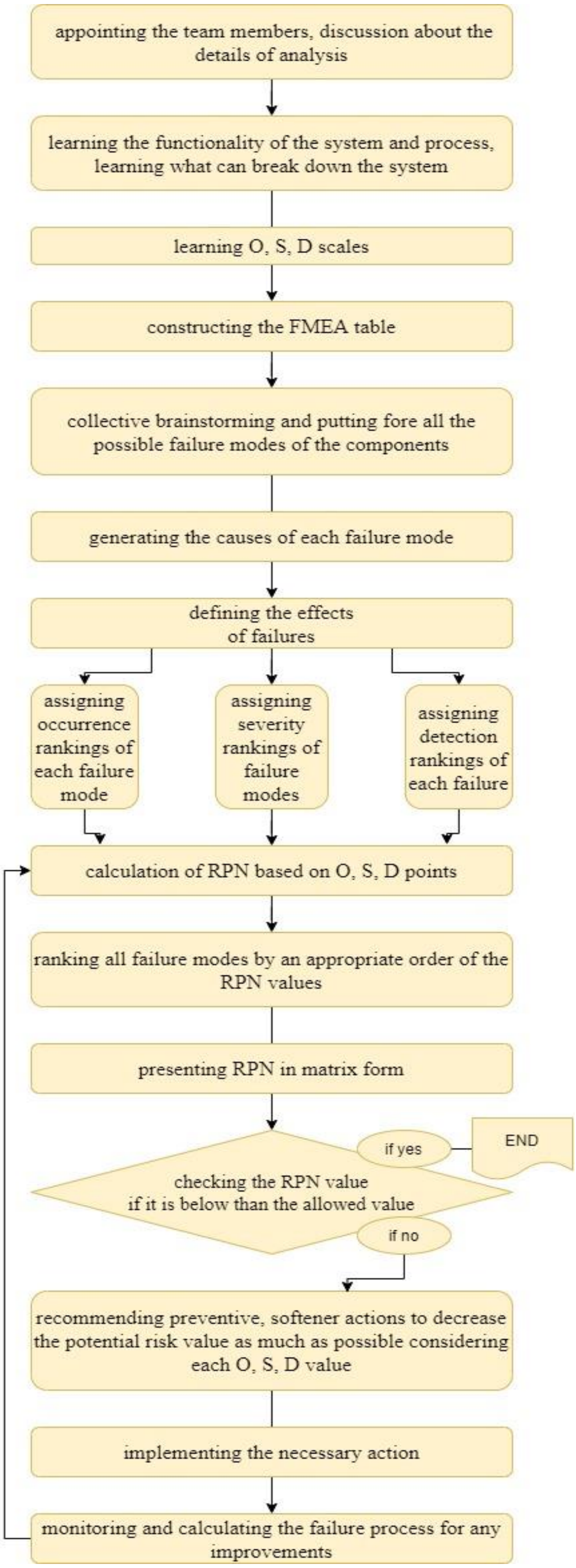

Figure 4: Steps of FMEA Method

3.1.5 Reason to perform Failure Modes and Effects Analysis

The sooner a failure is discovered, the cost of fixing it will not be heartbreaking. But if the failure is not discovered while on product development, the impact can be catastrophic. FMEA is a friendly tool helping us to discover failure mode at its early stages in product design. Discovering a failure before the manufacturing or processing of the product provides benefits of:

a) Multiple options to ease the risk
b) Reduced charge rate
c) A better combination of design and process of the product

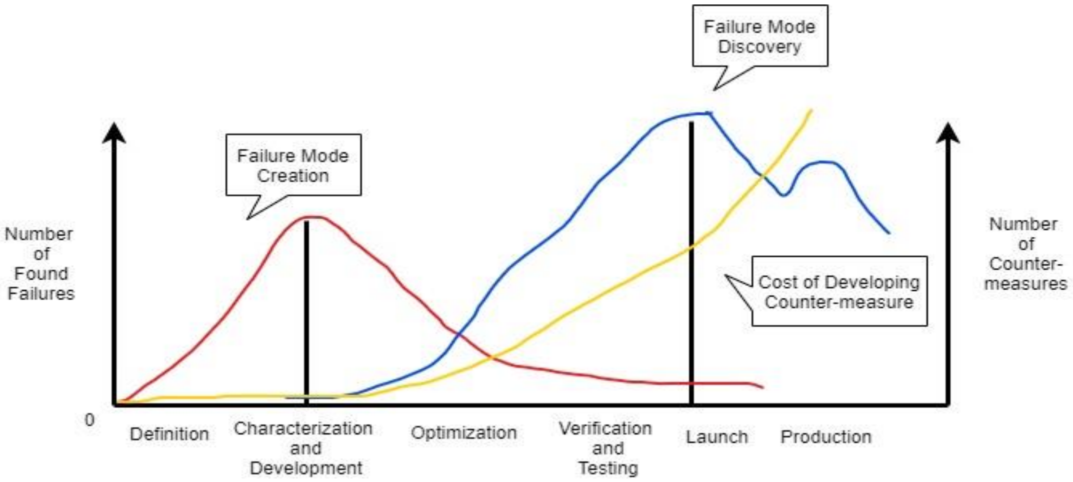

Figure 5: Late Failure Mode Discovery

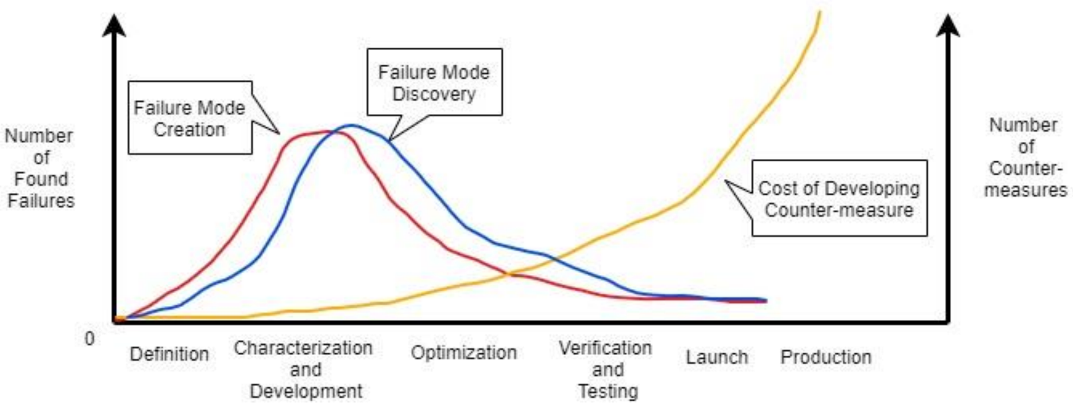

Figure 6: Early Failure Mode Discovery

3.1.6 Advantages and drawbacks of FMEA

Advantages:

- Provides better progress for system quality and safety
- Captures aggregated information of a team
- Minimizes the failures for the next applied process
- Efficiency of manufacturing increases
- Having a practical arrangement makes it easy to combine with different models

Drawbacks:

- Having less experienced team members
- The high expense of necessary actions
- System or process data must be learned strictly to apply the method correctly
- FMEA can’t solve problems directly
- The study may remain uncompleted
- It is a tiresome method to solve deep and complicated problems.

3.2 Data Envelopment Analysis (DEA)

3.2.1 Definition of DEA

Data envelopment analysis (DEA) is a distribution-free process in operations research and economics for the evaluation of production frontiers(A. Charnes, 1978). It is used to analytically evaluate the productivity of decision-making units (DMUs). Although DEA has a powerful connection to production theory in economics, the technique is also used for testing in operations management, where a set of countable values is selected to test the performance of manufacturing operations. In contrast with parametric techniques that demand the forecasted details of a product function, non-parametric approaches differentiate feasible input and output synthesis based on the accessible data only(William W Cooper, Seiford, & Tone, 2007). DEA, as one of the most regularly used non-parametric methods, grants its name to its enveloping characteristic of the dataset's productive DMUs, where the pragmatically found out, most productive DMUs establish the production frontier in opposition to which all DMUs are correlated. DEA's reputation withstands from its relative shortage assumptions, capability to benchmark multi-proportioned inputs and outputs as well as computerized ease owing to it being specific as a linear program, regardless of aiming to calculate efficiency proportions(William W. Cooper, Seiford, & Zhu, 2011).

3.2.2 Development of DEA

Structuring on the opinions of Farrell(Farrell, 1957), the innovative work "Measuring the efficiency of decision-making units" by Charnes, Cooper, and Rhodes implements linear programming to evaluate a pragmatic production mechanism frontier for the first time(A. Charnes, 1978). The procedure was used earlier in Germany to evaluate the approximate efficiency of R&D investments and other various factors. Since then, a bulky number of journal articles have been written on implementing DEA on unique sets of problems.

Beginning with the CCR model by Charnes, Cooper, and Rhodes(A. Charnes, 1978), many developments to DEA have been initiated in the literature. The scope ranged from altering practical model assumptions such as input and output alignment, differentiating technical and designative efficiency(Fried, Lovell, Schmidt, & Schmidt, 2008), adding bounded disposability(William W Cooper, Seiford, & Zhu, 2000) of inputs and outputs or inconstant RTS(Banker, Charnes, & Cooper, 1984) to techniques that take advantage of DEA results and enhance them for more complex analyses such as cross-efficiency analysis(Sexton, Silkman, & Hogan, 1986).(wikipedia, 2019)

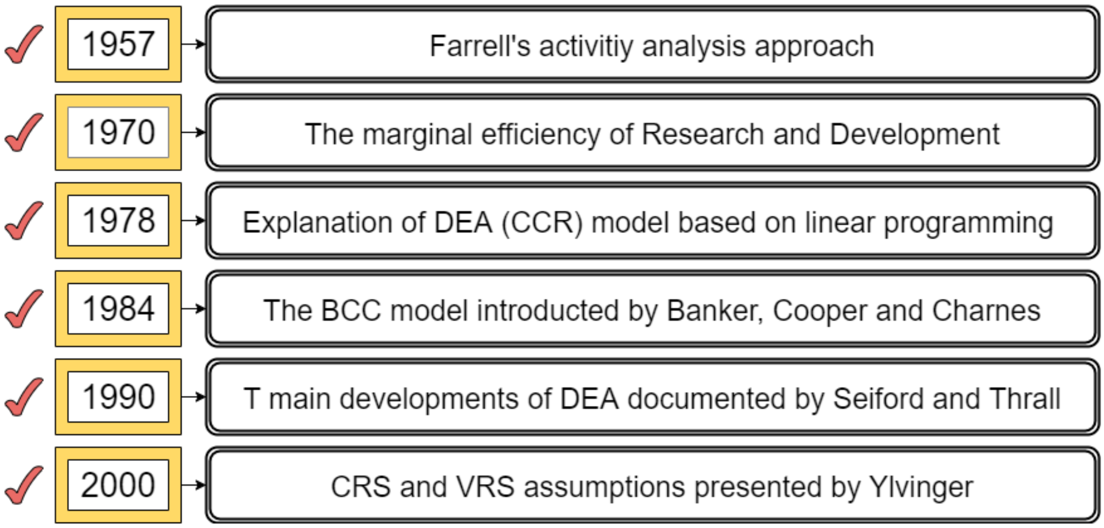

Figure 7: Main history of the DEA development

3.2.3 Principles of DEA technique

The concept of the DEA technique is to contrast the effectiveness of the DMU_L ('L' varies from 1 to g) with the effectiveness of all the other DMUs associated with the PPS, all corresponding DMUs should consume (a) inputs and generate (b) outputs. The belief is that if a DMU performs well, then perhaps the other corresponding DMU will perform better.

Consider we have a fixed number of f inputs, and h outputs, then the number of DMUs should be more than the summation of inputs and outputs multiplied by 3.

$$g \geq 3 \times (f + h)$$

For example, consider that our DMUs are fast-food companies, they are using bread, meat, cheese, and electricity (f=4) to produce burgers (h =1), then with corresponding data we should have at least 12 DMUs. $(e_c, c = 1,2, \dots, f)$ and $(z_d, d = 1,2, \dots, h)$ are the weights of the input, output vectors. These weights can be conducted with different measures for inputs and outputs. The target of the DEA technique is to assess and calculate the relevant values for each input and output values that increase the impact amount for each DMU. The effectiveness is equal to virtual output divided by virtual input (WILLIAM W. COOPER, 2007).

Virtual input and the virtual output are equal to $\sum_1^f e_c a_{cq}$, $\sum_1^h z_d b_{dq}$ respectively.

The DMU effectiveness (under monitoring) is equal: $\alpha = \frac{\sum_1^h e_c a_{cq}}{\sum_1^f z_d b_{dq}}$

The output and the input line for each DMU_j will be in the order given as:

$$a_m = (a_{1m}, a_{2m}, a_{3m}, a_{4m}) \text{ and } b_m = (b_{1m})$$

There are various models of DEA which we can use in our research. We preferred to use the CCR model but, any other model is also applicable.

3.2.4 Primary CCR model hypotheses

1: All the detected DMUs are the properties of the PPS.

$$DMU_m \in PPS \; for \; all \; m = 1,2, \dots, g$$

2: If $(\mathrm{a}, \mathrm{b}) \in \mathrm{PPS} \rightarrow$ all actions $(\bar{a}, \bar{b})$ having $\bar{a} \geq a \; and \; \bar{b} \leq b$, $(\mathrm{a}, \bar{b}) \in PPS$.

3: CRS hypothesis

If $(\mathrm{a}, \mathrm{b}) \in \mathrm{PPS} \rightarrow \forall \; \mathrm{x} \geq 0$ we get, $(\mathrm{xa}, \mathrm{xb}) \in \mathrm{PPS}$.

4: Clear linear synthesizes: If (a, b) and $(\bar{a}, \bar{b}) \in \mathrm{PPS} \rightarrow \forall \; \beta \in [0,1]$,

$[\; \beta(a, b) + (1 - \beta)(\bar{a}, \bar{b})] \in PPS$ will be obtained.

5: PPS is the minimal set fulfilling all the recent hypotheses.

$PPS = (\mathrm{a}, \mathrm{b}), a \geq \sum_{m=1}^{g} \beta_m a_m \; and \; b \leq \sum_{m=1}^{g} \beta_m b_m$, where $\beta_m \geq 0$.

Efficient DMUs are always positioned on the borderline of the PPF.

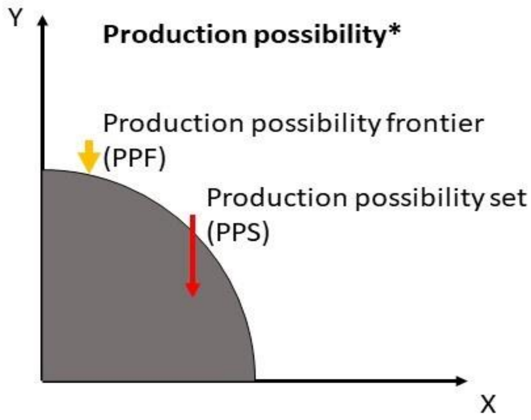

Figure 8: Production Possibility Borders

3.2.5 RTS

If $(a, b) \in PPS \rightarrow \forall p \geq 0$ we get: $(pa, pb) \in PPS$. Increasing or decreasing of inputs and outputs is proportional.

1-CRS:

$$f(a) = b$$

$$f(pa) = pb$$

2-IRS: RTS is increasing when inputs increasing the outputs are more than expectations.

$$f(a) = b$$

$$f(pa) > pb$$

3-DRS: RTS is decreasing when inputs increasing the outputs are less than expectations.

$$f(a) = b$$

$$f(pa) < pb$$

3.2.6 The primary CCR model

3.2.6.1 Input-oriented CCR

1- Fractional program form

$$(\boldsymbol{FP_o}) \qquad \max_{e,z} \qquad \alpha = \frac{\sum_1^h e_d b_{dq}}{\sum_1^f z_c a_{cq}}$$

$$subject\ to \qquad \frac{\sum_1^h e_d b_{dq}}{\sum_1^f z_c a_{cq}} \le 1, \quad (m = 1,2, \dots, g)$$

$$z_c \ge 0\,, \quad (c = 1,2, \dots f)$$

$$e_d \ge 0, (d = 1,2, \dots, h)$$

2- Linear program form

$$(\boldsymbol{LP_o}) \qquad \max_{e,z} \qquad \alpha = \sum_1^h e_d b_{dq}$$

$$subject\ to \qquad \sum_1^f z_c a_{cq} = 1, \quad (m = 1,2, \dots, g)$$

$$\sum_1^h e_d b_{dm} - \sum_1^f z_c a_{cq} \le 0$$

$$z_c \ge 0\,, \quad (c = 1,2, \dots f)$$

$$e_d \ge 0, (d = 1,2, \dots, h)$$

Note : $FP_o \leftrightarrow LP_o$

3-Multiplier form:

The matrices form for a system having:

INPUTS MATRIX : X

$$\begin{matrix} a_{11} & a_{12} & \cdots & a_{1g} \\ a_{21} & a_{22} & \cdots & a_{2g} \\ \vdots & \vdots & \cdots & \vdots \\ a_{f1} & a_{f2} & \cdots & a_{fg} \end{matrix}$$

Quantity of DMUs = g
Quantity of inputs = f
Quantity of outputs = h

OUTPUTS MATRIX : Y

$$\begin{matrix} b_{11} & b_{12} & \cdots & b_{1g} \\ b_{21} & b_{22} & \cdots & b_{2g} \\ \vdots & \vdots & \cdots & \vdots \\ b_{h1} & b_{h2} & \cdots & b_{hg} \end{matrix}$$

input multipliers vector
$z = (z_1, z_2, \dots, z_f)$

output multipliers vector
$e = (e_1, e_2, \dots, e_h)$

$$(\boldsymbol{LP_o}) \qquad \max_{e,z} \qquad \alpha = e b_q \qquad subject\ to \qquad \begin{aligned} z a_q &= 1 \\ e\ B - zA &\le 0 \\ z &\ge 0 \\ e &\ge 0 \end{aligned}$$

4-Dual model:

$$(\boldsymbol{DLP_o}) \quad \min_{\alpha,\beta} \quad \alpha$$
$$\text{subject to} \quad \alpha a_q - A\beta \geq 0$$
$$B\beta \geq b_q$$
$$\beta \geq 0$$

Where $\alpha \in \mathbb{R}$, and $\beta \in \mathbb{R}_g^+$.

3.2.6.2 Output-aligned model

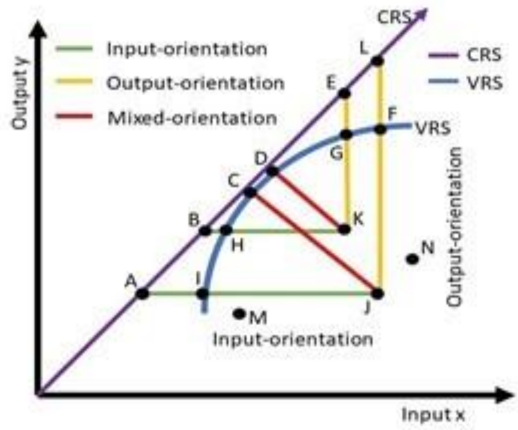

Figure 9: Orientations of DEA models

A-dual model or envelopment form:

$$(\boldsymbol{DLPO_o}) \quad \max_{\gamma,\eta} \quad \eta$$
$$\text{subject to} \quad a_q - A\eta \geq 0$$
$$\gamma b_q - B\eta \leq 0$$
$$\eta \geq 0$$

Where $\gamma \in \mathbb{R}$, and $\eta \in \mathbb{R}_g^+$.

The relations of the efficient frontier of the output-aligned and the input-aligned model are:

$\gamma^* = 1/\alpha^*$ and $\eta^* = \beta^*/\alpha^*$

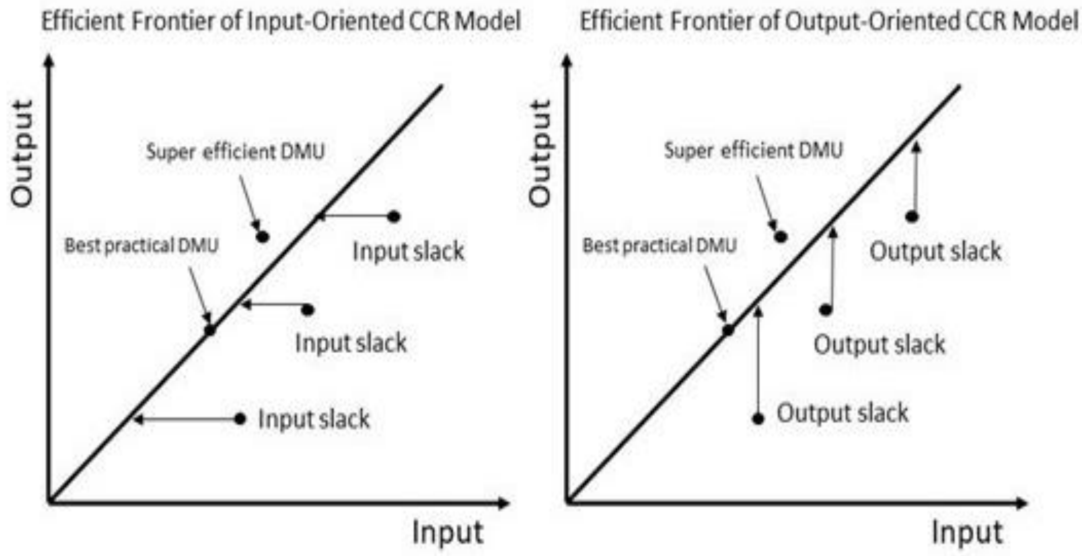

Figure 10: Input-Output-Aligned CCR Models

There are many different models proceeded from the basic CCR model. In this study, the basic input-oriented CCR model was used in the envelopment form because the case study satisfy in the CRS situation, this means that the increasing in the inputs is caused proportional increasing in outputs, but other models could be chosen too based on the aims of the research.

3.2.7 Benefits and disadvantages of DEA

Advantages:

- It does not care about the relationship between outputs and inputs
- Can be implemented in any type of research
- There is no need to construct any mathematical model
- CRS and VRS considered
- It can quantify each DMUs inefficiency sources

Disadvantages:

- It requires serious attention as the result is sensitive to inputs and outputs
- Collecting the right data can be complicated.

3.3 Mattress manufacturing system (description)

To conduct this research, all the information should be gathered about mattress production in case study. Figure 11 illustrates the factory plan:

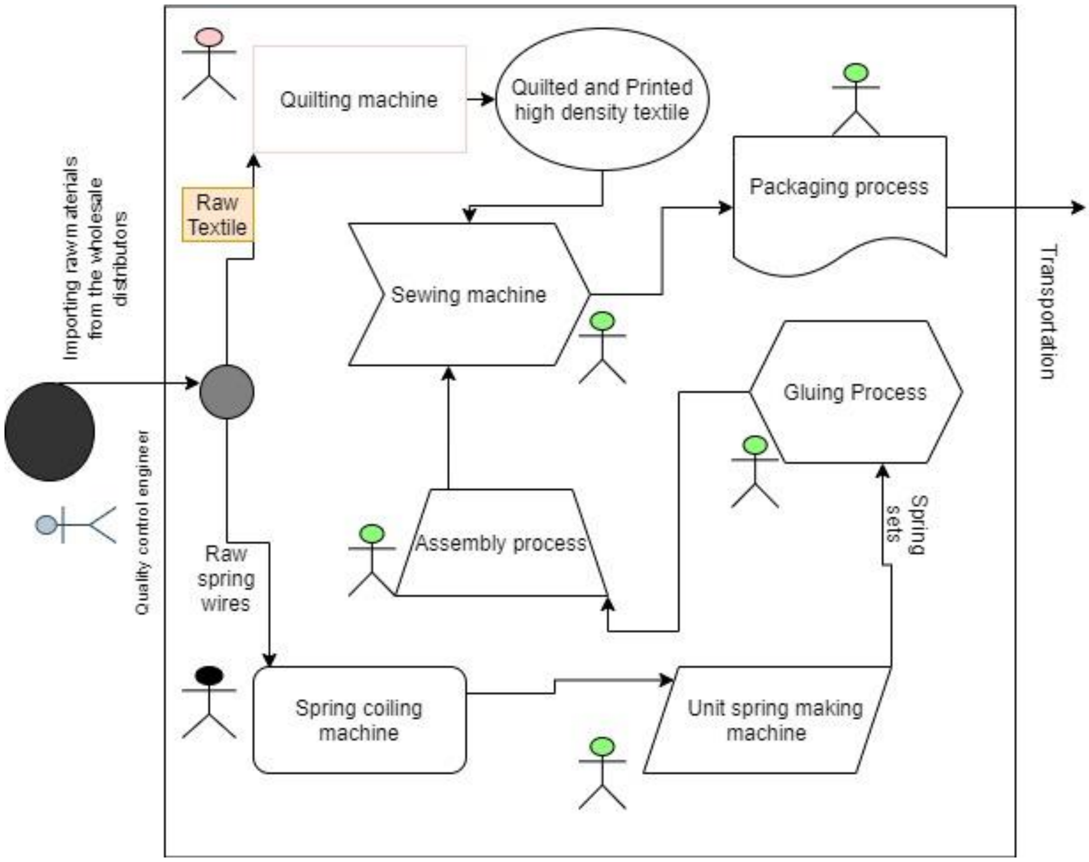

Figure 11: Mattress Factory plan

In Figure 11, the mattress production layout is presented where the case study was implemented. In the next section, the information was given about the production scheme of the orthopedic Bonnell spring mattress.

3.3.1 Sequence of the production

The choice of raw materials plays an important role in the production of mattresses. Before starting production, the quality control specialist must inspect the imported raw materials because of any problems in material. The primary materials of the Bonnell spring mattresses are steel wire, raw quality fabric, and quality foam that comprise chemical ingredients. The quality control specialist should carefully examine all raw materials as any wrong inspection can cause different serious problems, varying from manufacturing failures to irreparable customer dissatisfaction. As the raw materials are obtained, firstly, the operator of the Bonnell spring coiling machine (shown in figure 12) starts producing coil springs.

Figure 12: Bonnell spring coiling machine

After producing enough amount of coil springs, unit-spring coiling machine operator produces a unit-spring to set up a Bonnell-spring base. The production of the mattress continues with the quilting or printing process. This process is requiring some technical and mathematical skills to prevent unintended time and price-consuming material damages.

The third step of the process is gluing process, which is very dangerous for the health of employees. The toxic emissions coming out of the sprayable can is the principal cause of this danger. In gluing process, the inner materials of the mattress are glued to the Bonnell-spring base using a professional spray gun.

The sewing process is the last primary operation after the gluing and assembling. The professional tape edge machines playing a big role in this operation but the operator should not stress him/herself in this operation because of the high working tension because high tension can cause mistakes that can harm the operator strictly.

Of course, these operations have different failures, even considering the facility layout failures that are included in point of interest in this study.

3.4 Productivity of FMEA by using DEA

The FMEA aims to find solutions to decrease the RPNs of each failure of the process. But sometimes, solving the FM with the highest RPN may not give the most effective result. In order to estimate the best set of RPNs for the evaluation, the DEA method was applied. The S, O, D indicators will be our input variables, while the RPN values will be the corresponding output variable.

Figure 13, illustrates inputs and outputs of each DMU i:

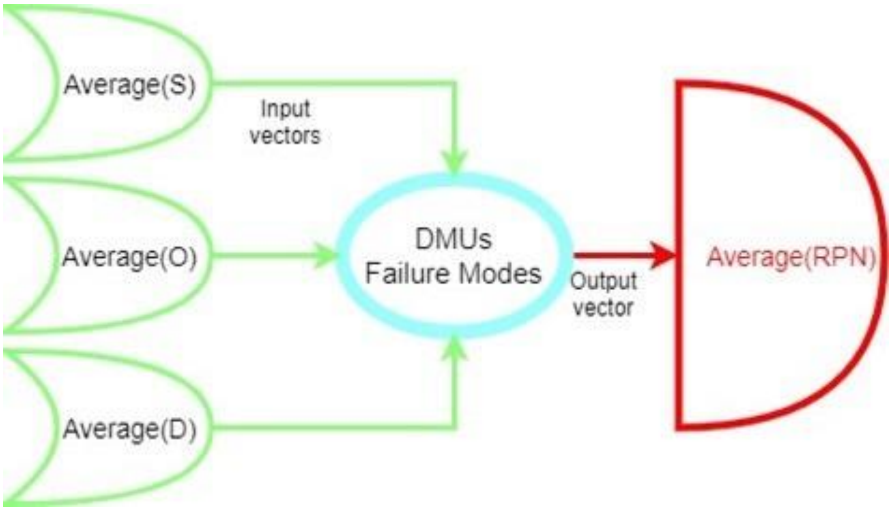

Figure 13: DEA input/output model

3.5 Data Collection

The data of this research was collected by expert opinions and, huge desire to conduct this research, helped us to design failures in a friendly environment. Firstly, all the information got about research area and the FMEA is conducted to find possible failures of the mattress production. 39 different failures were found with 55 causes of failures (sub failures). The S, O, D values assigned by all experts respectively and the average of all S, O, D and RPNs are calculated.

All experts were from the 'BRT YATAK' mattress production factory with enough experience and they shared all necessary information individually for conducting the method:

Expert 1. Birol Turhan- The founder of 'BRT YATAK' since the year of 1995.

Expert 2. Səid Ələkbərov- The experienced multi-operator of the factory having over 22 years of experience.

Expert 3. Dmitri Vorontsev- Another experienced operator and quality controller of the factory having over 19 years of experience in mattress industry.

The average of the given O, S, D values (Appendix C) by the experts are used in the next step of the procedure (Results chapter).

Initial values for each sub failure modes are shown in **Appendix C**.

Of course, there were some difficulties while assigning failure modes of the mattress production, as experts had opposing views related their point of view to the problem. In any case, almost all the dominant failure modes were included to the data sheet for implementing this research.

3.5.1 Failure modes (findings) of mattress production factory

Based on experts' suggestions and the researchers' view of issue, the failure mode table was constructed consisting failures of mattress production and other risky failures. **Appendix D**, consists of failure modes generated by our revisions.

Chapter 4

RESULTS

4.1 Results of the conventional FMEA

4.1.1 Calculation of the RPN

The FMEA method mentioned in figure 4 will be implemented in this section of the thesis. The failure modes and its risks were summarized on the table 4. The next step is to calculate different measures of RPN and S, O, D levels based on experts' opinions. As seen from **Appendix D**, that some failure modes that have more than one sub failure mode. Now it is time to calculate average values of each corresponding experts' opinions respectively by taking the average value of each FMs and SFMs (AHP method) with their RPNs: here are the first steps of our method:

a) Collection data of S, O, D failures from the l experts ($j = 1, 2, \ldots\ l$) and draw a table for all f number of SFMs ($i = 1,2,3, \ldots , f \quad and\ f = 55$)

b) calculation of Average S, O, D: $average\ \ S, O, Dj = average\ (Sj, Oj, Dj,)\ , j = 1, 2, 3$

c) computing RPNs for each SFMs: $RPNf = aveSf * aveOf * ave\,D\,f\ , f = (1\,..\,55)$.

d) Ranking all RPNs.

Tables 4 and 5 consists calculated data of the conventional FMEA with the corresponding rankings.

All the rankings are calculated by using MS Excel program software.

Table 4: Conventional RPNs

	Process type		**Failure modes**	**SFM NO**	**SFMs**		**Ave O**	**Ave S**	**Ave D**	**RPN**
1	Inspection of raw materials		The density of the polyurethane foam does not meet the requirements	1	Inspection failure		2	2.3	2.3	10.58
2			An unpleasant chemical smell coming from the polyurethane foam	2	Inspection failure		2.1	2	2.3	9.66
3			Wadding fibers are not properly bonded	3	Inspection failure		3.3	1.7	2	11.22
4			Gaps on the surface of support buckram	4	Inspection failure		2	2.3	2.15	9.89
5			Uneven Dyeing/Printing/Dye marks on the surface of raw textile	5	Inspection failure		2.7	2	1.95	10.53
6			Random drop stitches appear in the fabric	6	Inspection failure		2	1.7	2.7	9.18
7			The inappropriate thickness of steel wire	7	Measurement failure		3	3.3	2.3	22.77
8	Spring making machine		Set of useless Bonnell springs during an operation	8	Using inferior starter coil		1.7	2.7	1	4.59
9			Corrupt monitor interface	9	Voltage stabilizer stopped working because of high output voltage supply		1.6	2.7	2	8.64
10			Machine overheating as the operator produces spring	10	Poorly lubricated particles		1.7	3.7	2	12.58
11	Unit-Spring Assembly Machine		Spring units are not firmly attached	11	Rupture on the valves connecting the units		1.65	2	2.7	8.91
12			Incorrect twisting of wires	12	System block changed the operational state because of high working tension		2	2.35	2.3	10.81
13			Hand injury of the worker	13	Momentary fault while assisting spring units with corresponding wire		2.3	4	3.7	34.04
14			Electrical shock while cleaning the machine	14	Leaving the emergency shutdown system active		2.7	3.7	3.7	36.963

FM number	Process type	Failure modes	SFM NO	SFMs		Ave O	Ave S	Ave D	RPN
15	Unit-Spring Assembly Machine	Oil leakage from the springs	15	Excessive oiling the details		2	2.3	2.85	13.11
16		The high temperature on the valve lines	16	Malfunction of temperature monitor		2	3	2.3	13.8
17	Gluing Process	The felt does not adhere properly to the foam	17	Materials to be glued are not clean enough		2.7	1.7	1.7	7.803
18		Musty smell coming from the mattress	18	Over spraying the surface of the materials		2.15	2.7	2	11.61
			19	Insufficient ambient lighting		1.7	3.7	3.2	20.128
19		Eye and skin problems on the workers	20	The canister spray system is not spraying correctly and the spray pattern is inadmissible wide		1.6	2.7	1.7	7.344
			21	Inadequate ventilation		1.2	3.6	2.5	10.8
20		Adhesive blocked the canister hose	22	The operator should ensure the value on the canister remained open		1.7	1.7	1.3	3.757
21		High pressure of compressed air pumped into the tank	23	Pressure gauge failure		1.3	3.3	1.3	5.577
			24	Compressor safety device malfunction		1	3.8	2.2	8.36
22		Too much glue spilling while spraying	25	The fluid knob of the spray gun is not working properly		1.7	2.3	1.7	6.647
23		Glue containers left open	26	Deformation of containers during transportation		2.7	4	1.3	14.04
			27	Deformation in containers during storage		3.2	4.1	1.9	24.928
			28	Insufficient ventilation		1.3	3.6	1.4	6.552
24		Compressor absorbs harmful toxic gas or dust	29	Insufficient ventilation		2.7	3.3	1.3	11.583
25	Quilting / printing / embroidery process	Misprinting, off printing, or absence of printing	30	Wrong leveling procedure by operator		2.3	1.7	1.3	5.083
26		Twisted or knotted rope	31	Incorrect loading of fabric into the machine		2	2.3	1.7	7.82
27		Crease marks on the fabric	32	Inadequate preparation, relaxation, or bulking of fabric		2.25	2.3	1.7	8.7975
28		Separation of the stitched materials	33	Having less highly compressed chemical fibers inside wadding		3	2	2.7	16.2

FM number	Process type	Failure modes	SFM NO	SFMs		Ave O	Ave S	Ave D	RPN
29	Quilting / printing / embroidery process – Gluing Process	Stacking fabric very close to the electricity line	34	Short circuit or high voltage in the power line		2	3.3	2	13.2
			35	Leaving fabric material in front of the electrical panel		1.4	4.4	1.5	9.24
30		Roughness of the inner surface of the machine	36	Residues adhering to the machine's inner surface		2.3	2.3	1.7	8.993
			37	Insufficient cleaning the inside of the machine		1.6	2.1	2.3	7.728
31		Failure of the conveyor chain system inside the machine	38	Loosening of chain links		2.7	2.3	2.3	14.283
32	Using tape edge sewing machine	Displacement on the bench during sewing	39	Mis-controlling the bench before sewing		2.3	4	1	9.2
33		Skipping stitch during sewing operation	40	The needle bar position is not correct		2.7	2.3	2	12.42
			41	The bottom line is not tight		2.2	2.6	2.2	12.584
34		Broken line during the operation	42	The bottom line is too loose or too tight		2.15	1.7	2.3	8.4065
			43	The position of the looper is not correct		3.2	1.5	1.8	8.64
35		Broken needle during the operation	44	Operator pulls or drags the mattress too roughly		2	1.7	1.3	4.42
			45	The needle hits the needle plate		1.8	2.1	1.3	4.914
			46	The crochet impact needle		1.4	2.4	3.1	10.416
			47	Needle quality is too bad		2.7	2.3	3.2	19.872
36	Using manual mattress packaging machine	Elongated resistor	48	Heated resistors		2.7	3.3	2.3	20.493
37		Gaps in packaging	49	Operator does not inspect the product after packaging		3.3	3.7	2.7	32.967
38	Storage of materials	Presence of electrical equipment in the warehouse	50	Leakage in electrical installation		2	5	1.3	13
			51	Overloading of electrical cables		1.6	4.2	2.4	16.128
			52	Short circuit		1.2	4.8	4.2	24.192
			53	Faulty grounding		1.7	3.3	5	28.05
39		Improper storage of solvents	54	Holes in solvent containers		2.7	2.7	2.3	16.767
			55	Empty solvent Containers		1.7	2.2	1.5	5.61

4.1.2 FM categorization

4.1.2.1 Arranging the SFMs conforming to corresponding RPNs

Table 5: Ranks of the Conventional RPNs

FM number	Process type	FMs	SFM NO	SFMs		RPN value	Ranks
1	Inspection of raw materials	The density of the polyurethane foam does not meet the requirements	1	Inspection failure		10.58	**28**
2		An unpleasant chemical smell coming from the polyurethane foam	2	Inspection failure		9.66	**32**
3		Wadding fibers are not properly bonded	3	Inspection failure		11.22	**25**
4		Gaps on the surface of support buckram	4	Inspection failure		9.89	**31**
5		Uneven Dyeing/Printing/Dye marks on the surface of raw textile	5	Inspection failure		10.53	**29**
6		Random drop stitches appear in the fabric	6	Inspection failure		9.18	**35**
7		The inappropriate thickness of steel wire	7	Measurement failure		22.77	**7**
8	Spring making machine	Set of useless Bonnell springs during an operation	8	Using inferior starter coil		4.59	**53**
9		Corrupt monitor interface	9	Voltage stabilizer stopped working because of high output voltage supply		8.64	**40**
10		Machine overheating as the operator produces spring	10	Poorly lubricated particles		12.58	**21**
11	Unit-Spring Assembly Machine	Spring units are not firmly attached	11	Rupture on the valves connecting the units		8.91	**37**
12		Incorrect twisting of wires	12	System block changed the operational state because of high working tension		10.81	**26**
13		Hand injury of the worker	13	Momentary fault while assisting spring units with corresponding wire		34.04	**2**
14		Electrical shock while cleaning the machine	14	Leaving the emergency shutdown system active		36.963	**1**

FM number	Process type	FMs	SFM NO	SFMs		RPN value	Ranks
15	Unit-Spring Assembly Machine	Oil leakage from the springs	15	Excessive oiling the details		13.11	**18**
16	Unit-Spring Assembly Machine	The high temperature on the valve lines	16	Malfunction of temperature monitor		13.8	**16**
17	Gluing Process	The felt does not adhere properly to the foam	17	Materials to be glued are not clean enough		7.803	**44**
18	Gluing Process	Musty smell coming from the mattress	18	Over-spraying the surface of the materials		11.61	**23**
			19	Insufficient ambient lighting		20.128	**9**
19	Gluing Process	Eye and skin problems on the workers	20	The canister spray system is not spraying correctly and the spray pattern is inadmissible wide		7.344	**46**
			21	Inadequate ventilation		10.8	**27**
20	Gluing Process	Adhesive blocked the canister hose	22	The operator should ensure the value on the canister remained open		3.757	**55**
21	Gluing Process	High pressure of compressed air pumped into the tank	23	Pressure gauge failure		5.577	**50**
			24	Compressor safety device malfunction		8.36	**42**
22	Gluing Process	Too much glue spilling while spraying	25	The fluid knob of the spray gun is not working properly		6.647	**47**
23	Gluing Process	Glue containers left open	26	Deformation of containers during transportation		14.04	**15**
			27	Deformation in containers during storage		24.928	**5**
			28	Insufficient ventilation		6.552	**48**
24	Gluing Process	Compressor absorbs harmful toxic gas or dust	29	Insufficient ventilation		11.583	**24**
25	Quilting / printing / embroidery process	Misprinting, off printing, or absence of printing	30	Wrong leveling procedure by operator		5.083	**51**
26	Quilting / printing / embroidery process	Twisted or knotted rope	31	Incorrect loading of fabric into the machine		7.82	**43**
27	Quilting / printing / embroidery process	Crease marks on the fabric	32	Inadequate preparation, relaxation, or bulking of fabric		8.7975	**38**
28	Quilting / printing / embroidery process	Separation of the stitched materials	33	Having less highly compressed chemical fibers inside wadding		16.2	**12**

FM number	Process type	FMs	SFM NO	SFMs		RPN value	Ranks
29	Quilting / printing / embroidery process, Gluing Process	Stacking fabric very close to the electricity line	34	Short circuit or high voltage in the power line		13.2	**17**
			35	Leaving fabric material in front of the electrical panel		9.24	**33**
30		Roughness of the inner surface of the machine	36	Residues adhering to the machine inner surface		8.993	**36**
			37	Insufficient cleaning the inside of the machine		7.728	**45**
31		Failure of the conveyor chain system inside the machine	38	Loosening of chain links		14.283	**14**
32	Using tape edge sewing machine	Displacement on the bench during sewing	39	Mis-controlling the bench before sewing		9.2	**34**
33		Skipping stitch during sewing operation	40	The needle bar position is not correct		12.42	**22**
			41	The bottom line is not tight		12.584	**20**
34		Broken line during the operation	42	The bottom line is too loose or too tight		8.4065	**41**
			43	The position of the looper is not correct		8.64	**39**
35		Broken needle during the operation	44	Operator pulls or drags the mattress too roughly		4.42	**54**
			45	The needle hits the needle plate		4.914	**52**
			46	The crochet impact needle		10.416	**30**
			47	Needle quality is too bad		19.872	**10**
36	Using manual mattress packaging machine	Elongated resistor	48	Heated resistors		20.493	**8**
37		Gaps in packaging	49	Operator does not inspect the product after packaging		32.967	**3**
38	Storage of materials	Presence of electrical equipment in the warehouse	50	Leakage in electrical installation		13	**19**
			51	Overloading of electrical cables		16.128	**13**
			52	Short circuit		24.192	**6**
			53	Faulty grounding		28.05	**4**
39		Improper storage of solvents	54	Holes in solvent containers		16.767	**11**
			55	Empty solvent containers		5.61	**49**

The rankings shown above were used to differentiate conventional FMEA with Criticality Analysis ranks.

4.1.2.2 Potential risk analysis

Table 6: Potential risk analysis

		Potential risk analysis		Ranks of RPNs	
FM NO	**SFM NO**	**(Criticality = O×S)**	**ACTION**	**RPN**	**RPN RANK**
1	1	4.6	Low risk	10.58	**28**
2	2	4.2	Low risk	9.66	**32**
3	3	5.61	Medium risk	11.22	**25**
4	4	4.6	Low risk	9.89	**31**
5	5	5.4	Medium risk	10.53	**29**
6	6	3.4	Low risk	9.18	**35**
7	7	9.9	Medium risk	22.77	**7**
8	8	4.59	Low risk	4.59	**53**
9	9	4.32	Low risk	8.64	**40**
10	10	6.29	Medium risk	12.58	**21**
11	11	3.3	Low risk	8.91	**37**
12	12	4.7	Low risk	10.81	**26**
13	13	9.2	Medium risk	34.04	**2**
14	14	9.99	Medium risk	36.963	**1**
15	15	4.6	Low risk	13.11	**18**
16	16	6	Medium risk	13.8	**16**
17	17	4.59	Low risk	7.803	**44**
18	18	5.805	Medium risk	11.61	**23**
18	19	6.29	Medium risk	20.128	**9**
19	20	4.32	Low risk	7.344	**46**
19	21	4.32	Low risk	10.8	**27**
20	22	2.89	Low risk	3.757	**55**
21	23	4.29	Low risk	5.577	**50**
21	24	3.8	Low risk	8.36	**42**
22	25	3.91	Low risk	6.647	**47**
23	26	10.8	High risk	14.04	**15**
23	27	13.12	High risk	24.928	**5**
23	28	4.68	Low risk	6.552	**48**
24	29	8.91	Medium risk	11.583	**24**
25	30	3.91	Low risk	5.083	**51**
26	31	4.6	Low risk	7.82	**43**
27	32	5.175	Medium risk	8.7975	**38**

		Potential risk analysis		RANKs of RPNs	
FM NO	**SFM NO**	**(Criticality = O×S)**	**ACTION**	**RPN**	**RPN RANK**
28	33	6	Medium risk	16.2	**12**
29	34	6.6	Medium risk	13.2	**17**
29	35	6.16	Medium risk	9.24	**33**
30	36	5.29	Medium risk	8.993	**36**
30	37	3.36	**Low risk**	7.728	**45**
31	38	6.21	Medium risk	14.283	**14**
32	39	9.2	Medium risk	9.2	**34**
33	40	6.21	Medium risk	12.42	**22**
33	41	5.72	Medium risk	12.584	**20**
34	42	3.655	**Low risk**	8.4065	**41**
34	43	4.8	**Low risk**	8.64	**39**
35	44	3.4	**Low risk**	4.42	**54**
35	45	3.78	**Low risk**	4.914	**52**
35	46	3.36	**Low risk**	10.416	**30**
35	47	6.21	Medium risk	19.872	**10**
36	48	8.91	Medium risk	20.493	**8**
37	49	12.21	**High risk**	32.967	**3**
38	50	10	Medium risk	13	**19**
38	51	6.72	Medium risk	16.128	**13**
38	52	5.76	Medium risk	24.192	**6**
38	53	5.61	Medium risk	28.05	**4**
39	54	7.29	Medium risk	16.767	**11**
39	55	3.74	**Low risk**	5.61	**49**

In the above table criticality analysis applied and it is seen that there are some failures affected by their detection values. In the next table results are ranked and interpreted in details.

4.1.2.3 Interpretation of the results

Table 7: Descendant ranking of RPNs

		Potential risk analysis		RANKs of RPNs	
FM NO	**SFM NO**	**(Criticality = O×S)**	**ACTION**	**RPN**	**RPN RANK**
14	14	9.99	Medium risk	36.963	**1**
13	13	9.2	Medium risk	34.04	**2**
37	49	12.21	**High risk**	32.967	**3**
38	53	5.61	Medium risk	28.05	**4**
23	27	13.12	**High risk**	24.928	**5**
38	52	5.76	Medium risk	24.192	**6**
7	7	9.9	Medium risk	22.77	**7**
36	48	8.91	Medium risk	20.493	**8**
18	19	6.29	Medium risk	20.128	**9**
35	47	6.21	Medium risk	19.872	**10**
39	54	7.29	Medium risk	16.767	**11**
28	33	6	Medium risk	16.2	**12**
38	51	6.72	Medium risk	16.128	**13**
31	38	6.21	Medium risk	14.283	**14**
23	26	10.8	**High risk**	14.04	**15**
16	16	6	Medium risk	13.8	**16**
29	34	6.6	Medium risk	13.2	**17**
15	15	4.6	**Low risk**	13.11	**18**
38	50	10	Medium risk	13	**19**
33	41	5.72	Medium risk	12.584	**20**
10	10	6.29	Medium risk	12.58	**21**
33	40	6.21	Medium risk	12.42	**22**
18	18	5.805	Medium risk	11.61	**23**
24	29	8.91	Medium risk	11.583	**24**
3	3	5.61	Medium risk	11.22	**25**
12	12	4.7	**Low risk**	10.81	**26**
19	21	4.32	**Low risk**	10.8	**27**

		Potential risk analysis		RANKs of RPNs	
FM NO	**SFM NO**	**(Criticality = O×S)**	**ACTION**	**RPN**	**RPN RANK**
1	1	4.6	**Low risk**	10.58	**28**
5	5	5.4	Medium risk	10.53	**29**
35	46	3.36	**Low risk**	10.416	**30**
4	4	4.6	**Low risk**	9.89	**31**
2	2	4.2	**Low risk**	9.66	**32**
29	35	6.16	Medium risk	9.24	**33**
32	39	9.2	Medium risk	9.2	**34**
6	6	3.4	**Low risk**	9.18	**35**
30	36	5.29	Medium risk	8.993	**36**
11	11	3.3	**Low risk**	8.91	**37**
27	32	5.175	Medium risk	8.7975	**38**
34	43	4.8	**Low risk**	8.64	**39**
9	9	4.32	**Low risk**	8.64	**40**
34	42	3.655	**Low risk**	8.4065	**41**
21	24	3.8	**Low risk**	8.36	**42**
26	31	4.6	**Low risk**	7.82	**43**
17	17	4.59	**Low risk**	7.803	**44**
30	37	3.36	**Low risk**	7.728	**45**
19	20	4.32	**Low risk**	7.344	**46**
22	25	3.91	**Low risk**	6.647	**47**
23	28	4.68	**Low risk**	6.552	**48**
39	55	3.74	**Low risk**	5.61	**49**
21	23	4.29	**Low risk**	5.577	**50**
25	30	3.91	**Low risk**	5.083	**51**
35	45	3.78	**Low risk**	4.914	**52**
8	8	4.59	**Low risk**	4.59	**53**
35	44	3.4	**Low risk**	4.42	**54**
20	22	2.89	**Low risk**	3.757	**55**

In order to apply sensiticity analysis(Criticality analysis) detection values excluded from the literation. As seen from the tables 6 and 7 some failure modes lose their ranks while others won noticeably huge ranks because of the occurrence and the severity values were very high for those failures. Failures had less than 5 value coloured with green as they have lesser risk than others. Failures valued between 5 and 10 had the medium risk coloured with yellow and the red ones are the failures grouped in the high risk level having more than 10 value(Chnina, 2020). The results in tables 6 and 7 show that there is no stable relation between the conventional RPN and the criticality analysis. Here there is need to enhance sub failure modes capabilities by calculating of SFMs to check its effect in ranks.

Table 8: Difference of minimum and maximum SFM in same FMs

F-Mode	**18**	**19**	**21**	**23**	**29**	**30**	**33**	**34**	**35**	**38**	**39**
Min SF-Mode rank	9	27	42	5	17	36	20	39	10	4	4
Max SF-Mode rank	23	46	50	48	33	45	22	41	54	19	49
GAP	14	19	8	43	16	9	2	2	44	15	45

From the table 8 it is seen that there are high gaps between the SFMs of one FM.

Now it is clarified that a weak failure mode consisting subfailures can be serious too. With this reason all subfailures were aggregated in the next section.

4.2 Aggregation procedure

4.2.1 Aggregation procedure of FMs

In order to apply aggregation procedure to SFMs of each FM, the RPN for each FM were computed. This weighted average prioritized the SFM having minimum or maximum RPN number:

a) Computing the aggregate $RPNi$ for each Failure i with having m_i SFM_k, with the formula below:

$$AGRPN_i = \frac{\sum_{k=1}^{n_i} b_{ik} \times RPN_k}{\sum_{k=1}^{n_i} b_{ik}}$$

b) Giving a rank (R_{ik}) to the aggregated FMs on descending order of $AGRPNi$

Table 9: Ranks of the aggregated FMs

FM NO	SFM NO	Common RPNs	a_{ij} rank	Aggregated RPNs	Aggregated rank c_{ij}
1	1	10.58	**28**	10.58	22
2	2	9.66	**32**	9.66	26
3	3	11.22	**25**	11.22	19
4	4	9.89	**31**	9.89	25
5	5	10.53	**29**	10.53	23
6	6	9.18	**35**	9.18	28
7	7	22.77	**7**	22.77	4
8	8	4.59	**53**	4.59	38
9	9	8.64	**40**	8.64	31
10	10	12.58	**21**	12.58	15
11	11	8.91	**37**	8.91	29
12	12	10.81	**26**	10.81	21
13	13	34.04	**2**	34.04	2
14	14	36.963	**1**	36.963	1
15	15	13.11	**18**	13.11	12
16	16	13.8	**16**	13.8	11
17	17	7.803	**44**	7.803	34
18	18	11.61	**23**	15.869	8
18	19	20.128	**9**		
19	20	7.344	**46**	12.744	14
19	21	10.8	**27**		
20	22	3.757	**55**	3.757	39
21	23	5.577	**50**	6.9685	35
21	24	8.36	**42**		
22	25	6.647	**47**	6.647	36
23	26	14.04	**15**	15.1733333	9
23	27	24.928	**5**		
23	28	6.552	**48**		
24	29	11.583	**24**	11.583	17

FM NO	SFM NO	Common RPNs	a_{ij} rank	Aggregated RPNs	Aggregated rank c_{ij}
25	30	5.083	**51**	5.083	37
26	31	7.82	**43**	7.82	33
27	32	8.7975	**38**	8.7975	30
28	33	16.2	**12**	16.2	7
29	34	13.2	**17**	11.22	19
29	35	9.24	**33**		
30	36	8.993	**36**	12.857	13
30	37	7.728	**45**		
31	38	14.283	**14**	14.283	10
32	39	9.2	**34**	9.2	27
33	40	12.42	**22**	12.502	16
33	41	12.584	**20**		
34	42	8.4065	**41**	8.52325	32
34	43	8.64	**39**		
35	44	4.42	**54**	9.9055	24
35	45	4.914	**52**		
35	46	10.416	**30**		
35	47	19.872	**10**		
36	48	20.493	**8**	20.493	5
37	49	32.967	**3**	32.967	3
38	50	13	**19**	20.3425	6
38	51	16.128	**13**		
38	52	24.192	**6**		
38	53	28.05	**4**		
39	54	16.767	**11**	11.1885	20
39	55	5.61	**49**		

From the table 9, it is seen that only one SFM of corresponding FM can break its efficiency. For example, FM 38 has 4 different SFMs and each of them has different ranks too. SFM 53 and SFM 52 plays an important role about the efficiency of this failure.

4.2.2 Arrangement of the Ranks (Normalization procedure)

For comparing the conventional results with the aggregated one, the ranks of each mode were normalized. So, the effects of each SFMs to the efficiency were determined by normalization. This leads to know the importance of each SFM individually. The ranks in the conventional FMEA were between 1 and 55 (55 SFMs), and after considering the aggregated FMEA, these ranks stood between 1 and 39 (39 FMs). Thus, to compare the results, the ranks for each method should be normalized. The percentage of priority was considered, for example if a SFM ranked in the first place this means it has the highest priority among other SFMs, so the percentage of any other SFM having more efficiency than the initial one will be 0%. By this way all the ranks were between 0% and 100%(Chnina, 2020).

The results delivered by applying the equations shown below:

a) Priority percentage of SFM_k: $P_{1k} = 100 - (a_{ik} / 55 * 100)$

b) Priority percentage of FM_i: $P_{2i} = 100 - (c_{ik} / 39 * 100)$

c) Progress ranks: $P = P_{2extended} - P_1$

$P_{2extended}$ is a vector consisting 55 entries.

Table 10 summarizes the rank normalization computations solved via Microsoft Excel.

Table 10: Normalization procedure

FM NO	SFM NO	Conventional RPN RANK a_{ij}	Aggregate RPNs RANK c_{ij}	% of SFM P_1	% of FM $P_{2extended}$	Progress-P
1	1	28	22	49.09	43.58	-5.5
2	2	32	26	41.81	33.33	-8.48
3	3	25	19	54.54	51.28	-3.26
4	4	31	25	43.63	35.89	-7.74
5	5	29	23	47.27	41.02	-6.25
6	6	35	28	36.36	28.20	-8.16
7	7	7	4	87.27	89.74	2.47
8	8	53	38	3.63	2.56	-1.07
9	9	40	31	27.27	20.51	-6.76
10	10	21	15	61.81	61.53	-0.28
11	11	37	29	32.72	25.64	-7.08
12	12	26	21	52.72	46.15	-6.57
13	13	2	2	96.36	94.87	-1.49
14	14	1	1	98.18	97.43	-0.74
15	15	18	12	67.27	69.23	1.96
16	16	16	11	70.90	71.79	0.88

FM NO	SFM NO	Conventional RPN RANK a_{ij}	Aggregate RPNs RANK c_{ij}	% of SFM P_1	% of FM $P_{2extended}$	Progress-P
17	17	44	34	20	12.82	-7.18
18	18	23	8	58.18	79.48	21.3
	19	9	8	83.63	79.48	-4.14
19	20	46	14	16.36	64.1	47.74
	21	27	14	50.9	64.1	13.19
20	22	55	39	0	0	0
21	23	50	35	9.09	10.25	1.16
	24	42	35	23.63	10.25	-13.38
22	25	47	36	14.54	7.69	-6.85
23	26	15	9	72.72	76.9	4.19
	27	5	9	90.9	76.9	-13.98
	28	48	9	12.72	76.9	64.19
24	29	24	17	56.36	56.41	0.05
25	30	51	37	7.27	5.12	-2.14
26	31	43	33	21.81	15.38	-6.43
27	32	38	30	30.9	23.07	-7.83
28	33	12	7	78.18	81.05	3.87
29	34	17	19	69.09	51.28	-17.8
	35	33	19	40	51.28	11.28
30	36	36	13	34.54	66.66	32.12
	37	45	13	18.18	66.66	48.5
31	38	14	10	74.54	74.35	-0.18
32	39	34	27	38.18	30.76	-7.41
33	40	22	16	60	58.97	-1.02
	41	20	16	63.63	58.97	-4.66
34	42	41	32	25.45	17.94	-7.5
	43	39	32	29.09	17.94	-11.15
35	44	54	24	1.81	38.46	36.64
	45	52	24	5.45	38.46	33
	46	30	24	45.45	38.46	-7
	47	10	24	81.81	38.46	-43.4
36	48	8	5	85.45	87.18	1.72
37	49	3	3	94.54	92.3	-2.23
38	50	19	6	65.45	84.61	19.16
	51	13	6	76.36	84.61	8.25
	52	6	6	89.09	84.61	-4.47
	53	4	6	92.72	84.61	-8.11
39	54	11	20	80	48.71	-31.3
	55	49	20	10.9	48.71	37.8

As seen from the table 10, normalization procedure helped to observe the positive and negative progresses of each SFM. For example, the FM 35 has 2 SFMs that one of them gained huge progress while other one lost huge amount of progress.

4.2.3 Simplification of the results

Table 11 consolidates the computations initiated in table 10.

Table 11: Ranking normalization scores by descending order

FM NO	SFM NO	% of SFM P_1	% of FM P_2	Progress- P	Specification of SFM	
23	28	12.72	76.9	64.19	Insufficient ventilation	Sub Failure modes that won ranks
30	37	18.18	66.6	48.5	Insufficient cleaning the inside of the machine	
19	20	16.36	64.1	47.74	The canister spray system is not spraying correctly and the spray pattern is inadmissible wide	
39	55	10.9	48.71	37.8	Empty solvent Containers	
35	44	1.81	38.46	36.64	Operator pulls or drags the mattress too roughly	
35	45	5.45	38.46	33	The needle hits the needle plate	
30	36	34.54	66.66	32.12	Residues adhering to the machine inner surface	
18	18	58.18	79.48	21.3	Over-spraying the surface of the materials	
38	50	65.45	84.61	19.16	Leakage in electrical installation	
19	21	50.9	64.1	13.19	Inadequate ventilation	
29	35	40	51.28	11.28	Leaving fabric material in front of the electrical panel	
38	51	76.36	84.61	8.25	Overloading of electrical cables	
23	26	72.72	76.9	4.19	Deformation of containers during transportation	
28	33	78.18	81.05	3.87	Having less highly compressed chemical fibers inside wadding	
7	7	87.27	89.74	2.47	Spring Machine malfunction	

FM NO	SFM NO	% of SFM P_1	%e of FM P_2	Progress-P	Specification of SFM	Group
15	15	67.27	69.23	1.96	Excessive oiling the details	SFMs that kept Its balance
36	48	85.45	87.18	1.72	Heated resistors	SFMs that kept Its balance
21	23	9.09	10.25	1.16	Pressure gauge failure	SFMs that kept Its balance
16	16	70.90	71.79	0.88	Malfunction of temperature monitor	SFMs that kept Its balance
24	29	56.36	56.41	0.05	Insufficient ventilation	SFMs that kept Its balance
20	22	0	0	0	The operator should ensure the value on the canister remained open	SFMs that kept Its balance
31	38	74.54	74.35	-0.18	Loosening of chain links	SFMs that kept Its balance
10	10	61.81	61.53	-0.28	Poorly lubricated particles	SFMs that kept Its balance
14	14	98.18	97.43	-0.74	Leaving the emergency shutdown system active	SFMs that kept Its balance
33	40	60	58.97	-1.02	The needle bar position is not correct	SFMs that kept Its balance
8	8	3.63	2.56	-1.07	Using inferior starter coil	SFMs that kept Its balance
13	13	96.36	94.87	-1.49	Momentary fault while assisting spring units with corresponding wire	SFMs that kept Its balance
25	30	7.27	5.12	-2.14	Wrong leveling procedure by operator	SFMs that kept Its balance
37	49	94.54	92.3	-2.23	Operator does not inspect the product after packaging	SFMs that kept Its balance
3	3	54.54	51.28	-3.26	Inspection failure	Sub Failure modes that lost ranks
18	19	83.63	79.48	-4.14	Insufficient ambient lighting	Sub Failure modes that lost ranks
38	52	89.09	84.61	-4.47	Short circuit	Sub Failure modes that lost ranks
33	41	63.63	58.97	-4.66	The bottom line is not tight	Sub Failure modes that lost ranks
1	1	49.09	43.58	-5.5	Inspection failure	Sub Failure modes that lost ranks
5	5	47.27	41.02	-6.25	Inspection failure	Sub Failure modes that lost ranks
26	31	21.81	15.38	-6.43	Incorrect loading of fabric into the machine	Sub Failure modes that lost ranks
12	12	52.72	46.15	-6.57	System block changed the operational state due to high working tension	Sub Failure modes that lost ranks
9	9	27.27	20.51	-6.76	Voltage stabilizer stopped working due to high output voltage supply	Sub Failure modes that lost ranks
22	25	14.54	7.69	-6.85	The fluid knob of the spray gun is not working properly	Sub Failure modes that lost ranks
35	46	45.45	38.46	-7	The crochet impact needle	Sub Failure modes that lost ranks

FM NO	SFM NO	%e of SFM P_1	%e of FM P_2	Progress-P	Specification of SFM	
11	11	32.72	25.64	-7.08	Rupture on the valves connecting the units	Sub Failure modes that lost ranks
17	17	20	12.82	-7.18	Materials to be glued are not clean enough	
32	39	38.18	30.76	-7.41	Miscontrolling the bench before sewing	
34	42	25.45	17.94	-7.5	The bottom line is too loose or too tight	
4	4	43.63	35.89	-7.74	Inspection failure	
27	32	30.9	23.07	-7.83	Inadequate preparation, relaxation, or bulking of fabric	
38	53	92.72	84.61	-8.11	Faulty grounding	
6	6	36.36	28.20	-8.16	Inspection failure	
2	2	41.81	33.33	-8.48	Inspection failure	
34	43	29.09	17.94	-11.15	The position of the looper is not correct	
21	24	23.63	10.25	-13.38	Compressor safety device malfunction	
23	27	90.9	76.9	-13.98	Deformation in containers during storage	
29	34	69.09	51.28	-17.8	Short circuit or high voltage in the power line	
39	54	80	48.71	-31.3	Holes in solvent containers	
35	47	81.81	38.46	-43.4	Needle quality is too bad	

What is learned so far is that aggregation of failure modes gives more genuine scores different than common one. The last findings showed that when we consider Sub-failures, the ranking priority of a sub failure mode also changes significantly, thus prioritization of the FMs is reliable. But, the impact of the Failure modes can vary under different conditions. As an example, FM_{38} has 4 different sub failure modes, but only 2 of them are serious failures with corresponding progresses of 19.16 and 8.25. But the other sub failures of FM_{38} have negative progresses of -4.47 and -8.11. This means that hidden sub failures can break the system if they are not measured in details. Table 11 shows the details of each SFMs. In the first category, the ranks of SFMs differ from conventional and aggregated approaches. As the categorizing continues, the results remaining same with corresponding approaches.

Until now, the RPNs of the Mattress Production calculated with different measurements, but the question arises with which FMs it can be more productive to deal with? That's why in the following step, the efficiency of each failure measured by implementing fixed method.

4.3 Measurement of the efficiencies by using DEA (with aggregation of SFMs)

The DEA method will be applied in this section of paper, which is explained in chapter 3. Also, the aggregated failure modes will be considered instead of sub failures.

We benefit from the rank b_{ik} acquired by the aggregation technique, as the DEA model will pay attention the maximum numbers of RPNs the rank b_{ik} helps to prioritize SFMs having maximum RPN numbers.

In order to apply the DEA method, all FMs should be aggregated by using a_{ik} ranks from the conventional method:

$$AGS_i = \frac{\sum_{k=1}^{n_i} S_{ik} \times a_{ik}}{\sum_{k=1}^{n_i} a_{ik}}$$

$$AGO_i = \frac{\sum_{k=1}^{n_i} O_{ik} \times a_{ik}}{\sum_{k=1}^{n_i} a_{ik}}$$

$$AGD_i = \frac{\sum_{k=1}^{n_i} D_{ik} \times a_{ik}}{\sum_{k=1}^{n_i} a_{ik}}$$

RPN will be the multiplication of each Aggregated S, O, D measured.

$$AGGRPN_i = AGGS_i \times AGGO_i \times AGGD_i$$

$$(i = 1,2, \dots ,39 \; and \; j = 1,2, \dots ,55)$$

a_{ik} is the rank of $Sfailure_k$ of the FM_i , and n_i is the number of SFM_j of each failure FM_i.

Table 12: Aggregated computation of S, O, D values

Failure mode FM_i	AGO_i	AGS_i	AGD_i	**Agg. RPN** $AGGRPN_i$
1	2	2.3	2.3	10.58
2	2.1	2	2.3	9.66
3	3.3	1.7	2	11.22
4	2	2.3	2.15	9.89
5	2.7	2	1.95	10.53
6	2	1.7	2.7	9.18
7	3	3.3	2.3	22.77
8	1.7	2.7	1	4.59
9	1.6	2.7	2	8.64
10	1.7	3.7	2	12.58
11	1.65	2	2.7	8.91
12	2	2.35	2.3	10.81
13	2.3	4	3.7	34.04
14	2.7	3.7	3.7	36.963
15	2	2.3	2.85	13.11
16	2	3	2.3	13.8
17	2.7	1.7	1.7	7.803
18	2.0234375	2.98125	2.3375	14.100672
19	1.452054795	3.032876712	1.995890411	8.78970811
20	1.7	1.7	1.3	3.757
21	1.163043	3.528261	1.71087	7.020589
22	1.7	2.3	1.7	6.647
23	1.748529	3.725	1.414706	9.214364
24	2.7	3.3	1.3	11.583
25	2.3	1.7	1.3	5.083
26	2	2.3	1.7	7.82
27	2.25	2.3	1.7	8.7975
28	3	2	2.7	16.2

Failure mode FM_i	AGO_i	AGS_i	AGD_i	**Agg. RPN** $AGGRPN_i$
29	1.604	4.026	1.67	10.78437
30	1.911111	2.188889	2.033333	8.50586
31	2.7	2.3	2.3	14.283
32	2.3	4	1	9.2
33	2.461905	2.442857	2.095238	12.60093
34	2.661875	1.6025	2.05625	8.771252
35	1.853425	2.027397	1.765753	6.635045
36	2.7	3.3	2.3	20.493
37	3.3	3.7	2.7	32.967
38	1.733333	4.561905	2.407143	19.034
39	1.29	1.365	1.106667	1.948674

Aggregated S, O, D and RPN values were used while applying DEA method.

4.3.1 Efficiency computation by applying DEA

Table 13 summarizing the variables of each DMU found by the DEA program software. CRS based CCR aligned model used in the envelopment form.

Table 13: DEA units

	INPUT values			**OUTPUT values**	**RESULTS**
DMU NO	**Aggregated O**	**Aggregated S**	**Aggregated D**	**RPN value**	**Efficiency value**
1	2	2.3	2.3	10.58	46
2	2.1	2	2.3	9.66	48.3
3	3.3	1.7	2	11.22	66.1
4	2	2.3	2.15	9.89	44.2
5	2.7	2	1.95	10.53	53.2
6	2	1.7	2.7	9.18	54.1
7	3	3.3	2.3	22.77	81.1

	INPUT values			OUTPUT values	RESULTS
DMU NO	Aggregated O	Aggregated S	Aggregated D	RPN value	Efficiency value
8	1.7	2.7	1	4.59	37.6
9	1.6	2.7	2	8.64	41.9
10	1.7	3.7	2	12.58	59.7
11	1.65	2	2.7	8.91	44.6
12	2	2.35	2.3	10.81	46.4
13	2.3	4	3.7	34.04	100
14	2.7	3.7	3.7	36.963	100
15	2	2.3	2.85	13.11	57.1
16	2	3	2.3	13.8	56.5
17	2.7	1.7	1.7	7.803	45.9
18	2.0234375	2.98125	2.3375	14.100672	56.9
19	1.452054795	3.032876712	1.995890411	8.78970811	44.2
20	1.7	1.7	1.3	3.757	24.4
21	1.163043	3.528261	1.71087	7.020589	42.6
22	1.7	2.3	1.7	6.647	34.9
23	1.748529	3.725	1.414706	9.214364	53.3
24	2.7	3.3	1.3	11.583	73
25	2.3	1.7	1.3	5.083	33
26	2	2.3	1.7	7.82	38.3
27	2.25	2.3	1.7	8.7975	42.7
28	3	2	2.7	16.2	81.1
29	1.604	4.026	1.67	10.78437	58.5
30	1.911111	2.188889	2.033333	8.50586	40
31	2.7	2.3	2.3	14.283	62.2

	INPUT values			OUTPUT values	RESULTS
DMU NO	Aggregated O	Aggregated S	Aggregated D	RPN value	Efficiency value
32	2.3	4	1	9.2	75.3
33	2.461905	2.442857	2.095238	12.60093	54.8
34	2.661875	1.6025	2.05625	8.771252	54.8
35	1.853425	2.027397	1.765753	6.635045	34.5
36	2.7	3.3	2.3	20.493	74.3
37	3.3	3.7	2.7	32.967	100
38	1.733333	4.561905	2.407143	19.034	79.7
39	1.29	1.365	1.106667	1.948674	15.5

As it is seen, the efficiency value of several DMUs is same with the same ranking. In order to solve this problem, DMUs were ranked according their corresponding aggregated RPN numbers shown in table 9. Table 14 shows new ranks for each DMU.

Table 14: New Ranks of each DMU

DMU	Eff. value	Eff. Ranks	Ag. RPN rank	New Eff. rank
DMU13	100	1	2	2
DMU14	100	1	1	1
DMU37	100	1	3	3
DMU28	81.1	2	7	5
DMU07	81.1	2	4	4
DMU38	79.7	3	6	6
DMU32	75.3	4	23	7
DMU36	74.3	5	5	8
DMU24	73	6	14	9
DMU03	66.1	7	15	10
DMU31	62.2	8	8	11
DMU10	59.7	9	13	12
DMU29	58.5	10	17	13
DMU15	57.1	11	10	14
DMU18	56.9	12	9	15
DMU16	56.5	13	10	16
DMU33	54.8	14	12	17

DMU	Eff. value	Eff. Ranks	Ag. RPN rank	New Eff. rank
DMU34	54.8	14	28	18
DMU06	54.1	15	24	19
DMU23	53.3	16	22	20
DMU05	53.2	17	19	21
DMU02	48.3	18	21	22
DMU12	46.4	19	16	23
DMU01	46	20	18	24
DMU17	45.9	21	32	25
DMU11	44.6	22	25	26
DMU04	44.2	23	20	27
DMU19	44.2	23	27	28
DMU27	42.7	24	26	29
DMU21	42.6	25	33	30
DMU09	41.9	26	29	31
DMU30	40	27	30	32
DMU26	38.3	28	31	33
DMU08	37.6	29	37	34
DMU22	34.9	30	34	35
DMU35	34.5	31	35	36
DMU25	33	32	36	37
DMU20	24.4	33	38	38
DMU39	15.5	34	39	39

What is seen in the table 14, there are some failure modes changed their efficiency after applying the DEA method. For example failure mode 28 has became in the 5st place in terms of efficiency after applying DEA method, but its aggregated FMEA rank was 7. This means that applying DEA method can easily change FMs rank priority.

4.3.2 Clarification of the results

Let's define the $\%\ of\ hazard\ priority$ of failure mode with P_2=P_r found in table 10. The ranks of table 14 normalized as follows:

$$P_e = 100 - ((^{new\ efficiency\ rank}/_{39}) \times 100)$$

$P = P_e - P_r$ is the progress of difference between the DEA ranks and the aggregated FMEA. Failure modes that won ranks, lost ranks and kept same rank symbolized by the red, green and white colors respectively. Results are presented in Table 15.

Table 15: Efficiency comparison of FMEA and DEA

F-mode FM_i	P_r	P_e	P
1	43.58	38.46	-5.12
2	33.33	43.59	10.26
3	51.28	74.36	23.08
4	35.89	30.77	-5.12
5	41.02	46.15	5.13
6	28.20	51.28	23.08
7	89.74	89.74	0
8	2.56	12.82	10.26
9	20.51	20.51	0
10	61.53	69.23	7.7
11	25.64	33.33	7.69
12	46.15	41.02	-5.13
13	94.87	94.87	0
14	97.43	97.43	0
15	69.23	64.1	-5.13
16	71.79	58.97	-12.82
17	12.82	35.89	23.07
18	79.48	61.53	-17.95
19	64.1	28.2	-35.9
20	0	2.56	2.56
21	10.25	23.07	12.82
22	7.69	10.25	2.56
23	76.9	48.71	-28.19
24	56.41	76.92	20.51
25	5.12	5.12	0
26	15.38	15.38	0
27	23.07	25.64	2.57
28	81.05	87.17	6.12
29	51.28	66.66	15.38
30	66.66	17.95	-48.71
31	74.35	71.8	-2.55
32	30.76	82.05	51.29
33	58.97	56.41	-2.56
34	17.94	53.84	35.9
35	38.46	7.69	-30.77
36	87.18	79.49	-7.69
37	92.3	92.3	0
38	84.61	84.61	0
39	48.71	0	-48.71

What can be seen from the table 15, applying DEA method shows different rankings than FMEA method in terms of efficiency. More than half of the failures have remained in same priority after applying DEA method and this means, in terms of efficiency FMEA method can perform very well regarding these failure modes but almost half of the failures won or lost ranks in terms of efficiency and this means solving these problems just using FMEA, can be inefficient under real world. For example, let's choose the most efficient failure mode after applying DEA method. For example, the FM number 32 was placed in the last rows in FMEA, but after applying DEA is prioritized over 51% of the FMs, the logic is, it has very high seriousness level but with low occurrence and high detectability which makes it lose ranks when applying FMEA and if this failure will not be detected as important one, it can harm working environment. Here, our DEA method works very well with the correct evaluation of failure modes.

Table 16: The most efficient failure modes

F-mode FM_i	P_r	P_e	P
14	97.43	97.43	0
13	94.87	94.87	0
37	92.3	92.3	0
7	89.74	89.74	0
28	81.05	87.17	6.12
38	84.61	84.61	0
32	30.76	82.05	51.29
36	87.18	79.49	-7.69
24	56.41	76.92	20.51
3	51.28	74.36	23.08
31	74.35	71.8	2.55
29	51.28	66.66	15.38
10	61.53	69.23	7.7
15	69.23	64.1	-5.13
18	79.48	61.53	17.95

In table 16, Failure modes with the most efficiency scores were listed. Most of them did not change their ranks even after applying DEA method but, for example failure mode 32 gained more than 51 efficiency score which made it very important to solve.

4.4 Recommendations to prevent Possible Failures

In the last section of result chapter deliver enough information was delivered about preventing failures with the probability of decreasing the occurrence value for each failure mode. All information got with collective brainstorming, using expert's suggestions and thanks to enormous internet database.

Table 17: Process control and recommendations

Failure mode FM_i	**Current Control**	**Recommended Action**
1	Permission must be obtained from the distributor for more accurate measurement of thickness	Using the thickness measurement device will decrease wrong inspection risk
2	Engineer must ensure that odorous gases are removed from the foam	The choice of foam made from better quality chemicals can greatly reduce the risk of odor
3	No current control	This is the most common case on producing wadding and the best recommendation is to select the most reliable distributor
4	No current control	It is not always possible to detect issues on buckram and the best case is to select the most reliable distributor after several checks
5	No current control	Engineer must ensure that the raw textile distributor is maintaining the correct pH level and using an appropriate dying agent in order to keep the quality of its products

Failure mode FM_i	**Current Control**	**Recommended Action**
6	Engineer and the operator should check the fabric carefully before stitching it using quilting machine	Engineer should get necessary information about producing the current raw textile before importing
7	Engineer / Operator must check the wires carefully in order to prevent	Engineer / Operator must check the wires carefully in order to prevent enormous production queue
8	Operator should make a point of duty to check the status of the starter coil before doing anything	Buying authentic starter coils will be the best choice even if they are more expensive than inferior coils
9	Operator should turn of the entire system in order to prevent additional failures	Operator should check the stabilizer every hour for any loading or heating issues
10	Operator must turn off the machine	Several particles of the machine are rotating and rubbing off one another so, adequately oiling these particles will lead machine to not overheat while producing springs
11	Stopping production until new valves are maintained	Operator must ensure that the temperature of the valves did not exceed the recommended peak temperature
12	Machine termination	As demand increases in time it is expected that the occurrence of this failure may almost reach to peak point. So, it is recommended to use another spring assembly machine in order to prevent the failure
13	Immediate first aid	Even if the operator is well educated It does not mean he will not take injury during working phase. Operator should rest enough after certain work time or if he feels exhausted
14	Shutting down the system in order to prevent possible failures	Operator training is necessary and the mistake is almost unforgivable
15	Operator should bring the machine to idle working phase in order to stabilize the oil on details	Operator should check the oiling on details before putting the springs inside the machine

Failure mode FM_i	**Current Control**	**Recommended Action**
16	Temperature gauge must be corrected	In case of high temperature, an automation system with a signaled high temperature alarm should be installed
17	Operator training	Operator should keep the felt materials on the dry and clean place in order to prevent material loss
18	Operator training	Operator should adjust the spray gun correctly / Ambient lighting should be well balanced in order to prevent mistakes during gluing process
19	Operator training	Operator should set up the compressor tank to automatically stop at 120 PS
20	Operator training	Operator should ensure that canister cap stood open after each gluing session
21	Operator training	Periodic control should be done by the authorized operator once a year \ Compressor pressure tests should be carried out at 1.5 times the maximum allowable pressure
22	Operator training	Operator should check the fluid needle for any deformations on each working phase
23	Done local ventilation using air extractors to decrease the risk	Adhesive chemicals should be checked by the operator on daily basis \ An automatic ventilation system should be installed
24	Local ventilation done	Compressor should be kept away from chemical components
25	Operator training	Operator must place the fabric parallel to the laser plates of the machine

Failure mode FM_i	**Current Control**	**Recommended Action**
26	Operator training	Operator should not start process without removing the wrinkles on the surface of the fabric / Operator should maintain proportion at right and left distances when placing the fabric
27	No current control	Hanging the raw fabric instead of laying it on the ground will dramatically decrease the creasing
28	Operator training	Operator should check the part of used wadding carefully before starting to stitch it together with fabric
29	Layout of power lines is not suitable for the working environment	When stacking fabric rolls, they should be stacked in the safe area so that they are not near the electrically active area
30	Deep cleaning	The inner surface of the machine should be cleaned after the operations
31	No current control	The maintenance of the carrier system inside the machine should be done periodically
32	Operator should check the bench at each sewing stage	Getting more advanced sewing machine will be the best choice for preventing this failure
33	Operator training	Operator should adjust the needle to make it 11.1 cm from the needle plate while it is at its highest position / Operator should adjust upper and lower wire clamp to adjust the line tight
34	Operator training	While crochet moves forward at the same time the needle should move upward from the lowest point / Bottom line should be properly tightened
35	Operator should slowly pull the mattress in place	Tightening the fastening screw, adjusting the position of crochet correctly and buying quality needles will decrease the risk

Failure mode FM_i	**Current Control**	**Recommended Action**
36	Operator should release the contact button in less than 5 seconds	
37	No current control	Double packaging may eliminate this failure with a big chance
38	No current control	Electrical equipment should be taken out of the warehouse and electrical devices should be prevented from being brought into the warehouse
39	No current control	Solvents should be stored in suitable stainless-steel cabinets and fireproof containers for explosives / Empty containers should never be kept in the work area, additional solvent may remain in the containers

Chapter 5

CONCLUSION AND FUTURE STUDY

5.1 Conclusion

Through this research, enough information retrieved related to mattress production in details, with respect to our specialists it was possible to get enough data about possible failures and effects of mattress production in a practical way. In the first part, FMEA explained to the specialists in an easy way to conduct the study more reliable and to get soft data in order to achieve better solution.

In a second part, the FMEA approach was utilized to achieve possible failure modes in mattress factory by gathering important data from experts after completion internet search to avoid possible missing failures can be found after the research. The RPN was computed for each failure modes, prioritized the effects of each failure mode and used aggregated approach to improve reliability of the methodology.

In a third part, the FMEA approach was combined with DEA method in order to achieve more successful result and to understand how DEA can change the failure priority. In order to apply DEA method, the SFMs (failure effects) were aggregated in the first phase, by calculating the aggregated severity, detection and occurrence to get new aggregated RPN numbers(ranked). After that, a CCR based DEA model was used to calculate the efficiency of resolving each of the FMs. Initial RPN values were the output values and the inputs were the aggregated occurrence, detection and severity respectively. Failure modes were listed according to their RPN numbers as some of FMs had same efficiencies. It has been found that after implementing DEA the new efficiency ranks were more reliable than the FMEA alone. It is also found that each working sector has its own efficient and inefficient failures. It has been figured that the choice of above methods without any doubt gave us the best results.

This research can shed the light for the researchers to conduct a better study related to combined FMEA-DEA approach and to gather necessary information about mattress production.

5.2 Future study

This is the first research conducted in mattress factory by applying multiple risk assessment and efficiency methods. In a forthcoming study, the research method can be enhanced to find much more reliable findings related to mattress production, including different sectors too. Aggregated RPN was used as output, but the research can be improved also, including time and cost variables(Chnina, 2020).

Some other DEA and FMEA models can be used; modified DEA BCC models, fuzzy FMEA as well as using different inputs and outputs can lead to improved reliability of the study.

Mattress manufacturing is developing day after day as other manufacturing sectors and this research may help other researchers to conduct better studies about mattress manufacturing.

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APPENDICES

Appendix A: The DEA Model Settings Applied in PIM DEA Solver

Name	CCRin		
Description			
Orientation	Input Oriented		
Return to Scale	CRS		
MPSS & Ident. RTS	Disabled		
Super Efficiency	Disabled		
Malmquist Index	Disabled		
Bootstrapping	Disabled		
Input Variables	Index1	Index2	Index3
Output Variables	Index4		
Selected Periods	Sheet2		
DMU Selections	NO		
Categorical Selections	NO		
Weight Restrictions	Disabled		

Appendix B: The Outputs of the CCR Model

Name	Efficiency
DMU1	46
DMU2	48.3
DMU3	66.1
DMU4	44.2
DMU5	53.2
DMU6	54.1
DMU7	81.1
DMU8	37.6
DMU9	41.9
DMU10	59.7
DMU11	44.6
DMU12	46.4
DMU13	100
DMU14	100
DMU15	57.1
DMU16	56.5
DMU17	45.9
DMU18	56.9
DMU19	44.2
DMU20	24.4
DMU21	42.6
DMU22	34.9
DMU23	53.3
DMU24	73
DMU25	33
DMU26	38.3
DMU27	42.7
DMU28	81.1
DMU29	58.5
DMU30	40
DMU31	62.2
DMU32	75.3
DMU33	54.8
DMU34	54.8
DMU35	34.5
DMU36	74.3
DMU37	100
DMU38	79.7
DMU39	15.5

Appendix C: Initial O, S, D values

Birol Turhan			
SFM	Occurrence	Severity	Detection
1	1.5	2.3	1.4
2	2	3	2.4
3	3.4	1.6	2.1
4	2.5	2.9	1
5	2.6	2.8	1
6	2.5	1.5	2.8
7	2.5	3	1.5
8	1	3	1
9	1	3.5	1.5
10	1	4.2	1.8
11	2.4	2.5	2
12	2	2	2.5
13	2.2	5	4.1
14	2.6	4	4
15	1.5	1.9	1.6
16	1.7	3	2.5
17	3.6	1	1
18	1.5	3.1	1.5
19	1.2	4	3
20	1.4	4.2	1
21	1	5	1.5
22	1.3	1.7	1
23	1	1	1
24	1	4	1.8
25	1.6	2	1.6
26	2.3	5	1
27	1.8	5	1.3
28	1	4	1
29	2	1	1
30	1.5	1	1
31	2	2.4	1.9
32	1.6	3	1.7
33	3.5	2	3.1
34	1.5	3.5	2.5
35	1	4.7	1.3
36	1.7	2.9	1.5
37	1	2	2.3

Appendix C: Continued

Birol Turhan			
SFM	Occurrence	Severity	Detection
38	2	2	2.5
39	2	5	1
40	2	1.5	2.5
41	1.5	3.3	1
42	1.6	1.7	2.85
43	2	2.5	2
44	1	1	1.35
45	1.3	2	1
46	1.2	2.2	2.8
47	2.6	1.8	3.7
48	2	3.9	2.5
49	2.4	5	2.5
50	1.8	5	1.3
51	1.2	5	2
52	1.3	5	4.3
53	1.3	4	5
54	2.4	1	2.4
55	1.7	1.2	1.3

Appendix C: Continued

Səid Ələkbərov			
SFM	Occurrence	Severity	Detection
1	2	2.6	3
2	2.3	1.5	2.5
3	4	2	2.9
4	1.5	2.5	2.7
5	2.8	2.2	2.35
6	1.5	2	2.8
7	3	3.4	3.9
8	2.4	2.1	1
9	1.8	3	2
10	1.5	4.3	2
11	1.3	2	3
12	2	2.55	1.9
13	2.3	3.8	3.5
14	2.5	3.5	3.8
15	2.5	3	3.8
16	1.5	3	2.5
17	2.5	2	2.1
18	2.65	3	1.5
19	2	3.6	3.5
20	2.2	2.2	1.9
21	1.2	2.8	3
22	2	1.4	1.9
23	1.4	4.5	1.2
24	1	3.6	2.6
25	2	2.2	1.8
26	2.8	3.5	1.45
27	4	3.4	1.8
28	1.7	3.2	1.7
29	3.1	5	1.35
30	2.8	2.1	1.6
31	2	3	1.4
32	2.25	1.8	1.8
33	2.5	2	2
34	1.8	3.5	1.6
35	1.7	4	1.8
36	2.8	2	1.65
37	2	1.8	1.6

Appendix C: Continued

Səid Ələkbərov			
SFM	Occurrence	Severity	Detection
38	3.1	2.9	2.1
39	2.4	3.7	1
40	3	1.3	1
41	3	2	3
42	2.35	1.7	1
43	4	1	1.8
44	2.5	1.8	1.2
45	2.6	2.2	1.4
46	1.6	2.7	3
47	3	2.8	2.8
48	3.5	3	1.95
49	3.7	3	2.1
50	2.2	5	1.6
51	1.75	3.2	2.5
52	1.1	4.5	4.5
53	2.1	2.8	5
54	1.8	3.7	2.3
55	1.9	2.9	1.65

Appendix C: Continued

Dmitri Vorontsev			
SFM	Occurrence	Severity	Detection
1	2.5	2	2.5
2	2	1.5	2
3	2.5	1.5	1
4	2	1.5	2.75
5	2.7	1	2.5
6	2	1.6	2.5
7	3.5	3.5	1.5
8	1.7	3	1
9	2	1.6	2.5
10	2.6	2.6	2.2
11	1.25	1.5	3.1
12	2	2.5	2.5
13	2.4	3.2	3.5
14	3	3.6	3.3
15	2	2	3.15
16	2.8	3	1.9
17	2	2.1	2
18	2.3	2	3
19	1.9	3.5	3.1
20	1.2	1.7	2.2
21	1.4	3	3
22	1.8	2	1
23	1.5	4.4	1.7
24	1	3.8	2.2
25	1.5	2.7	1.7
26	3	3.5	1.45
27	3.8	3.9	2.6
28	1.2	3.6	1.5
29	3	3.9	1.55
30	2.6	2	1.5
31	2	1.5	1.8
32	2.9	2.1	1.6
33	3	2	3
34	2.7	2.9	1.9
35	1.5	4.5	1.4
36	2.4	2	1.95
37	1.8	2.5	3

Appendix C: Continued

Dmitri Vorontsev			
SFM	Occurrence	Severity	Detection
38	3	2	2.3
39	2.5	4.3	1
40	3.1	3.8	2.5
41	2.1	2.5	2.6
42	2.5	1.7	3.05
43	3.6	1	1.7
44	2.5	2.3	1.35
45	1.5	2.1	1.5
46	1.4	2.3	3.5
47	2.5	2.3	3.1
48	2.6	3	2.45
49	3.8	3.1	3.5
50	2	5	1
51	1.85	4.4	2.7
52	1.2	4.9	3.8
53	1.7	3.1	5
54	3.9	3.4	2.2
55	1.5	2.5	1.55

Appendix D: Failure modes of the mattress production factory

	Process type	Failure modes	SFM	Cause of failure (Sub Failure modes)		Effects of failure
1	Inspection of raw materials	The density of the polyurethane foam does not meet the requirements	1	Inspection failure		Customers might feel overheat while using mattress
2		An unpleasant chemical smell coming from the polyurethane foam	2	Inspection failure		Customer dissatisfaction
3		Wadding fibers are not properly bonded	3	Inspection failure		Bearding on the surface of the mattress
4		Gaps on the surface of support buckram	4	Inspection failure		High water permeability
5		Uneven Dyeing/Printing/Dye marks on the surface of raw textile	5	Inspection failure		Customer dissatisfaction
6		Random drop stitches appear in the fabric	6	Inspection failure		Work delays
7		The inappropriate thickness of steel wire	7	Measurement failure		Machine malfunction
8	Spring making machine	Set of useless Bonnell springs during an operation	8	Using inferior starter coil		Material loss
9		Corrupt monitor interface	9	Voltage stabilizer stopped working because of high output voltage supply		Operator can not transfer digital information to the computer
10		Machine overheating as the operator produces spring	10	Poorly lubricated particles		Serious damage to the machine
11	Unit-Spring Assembly Machine	Spring units are not firmly attached	11	Rupture on the valves connecting the units		Poor quality of the mattress
12		Incorrect twisting of wires	12	System block changed the operational state because of high working tension		Poor quality of the mattress
13		Hand injury of the worker	13	Momentary fault while assisting spring units with corresponding wire		Work delays
14		Electrical shock while cleaning the machine	14	Leaving the emergency shutdown system active		System malfunction

Appendix D: Continued

FM number	Process type	FMs	SFM NO	SFMs		Effects of failure
15	Unit-Spring Assembly Machine	Oil leakage from the springs	15	Excessive oiling the details		Customer dissatisfaction
16		The high temperature on the valve lines	16	Malfunction of temperature monitor		Risk of damage to the springs with thermal expansion
17	Gluing Process	The felt does not adhere properly to the foam	17	Materials to be glued are not clean enough		Loss of materials
18		Musty smell coming from the mattress	18	Over-spraying the surface of the materials		Customer dissatisfaction
			19	Insufficient ambient lighting		
19		Eye and skin problems on the workers	20	The canister spray system is not spraying correctly and the spray pattern is inadmissible wide		Work delays
			21	Inadequate ventilation		
20		Adhesive blocked the canister hose	22	The operator should ensure the value on the canister remained open		Work delays
21		High pressure of compressed air pumped into the tank	23	Pressure gauge failure		When compressed air rises above the set pressure, the engine continues to run and excess pressure can cause an explosion
			24	Compressor safety device malfunction		
22		Too much glue spilling while spraying	25	The fluid knob of the spray gun is not working properly		Material loss
23		Glue containers left open	26	Deformation of containers during transportation		Accumulation of used adhesive in the environment may cause explosion and fire
			27	Deformation in containers during storage		
			28	Insufficient ventilation		
24		Compressor absorbs harmful toxic gas or dust	29	Insufficient ventilation		Contact of gases in the compressor with different substances may cause fire and explosion
25	Quilting / printing / embroidery process	Misprinting, off printing, or absence of printing	30	Wrong leveling procedure by operator		Patterns are completely or partially missing
26		Twisted or knotted rope	31	Incorrect loading of fabric into the machine		Loss of materials
27		Crease marks on the fabric	32	Inadequate preparation, relaxation, or bulking of fabric		Laser needle failure
28		Separation of the stitched materials	33	Having less highly compressed chemical fibers inside wadding		Loss of materials

Appendix D: Continued

FM number	Process type	FMs	SFM NO	SFMs		Effects of failure
29	Quilting / printing / embroidery process – Gluing Process	Stacking fabric very close to the electricity line	34	Short circuit or high voltage in the power line		Work delays
29	Quilting / printing / embroidery process – Gluing Process	Stacking fabric very close to the electricity line	35	Leaving fabric material in front of the electrical panel		Fire risk because of fabrics catching fire
30	Quilting / printing / embroidery process – Gluing Process	Roughness of the inner surface of the machine	36	Residues adhering to the machine inner surface		Damage the texture of the fabric
30	Quilting / printing / embroidery process – Gluing Process	Roughness of the inner surface of the machine	37	Insufficient cleaning the inside of the machine		Loss of material
31	Quilting / printing / embroidery process – Gluing Process	Failure of the conveyor chain system inside the machine	38	Loosening of chain links		Failure of the machine
32	Using tape edge sewing machine	Displacement on the bench during sewing	39	Mis-controlling the bench before sewing		Finger injury
33	Using tape edge sewing machine	Skipping stitch during sewing operation	40	The needle bar position is not correct		Loss of material
33	Using tape edge sewing machine	Skipping stitch during sewing operation	41	The bottom line is not tight		Loss of material
34	Using tape edge sewing machine	Broken line during the operation	42	The bottom line is too loose or too tight		Loss of material
34	Using tape edge sewing machine	Broken line during the operation	43	The position of the looper is not correct		Loss of material
35	Using tape edge sewing machine	Broken needle during the operation	44	Operator pulls or drags the mattress too roughly		Machine stitching failure
35	Using tape edge sewing machine	Broken needle during the operation	45	The needle hits the needle plate		Machine stitching failure
35	Using tape edge sewing machine	Broken needle during the operation	46	The crochet impact needle		Machine stitching failure
35	Using tape edge sewing machine	Broken needle during the operation	47	Needle quality is too bad		Machine stitching failure
36	Using manual mattress packaging machine	Elongated resistor	48	Heated resistors		Resistor breakage
37	Using manual mattress packaging machine	Gaps in packaging	49	Operator does not inspect the product after packaging		High level of humidity, smell of the mattress
38	Storage of materials	Presence of electrical equipment in the warehouse	50	Leakage in electrical installation		The presence of electrical equipment and panels in the warehouse may trigger sparks, fire and explosion may occur in the warehouse
38	Storage of materials	Presence of electrical equipment in the warehouse	51	Overloading of electrical cables		The presence of electrical equipment and panels in the warehouse may trigger sparks, fire and explosion may occur in the warehouse
38	Storage of materials	Presence of electrical equipment in the warehouse	52	Short circuit		The presence of electrical equipment and panels in the warehouse may trigger sparks, fire and explosion may occur in the warehouse
38	Storage of materials	Presence of electrical equipment in the warehouse	53	Faulty grounding		The presence of electrical equipment and panels in the warehouse may trigger sparks, fire and explosion may occur in the warehouse
39	Storage of materials	Improper storage of solvents	54	Holes in solvent containers		Solvent vapors can spread in the environment and create an explosive atmosphere
39	Storage of materials	Improper storage of solvents	55	Empty solvent Containers		Solvent vapors can spread in the environment and create an explosive atmosphere