Failure Modes and Effects Analysis (FMEA) Method Based on Data Envelopment Analysis (DEA) Approach for the Efficiency Measurment of Radio Frequency Identification (RFID)

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ABSTRACT

There are many papers which emphasize on the benefits of radio frequency identification (RFID) technology implementation in the management and the production. This technology is used in many fields such as inventory, logistics, return management, order picking in a warehouse, assembly and testing and health care Etc. The existing literature examined the efficiency of RFID based on one of the following factors: accuracy, reliability, service enhancement, cost, time, work efficiency, flexibility, interactivity, risk management, emergency, privacy, energy and big Data.

In this research, we will shed the light on the failure modes of this technology by using FMEA Approach, then we will measure the efficiency of solving each of these failures according to their severity, occurrence, detection, cost and time; using data envelopment analysis (DEA). DEA is a non-parametric method that evaluates the efficiency of the collection of decision making units (DMUs) when all of them consume and produce the same inputs and outputs respectively. A DMU can be efficient when it is able to produce more outputs by consuming fewer inputs. This economical point of view transforms the issue into a linear programming problem. Based on DEA concept, each failure mode of the RFID technology will be considered as a DMU, and the above mentioned criteria as inputs/outputs. Then the efficiency of these DMUs will be evaluated by DEA models.

Keywords: FMEA, RFID, DEA, efficiency, cost and time based DEA, DEA based FMEA

ÖZ

Yönetim ve üretimde radyo frekansı tanımlama (RFID) teknolojisini kullanmanın avantajlarını vurgulayan birçok makale bulunmaktadır. Bu teknoloji envanter, lojistik, iade yönetimi, herhangi depoda sipariş toplama, montaj ve test ve sağlık vb,konularını içermektedir. Mevcut literatür RFID'nin verimliliğini şu faktörlerden birine göre inceledi: doğruluk, güvenilirlik, hizmet geliştirme, maliyet, zaman, iş verimliliği, esneklik, etkileşim, risk yönetimi, acil durum, gizlilik, enerji ve büyük veri.

Bu araştırma, FMEA Yaklaşımı kullanarak bu teknolojinin hata modlarına ışık tutacak, daha sonra bu hataların her birini şiddet, ortaya çıkma, tespit, maliyet ve zamanlarına göre çözme verimliliğini olcecelim bu celismede bu veri DEA kullonerek hesaplanir. DEA, hepsi aynı itici güçleri tüketip aynı çıktıları ürettiğinde, karar verme birimlerinin (DMU'lar) toplanmasının etkinliğini değerlendiren parametrik olmayan bir yöntemdir. Bir DMU, daha az itme tüketerek daha fazla çıktı üretebiliyorsa verimli olabilir. Bu ekonomik bakış açısı, konuyu doğrusal bir programlama problemine dönüştürür. DEA konseptine dayanarak, RFID teknolojisinin her arıza modu bir DMU ve yukarıda belirtilen kriterler girdi / çıktı olarak kabul edilecektir. Daha sonra bu DMU'ların verimliliği DEA modelleri ile değerlendirilecektir.

Anahtar Kelimeler: FMEA, RFID, DEA, etkinlik, maliyet ve zaman bazlı DEA, DEA bazlı FMEA

DEDICATION

★★★★★★★★★★

To the soul of my father Mohamed Chnina
To the soul to my grandfather Touhami Houmairat
To the source of my power, my mother Bouchra Houmairat
To my brother Ibrahim El Khalil Chnina, and his wife Izdihar Belhaimer, my sister
To my babies, my niece and my nephew Soundouss and Mohamed Barae Chnina
Everything I do…I do it for you

★★★★★★★★★★

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LIST OF ABBREVIATIONS

ACA	Anisotropic Conductive Adhesive
ADC	Analog Digital Converter
API	Application Programming Interface
ATM	Automated Teller Machine
BCC	Banker, Charnes and Cooper
CCR	Charnes, Cooper and Rhodes
CPU	Central Processing Unit
CRS	Constant Returns to Scale
DAC	Digital Analog Converter
DC	Direct Current
DFA	Determinist Frontier Analysis
DLP	Dual Linear Program
EEPROM	Electrically Erasable Programmable Read Only Memory
EM	Electromagnetic
EOS	Electrical Overstress
EPC	Electronic Product Code
ERP	Enterprise Resource Planning
ESD	Electro-Static Discharge
FM	Failure Mode
FP	Fractional Program
GPS	Global Positioning System
HF	High Frequency
IC	Integrated Circuit

IOT	Internet Of Things
ISM	Industrial-Scientific-Medical
ISO	International Standards Organization
IT	Information Technology
LF	Low Frequency
LP	Linear Program
MODEM	Modulator Demodulator
NFC	Near Field Communication
NIRS	Non Increasing Returns to Scale
PC	Post Computer
PPF	Production Possibilities Frontier
PPS	Production Possibility Set
RF	Radio Frequency
RPN	Risk Priority Number
RTLS	Real Time Location Systems
RTS	Returns to Scale
SAR	Specific Absorption Rate
SD	Secure Digital
SFA	Stochastic Frontier Analysis
SFM	Sub Failure Mode
SHF	Super High Frequency
SMA	Surface Mount Assembly
UHF	Ultra-High Frequency
USB	Universal Serial Bus
UV	Ultra-Violet

VRS	Variable Returns to Scale
Wi-Fi	Wireless Fidelity

Chapter 1

INTRODUCTION

1.1 Preamble

We are in the 21st century, where industry has already seen its four revolutions and people are dealing with inventions undreamed by the previous generations.

The change began with the introduction of the Industry 1.0 at the end of the 18th and the beginning of the 19th century, with the invention and refinement of the steam and water power leading to the mechanization of manufacturing. Then Industry 2.0 was born in late 19th and early 20th century by the use of electrical power in mass production assembly lines. The evolution boomed with the discovery of the usefulness of the silicon in the late 20th century, the industry 3.0 saw the light with the digital revolution, the production became then automated using electronics, programmable logic controllers, IT systems and robotics . By the 21st century, the concept of 4.0 has become the trend; we started hearing about Industry 4.0, Web 4.0, Education 4.0, logistics 4.0. Everything became smart; we have smart factory, smart home, smart city, and smart phone Etc. The decision making of cyber physical systems became autonomous using machine learning and huge data analysis. The Internet of things (IOT) and the cloud technology made everything linked together and interoperate with each other.

These connections are made through sensors, Global Positioning System (GPS), laser scanners, internet, and radio frequency identification (RFID) (Smart-tec.com, 2019, Day, 2018).

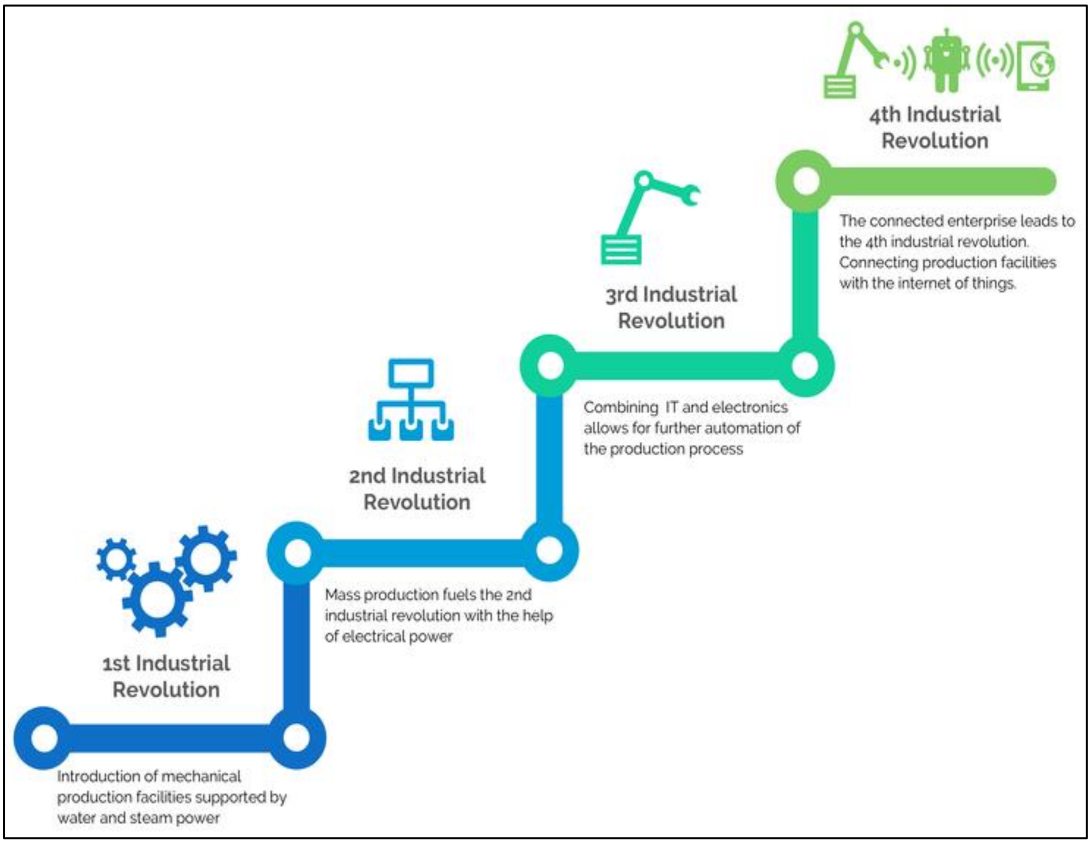

Figure 1: The Industrial Revolutions (Group, 2019)

The main goal of industry 4.0 is the optimization of digital communication between man and machine, which means that the work pieces (tools, equipment, machinery and containers) require a digital identification and the possibility to exchange information with each other in real time.

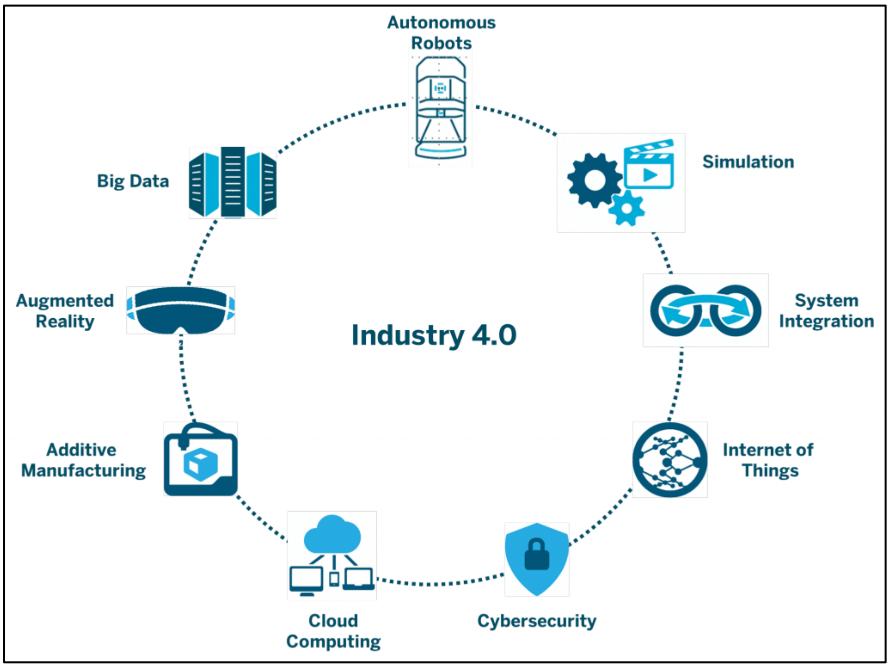

Figure 2: The Industry 4.0 Concept (Group, 2019)

A barcode would fulfill this role, but unfortunately it is not possible to modify the data on the barcode, information can only flow in one direction, unlike RFID and NFC technology, where the communication can be in both directions; this means that the data can be read, updated and added. The digital product memory gives information about the stages of the production process already done and the next steps as well. Real time data can be provided then about any step of the process of production, which allows the detection of any irregularities or setbacks. An automatic selection of which machine is going to take the job of the defective one can be done, avoiding interruption while a machine requests repair. All the information is managed from the production floor, improving the efficiency of cataloging and producing better results.

After the production process, hundreds of goods can be tracked and checked simultaneously using the RFID transponders. Once this data is incorporated into an ERP system, it will be easy to compare the submitted orders with the existing articles on line, this facilitates the detection of critical levels of stock across the logistics chain; the supply chains can then monitor the arrival of goods and prevent counterfeiting products. Customers can view and visit the stores which have the product when it is places for sale; the product is classified as sold after its sale, and taken out of the system, preventing loss costs and overheads.

By connecting different machines, RFID makes managing products more efficient, improves production logistics and manufacturing, reduces downtimes, minimizes errors, lowers costs, and therefore contributes in controlling globalized goods flows and supply chains from manufacturing and sales to shipping and distribution, from the beginning to the end (Group, 2019).

1.2 Problem description

The RFID technology is not used only in production and supply chains, but in variant fields as well, like logging, baggage, and road applications, as well as healthcare processes, pharmaceutical industry, commerce, cloths stores, connected trees, connected bins, flooding warning, banking, access control…

This technology surrounds us whenever and wherever we go, everyone has at least one RFID tag in their pocket, it can be a bank card or access card to the parking or to the residence, even our passports contains a micro RFID label; these small parts play critical roles in our daily life, if they fail to accomplish their missions then the damages would be crucial. For example if the bank card is decrypted or hacked we may lose important amounts of money; imagine you want to pay by card in the market, when you are in front of the cashier they told you there is no money in your card, you connect to internet to check your account from the application or the web site, but there is a bug, impossible to connect or to convert money, as a result you will have to leave your goods there or go to the ATM or the bank and solve the problem, this embracing situation happens many times. Another example is the manufacturing process or sales management, a failure in the system can cost a lot, and customers can be lost.

For these reasons we are interested in detecting the RFID failure modes and trying to find adequate solutions.

Previously, many researches got into the RFID technology and its problems; some of them aborded the problems related to the security, privacy, ethics, software and physical drawbacks without specifying the causes and the effects or giving a classification of these failures. Other studies were interested in the impact of the RFID tags on the environment and health. While some researchers were interested in the impact of the harsh conditions of environment on the RFID tags. The FMEA method was used for the analog subsystems of the RFID system in a set of studies, but they neither compute the RPN nor gave a rate for each failure mode. Some thesis used the FMEA method to sort the failure modes dependent on the middleware components.

In our research, we are going to abord the failure modes related to both the hardware or physical part and the software components of the RFID system, from the tag to the reader and the host, as well as the failures concerning human being and the environment, we will provide the causes and the consequences of each of these failure modes as well, then we will compute the RPN to give them a rank for their risk priority.

Sometimes a given failure mode can have the highest RPN value, but solving it will not be more efficient than the other failure modes, for this reason we are going to use the cost and time factors to decide which failure mode will be the most efficient to solve, the efficiency will be computed using the DEA method.

This method will help us to avoid losing time and costs and make the system more efficient, the only problem that we may have is the data collection.

Advantages:

- ✓ Direct criticality assessment of components
- ✓ Identification areas of weak design
- ✓ Identification areas of high risk
- ✓ Identification change requirements
- ✓ Enhance design and manufacturing efficiencies
- ✓ Minimize exposure to failures
- ✓ Generates an information base reference throughout the life of the product.

Disadvantages:

- ✓ Extensive testing to gain information
- ✓ Some failure modes can be missed
- ✓ Time pressures
- ✓ Information can be missing
- ✓ Human error overlooked
- ✓ It is not a problem solving method
- ✓ It doesn’t allow the study of combinations of failures (rather reserved for Failure Trees, Markov Graph …)

1.3 Thesis structure

This work will contain five chapters, starting from the introduction and problem description; then a literature review of the previous researches related to the FMEA and DEA methods will be presented in the second chapter; after that we will discuss our methodology in the third chapter, the RFID system and its failure modes will be discussed in details, as well as the DEA inputs and outputs, we will make an experiment to show how the system works; the results of the FMEA and DEA tables will be presented and analyzed in the fourth chapter; and finally we will conclude with the fifth chapter.

The graph below summarizes the structure of this thesis:

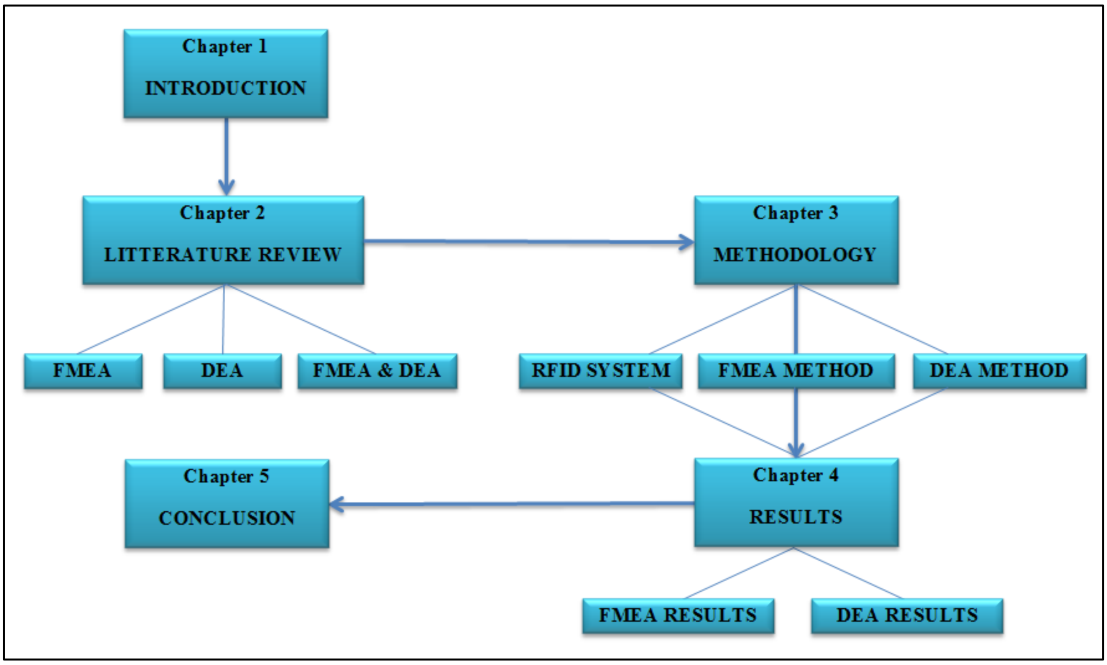

Figure 3: Thesis Structure

Chapter 2

LITERATURE REVIEW

2.1 Failure Mode and Effect Analysis

The FMEA method (Failure Mode and Effect Analysis) has been used in several fields like military, radiotherapy, chemotherapy, medication, healthcare, hospitals and laboratories, food industry, building systems, renewable energy, nuclear energy, electrical and electronic production including RFID systems, and manufacturing industry.

Some researchers focused on the improvement of FMEA tools, protocols and frameworks, such as software used to apply it, while an important set of publications aimed to optimize the effectiveness and efficiency of FMEA and overcome its limitations by combining it with other methods. In a group of papers, this method was compared with other approaches.

The following table summarizes a selection of papers and publications we could find in open access, related the FMEA approach, its fields of use, and methods with which it was combined or compared:

Table 1: FMEA Literature Review

	Year of publication	Topic	Author (s)	Summary
1	1980	MILITARY STANDARD PROCEDURES FOR PERFORMING A FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS(Washington, 1980).	DEPARTMENT OF DEFENSE Washington	Basics of the FMEA method, its types, when and how it is used (Washington, 1980).
2	2003	Reducing Medication Errors and Increasing Patient Safety: Case Studies in Clinical Pharmacology (Benjamin, 2003).	David M. Benjamin	Summary of current medication errors through case studies illustrating common scenarios leading to medication errors (Benjamin, 2003).
3	2004	An Improved Failure Mode Effects Analysis for Hospitals (Krouwer, 2004).	Jan S. Krouwer	Review of the FMEA process recommended by the Joint Commission on Accreditation of Health Organizations, where it was shown that this tool originated from reliability engineering is not familiar to hospital personnel (Krouwer, 2004).
4	2005	Methods of Failure and Reliability Assessment for Mechanical Heart Pumps (Sonna M. Patel, 2005).	Sonna M. Patel Et al	Discussion and summary of studies that evaluated the reliability, safety and the failure of artificial blood pumps. As well as human and mechanical faults. In addition to failure and reliability testing recommendations of NIH, STS, ASAIO, ANSI, AAMI, and the Bethesda Conference (Sonna M. Patel, 2005).
5	2005	The Development of FMEA Information System for Manufacturing Industry (Khairul Annuar bin Abdullah, 2005).	Khairul Annuar bin Abdullah, Jafri bin Mohd. Rohani, Mohd. Salihin bin Ngadiman	A prototype of FMEA development based on Borland Delphi Enterprise and Microsoft Access ,instead of the existing FMEAs that are done manually or by the mean of excel (Khairul Annuar bin Abdullah, 2005).
6	2006	Using failure mode and effects analysis to plan implementation of smart i.v. pump technology (Wetterneck et al., 2006)	TOSHA B. WETTERNECK, KATHLEEN A. SKIBINSKI, TANITA L. ROBERTS, Et al	The potential failures in the medication use process were identified after the implementation of new smart i.v., using FMEA method (Wetterneck et al., 2006).
7	2007	Application of Failure Mode and Effect Analysis (FMEA), Cause and Effect Analysis, and Pareto Diagram in Conjunction with HACCP to a Corn Curl Manufacturing Plant (Varzakas and Arvanitoyannis, 2007)	Theodoros H. Varzakas & Ioannis S. Arvanitoyannis	The analysis and prediction of failure modes in a food chain system (corn curls processing plant), by using the Fault Tree and the Preliminary Hazard Analysis. Then the GMOs detection of FMEA were optimized using pareto diagrams (Varzakas and Arvanitoyannis, 2007).
8	2008	Failure Site Isolation on Passive RFID Tags (Sood et al., 2008).	Bhanu Sood, Diganta Das, Michael Azarian, and Michael Pecht, Brian Bolton, Tingyu Lin	Failure modes, mechanisms and effects analysis (FMMEA) is applied for the evaluation of the materials, production and assembly processes, as well as testing environment of qualification of the RFID system (Sood et al., 2008).

Table 1 (Continued)

	Year of publication	Topic	Author (s)	Summary
9	2009	Application of Failure Mode and Effect Analysis (FMEA) and Cause and Effect Analysis in Conjunction with ISO 22000 to a Snails (Helix aspersa) Processing Plant; A Case Study (Arvanitoyannis and Varzakas, 2009).	Ioannis S. Arvanitoyannis & Theodoros H. Varzakas	ISO22000 and HACCP are compared through snails process and packaging. RPN was calculated a second time after the corrective actions were applied, lower values were found. It was found that the use of FMEA analysis within the ISO22000 system of a snails processing industry is considered important (Arvanitoyannis and Varzakas, 2009).
10	2009	A Comparative Presentation of Implementation of ISO 22000 Versus HACCP and FMEA in a Small Size Greek Factory Producing Smoked Trout: A Case Study (Sonna M. Patel, 2005).	Ioannis S. Arvanitoyannis , Christos Palaiokostas & Panagiota Panagiotaki	HACCP and ISO 22000 comparison in a smoked salmon production company, similarities and differences. Moreover, FMEA was applied, and RPN values agreed with the HACCP, which indicates that corrective actions should be done (Arvanitoyannis et al., 2009).
11	2010	Chemical safety of meat and meat products (Andree et al., 2010)	Sabine Andrée, W. Jira, K.-H. Schwind, H. Wagner, F. Schwägele	The FMEA system may be effective in order to eliminate vulnerability in the meat products production chain steps. In addition to chemical and toxicology analysis (Andree et al., 2010).
12	2010	Decision-making in product quality based on failure knowledge(Wei Dai1, 2010)	Wei Dai1, Paul G. Maropoulos , Wai Ming Cheung, Xiaoqing Tang	A new decision-making method is introduced based on the discussion of the defects of Quality Function Deployment (QFD) and Failure Modes and Effects Analysis (FMEA) (Wei Dai1, 2010).
13	2010	Read-Error-Rate evaluation for RFID system on-line testing (G. Fritz, 2010)	G. Fritz, V. Beroulle, M.D Nguyen, O. Aktouf, I. Parissis	FMEA was used for the analogic part of the RFID system, the digital part is assumed to be fault-free. The Read-Error-Rate on-line characterization was used to develop a new middleware that aims to detect the defective components of the RFID system on-line (G. Fritz, 2010).
14	2010	RFID System On-line Testing Based on the Evaluation of the Tags Read-Error-Rate (Fritz et al., 2010).	Gilles Fritz & Vincent Beroulle & Oum-El-Kheir Aktouf & Minh Duc Nguyen & David Hély	The FMEA method is used for the description of failures modes and their effects of the RFID system. Then, the proposed solutions are evaluated by a system C model of the RFID system. The new testing approach detects the defects of the tags. The approach is validated by a system-level simulation (Fritz et al., 2010).
15	2011	Fuzzy methodology applied to Probabilistic Safety Assessment for digital system in nuclear power plants (Guimarães et al., 2011).	Antonio César Ferreira Guimarães, Celso Marcelo Franklin Lapab, Maria de Lourdes Moreira	A nuclear reliability engineering problem is treated using (FIS) modeling method RPN and FRPN were calculated and compared. The method was illustrated by a digital feed water control system (Guimarães et al., 2011).
16	2011	Using FMECA and RPI for RFID-enabled process reengineering performance assessment (G. Borelli, 2011).	G. Borelli, P. F. Orrù, M. T. Pilloni, F. Zedda	The patient safety and blood inventory management processes improvement, clinical risk reduction by using an RFID-based process reengineering, were the objectives of this study (G. Borelli, 2011).

Table 1 (Continued)

	Year of publication	Topic	Author (s)	Summary
17	2011	Application of ISO22000, Failure Mode, and Effect Analysis (FMEA) Cause and Effect Diagrams and Pareto in Conjunction with HACCP and Risk Assessment for Processing of Pastry Products (Varzakas, 2011).	Theodoros H. Varzakas	The failure modes in a food chain system (pastry processing plant) were analyzed by a Preliminary Hazard analysis. The ISO22000 analysis and HACCP Hazard Analysis Critical Control Points) were compared. Then a combination of FMEA and ISO22000 was attempted (Varzakas, 2011).
18	2011	Application of Failure Mode and Effect Analysis in a Radiology Department (Eavan Thornton, 2011)	Eavan Thornton, Olga R. Brook, Mishal Mendiratta-Lala, Donna T. Hallett, Jonathan B. Kruskal	The explanation of the steps of FMEA process, and a review of Healthcare Failure Mode and Effect Analysis. Clinical magnetic resonance imaging services in a radiology department are used to apply the FMEA method (Eavan Thornton, 2011).
19	2012	Integration technique of digital I&C replacement and its Critical Digital Review procedure (Huang and Yang, 2013)	Hui-Wen Huang , Wen-Long Yang	Development of a digital Instrumentation and Control (I&C) replacement integration technique and the related Critical Digital Review (CDR) procedure. This CDR contains FMEA and other procedures (Huang and Yang, 2013).
20	2012	A Robustness Approach to Reliability (Johannesson et al., 2013)	Pär Johannesson, Bo Bergman, Et al	The presentation of extended FMEA methods, based on critical product functions (Johannesson et al., 2013).
21	2012	An extended LLRP model for RFID system test and diagnosis (Kheddam et al., 2012)	Rafik KHEDDAM, Oum-El-Kheir AKTOUF, Ioannis PARISSIS	Presentation of a two-steps dependability approach. The first step is the application of the FMEA for the RFID middleware and its impacts on the whole RFID system. The communication protocol of RFID system is modeled by a low level reader protocol in the second step that takes into consideration the findings of the first step, which allows to test and diagnose the RFID system (Kheddam et al., 2012).
22	2013	Monitoring of RFID Failures Resulting from LLRP Misconfigurations (Rafik Kheddam, 2013).	Rafik Kheddam, Oum-El-Kheir Aktouf, Ioannis Parissis	The default LLRP logging format is modified, then the RFID failure were considered using FMEA approach,. The user misconfigurations were solved by a log file (Rafik Kheddam, 2013).
23	2013	SafeRFID-MW: a RFID Middleware with runtime fault diagnosis (Kheddam, 2013)	Rafik KHEDDAM, Oum-El-Kheir AKTOUF and Ioannis PARISSIS	A new fault-tolerant RFID middleware that identifies the faulty components of the TFID system via two mechanisms. An online diagnosis algorithm is performed to detect the faulty readers and tags first. Then, the causes of the diagnosed defects are verified by the Low Level Reader Protocol (LLRP). The FMEA method is performed in order to analyze failure modes of the RFID middleware (Kheddam, 2013).

Table 1 (Continued)

	Year of publication	Topic	Author (s)	Summary
24	2013	'Why is there another person's name on my infusion bag?' Patient safety in chemotherapy care e A review of the literature (Kullberg et al., 2013)	Anna Kullberg , Joacim Larsen, Lena Sharp	Identification and evaluation of the existing interventions that aim to the improvement of the safety of patient in chemotherapy care. A review is accomplished, as a result 12 studies describing five interventions were found: nurses education, surveillance systems and error reporting, Computerized Prescription Order Entry (CPOE), Administration Checklist, lean Sigma and FMEA (Kullberg et al., 2013).
25	2013	Failure mechanisms of radar and RF systems (Wileman and Perinpanayagam, 2013)	A.J.Wileman, S.Perinpanayagam	Failure Modes Effects and Criticality Analysis (FMECA) is used for a military radar system (Wileman and Perinpanayagam, 2013).
26	2013	Electric Vehicle Circuit and Electrical System Senior Lab Project (Northru, 2013)	Dr. Steven G Northru	An overview of a small-scale electric vehicle project realized by student from different departments, as well as the FMEA related to the system wiring (Northru, 2013).
27	2013	FMEA Analysis for Reducing Breakdowns of a Sub System in the Life Care Product Manufacturing Industry (Rakesh.R, 2013)	Rakesh.R, Bobin Cherian Jos, George Mathew	The FMEA method is used for an automatic plastic welding machine that is used to produce blood bags in a life care production firm (Rakesh.R, 2013).
28	2013	QUALITY ANALYSIS USING FMEA METHOD ON ASSEMBLY PROCESSES OF WASHING MACHINE (Case Study In Panasonic Manufacturing Indonesia) (Rifa Arifati, 2013)	Rifa Arifati, Ardika Rismayana	The FMEA technique is applied on a washing machine production system, where the highest RPN values were related to the operator errors. The RPN numbers decreased from 160 and 125 to 64 and 96 when the corrective actions were applied (Rifa Arifati, 2013).
29	2014	Software Dependability Approaches for RFID Systems	Rafik Kheddam	the contribution of this memory comes in a fault-tolerant RFID middleware hosting three mechanisms of fault tolerance: a probabilistic diagnostic algorithm, an extension of the communication protocol to take into account the lack of precision of RFID readers especially in hostile environments, and a log file analyzer whose purpose is to extract the sequence of events that led the system to failure and thus derive the cause of this failure (Kheddam., 2014).
30	2015	Risk assessment of wind turbines: Transition from pure mechanistic paradigm to modern complexity paradigm (Ashrafi et al., 2015)	Maryam Ashrafi , Hamid Davoudpour , Vahid Khodakarami	A review of the current risk assessment approaches used for complex technological systems, especially those related to wind turbines. Then, a Bayesian network considering various system levels and their interaction using FMEA approach is proposed as an integrated framework to assess the risks for those systems (Ashrafi et al., 2015).
31	2015	Failure mode and effect analysis for photovoltaic systems (Colli, 2015)	Alessandra Colli	The FMEA analysis is applied for a photovoltaic system. Results, advantages and limitations are discussed (Colli, 2015).

Table 1 (Continued)

	Year of publication	Topic	Author (s)	Summary
32	2015	HACCP-Based Programs for Preventing Disease and Injury from Premise Plumbing: A Building Consensus (McCoy and Rosenblatt, 2015)	William F. McCoy , and Aaron A. Rosenblatt	FMEA is adapted to HACCP in management of building water systems (McCoy and Rosenblatt, 2015).
33	2015	RADIANCE—A planning software for intra-operative radiation therapy (Manlio F. Valdivieso-Casique, 2015)	Manlio F. Valdivieso-Casique, Et all	The presentation of an intra-operative radiation therapy (IORT) planning system called RADIANCE. It includes basic tools used for radiotherapy planning: like image visualization, DVH calculation and reporting, and other tools. FMEA analysis in applied to this system to assess its effects on the on the global IORT technique (Manlio F. Valdivieso-Casique, 2015).
34	2015	Performance analysis of a healthcare supply chain for RFID-enabled process reengineering (Borelli et al., 2015)	Gianluca Borelli, Pier Francesco Orrù, Francesco Zedda	Study and evaluation of the efficiency and levels of safety of BTC, and description of the design of UHF RFID systems (Borelli et al., 2015).
35	2015	Support strategy for care units to implement tools for securing medication management (GIRAUD, 2015)	Jean GIRAUD	In the first part of this thesis, the areas of improvement mentioned in order to secure and optimize the Medicated Management are essentially based on new activities or technologies to be implemented and require significant human and financial resources. The second part describes the deployment, in a clinical hematology department, of tools drawn from industrial organizations and adapted to the hospital organization. These tools enable the identification of risks and the development of a security strategy by integrating organizational and human factors. The combination of field proposals with those from the literature makes it possible to offer a wide and complete panel of security solutions (GIRAUD, 2015).
36	2015	Integrated approach for risk analysis and performance evaluation: application to hospital sterilization services (negrichi, 2015)	Khalil NEGRICHI	First, the risk analysis methods were compared including FMEA, the Function Interaction Structure (FIS) was chosen. In a second part, a new FIS view is introduced. Then, the dynamic behavior of the FIS model was simulated by a new Petri Net class: PTPS (Predicate-Transition, Prioritized, and Synchronous). At the end, the switching between the simulation model and risk model was automated. As a result, The SIMRISK, which is a simulation tool in degraded mode, is created. Some examples in the sterilization process illustrate the importance of this tool(negrichi, 2015).
37	2015	Model based FMEA for electronic products (Jingjing Cui, 2015)	Jingjing Cui, Yi Ren, Dezhen Yang, Shengkui Zeng	A new model-based FMEA (MBFMEA) approach is presented and used for loadings of electronic products. The method is tested for strain PCB (Jingjing Cui, 2015).

Table 1 (Continued)

	Year of publication	Topic	Author (s)	Summary
38	2016	A REVIEWOF HEALTHCARE FAILURE MODE AND EFFECTS ANALYSIS (HFMEA) IN RADIOTHERAPY (Giardina et al., 2016)	M. Giardina,M.C. Cantone, E. Tomarchio,and I. Veronese	Risk analyses in radiotherapy (RT) processes papers between 2009 and 2014 are reviewed. It was found that there are HFMEA shortcomings that need to be addressed (Giardina et al., 2016).
39	2016	Application of failure mode and effect analysis in an assisted reproduction technology laboratory (Intra et al., 2016)	Giulia Intra, Alessandra Alteri, Laura Corti, Elisa Rabellotti, Enrico Papaleo, Liliana Restelli, Stefania Biondo, Maria Paola Garancini, Massimo Candiani, Paola Viganò	The FMEA technique was and the RPN was reduced to 50% after the training of the staff (Intra et al., 2016).
40	2016	RFID technology for blood tracking: An experimental approach for benchmarking different devices (Caredda et al., 2016)	V. Careddaa, P.F. Orr´ua, G. Romagnoli, A. Volpib and F. Zedda	A design and test of a protocol useful in the performances measurement of the RFID devices used in the blood supply chain. FMEA was used to detect the departments that need reengineering (Caredda et al., 2016).
41	2016	Extended FMEA for Sustainable Manufacturing: An Empirical Study in the Non-Woven Fabrics Industry (Nguyen et al., 2016)	Thanh-Lam Nguyen , Ming-Hung Shu and Bi-Min Hsu	An extended FMEA approach is proposed, this new approach takes into consideration production capacity, economic and technical severity. The priority levels are determined by taking into account the cost of quality and the capability of the detection of the failures (Nguyen et al., 2016).
42	2017	Development of the Sports Organization Concussion Risk Assessment Tool (SOCRAT) (Yeung et al., 2017)	A. Yeung, V. Munjal & N. Virji-Babul	The description of a new tool called SOCRAT ,providing an RPN for each risk factor and a global RPN that considers all the risk factors. SOCRAT is compared with FMEA (Yeung et al., 2017).
43	2017	A state-of-the-art review of FMEA/FMECA including patents (Spreafico et al., 2017)	Christian Spreafico, Davide Russo , Caterina Rizzi	A review of a 70 years old method: the FMEA. A total of 220 papers and 109 patents were analyzed and classified. Other methods are proposed to be combined with FMEA to increase its effectiveness (Spreafico et al., 2017).
44	2017	A study on solving the production process problems of the photovoltaic cell industry model (Tsai et al., 2018)	Sang-Bing Tsaia, Jian Yue, Li Mac, Feng Luo Jie Zhou, Quan Chena, Lei Xug	The integration of three methods and introduction of new one called FMEA-IPA-DEMATEL analysis model, which improved the performance of management. The Chinese photovoltaic cell manufacturing companies is used to illustrate this new model (Tsai et al., 2018).
45	2017	An extension to Fuzzy Developed Failure Mode and Effects Analysis (FDFMEA) application for aircraft landing system (Yazdi et al., 2017)	Mohammad Yazdi , Sahand Daneshvar , Hashem Setareh	An extended FMEA that considers a group decision-making under the fuzzy environment is used to manage the risk of accidents happening in aircraft systems' components, the results of the traditional FMEA and Fuzzy Developed FMEA (FDFMEA) were compared and it was found that the risky failure modes accompanied with FDFMEA are more reliable (Yazdi et al., 2017)

Table 1 (Continued)

	Year of publication	Topic	Author (s)	Summary
46	2017	Failure Mode and Effect Analysis Using Cloud Model Theory and PROMETHEE Method (Liu et al., 2017).	Hu-Chen Liu , Zhaojun Li, Wenyan Song , and Qiang Su	A framework using cloud model to deal with randomness and fuzziness, and PROMETHEE method to manage the group behaviors, in order to improve the FMEA method effectiveness, a healthcare risk analysis case is used to illustrate the new approach (Liu et al., 2017).
47	2018	A review of applications of fuzzy sets to safety and reliability engineering (sohag kabir, 2018)	Sohag Kabir, Yiannis Papadopoulos	A review of the methodologies based on fuzzy sets theory, used for safety and reliability engineering including fuzzy Petri nets, fuzzy Bayesian networks, fuzzy ETA, fuzzy FTA, fuzzy Markov chains, and fuzzy FMEA(sohag kabir, 2018) .
48	2018	What's to Be Done About Laboratory Quality? Process Indicators, Laboratory Stewardship, the Outcomes Problem, Risk Assessment, and Economic Value Responding to Contemporary Global Challenges (sohag kabir, 2018)	Frederick A. Meie,Tony C.Badrick,and Kenneth A. Sikaris	A review of papers related to clinical laboratory quality systems assessment (sohag kabir, 2018)
49	2019	Improving Risk Evaluation in FMEA With Cloud Model and Hierarchical TOPSIS Method (Liu et al., 2019b)	Hu-Chen Liu , Li-En Wang , ZhiWu Li and Yu-Ping Hu	A new FMEA approach based on TOPSIS methods (technique for order of preference by similarity to ideal solution) where FM are converted into clouds (Liu et al., 2019b).
50	2019	Applications of Bayesian networks and Petri nets in safety, reliability, and risk assessments: A review (Kabir and Papadopoulos, 2019).	Sohag Kabir, Yiannis Papadopoulos	A review of the publications that applied the Bayesian networks and Petri nets in system safety, reliability and risk assessments (Kabir and Papadopoulos, 2019).
51	2019	An extended generalized TODIM for risk evaluation and prioritization of failure modes considering risk indicators interaction (Wang et al., 2019).	Weizhong Wang, Xinwang Liu, Jindong Qin & Shuli Liu	Development of an hybrid FMEA framework integrating generalized TODIM (Interactive and Multi-criteria Decision Making) method that uses fuzzy measures and Shapley index. The psychological behavior characteristics of FMEA team members are simulated by TODIM, and the RPN are computed (Wang et al., 2019).
52	2019	Risk evaluation and mitigation of sustainable road freight transport operation: a case of trucking industry (Kumar Dadsena et al., 2019)	Krishna Kumar Dadsena, S. P. Sarmah and V. N. A. Naikan	FMEA approach is used in the selection of risk-mitigation strategy on the trucking industry.it was found that the managers should select risk mitigation strategies by taking in consideration the criticality of risks along with the limited budget .The subjective judgment of experts and cost benefit lead to a convincing outcome in the computation of risk-mitigation number in FMEA (Kumar Dadsena et al., 2019).
53	2019	Failure mode and effect analysis using multi-criteria decision making methods: A systematic literature review (Liu et al., 2019a).	Hu-Chen Liu, Xu-Qi Chena, Chun-Yan Duanb, Ying-Ming Wang	Review of 169 publications related to the multi-criteria decision making (MCDM) methods used to improve the effectiveness of FMEA, appeared on line between 1998 and 2018. According to the MCDM used, risk factors and their weighting methods, and risk assessment methods in FMEA, These articles were classified into 10 groups (Liu et al., 2019a).

2.2 Data Envelopment Analysis

The Data Envelopment Analysis (DEA) technique is used to measure the efficiency of organizations, educational institutes, energy and environment, internet companies, petroleum firms, renewable energies, natural gas, healthcare, batteries production, banking, sustainability, supply chains, road projects, level of life in some countries and regions, and more fields.

In this section, we will see some applications of the DEA approach, as well as its different models, the improved and extended models of DEA based on different theories and approaches, and the models that integrate or combine DEA with other methods.

The following table presents a brief summary of a set of the work related to DEA models and applications:

Table 2: DEA Literature Review

	Year of publication	Topic	Author (s)	Summary
1	2001	Data envelopment analysis	Quanling WEI	The review of DEA research and its models, its past and present (in 2001).Management, economics and mathematics are the main sources of power of DEA development (Wei, 2001).
2	2005	DATA ENVELOPMENT ANALYSIS AND ITS APPLICATION TO THE MEASUREMENT OF EFFICIENCY IN HIGHER EDUCATION (johnes, 2005).	Jill Johnes	Presentation of the advantages and the drawbacks of the methods used in the measurement of the efficiency in the higher education, as well as the extended approaches developed to deal with these drawbacks. As a result of DEA, technical and scale efficiency in the English higher education sector are high on average (johnes, 2005).

Table 2 (Continued)

	Year of publication	Topic	Author (s)	Summary
3	2007	A survey of data envelopment analysis in energy and environmental studies (Zhou et al., 2007)	P. Zhou , B.W. Ang, K.L. Poh	Classification and summary of 100 publications related to the application of data envelopment analysis (DEA) techniques in energy and environmental (E&E) studies (Zhou et al., 2007).
4	2007	Connective Technologies in the Supply Chain Chapter 11: RFID Technology Innovators: DEA Analysis (Kumar, 2007)	Sameer Kumar	The efficiency of 15 RFID companies was measured by using DEA models: BCC, CCR, cross-efficiency, A&P, and Equal Weight (E-W) (kumar, 2007).
5	2008	Data envelopment analysis (DEA) – Thirty years on (Cook and Seiford, 2008)	Wade D. Cook , Larry M. Seiford	Review of the major publications in DEA since 1978. The focus was on: the different models for efficiency measurement, approaches used to incorporate restrictions on multipliers, considerations regarding the status of variables, and modeling of data variation (Cook and Seiford, 2008).
6	2010	Improving weak efficiency frontiers in the fuzzy data envelopment analysis models (Khoshfetrat and Daneshvar, 2010)	Sahar Khoshfetrat, Sahand Daneshvar	Improvement of the weak efficiency frontiers of PPS, by introducing a new method based on fuzzy CCR model to determine the minimal bounds of fuzzy inputs /outputs. (Khoshfetrat and Daneshvar, 2010).
7	2011	Measuring the performance of Internet companies using a two-stage data envelopment analysis model (Cao and Yang, 2011).	Xiongfei Cao & Feng Yang	The 40 dot com companies' efficiency was measured using a relational two-stage DEA. This new model can detect the causes of inefficiency and it measures the efficiency better (Cao and Yang, 2011).
8	2012	Environmental efficiency evaluation based on data envelopment analysis: A review (Song et al., 2012).	Malin Song , QingxianAn , WeiZhang , ZeyaWang, JieWu	Review of the work related to the theory of efficiency analysis and its applications in environmental efficiency assessment (Song et al., 2012).
9	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,and M. Vaez-Ghasemi	Ranking models in DEA are reviewed and divided into seven groups (Hosseinzadeh Lotfi et al., 2013).
10	2014	Review of the network environmental efficiencies of listed petroleum enterprises in China (Song et al., 2015).	Malin Song , JieZhang , ShuhongWang	Creation of a set of network DEA models dividing the scores of efficiency in two subunits. This allows the determination of advantages and drawbacks of subunits in each DMU, as well as opening the "black box" of efficiency measurement. The efficiency of changes in production and environment was examined for 20 Chinese petroleum enterprises between 2006 and 2011, the input excesses and output deficits are analyzed from 2011 (Song et al., 2015).

Table 2 (Continued)

	Year of publication	Topic	Author (s)	Summary
11	2014	Sensitivity analysis on modified variable returns to scale model in Data Envelopment Analysis using facet analysis (Daneshvar et al., 2014).	Sahand Daneshvar , Gokhan Izbirak , Alireza Javadi	Development of a new sensitivity analysis method based on BCC model, modified by facet analysis. And determining of an extended stability region, particularly for DMUs placed on the intersection of weak efficient and efficient frontier. A numerical example is used to show the results (Daneshvar et al., 2014).
12	2014	Evaluating capital and operating cost efficiency of offshore wind farms: A DEA approach (Ederer, 2014)	Nikolaus Ederer	The offshore wind farms were molded as entities by using DEA approach, the costs were related to the water depth and the distance to shore, stakeholders were provided, the offshore wind capacity was benchmarked by taking in consideration the efficiency of the capital and the operating cost (Ederer, 2014).
13	2014	Network data envelopment analysis: A review view (Kao, 2014).	Chiang Kao	Review of studies on network DEA, and highlighting of possible studies directions in the future from the empirical point of view (Kao, 2014).
14	2014	Primary Care Efficiency Measurement Using Data Envelopment Analysis: A Systematic Review (Ricciardi, 2014).	Ferruccio Pelone & Dionne Sofia Kringos & Alessandro Romaniello &Monica Archibugi & Chiara Salsiri & Walter Ricciardi	Review and combination of 39 applications of DEA in the measurement of primary care efficiency. The data were reported for each research on: evaluation context; model specifications; application of methods to test the robustness of findings; presentation of results. The application of DEA in this field is still in progress and requires improvement such as the outcome and the standardization and extensive uncertainty (Ricciardi, 2014).
15	2015	Human development and data envelopment analysis: A structured literature review (Mariano et al., 2015).	Enzo Barberio Mariano , Vinicius AmorimS obreiro , Daisy Aparecida do Nascimento Rebelatto	A review and a summary of the research in the database of Scopus and Web of Science, that used DEA approach in the development process, in addition to the assessment of the main gaps in each analysis dimension. The following dimensions were considered: DEA models and extensions used, units analyzed and depth of analysis, interfaces with other techniques, scope and bibliometrics (Mariano et al., 2015).
16	2015	Research fronts in data envelopment analysis (Liu et al., 2015).	John S.Liu, LouisY.Y.Lu, Wen-MinLu	The literature of DEA between 2000 and 2014 is compared and grouped in four groups, by using a network clustering method. These groups are: undesirable factors, cross-efficiency and ranking, network DEA, dynamic DEA, SBM and boots trapping and two-stage analysis (Liu et al., 2015).
17	2016	Allocative efficiency of high-power Li-ion batteries from automotive mode (AM) to storage mode (SM) (Lee and Chang, 2016).	Meng HongLee, Dong-ShangChang	The evaluation of the best shift point from automotive mode to storage mode of LFP batteries, by using DEA. By taking into consideration the price between 2009 and 20122, electrical conductance, AM/SM capacity decay, SOH% and total kWh generated; The optimal value was used in a 1:1ratio (time in AM to time in SM) (Lee and Chang, 2016).

Table 2 (Continued)

	Year of publication	Topic	Author (s)	Summary
18	2016	Variable portfolio proposal for banking efficiency assessment (Macoris et al., 2016).	Lucas Serrao Macoris, Alexandre Pereira Salgado Jr, Adriel Martins de Freitas Branco, Fábio Neves Ciribelli	Proposition of a reliable set of inputs and outputs suitable of the theory related to banking efficiency and decision-making, based on a critical analysis and review of existing research (Macoris et al., 2016).
19	2017	Integrated Analysis of Healthcare Efficiency: A Systematic Review (Cantor and Poh, 2017).	Victor John M. Cantor1 & Kim Leng Poh	57 studies using DEA in the healthcare industry were reviewed, It was found that in order to deal with the limitations of DEA in viewing the full healthcare efficiency, other statistical methods and techniques should be integrated with DEA. (Cantor and Poh, 2017).
20	2017	A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency (Mardani et al., 2017).	Abbas Mardania, Edmundas Kazimieras Zavadskasb, Dalia Streimikienec,, Ahmad Jusoha, Masoumeh Khoshnoudi	A review and summary of 144 papers between 2006 and 2015, where various models of DEA were applied in the energy efficiency development (Mardani et al., 2017).
21	2017	Data envelopment analysis application in sustainability: The origins, development and future directions (Zhou et al., 2017).	Haibo Zhou , Yi Yang ,Yao Chen, Joe Zhu	Construction of a network based on citation relationships between the papers that treated the application of DEA in sustainability, published in the Web of Science database between 1996 and 2016. Four research clusters were found through the Kamada–Kawai layout algorithm: regional sustainability assessment, sustainability performance analysis, sustainability composite indicator construction, and corporate sustainability assessment (Zhou et al., 2017).
22	2017	Review of efficiency ranking methods in data envelopment analysis (Aldamak and Zolfaghari, 2017).	Abdullah Aldamak , Saeed Zolfaghari	Review of DEA methods published before 2016, their advantages and disadvantages (Aldamak and Zolfaghari, 2017).
23	2017	Inputs optimization to reduce the undesirable outputs by environmental hazards: a DEA model with data of PM 2.5 in China (Wu et al., 2017).	Xianhua Wu, Yufeng Chen, Ji Guo, Ge Gao	Calculation of the efficiency of 29 provinces in china, 7 inputs and 2 outputs (1 output is undesirable) are used. The haze emission was controlled by readjusting input indicators (Wu et al., 2017).
24	2017	Measuring the Technical Efficiency for the Shipping Banks—An Approach Using Data Envelopment Analysis (Maniati and Sambracos, 2017).	Marina Maniati, Evangelos Sambracos	The examination of the technical Efficiency of 71 banks that operate worldwide in the maritime field between 2005 and 2010, by using DEA ,and the presentation of the factors affecting their technical efficiency, by the mean of Regression Analysis. As a result, most banks were technically inefficient, whereas TE was higher under the VRS DEA model when compared CRS DEA model (Maniati and Sambracos, 2017).

Table 2 (Continued)

	Year of publication	Topic	Author (s)	Summary
25	2017	Quantitative models for supply chain performance evaluation: A literature review used (Lima-Junior and Carpinetti, 2017)	Francisco Rodrigues Lima-Junior, Luiz Cesar Ribeiro Carpinetti	Review of 84 studies related to quantitative models used in the evaluation of the performance of supply chain, published in Science Direct, Scopus, Emerald Insight, IEEE Xplore, and the Google Scholar search databases, between 1995 and 2017. The factors taken in consideration are: data source for performance evaluation and validation approach, supply chain strategy, type of model, its purpose and scope, techniques, choice of metrics, type of application, , modeling uncertainty and learning capacity. The techniques that are used the most are AHP and DEA; to deal with uncertainty, the fuzzy set theory and pairwise comparisons are used (Lima-Junior and Carpinetti, 2017).
26	2017	Environment-adjusted operational performance evaluation of solar photovoltaic power plants: A three stage efficiency analysis) (Zhaohua Wang, 2017).	Zhaohua Wang, Yi Li, Ke Wang, Zhimin Huang	The environment adjusted operational efficiency of solar PV power plants is computed by DEA, while the environmental factors impacts are attributed by stochastic frontier analysis (SFA) (Zhaohua Wang, 2017).
27	2018	Data Envelopment Analysis in Energy and Environmental Economics: An Overview of the State-of-the-Art and Recent Development Trends (Mardani et al., 2018).	Abbas Mardani, Dalia Streimikiene, Tomas Balezentis, Muhamad Zameri Mat Saman, Khalil Md Nor and Seyed Meysam Khoshnava	A review and classification of 145 articles extracted from Web of Science and Scopus where DEA models were applied in the fields of environmental and energy economics (Mardani et al., 2018).
28	2018	Efficiency Analysis of Healthcare System in Lebanon Using Modified Data Envelopment Analysis 2005 (Ibrahim and Daneshvar, 2018)	Mustapha D. Ibrahim and Sahand Daneshvar	The evaluation of the efficiency of healthcare system in Lebanon between 2000 and 2015 using a modified DEA model, there was an improvement in this efficiency after 2005, when the health system reform spread (Ibrahim and Daneshvar, 2018).
29	2018	Efficiency performance and cost structure of Portuguese energy “utilities” – Non-parametric and parametric analysis (Rita et al., 2018).	Rui Rita, Vitor Marques, Ana Lúcia Costa, Ines Matos Chaves, Joana Gomes, Paulo Paulino	The evaluation of the efficiency of natural gas companies (DSO), by employing data regression and DEA. Then the cost structure understanding by the mean of data panel regression and a questionnaire. As a result, the number of clients is the major inductor of the cost, and fixed costs represent 1/3 of total operating costs (Rita et al., 2018).
30	2018	An Estimation of the Efficiency and Productivity of Healthcare Systems in Sub-Saharan Africa: Health-Centred Millennium Development Goal-Based Evidence (Ibrahim et al., 2018).	Mustapha D. Ibrahim, Sahand Daneshvar , Mevhibe B. Hocaoğlu, Olasehinde-Williams G. Oluseye	DEA is used for ranking and estimating the annual performance of SSA’s healthcare systems between 2010 and 2015.The results show that these systems are inefficient except three countries, due to the incapability to achieve technological advancements and the government and law (Ibrahim et al., 2018).

Table 2 (Continued)

	Year of publication	Topic	Author (s)	Summary
31	2018	From data to big data in production research: the past and future trends (Kuo and Kusiak, 2018).	Yong-Hong Kuo and Andrew Kusiak	The published researches indicate that the production research enabled by data were based on the analytical models and shifted to data-driven methodologies, where DEA and manufacturing have been the most popular. Currently, the data mining methodology dominates the production research. The data-driven production research opportunities and future trends are presented in this article (Kuo and Kusiak, 2018).
32	2018	Modified variable return to scale back-propagation neural network robust parameter optimization procedure for multi-quality processes model (Daneshvar and Adesina, 2018)	Sahand Daneshvar & Kehinde Adewale Adesina	Previous methods used to select the optimum process parameter level setting for multi-quality processes were complex, with unrealistic assumptions, and ignore the interrelationship between responses and failure. To solve this problem, this research proposes a modified VRS–adequate BPNN topology model (Daneshvar and Adesina, 2018).
33	2018	Operations research for sustainability assessment of products: A review (Thies et al., 2018).	Christian Thies, Karsten Kieckhäfer , Thomas S. Spengler , Manbir S. Sodhi	The review of 142 articles using OR methods for product related sustainability assessments (Thies et al., 2018).
34	2019	Cost and Time Management Efficiency Assessment for Large Road Projects Using Data Envelopment Analysis (Ahbab et al., 2019).	Changiz AHBAB , Sahand DANESHVAR, Tahir ÇELIK	The cost and time management efficiency of the road projects was calculated by DEA. It was found that the four critical causes affecting the efficiency of cost and time management are: design changes, inaccurate initial project scope, increase or change in the project scope, and additional works (Ahbab et al., 2019).
35	2019	Transnational resource generativity: Efficiency analysis and target setting of water, energy, land, and food nexus for OECD countries (Ibrahim et al., 2019)	Mustapha D. Ibrahim, Diogo Cunha Ferreira , Sahand Daneshvar , Rui Cunha Marques	The efficiency of Organization for Economic Co-Operation and Development countries in terms of Water-Energy-Land-Food is evaluated, by introducing intrinsic and composite factors. It was shown by using DEA that the implementation of a win-win strategy is necessary to achieve the efficiency of WELF-Nexus (Ibrahim et al., 2019).
36	2019	A New DEA Model for Evaluation of Supply Chains: A Case of Selection and Evaluation of Environmental Efficiency of Suppliers (Krmac and Djordjević, 2019)	Evelin Krmac and Boban Djordjevi	A non-radial DEA model used to evaluate the deferent components of SCM is introduced and applied to select and evaluate the suppliers, unwanted inputs and outputs were considered, as a result the suppliers were better ranked. (Krmac and Djordjević, 2019).
37	2019	PROVIDING A MODEL FOR RANKING SUPPLIERS IN THE SUSTAINABLE SUPPLY CHAIN USING CROSS EFFICIENCY METHOD IN DATA ENVELOPMENT ANALYSIS (Bazrkar and Hashemi Tabatabaei, 2019)	Mohammad Hashemi Tabatabaei, Ardeshir Bazrkar	Review of previous research and use of a cross efficiency approach to rank the suppliers in order to determine the basic indices of sustainability in terms of economic, social and environmental dimensions in automotive industry in Iran (Bazrkar and Hashemi Tabatabaei, 2019).

2.3 Combination of FMEA and DEA

In this section, we will review the models were the FMEA technique was combined with the DEA approach and some of their applications, like fuzzy logics, fuzzy weighted geometric mean, SOD efficiencies, exponential RPN, multi criteria decision making theory; applied in feed water systems, automobile production, and others. The following table contains the papers used for this issue and their summaries:

Table 3: Combination of FMEA and DEA Literature Review

	Year of publication	Topic	Author (s)	Summary
1	2005	A FUZZY DATA ENVELOPMENT ANALYSIS APPROACH FOR FMEA (Garcia et al., 2005).	P. A. A. GARCIA, R. SCHIRRU & P. F. FRUTUOSO E MELO	The FMEA ranking indices are modeled as fuzzy sets by the mean of a DEA approach. An OWR auxiliary feed water system is used to illustrate this method. The comparison of results obtained by this approach with RPN numbers, pure fuzzy logic concepts, and finally the profiling of severity efficiency approach (DEA-APGF), proves that the combination of DEA and fuzzy logic concepts is potential (Garcia et al., 2005).
2	2009	Risk evaluation in failure mode and effects analysis using fuzzy weighted geometric mean (Wang et al., 2009).	Ying-Ming Wang, Kwai-Sang Chin, Gary Ka Kwai Poon, Jian-Bo Yang	A FMEA model based on DEA, where the risk factors are treated as fuzzy variables. The fuzzy RPNs (FRPNs) are then fuzzy weighted geometric means of the fuzzy O, S and D; The FRPNs are defuzzified after based on alpha-level sets. A numerical example illustrates this method (Wang et al., 2009).
3	2009	Applying DEA to enhance assessment capability of FMEA (Chang and Paul Sun, 2009).	Dong-Shang Chang, Kuo-Lung Paul Sun	A novel FMEA approach based on DEA technique, that analyzes the ranking of the FMs considering the contribution of the failure indices in addition to their impacts, by taking in consideration restricted weighted and multiple criteria. It investigates the SOD instead of the RPN. Moreover, it considers the costs and the efficiency (Chang and Paul Sun, 2009).
4	2009	Failure mode and effects analysis by data envelopment analysis (Chin et al., 2009)	Chin, Kwai-Sang Wang, Ying-Ming Poon, Gary Ka Kwai Yang, Jian-Bo	An FMEA approach using DEA to determine the RPNs. The overall RPN of each failure mode is equal to geometric average of its minimum and its maximum risks (Chin et al., 2009).

Table 3 (Continued)

	Year of publication	Topic	Author (s)	Summary
5	2012	A novel approach for evaluating the risk of health care failure modes (Chang et al., 2012).	Chang, D. S. Chung, J. H. Sun, K. L. Yang, F. C.	A new approach that combines DEA with SBM and FMEA. The inputs of the DEA SBM model are O, S, and D. As a result, the patient safety increased and the medical costs are reduced (Chang et al., 2012).
6	2013	Risk evaluation approaches in failure mode and effects analysis: A literature review (Liu et al., 2013).	Hu-Chen Liu, Long Liu, Nan Liu	Review and categorizing of 75 FMEA publications appeared from 1992 to 2012. The categories depend on the approaches used to deal with the shortages of the conventional RPN method (Liu et al., 2013).
7	2013	Applying the concept of exponential approach to enhance the assessment capability of FMEA (Chang et al., 2013).	Kuei-Hu Chang , Yung-Chia Chang , Pei-Ting Lai	The exponential risk priority number (ERPN)is calculated, by adding an exponential form of D, O, and (CCR AR) (Chang et al., 2013).
8	2013	A weight restricted DEA model for FMEA risk prioritization (Garcia et al., 2013).	Garcia, Pauli Adriano de Almada Leal Junior, Ilton Curty Oliveira, Murilo Alvarenga	A DEA linear program based model that considers weight restriction to rank the RPN numbers of FMEA (Garcia et al., 2013).
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 et al., 2016)	Majid Baghery , Samuel Yousefi , Mustafa Jahangoshai Rezaee	The PFMEA technique was used for 3 automobiles types produced by Iran-khodro company. Followed by an interval DEA analysis. Then the interval DEA and Grey relational analysis (GRA) were combined, results showed that core making and pouring were the most crucial processes in this case (Baghery et al., 2016).
10	2016	Identifying and managing failures in stone processing industry using cost-based FMEA (Jahangoshai Rezaee et al., 2016).	Jahangoshai Rezaee, Mustafa Salimi, Akram Yousefi, Samuel	Ranking the failure modes of an Iranian stone industry, using an FMEA-DEA approach. Where the inputs are O, S, and D, and the output is the cost (Jahangoshai Rezaee et al., 2016).
11	2018	HSE risk prioritization using robust DEA-FMEA approach with undesirable outputs: A study of automotive parts industry in Iran (Yousefi et al., 2018).	Yousefi, Samuel Alizadeh et al	An FMEA approach based on robust DEA (RDEA) that aims to determine the risk priority in health, safety and environment (HSE). The inputs are O, S, and D, and the outputs are the costs and the durations of treatments (Yousefi et al., 2018).
12	2019	Fuzzy smart failure modes and effects analysis to improve safety performance of system: Case study of an aircraft landing system (Daneshvar, Yazdi and Adesina, 2020).	Sahand Daneshvar, Mohammad Yazdi, Kehinde A. Adesina	A new integrated fuzzy smart FMEA framework where the combination of fuzzy set theory, analytical hierarchy process (AHP), and (DEA) is used in order to determine the efficiency of FMEA mode with adequate priority and corrective actions using RPN, time, and cost as indicators. (Daneshvar, Yazdi and Adesina, 2020).

In the light of what has been seen, we conclude that the FMEA approach was used to detect and analyze the causes and effects of the RFID system failure modes related to the middleware, the tags or the readers, separately. In our study we are going to treat failure modes of RFID system and sub system from the tag, to the area between the tag and the reader, the reader and the host, as well as its interaction with the human body and the environment.

The DEA technique was used to compute the efficiency of the RFID companies, but it was never used to measure the efficiency of the RFID system itself.

The efficiency of the implementation of the RFID system in organizations, manufacturing, supply chains, warehouses, is measured by CFA (Confirmatory Factor Analysis) (Zelbst et al., 2012), shrinkage and misplacement functions (Biswal et al., 2018) and others (Chen et al., 2015), strategic values (Sabbaghi and Vaidyanathan, 2008). But none has used the DEA approach.

The FMEA method was modified and combined with other methods in order to enhance its reliability, like DEA. Sometimes the efficiency of the FMEA was computed by considering occurrence, severity and detection only; in other researches the cost or/and time were considered as well in different ways.

The FMEA can be based on cost uniquely, and at this time the DEA is not used in order to compute the efficiency (Seung Rhee and Spencer, 2009, Amine Boufaied et al., 2016, Carmignani, 2009, Jamshidi, 2010, Rhee and Ishii, 2003, von Ahsen, 2008).

As a conclusion, our new FMEA approach based on cost and time is totally new and different. In the following sections we will see the added value and the usefulness of this method.

Chapter 3

METHODOLOGY

3.1 Failure Modes and Effects Analysis method (FMEA)

3.1.1 Origins of the FMEA

Edward A. MURPHY, engineer at Wright Field Aircraft, was working on the project MX 981 of the US Air Force, between 1947 and 1949, stated the first principle of FMEA with his adage which became a theorem: “If it can go wrong, it will” (En.wikipedia.org, 2019b). The FMEA approach was introduced in 1949 by US army, in the form of the branch Military Procedure MIL-P-1629, to analyze the malfunctions of the military system. The FMEA was adopted by the civil aviation industry in 1967, by the Society for Automotive Engineers (SAE), who published related standard J1739 in 1994 for the first time, which is now in its 4rd edition. The NASA adopted and developed this method for purpose of the improvement and the verification of space program hardware in 1971. Then, U.S. ENVIRONMENTAL PROTECTION AGENCY described the application of FMEA to wastewater treatment plants in their report in 1973. Later, in 1980, the department of defense in Washington published the military procedure MIL-STD-1629A, the revision of the MIL-P-1629 appeared before, which contained the procedures for performing a FMEA, and it is the most accepted and used in the military and commercial industry. In February 1993, the automotive Industry Action Group (AIAG) and the American Society for Quality Control (ASQC) formalized a new approach for FMEA. They defined it as follows: The FMEA is a systematic process to identify the potential modes and address failures before they occur, with the intention of eliminating them or minimizing the associated risks. In January 2006, FMEA was entitled “Technique for analyzing the reliability of the system – Procedure for failure modes and their effects analysis”, and was associated to the CEI IEC 60812 NORM, which is not an ISO norm, but it is admitted by the CEN and the AFNOR NFEN 60812. Some commonly used FMEA standards include SAE J1739, ARP5580, AIAG, and MIL-STD-1629A. In the automobile industry, the FMEA was adopted by the QS9000 norm (En.wikipedia.org, 2019a).

Because of its effectiveness and usefulness, the FMEA approach spread and it was used in variety of fields like nuclear, aerospace, chemical, automotive, healthcare, electronic industries, semiconductor processing, electricity, mechanic, organizations, informatics and software, food service, plastics. Etc.

Actually, this type of qualitative analysis is typically applied in all the types of societies and services, and used both at the design and control stages.

3.1.2 FMEA definition

FMEA is a prediction analysis method of reliability, which eases the identification and the control of the potential failure modes whose consequences affect the proper functioning of the means of production, the equipment or the process studied, and then to estimate the risks associated with the appearance of these failures, in order to initiate corrective or preventive actions to be taken during the design, production or operation of the means of production, the product or the process. It is a comprehensive analysis and a rigorous group work. This method is very effective when it is put in the experience and expertise of each participant in the working group.

FMEA therefore allows:

- The identification of the potential weaknesses of the system: likely modes of failure, possible causes for each failure, its effects depending on the phase of the mission or life cycle in which it occurs.
- The definition and the application of actions (preventive and / or corrective) throughout the life cycle of the product, as well as the establishment of operation, use and maintenance.

3.1.3 Types of FMEA

There are numerous types of FMEA like:

- System / Functional FMEAs: built on a functional disruption of the system, it is used in order to decrease the effects of functional breakdowns or the probability of their manifestation early.
- Design FMEAs (DFMEA): early analysis of systems during the design stages for the management of the failure mechanisms and to decrease the level functional defects.
- Process FMEAs (PFMEA): Ensures the quality of a product by improving the production operations of it.
- Service FMEAs: It allows the elimination of product failures due to – improper installation, operation, maintenance and repair.
- Software FMEAs: Permit the anticipation of the defects before they occur, thus it allows to build high quality software products.
- Manufacturing FMEAs: It ensures the availability and security of a means of production improving its maintenance.
- Failure Mode, Effects & Criticality Analysis (FMECA): the criticality analysis is performed in addition to the traditional FMEA.

- FMEA PRODUCT: It serves to ensure the reliability of a product by improving its design.

3.1.4 Steps of FMEA

To make an FMEA analysis, it is compulsory to know the functioning of the analyzed system, process or product. The FMEA method is deployed in 6 major steps:

A-The preparation and initialization

1- Constitute the team , fix de delay and the detail of the analysis
2- Study about the system and find its subsystems and components, why and how it functions, to understand why and how it breaks down.
3- Definition of the scale table related to O, S, and D
4- Define the FMEA table

B- Functional decomposition – Failures analysis

5- Brainstorm all the possible failure modes of these components and subsystems
6- Finding the causes of each failure mode
7- Determining the effects of each failure mode

C- The criticality analysis phase – Failures evaluation

8- Assign Occurrence rankings (O) according to the probability of incidence of each failure.
9- Assign Severity rankings (S) according to the impacts of the effects
10- Assign Detection rankings (D) according to possibility and the difficulty to detect each failure
11- Calculation of the Risk Priority Number (RPN): $RPN = O \times S \times D$
12- Ranking the failure modes by the descending order of the RPN values.

13- Represent the RPN in the matrix form (Farmer diagram)

14- Check if the RPN value is below the allowed value according to the criticality grille (the matrix). (below 75 if the ranking scales are between 1-10 for example)

D- Propose actions to reduce the risks – Optimization and development of the maintenance

15- Recommendation of corrective, preventive, or ameliorative actions to decrease the criticality of the causes of failure, by reducing their probability of occurrence or/and the severity of their effects.

E- Implementation and monitoring of action plans

16- Take the action

17- Recalculate the RPNs again and determine the impact of the improvement.

F-Exploitation of FMEA

18- FMEA generates an information base reference throughout the life of the product. The exploitation is translated by a list of syntheses like:

- List of the effects of failures
- List of observable symptoms
- List of undetected failures
- List of critical articles
- List of single points of failure
- List of common modes

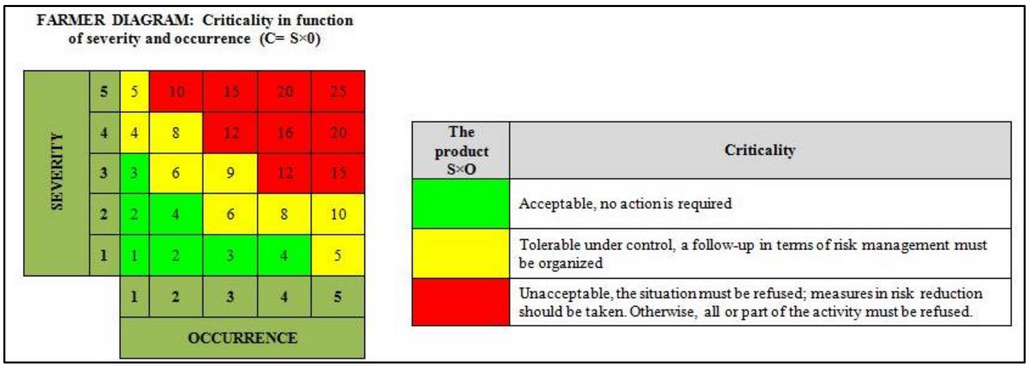

Figure 4: Farmer Diagram

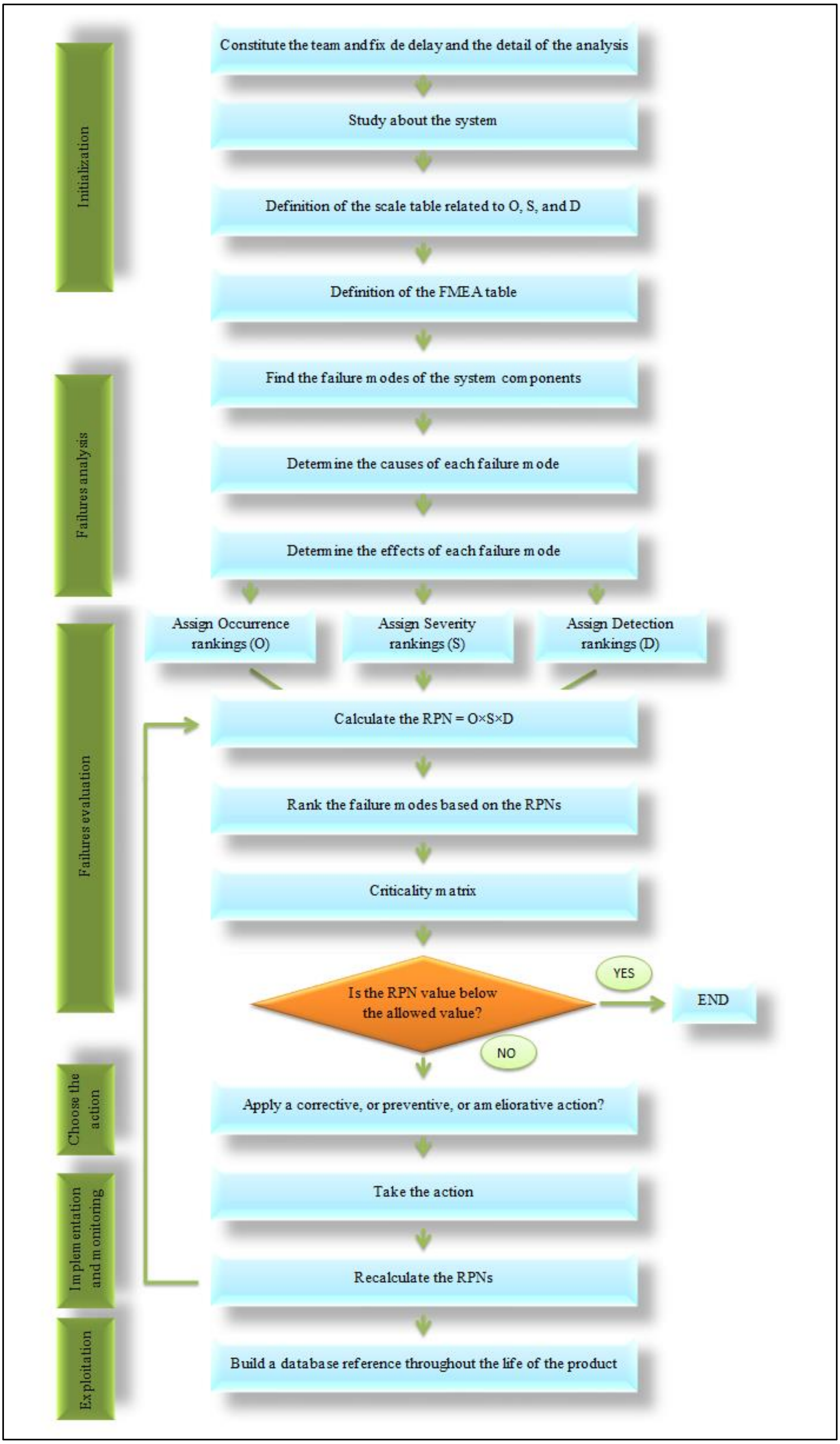

Figure 5: Steps of FMEA Method

3.1.5 Benefits and limitations of FMEA

Advantages:

- Improvement of the system reliability
- Minimization of the failures exposure
- Manufacturing and design efficiencies are enhanced
- Rest on a group work and capitalize the experience of each
- It is in the form of tables arranged in columns, which makes it applied easily to linear processes

Drawbacks:

- The team members should be trained
- Cost required to implement necessary actions
- Requires a detailed knowledge of the functioning of the product, the mean or the service analyzed.
- It is not a problem solving method
- It doesn't allow the study of combinations of failures
- It cannot guarantee the completeness of the study
- It is a tedious method for studying complex systems

3.1.6 Software Used for FMEA

The following figure contains a set of some software used to perform the FMEA method; in our study we used MS.EXCEL (Moodle.utc.fr, 2019).

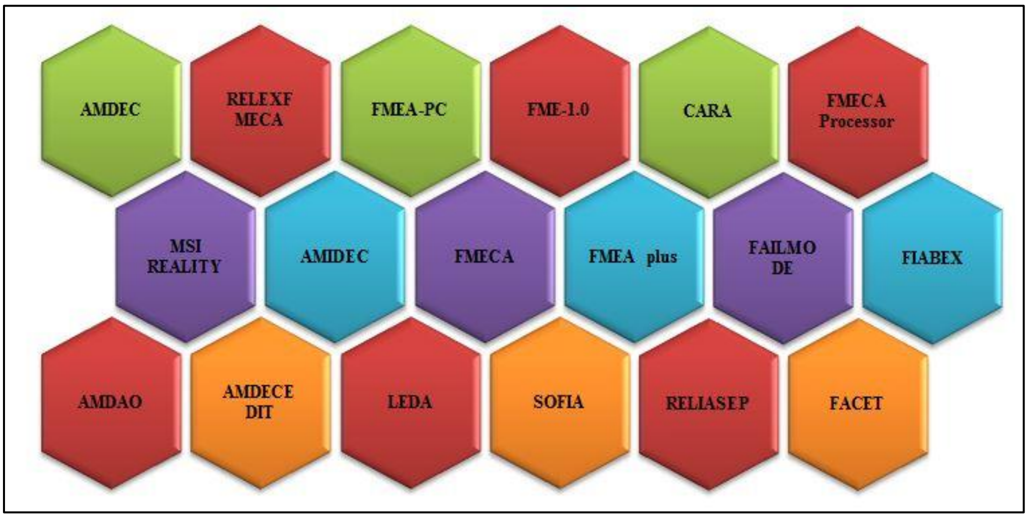

Figure 6: Processing Software Used to Realize the FMEA

3.2 Radio Frequency Identification (RFID) system

In order to apply the FMEA method for the RFID system, we should first study how does it work, and its purpose, as well as its components.

3.2.1 History

The RFID was used the first time in the military field 1935, when Robert Watson-Watt developed an application for the British army, IFF "Identification friend or foe", in order to differentiate enemy planes from allies. In 1945, during the World War II, "The thing" was invented by Léon Theremin, a spying device for the Soviet Union, providing the function of a wireless microphone by the transmission of an acoustic signal on an RF carrier wave. The first scientific papers were published between 1948 and 1952 by H. Stockman and F. L. Vernon. In 1952, the first patent for a transmission system that can communicate with a passive target was deposed by Donald Harris. Another patent was filed by J. Vogelman in 1959, on a system communicating with a target, which modulates the radar signal through the variation of the radar equivalent surface of an antenna. The first tag was commercialized in 1966, under the acronym EAS (Electronic Article Surveillance), and it contained only the information on the detection or not of the tag, and it was used for theft prevention in stores. Since then, the fundamental theory on which RFID is based is described precisely through several publications, including those of R. Harrington and J. K. Schindler, and other patents are filed around the problematic of access control. Mario Cardullo and William Parks patented, on January 23, 1973, the dispositive that is considered as the effective ancestor of the modern RFID, a transponder with 16 bits memory. Steven Depp, Alfred Koelle and Robert Frayman demonstrated the modulated backscatter of the RFID, at the Los Alamos National Laboratory in 1973, the system functioned at 915 MHz with 12-bit memory tags; this technique is used by the majority of today's UHRFID and microwave RFID tags. In 1978, Norway established the first RFID integrated road toll. The 1990s mark the beginning of standardization of RFID equipment; in 1999, some industrialists established the Auto-ID Center that aimed to standardizing the RFID technology. This center was closed in 2003 after the end of the work on the Electronic Product Code (EPC), and the results were transferred to newly created EPC global Inc. by the Uniform Code Council (UCC) and EAN International (now GS1 US and GS1). In January 2005, the distributor Wal-Mart imposed RFID technology on its suppliers for inventory management to enhance the supply chain. Carrefour, Metro, Tesco and Intel join forces to develop the new EPC radio frequency label technology, which is expected to succeed barcodes. Since 2005, RFID technologies kept being improved and have spread over the world, and became an indispensable in our daily life (Fr.wikipedia.org, 2019).

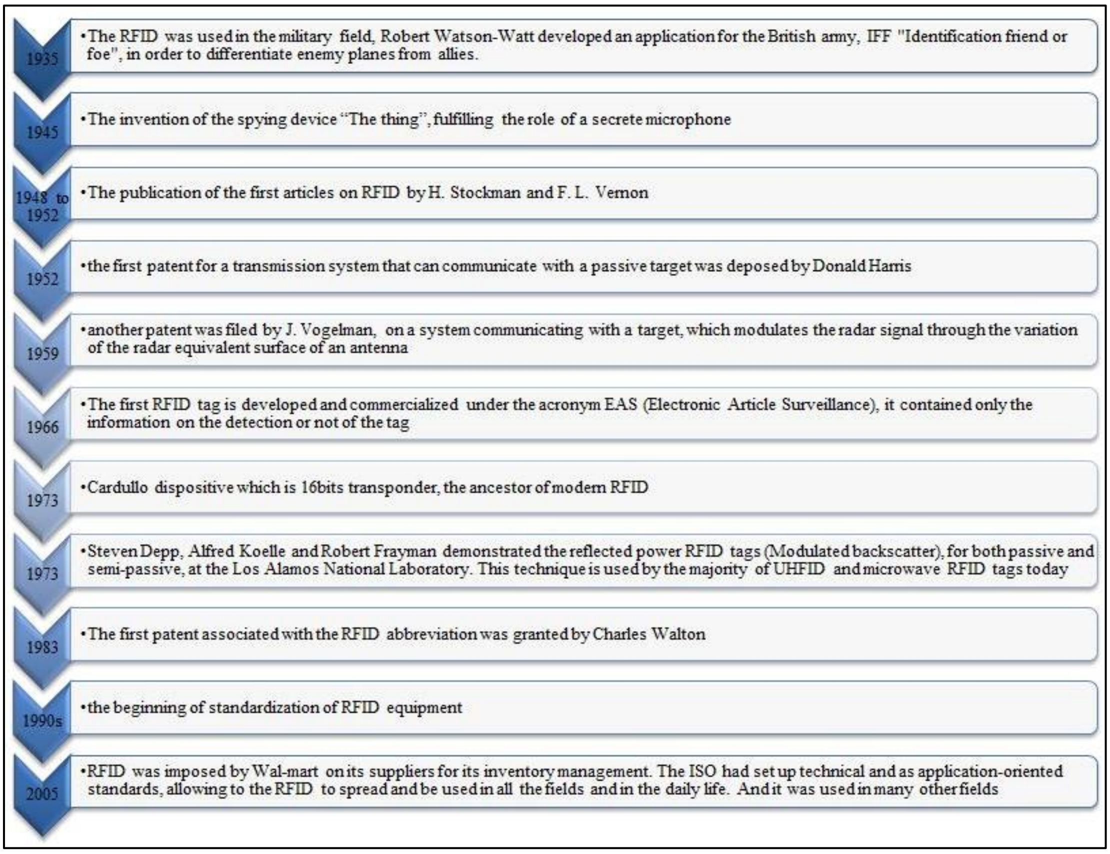

Figure 7: RFID History

3.2.2 Principle of the RFID technology

The RFID concept resulted from the fusion of two technologies, the Continuous Wave radio generation and the Radar device. Thus, it is a wireless technology using the radio frequency electromagnetic field (EM).

The RFID system contains four principal components: The tag or the label (transponder), the reader (interrogator or base station), the middleware, and the host (Database storage, computer, ERP…).

The RFID technology is based on electromagnetic field emission by a reader, which transmits a signal at a specified frequency to one or more tags within its reading range, this signal is received by the antenna of this (these) tag(s). This electric or magnetic field serves as a support for the activation energy of these tags, if they are passive ones, as well as a vector for the information between the label and its reader. Once “woken up” by the reader, these tags send back a signal and a dialogue is established according to a predefined communication protocol and the data is exchanged. The identification principle is based on the fact that each transponder has its unique identifier UID (Unique ID). The reader and the host communicate via the middleware. When identified, the data contained in the tags can be sent to the host to be saved, managed, edited and used.

We will illustrate the functioning of the RFID system by an experiment using low frequency tags, reader module, finger print sensor and Arduino as shown in appendix C, if the tag is correct the door will be opened, and a welcoming message will appear on the LCD, otherwise the system will be locked.

The RFID system can function correctly only if all the components are logically connected and compatible with each other (Rao, 1999). The following figure illustrates the infrastructure of the RFID system.

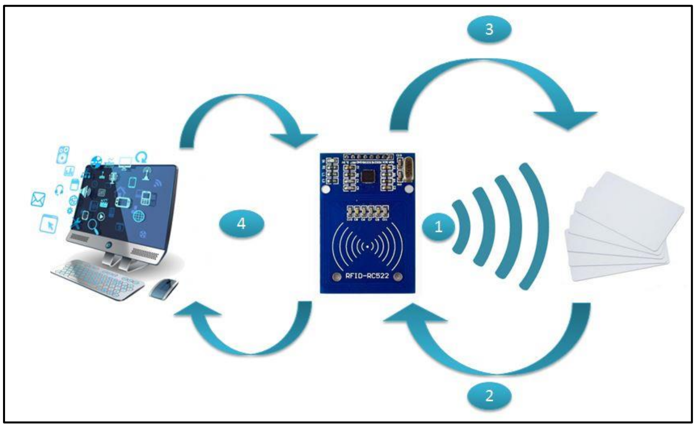

Figure 8: RFID Infrastructure

3.2.3 Examples of RFID Usage

The RFID technology can be used in all the identification and tracking applications (Ahsan, 2011, Peter Darcy, 2011, Chang-He Li, 2018). Thus, it surrounds us in our daily life, some of the applications of the RFID are:

- Internet of Nano things	- Supply chain management
- Track and trace systems	- Warehouses
- Stock management	- Logistics
- Order picking	- Facility and equipment maintenance
- Thefts prevention	- Smart shelf
- Highways	- Automated electronic payment system
- Parking system	- Connected taxis
- Defense and military	- Aviation industry
- Access control	- Banking and credit cards
- Identification of employees	- Animal and Human localization and tracking
- Passport	- Baggage and passenger tracking
- Postal package tracking	- Healthcare
- Blood inventory	- Anatomic pathology
- Patient safety	- Magic medicine cabinet
- Smart box	- Libraries
- The connected bins	- Connected trees
- Flooding warning system	- Gas sensing applications
- Production process	- Software reliability assessment
- Drilling	- Displacement and tilt detection
- Packaging	- Assembly
- Crack depths sensors	- Pedestrians safety

Figure 9: Examples of RFID Applications

3.2.4 The components of the RFID system

3.2.4.1 The tag

The RFID tag is constituted from a die (chip) connected to an antenna; both are carried by a substrate with anisotropic conductive adhesives (ACAs), and covered by a sensing film. These tags exist in two different forms, labels or inlays and the hard tags (Atlasrfidstore.com, 2019). The table below shows the main differences between them:

Table 4: Labels vs Hard Tags

	 **Inlays and labels**	 **Hard tags**
Description	Paper thin, flexible, low weight, supporting text and graphics printing. Usually peel and stick, unobtrusive.	Thick and rigid, constructed from materials like plastic, ABS, ceramics, polycarbonate, steel, polystyrene, or polymer, heat and cold resistant.
Advantages	- Low cost - Easy to use - Can be used with an RFID printer for mass printing/encoding.	- Attachment methods are variable. - Increased read range - Supports different temperatures (depends on the tag)
Drawbacks	- Don't resist to harsh conditions - Only adhesive attachment method - Most of them are not metal-mount	- High cost - Slow labeling and encoding - Some types don't support labeling

The power supply is another factor that differentiates the RFID tags; the passive tags are not equipped with a battery, they are alimented by the inducted current resulting from the electromagnetic field of the reader; the semi-passive tags are equipped with an internal battery, they are faster and more robust than the passive ones; the third type is the active tags, which have also an internal battery, but they can fulfill other mission rather than emission and transmission of the data, they can contain sensors, and process the information as well.

The RFID system generates and reflects electromagnetic waves, and it should not disturb the functioning of the other systems. Thus, the authorized frequencies for use with RFID, called ISM (Industrial-Scientific-Medical) are reserved to restrict applications. Which means that to the frequency of utilization is another factor that makes the difference between the RFID tags, we can distinguish between three types of operating frequencies tags: low frequency LF, high frequency HF, and ultra-high frequency UHF. The ranges of frequencies allowed for the RFID use are illustrated in figure 10.

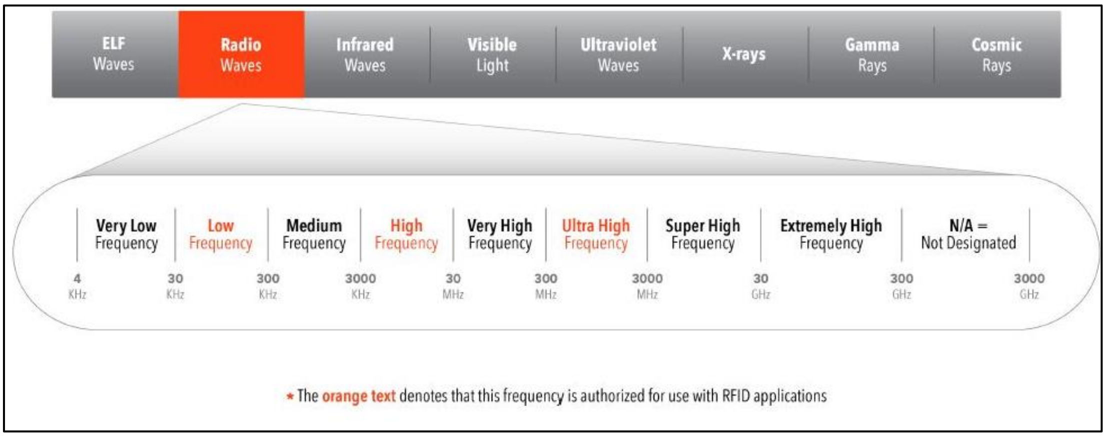

Figure 10: Electromagnetic Spectrum (Atlasrfidstore.com, 2019)

The microchip inside the RFID tag has memory where the ID and other data are stored, this small silicon chip can have read-only or writable characteristics, which depend on the microchip circuitry, and there are four types of tags regarding the memory type:

- Read-only
- Read- Write
- Read-write with sensors: can be semi passive or active tags
- Read-write with integrated transmitters: active tags those are able to establish a communication with other tags and devices without the presence of a reader.

3.2.4.2 The reader

The reader or the receiver is the brain of the system, they exist in three forms: handheld readers, fixed readers, and reader modules. A reader is composed from an integrated circuit responsible of emission of the electromagnetic energy using an antenna, and an integrated circuit containing analog and digital components, that receive and decode the information sent by the tag, then transfer them to the host, to be collected. The reader can read and edit the context of the tags. It works in a single frequency at a time even if it can have multiple frequency capability. The connection between the reader and the computer can be wired or wireless.

Figure 11: Types of RFID Readers

3.2.4.3 The antennas

The RFID antennas are the middle-wares technology linking the tag and the reader. There are numerous differences between the types of antennas, like the shape, direction of signals, polarities. The most used antennas are Omni-directional, adaptive, phased array element, beam-forming, patch, dipole or multi-pole, linear polarized, circular polarized, gate, and stick antennas.

3.2.4.4 The host

The host is the interface or the terminal device that makes the link between the user and the RFID system; it includes the middleware, and it can be a computer, a smartphone, Database, server, ERP, Arduino card or others, depending on the application. It is the component responsible of the data edition, saving and processing. The connection between the host and the reader can be wired, via USB, cables; or wireless connection, like blue tooth or Wi-Fi.

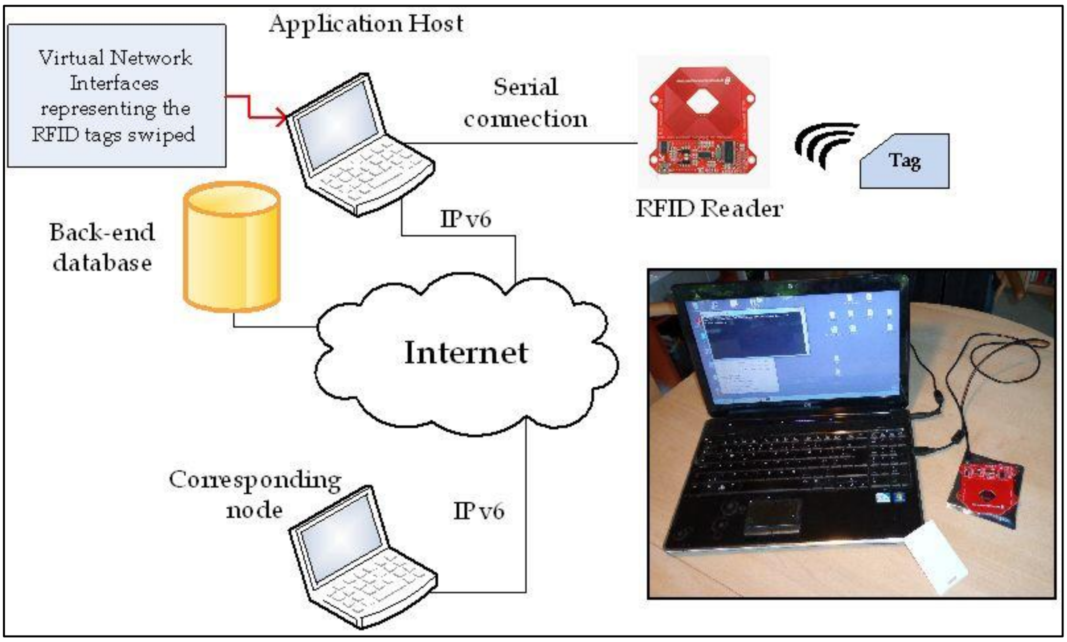

Figure 12: An Example of RFID Host

The Table 5 summarizes the types of RFID tags characteristics.

Table 5: Types and Frequencies of RFID Tags

		Near Field Communication NFC	**far-field radiative coupling**			
Frequency band	Low Frequencies LF	High Frequencies HF	Ultra High Frequencies UHF		Microwaves SHF	
Frequency used	125-134 KHZ	13.56 MHz	860-960 MHz	433 MHZ	5.8 GHz	2.45 and 5.8 GHz
read range	0.5 meter	1 meter	3-5 meters		1-10 meters	3.5 meters
Power	Passive tags	Passive tags	Passive tags and some semi-passive tags	Active tags	Passive tags and semi-passive tags	active tags
Futures	- Magnetic coupling. - Can last for a very long time (20 years) depending on the tear and the wear of the application. - Can penetrate wet surfaces (water, blood) and metal. - More expensive than HF tags and UHF tags. - Small amount of data (16 bits). - Slow read rates. -Very expensive readers. -Expensive tags.	- Magnetic coupling. - Can last to the lifespan of the application, like LF tags. - Can penetrate thin metals (aluminum), plastic and most materials. Can't pass through dense metals and water. Inexpensive. - Small to medium amount of data - Medium read speed. - Low costing reader. - The tag is less expensive than LF tags.	- Passive backscatter or far-field radiative coupling. - Long life span, like LF and HF tags, because they don't have a battery. - Very sensitive to liquid and metal. Can resist to high/low temperature and other conditions, according to the application. - High memory. - Better read rates than LF and HF - Relatively expensive readers. - Lower cost compared to all other tags.	- Interne battery. - They don't last for a long time; their life span depends on their battery. - Very sensitive to liquid and metal. Can resist to high/low temperature and other conditions, according to the application. - Big memory - Better read rates than LF and HF - Can have sensors. - The reader is relatively expensive - The cost is lower than LF, HF and microwave tags, but more expensive than UHF passive tags.	- Use backscatter coupling. - Long life span - Very sensitive to metals and liquids. - easy to work with metallic objects - Big memory - Fast reading - Expensive reader - More expensive and less demanded than passive UHF tags. - Usually smaller than passive UHF tags.	- The most used frequency is 2.45 GHz, in some cases 5.8 GHz is used as well. - They use their own transmitter to communicate. - Short life span. - Very sensitive to metals and liquids. - Easier to design to work with metallic objects than passive ones. -Big memory - Fast reading - Can contain sensors - Expensive reader - Small size
Applications	- In close reads - Animal tracking - Access control - Inventory control	- Marketing applications. - Advertising posters. - Smart items. - Access control - Data transfer. - Ticketing. - Passports.	- Tool and asset tracking. - Race timing - Laundry management Etc.	- Oil and gas applications. - Transportation. - Highways. - Vehicle tracking. - Cargo containers tracking. - Pipes and construction equipment tracking.	- Long-range access control for vehicles, - Fleet identification, -Highway toll collection.	- Active microwave tags are used for real time location systems (RTLS).
Norms	ISO/IEC 18000 -2 ISO 14223/1	ISO/IEC 18000 -3 ISO 14443 ISO 15693	ISO/IEC 18000 -6c		ISO/IEC 18000 -4	

3.2.4.5 Sub components

The tag components are illustrated in the following figures:

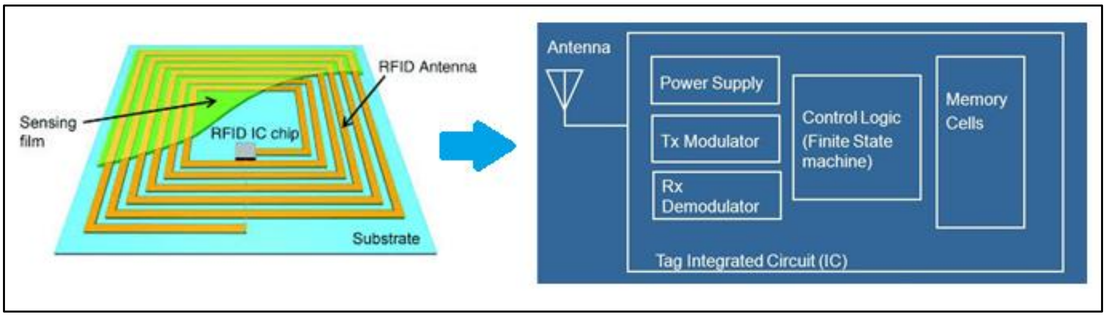

Figure 13: RFID Tag Components (kangfadlan, 2019)

The RFID reader integrated circuit is illustrated in the following figure:

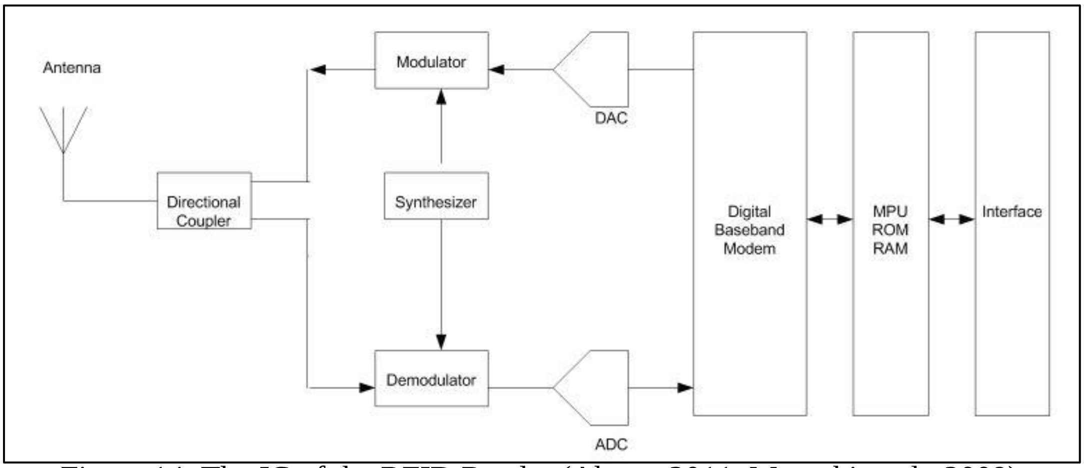

Figure 14: The IC of the RFID Reader (Ahsan, 2011, Marzuki et al., 2009)

The following figure summarizes the RFID system and sub systems:

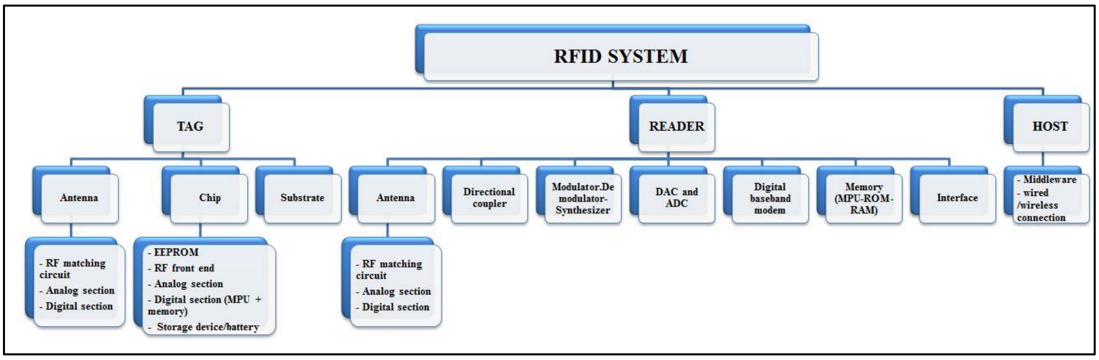

Figure 15: RFID Sub Components

3.2.4.6 Advantages and drawbacks of the RFID technology

Advantages

- The ability of stakeholders to edit the content unlike the barcode (read & write tags).

- In a radiofrequency label it easy to store one thousand on 1mm², this capacity can reach 10,000 characters in some cases.

- The data concerning the objects contained or transported or tracked are updated automatically in a fraction of a second and in real time.

- The radio frequency tag can be protected by a password for writing or reading, and we can make some data accessible and others encrypted in the same label.

- The RFID tag can be reused million times unlike the barcode.

- With the radio frequency label, it is possible to get away from difficulties related to optical reading; the reader can read its contains one it is detected.

- RFID tags can be protected by a material and don't need to be exposed to storage or transportation or handling attacks.

Drawbacks

- Prices remain significantly high. And it can be more than the price of the product tracked itself in some cases.

- Electromagnetic disturbance by the environment; like metals and liquids; or other parasitic radiations coming from the neighbor equipment like computers, lighting systems, or any other electrical device.

- Interferences between labels or readers.

- The RFID has an impact on health; especially when it is used with in a frequent way or when it is very close to the human body, like anti-theft gates and mobile phones.

3.2.5 Failure modes of the RFID system

Based on experts' explanations, and the published studies related to the problems occurring while using the RFID; we could dress the Table 6, containing RFID system and sub system components, their failure modes, their causes and their effects (S Taoufik, 2016, Sanae Taoufik, 2017, Mandeep Kaur, 2011, Mohamed El Beqqal, 2017, Arumugam and Engels, 2008, Cmiljanic et al., 2018, Peter Darcy, 2011, IT, 2019, G. Fritz, 2010, Kheddam, 2013, Sood et al., 2008).

Table 6: RFID Failure Modes

RFID SYSTEM	Sub systems	Failure modes	Cause of failure	Effects
TAG	Tag power supply	Inefficient conversion of RF to DC energy	The antenna doesn't provide sufficient power	Tag does not turn on since it is not alimented, thus it cannot send signals
			Threshold voltage due to the diode connected MOS	
		Over conversion of electrical power	The reader emits too much energy	Tag alimented and communicates with reader when it should not
	Integrated Circuit and connections	Shortages between bumps	over cured adhesive with age	Wrong or degraded functioning of the tag
		Shortages between the pads of the antenna	Under cured adhesive due to high temperature	
		Insufficient impedance between bumps	Corrosion of antenna in low temperature	
		Impedance is insufficient between the pads of antenna	Corrosion of bumps due to humidity	
		Bump is open and antenna pad	Corrosion of filter particle because of temperature and humidity	
		Excess of impedance between the bump and the pads of antenna at the bond line	Adhesive swelling due to temperature cycling	
		Antenna lead is partially fractured and the impedance in antenna is excessive	Die lift because of humidity cycling	
		Antenna is open and its impedance is excessive	Die separation from adhesive due to temperature and humidity cycling	
		The contact between bump and antenna pad is not continuous	Adhesive separation from antenna due to ESD	
		Short in IC	Adhesive void due to excessive bond force	
		Open in IC	The filler doesn't have enough compression because of lack of bond force	
		Damaged IC	Excessive bond temperature	Damaged tag
			Current leakage caused by electrical overstress(EOS)	
		The gap separating the antenna and the chip is not sufficient	The bond temperature is deficient	The tag may not be detected
			Bond time more than required	
			Bond time less than required	
			Mechanical crop	
			Mechanical curving	
			Mechanical squeezing	
	EEPROM	Insufficient memory	Limited storage memory	The data that are not will be lost
		The EPC number is the same for two tags or more. (EPC memory bank of the tag)	The Electronic product code is random repeating number used by the manufacturer	Reader cannot differentiate between two tags sharing the same EPC value
		Contactless cards are more exposed than regular credit cards.	A suitable reader can interrogate the Tag if it is not secured	Thefts and cloning ; Ethical issues
		Decryption of the user data in the User memory bank	Insufficient or inefficient tag encryption	Blackmail, tracking, coercion, privacy issues
		Non authorized access to the tag data in the reserved memory bank	Access and lock password not secured enough	The tag can be hacked, copied, counterfeited

Table 6 (Continued)

RFID SYSTEM	Sub systems	Failure modes	Cause of failure	Effects
TAG	Positioning	Incorrect tag orientation	Miss much between tag antenna orientation and reader antenna orientation	the reader will not detect the tag / or it will detect it with errors
		Steep angle of the tag	The front of the tag is not facing the antenna	Short read range
	Application surface	Incompatible type of surface material with the type of tag	Due to the way the antenna sends and receives signals, it is very sensitive to t type of material where it is put	Lower read range/lower read rate/no reading at all
	Tag attachment	The tag fall off the item	Damaged attachment because of dust, water, UV light, chemicals, temperatures, lifespan…	Item not trackable
	Encasement	Fails to protect the tag IC and antenna	Damaged encasement in harsh environment like water and temperature or metallic surface	The tag can be damaged
Reader	Reader API communications event management	Reader collision problem (reader-reader collision)	The reader communicates with tags covered by another reader	The tag is read many times simultaneously by the overlying readers
			The coverage areas of two readers overlap	The signals interfere if the readers coverage areas overlap
		Tag collision problem (Tag-Tag collision)	Multiple tags are trying to send data simultaneously	The reader can't make the difference between signals
		Interference between multiple readers (Reader-Tag collision)	Insufficient distance between two readers	Wrong information
			Wrong settings of The operating frequency of two adjacent readers	
		Short reading distance	The reader frequency settings are not correct	Tag is not read
			Label and antenna polarization	
			Label surface is covered with other materials like metal	
			The RF cable is not connected to reader and antenna.	
			RFID label's properties	
		Cannot read card	The serial cable or the network cable is not properly connected	The PC command can't be sent to the reader
			The RFID antenna SMA connector is tightened	Missed reading
			Miss matching ISO standard between the transponder and the reader	
			The construction size of the tag and the receiver don't match	
			Miss matching frequency between the tag and the head	
			Label is damaged	
		Read EPC instead of TID	Reader setting are not accommodate	Incorrect ID thus wrong information
		Self-jammer	Continuous waves signal sent to the tag	Saturation of receiver block and degradation of sensitivity
		The rectifier converts small sinusoidal voltage to DC voltage	The power link between the antenna and the rectifier input mismatch	The integrated circuit of the reader is not correctly alimented

Table 6 (Continued)

RFID SYSTEM	Sub systems	Failure modes	Cause of failure	Effects
The "between" tag and reader	Antenna MODEM	Signals are not received by tag or reader	The sensibility detection of the tag or the reader is defective	LOSS of INFORMATION
			Electromagnetic field disturbances	
			Outer aggression of the antennas in the tag or the reader	
			Interior failure in the Reader	
		Signals are not transmitted to the tag or the reader	Interior failure in the Tag	
			Interior failure in the Reader	
		The transmission in continuous	Interior failure in the Tag	Channel overload
			Interior failure in the reader	
			Repetitive trials to communicate by the software	
	Electromagnetic field	The EM waves emitted by the tag can't reach the reader and vice versa	Harsh environment (metal – liquid…)	Loss of information
HOST	Computer middleware data base SD card …	Hack	Insufficient or inefficient protection tools	Violation of the privacy and security of users
		Software bugs	Ignorance ,big data ,slow system	Wrong ,duplicate and missed reading
		Data transfer	Poor connection between the reader and the host (Wi-Fi/serial interface/Bluetooth …)	Data are not received by the host and not transmitted to the tag
		Virus attack	Inappropriate antivirus	Hack , degraded functioning or dysfunction of the system
Health	RF waves	- Thermal effects: can damage the lens of the eye, and heats cells and biological tissues - Possibly carcinogenic	The distance between the reader and the human body is less than 10 cm	High specific absorption rate (SAR) of the human head (above 1.6 / the maximum value allowed by FCC in the US) (Arumugam and Engels, 2008).
Green IT	Heavy metals, silicon, aluminum, plastics PVC or PA6	The number of RFID tags is increasing drastically, consuming metals and toxic materials	Chemical reactions with environment	Pollution and use of rare metals

3.3 Data Envelopment Analysis (DEA)

The measurement of the efficiency is crucial in the evaluation of the performance of any system, company, organization or a process. Etc. In general the efficiency of a system is equal to the fraction of the output (Y) that it produces, over the input vector (X) that it consumes, the parametric methods can work if we have a relation (the production function is known) between these two vectors (Y=f(X)); but in some cases this function is unknown, which means that the parametric methods (like linear regression, DFA, SFA) cannot work, so the solution is to introduce a method which is non-parametric , like Data Envelopment Analysis.

Data Envelopment Analysis (DEA) is a non-parametric and comparative analysis method of efficiency. It aims to give an estimated production frontiers (called also the production function) and to compare production units (decision making unit shortened DMU) according to the resources they use (the factors of production, or inputs) and the goods or services produced products (outputs). DEA is based on the concept of the set of technologies which is the set of production plans, that is, the outputs for given production factors, technologically feasible. In order to estimate the production function, the mathematical model's objective function is to maximize the efficiency, which is equal to the weighted summation of the outputs vector divided by the weighted summation of the inputs vector. In the following sections we are going to see the origins of DEA, and how the efficiency is maximized based on different models.

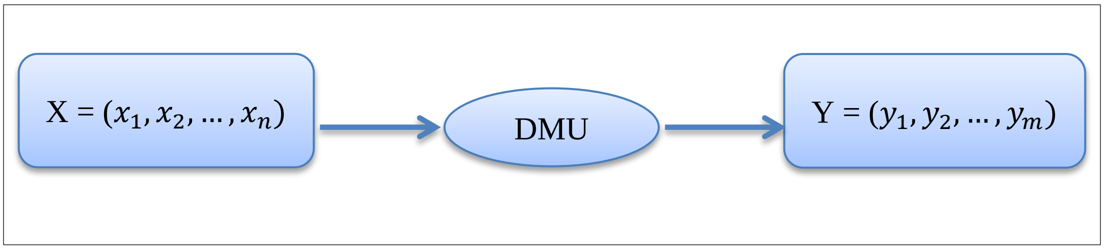

Figure 16: Inputs and Outputs Vectors

3.3.1 Origins of DEA

The DEA originates from the activity analysis approach of Farrell in 1957, explained in his seminal article "The Measurement of Productive Efficiency" (Farrell, 1957), which expanded the "productivity" concept to the "efficiency" concept which is more general , in order to cope with the problems occurring in the measurement of efficiency more adequately. In Germany, the marginal productivity of Research and Development as well as other factors of production were estimated using the DEA approach in 1970. Building on the work of Farrell; Charnes, Cooper and Rhodes created for the first time a mathematical linear program able to estimate an experimental production frontier in 1978, introduced in their seminal work "Measuring the efficiency of decision making units" (A. Charnes, 1978). This initial DEA model (CCR) was used for the evaluation of educational programs dedicated to deprived students. The BCC model was developed by Banker, Charnes and Cooper in 1984. Since then, a huge collection of papers and books explaining DEA or using DEA in some applications were published, DEA was used not only to compare the efficiency across DMUs within a given system, but it was applied to compare the performance across different firms as well. The prime developments of DEA that are achieved between 1970s and 1980s were cataloged by Seiford & Thrall in 1990. In 2000, several types of DEA assumptions were presented by Ylvinger to treat varying returns to scale, that include CRS (constant returns to scale), VRS (variable returns to scale), non-increasing returns to scale and the non-decreasing returns to scale (wikipedia, 2019). A survey of studies run by Jamas and Pollitt in 2001 identified DEA analyses applications to electricity distribution whose number exceeded 30, the thing that indicates the widespread application of this technique. It was used in several fields like water utilities, energy and environmental studies, supply chains, health care, human development, batteries industry, electronics, banking, shipping, roan projects, countries and regions. Etc. This technique became very popular, and it was combined with many other approaches and techniques in order to enhance the efficiency measurement (Cooper et al., 2011). The most important stations in the DEA history are summarized in the figure 17.

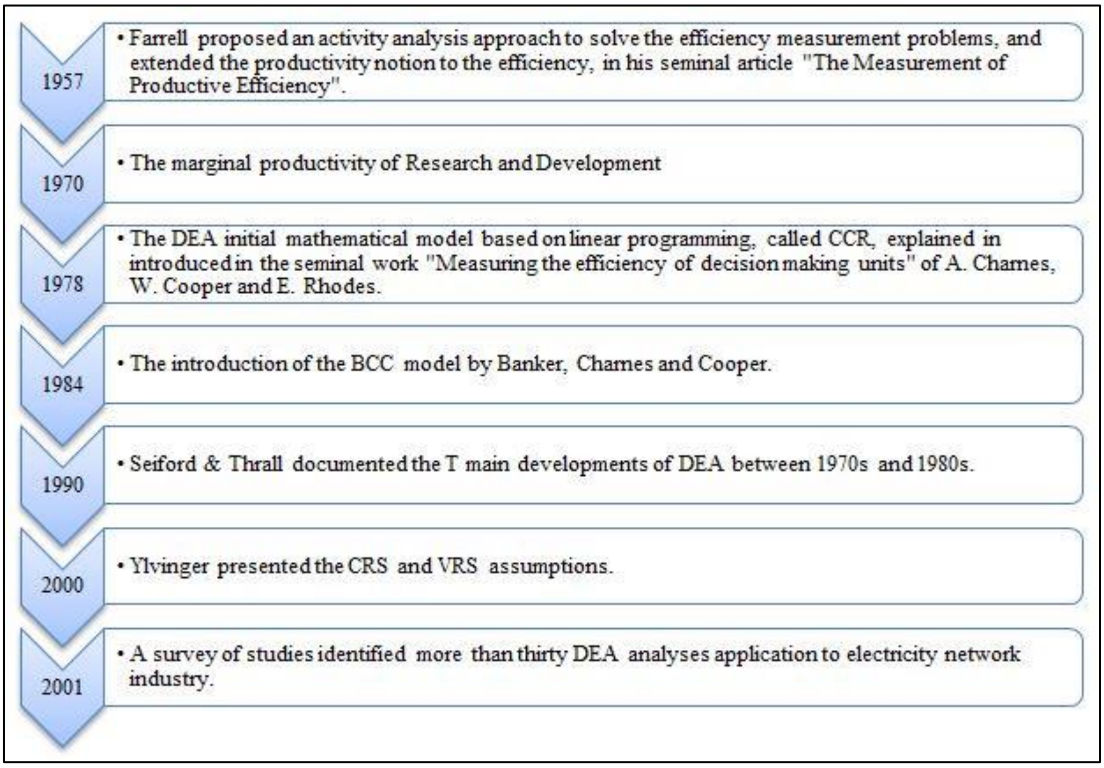

Figure 17: DEA Origins

3.3.2 Generalities about DEA approach

The principle of DEA approach is to compare the efficiency of the DMU_o(under observation, o ranges from 1 to n) with the efficiencies of all the other DMUs belonging to the production possibility set (PPS), all these DMUs should utilize the same inputs (X) and yield the same outputs (Y). The idea is that if a DMU can perform well, then the other one can have a better performance as well.

Suppose we have certain number m of inputs, and s outputs, then the number of DMUs that we should have is at least equal to the summation of inputs and outputs multiplied by 3.

$$n \geq 3 \times (m + s)$$

For example, if our DMUs are bakeries, they are using floor, water, and electricity (m=3) to produce bread and simit (s =2), and then we have to use at least 15 DMUs.

The weights assigned to the elements of the inputs and outputs vectors are respectively $(v_i, i = 1,2, \dots, m)$ and $(u_r, r = 1,2, \dots, s)$. These weights can be the costs for the inputs and the selling prices for the outputs for example. The objective of the DEA method is to estimate and compute the appropriate values for the weights related to each input and output that maximize the efficiency value for each DMU. The efficiency will be the ratio of virtual output over virtual input (WILLIAM W. COOPER, 2007).

The virtual output is: $\sum_1^s u_r y_{ro}$

The virtual input is: $\sum_1^m v_i x_{io}$

The efficiency of the DMU under observations is $\theta = \frac{\sum_1^s u_r y_{ro}}{\sum_1^m v_i x_{io}}$

The input and the output vectors for each DMU_j will be respectively:

$$x_j = (x_{1j}, x_{2j}, x_{3j}) \text{ and } y_j = (y_{1j}, y_{2j})$$

In order to maximize the efficiency, several models were presented. In the following section we will present some of the basic DEA models.

3.3.3 Postulates (basic CCR model assumptions)

1- All the observed DMUs belong to the production possibility set (PPS).

$$DMU_j \in PPS \; for \; all \; j = 1,2, \dots, n$$

2-If $(x, y) \in \text{PPS} \rightarrow$ all activities $(\bar{x}, \bar{y})$ having $\bar{x} \geq x \; and \; \bar{y} \leq y$, $(\bar{x}, \bar{y}) \in PPS$.

3- Constant returns to scale assumption CRS

If $(x, y) \in PPS \rightarrow \forall k \geq 0$ we have, $(kx, ky) \in PPS$.

4- Convex linear combinations: If (x, y) and $(\bar{x}, \bar{y}) \in PPS \rightarrow \forall \lambda \in [0,1]$ we will have $[\lambda(x, y) + (1-\lambda)(\bar{x}, \bar{y})] \in PPS$.

5- PPS is the smallest set satisfying the four previous assumptions.

$PPS = (x, y), x \geq \sum_{j=1}^{n} \lambda_j x_j \ and \ y \leq \sum_{j=1}^{n} \lambda_j y_j$, where $\lambda_j \geq 0$.

A given DMU is said efficient if and only if it is situated on the frontier of the production possibilities frontier (PPF).

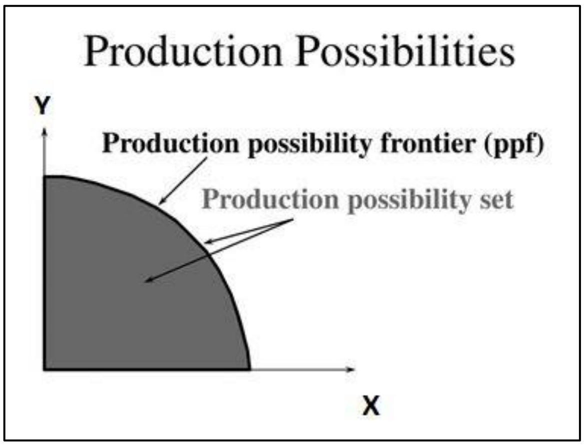

Figure 18: PPS and PPF

3.3.4 Returns to scale RTS

If $(x, y) \in PPS \rightarrow \forall k \geq 0$ we have: $(kx, ky) \in PPS$.

1-Constant returns to scale:

$$f(x) = y$$

$$f(kx) = ky$$

2-Increasing returns to scale: when we increase the inputs, and increasing in the outputs are more than our expectation, then RTS is increasing.

$$f(x) = y$$

$$f(kx) > ky$$

3-Decreasing returns to scale: when we increase the inputs, and increasing in the outputs are less than our expectation, then RTS is decreasing.

$$f(x) = y$$

$$f(kx) < ky$$

3.3.5 The basic CCR model

3.3.5.1 Input-oriented CCR

A- Fractional program form

$$(\boldsymbol{FP_o}) \qquad \max_{u,v} \qquad \theta = \frac{\sum_1^s u_r y_{ro}}{\sum_1^m v_i x_{io}}$$

$$\begin{aligned} \text{subject to} \qquad & \frac{\sum_1^s u_r y_{rj}}{\sum_1^m v_i x_{ij}} \le 1, \ \ (j = 1,2, \dots, n) \\ & v_i \ge 0\,, \ \ (i = 1,2, \dots m) \\ & u_r \ge 0, (\, r = 1,2, \dots, s) \end{aligned}$$

B- Linear program form

$$(\boldsymbol{LP_o}) \qquad \max_{u,v} \qquad \theta = \sum_1^s u_r y_{ro}$$

$$\begin{aligned} \text{subject to} \qquad & \sum_1^m v_i x_{io} = 1, \ \ (j = 1,2, \dots, n) \\ & \textstyle\sum_1^s u_r y_{rj} - \sum_1^m v_i x_{ij} \ \le 0 \\ & v_i \ge 0\,, \ \ (i = 1,2, \dots m) \\ & u_r \ge 0, (\, r = 1,2, \dots, s) \end{aligned}$$

Remarque : $FP_o \leftrightarrow LP_o$

C-Multiplier form:

The matrices form for a system having:

Number of DMUs = n
Number of inputs = m
Number of outputs = s

INPUTS MATRIX : X

$$\begin{matrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{matrix}$$

OUTPUTS MATRIX : Y

$$\begin{matrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ y_{s1} & y_{s2} & \cdots & y_{sn} \end{matrix}$$

input multipliers vector
$v = (v_1, v_2, \dots, v_m)$

output multipliers vector
$u = (u_1, u_2, \dots, u_s)$

$$(\boldsymbol{LP_o}) \qquad \max_{u,v} \quad \theta = uy_o$$

$$\begin{aligned} \textit{subject to} \qquad vx_o &= 1 \\ u\ Y - vX &\leq 0 \\ v &\geq 0 \\ u &\geq 0 \end{aligned}$$

D-Envelopment form (dual model of the linear program):

$$(\boldsymbol{DLP_o}) \qquad \min_{\theta,\lambda} \quad \theta$$

$$\begin{aligned} \textit{subject to} \qquad \theta x_o - X\lambda &\geq 0 \\ Y\lambda &\geq y_o \\ \lambda &\geq 0 \end{aligned}$$

Where $\theta \in \mathbb{R}$, and $\lambda \in \mathbb{R}_n^+$.

3.3.5.2 Output-oriented model

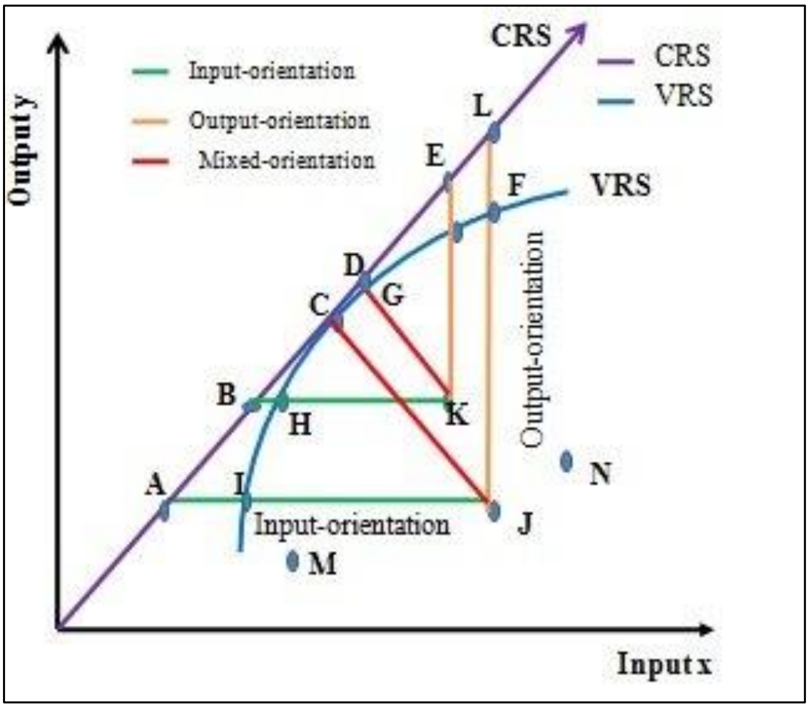

Figure 19: Different Orientations of DEA Models

A-dual model or envelopment form:

$$(\boldsymbol{DLPO_o}) \qquad \max_{\eta,\mu} \quad \eta$$

$$\text{subject to} \quad \begin{aligned} x_o - X\mu &\geq 0 \\ \eta y_o - Y\mu &\leq 0 \\ \mu &\geq 0 \end{aligned}$$

Where $\eta \in \mathbb{R}$, and $\mu \in \mathbb{R}_n^+$.

The relations between optimal solutions found by the output-oriented model and the input-oriented model are:

$\eta^* = 1/\theta^*$ and $\mu^* = \lambda^*/\theta^*$

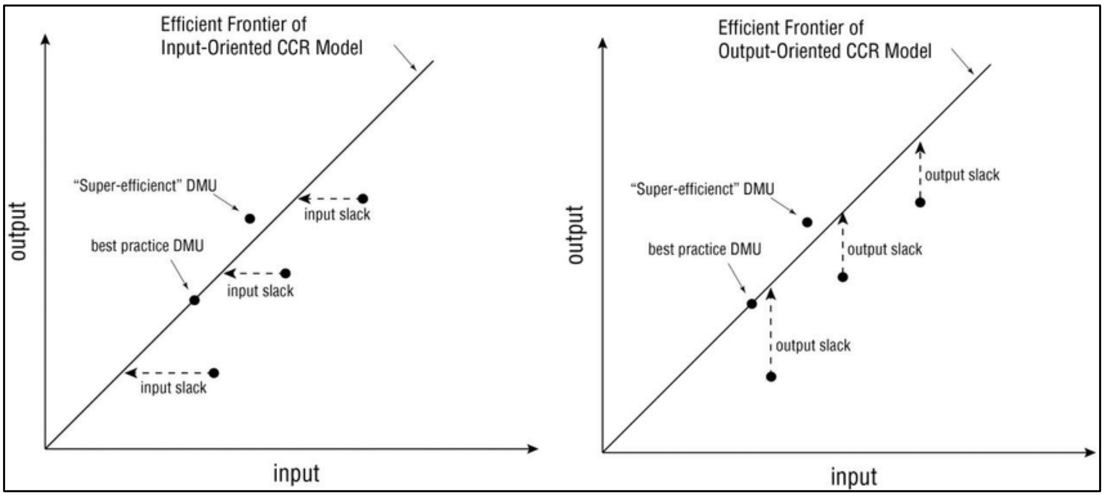

Figure 20: The CCR- Input Oriented Model and the CCR-Output Oriented Model

3.3.6 The BCC model

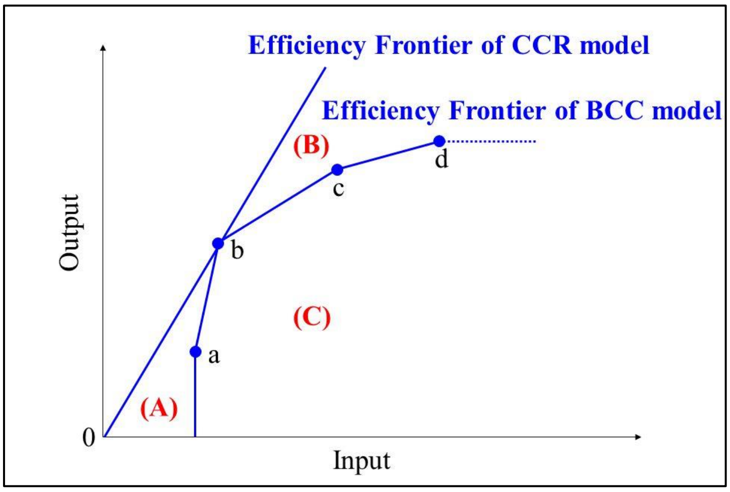

Figure 21: BCC and CCR PPF

3.3.6.1 Postulates

1- All the observed DMUs belong to the production possibility set (PPS').

$$DMU_j \in PPS' \; for \; all \; j = 1,2, \ldots, n$$

2-If $(x, y) \in PPS'$, then for all activities $(\bar{x}, \bar{y})$ having $\bar{x} \geq x \; and \; \bar{y} \leq y$, we will get $(\bar{x}, \bar{y}) \in PPS'$.

3- Convex linear combinations: If (x, y) and $(\bar{x}, \bar{y}) \in PPS' \rightarrow \forall \lambda \in [0,1]$ we will have $[\lambda(x, y) + (1-\lambda)(\bar{x}, \bar{y})] \in PPS'$.

4- PPS' is the smallest set fulfilling the four previous assumptions.

$PPS' = (x, y) | x \geq \sum_{j=1}^{n} \lambda_j x_j \text{ and } y \leq \sum_{j=1}^{n} \lambda_j y_j$, where $\lambda_j \geq 0, and \sum_{j=1}^{n} \lambda_j = 1$.

3.3.6.2 The basic input-oriented BBC model

A-Fractional program form

$$(\boldsymbol{FBCC_o}) \quad \max_{u,v,u_o} \quad z = \frac{\sum_1^s u_r y_{ro} - u_o}{\sum_1^m v_i x_{io}}$$

$$\text{subject to} \quad \frac{\sum_1^s u_r y_{rj} - u_o}{\sum_1^m v_i x_{ij}} \leq 1, \quad (j = 1,2, \dots, n)$$

$$v_i \geq 0, \quad (i = 1,2, \dots m)$$

$$u_r \geq 0, (r = 1,2, \dots, s)$$

$$u_o \; free$$

B- Linear program form:

$$(\boldsymbol{LBCC_o}) \quad \max_{u,v,u_o} \quad z = \sum_1^s u_r y_{ro} - u_o$$

$$\text{subject to} \quad \sum_1^m v_i x_{io} = 1, \quad (j = 1,2, \dots, n)$$

$$\sum_1^s u_r y_{rj} - \sum_1^m v_i x_{ij} - u_o \leq 0$$

$$v_i \geq 0, \quad (i = 1,2, \dots m)$$

$$u_r \geq 0, (r = 1,2, \dots, s)$$

$$u_o \; free$$

C- Multiplier form:

$$(\boldsymbol{LBCC_o}) \quad \max_{u,v,u_o} \quad z = uy_o - u_o$$

$$\text{subject to} \quad vx_o = 1$$

$$uY - vX - u_o \leq 0$$

$$v \geq 0$$

$$u \geq 0$$

$$u_o \; free$$

D-Envelopment form (dual model of the linear program):

$$(\boldsymbol{DLBCC_o}) \quad \min_{\theta_B, \lambda} \quad \theta_B$$

$$\text{subject to} \quad \theta_B x_o - X\lambda \geq 0$$

$$Y\lambda \geq y_o$$

$$\lambda \geq 0$$

$$e\lambda = 1,$$

Where $\theta_B \in \mathbb{R}$, and $\lambda \in \mathbb{R}_n^+$

3.3.6.3 Output-oriented model of BCC

A-dual model or envelopment form:

$$(\boldsymbol{DLBCCO_o}) \qquad \max_{\eta_B,\lambda} \quad \eta_B$$

$$\begin{array}{lr} \text{subject to} & x_o - X\lambda \geq 0 \\ & \eta_B y_o - Y\lambda \leq 0 \\ & \lambda \geq 0 \\ & e\lambda = 1, \end{array}$$

B-The Multiplier form of the output-oriented BCC model:

$$(\boldsymbol{LBCC_o}) \qquad \min_{u,v,u_o} \quad z = vx_o - v_o$$

$$\begin{array}{lr} \text{subject to} & uy_o = 1 \\ & -uY + vX - v_o e \geq 0 \\ & v \geq 0 \\ & u \geq 0 \\ & v_o \ free \end{array}$$

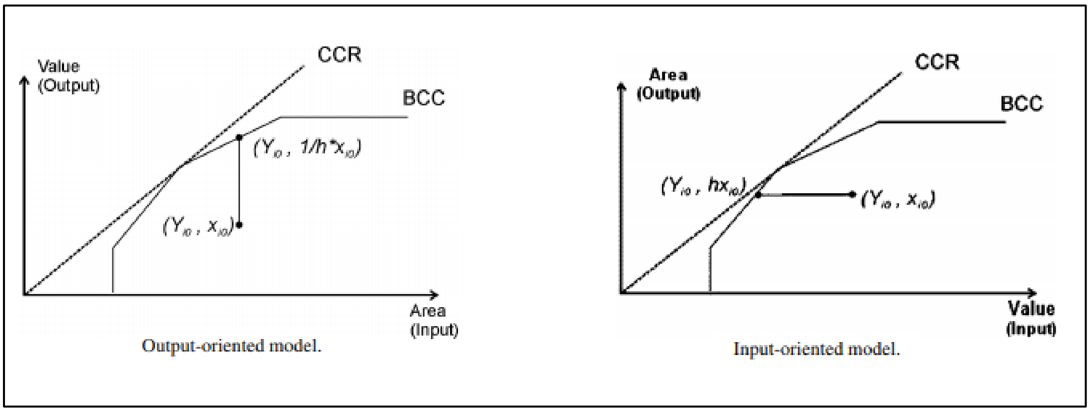

Figure 22: the BCC-input and output-oriented models

3.3.7 The BCC-CCR model (increasing RTS) – Envelopment Side

$$(\boldsymbol{BCC - CCR_o}) \qquad \min_{\theta,\lambda} \quad \theta$$

$$\begin{array}{lr} \text{subject to} & \theta x_o - X\lambda \geq 0 \\ & Y\lambda \geq y_o \\ & \lambda \geq 0 \\ & e\lambda \leq 1 \end{array}$$

3.3.8 The CCR-BCC model (Decreasing RTS) – Envelopment Side

$$(\boldsymbol{CCR-BCC_o}) \qquad \min_{\theta,\lambda} \quad \theta$$

$$\begin{aligned} \text{subject to} \qquad \theta x_o - X\lambda &\geq 0 \\ Y\lambda &\geq y_o \\ \lambda &\geq 0 \\ e\lambda &\geq 0 \end{aligned}$$

There are other models derived from the basic CCR model. In this research we are going to use the basic CCR model, input-oriented in the envelopment form.

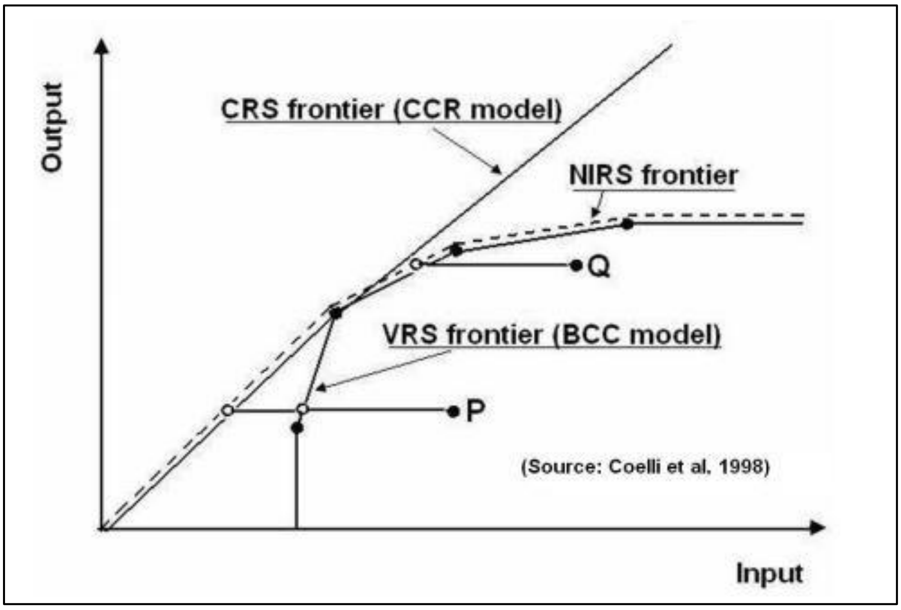

Figure 23: Frontiers of the CCR, BCC and NIRS Models

3.3.9 Benefits and drawbacks of DEA

Advantages

- Useful even when the relation is unknown between the inputs and outputs.

- Can deal with multiple inputs and outputs.

-Used with any inputs and outputs measured in any field

-No need to form a mathematical model from the beginning

- Returns to scale are considered

- It is not complicated and easy to apply

-Inefficiency sources can be quantified and analyzed for each DMU.

Drawbacks:

- The results are sensitive to the selection of inputs and outputs.

- The collection of enough data can be difficult.

-Necessity of the DEA solver software.

Table 7: Summary of the Basics of DEA

	CCR (Charnes, Cooper, Rhodes)		BCC (Banker, Charnes, Cooper)	
Postulates	1- All the observed DMUs belong to the production possibility set (PPS). $DMU_j \in PPS \; for \; all \; j = 1,2,\dots,n$ 2-If $(x,y) \in PPS \rightarrow$ all activities $(\bar{x},\bar{y})$ having $\bar{x} \geq x \; and \; \bar{y} \leq y$, $(\bar{x},\bar{y}) \in PPS$. 3- Constant returns to scale assumption CRS If $(x,y) \in PPS \rightarrow \forall k \geq 0$ we have, $(kx, ky) \in PPS$. 4- Convex linear combinations: If (x, y) and $(\bar{x},\bar{y}) \in PPS \rightarrow \forall \lambda \in [0,1]$ we will have $[\lambda(x,y) + (1-\lambda)(\bar{x},\bar{y})] \in PPS$. 5- PPS is the smallest set satisfying the four previous assumptions. $PPS = (x,y), x \geq \sum_{j=1}^{n} \lambda_j x_j \; and \; y \leq \sum_{j=1}^{n} \lambda_j y_j$, where $\lambda_j \geq 0$. A given DMU is said efficient if and only if it is situated on the frontier of the production possibilities frontier (PPF).		1- All the observed DMUs belong to the production possibility set (PPS'). $DMU_j \in PPS' \; for \; all \; j = 1,2,\dots,n$ 2-If $(x,y) \in PPS'$, then for all activities $(\bar{x},\bar{y})$ having $\bar{x} \geq x \; and \; \bar{y} \leq y$, we will get $(\bar{x},\bar{y}) \in PPS'$. 3- Convex linear combinations: If (x, y) and $(\bar{x},\bar{y}) \in PPS' \rightarrow \forall \lambda \in [0,1]$ we will have $[\lambda(x,y) + (1-\lambda)(\bar{x},\bar{y})] \in PPS'$. 4- PPS' is the smallest set fulfilling the four previous assumptions. $PPS' = (x,y) \| x \geq \sum_{j=1}^{n} \lambda_j x_j \; and \; y \leq \sum_{j=1}^{n} \lambda_j y_j$, where $\lambda_j \geq 0, and \; \sum_{j=1}^{n} \lambda_j = 1$. A given DMU is said efficient if and only if it is situated on the frontier of the production possibilities frontier (PPF).	
Returns to Scale RTS	If $(x,y) \in PPS \rightarrow \forall k \geq 0$ we have: $(kx, ky) \in PPS$, And $f(x) = y$ Constant returns to scale CRS: $f(kx) = ky$ Increasing returns to scale IRS: $f(kx) > ky$ Decreasing returns to scale DRS: $f(kx) < ky$			
Models	**Primal Model**	**Envelopment Form (Dual)**	**Primal Model**	**Envelopment Form (Dual)**
Input Oriented	$\max_{u,v} \; \theta = uy_o$ subject to $vx_o = 1$ $u\,Y - vX \leq 0$ $v \geq 0$ $u \geq 0$	$\min_{\theta,\lambda} \; \theta$ subject to $\theta x_o - X\lambda \geq 0$ $Y\lambda \geq y_o$ $\lambda \geq 0$ Where $\in \mathbb{R}$, and $\lambda \in \mathbb{R}_n^+$.	$\max_{u,v,u_o} \; z = uy_o - u_o$ subject to $vx_o = 1$ $uY - vX - u_o e \leq 0$ $v \geq 0$ $u \geq 0$ $u_o \; free$	$\min_{\theta_B,\lambda} \; \theta_B$ subject to $\theta_B x_o - X\lambda \geq 0$ $Y\lambda \geq y_o$ $\lambda \geq 0$ $e\lambda = 1$, Where $\theta_B \in \mathbb{R}$, and $\lambda \in \mathbb{R}_n^+$
Output Oriented	$\min_{u,v} \; z = vx_o$ subject to $uy_o = 1$ $-uY + vX \geq 0$ $v \geq 0$ $u \geq 0$	$\max_{\eta,\mu} \; \eta$ subject to $x_o - X\mu \geq 0$ $\eta y_o - Y\mu \leq 0$ $\mu \geq 0$ Where $\eta \in \mathbb{R}$, and $\mu \in \mathbb{R}_n^+$. $\eta^* = 1/\theta^*$ And $\mu^* = \lambda^*/\theta^*$	$\min_{u,v,u_o} \; z = vx_o - v_o$ subject to $uy_o = 1$ $-uY + vX - v_o e \geq 0$ $v \geq 0$ $u \geq 0$ $v_o \; free$	$\max_{\eta_B,\lambda} \; \eta_B$ subject to $x_o - X\lambda \geq 0$ $\eta_B y_o - Y\lambda \leq 0$ $\lambda \geq 0$ $e\lambda = 1$,

3.4 FMEA based on DEA approach

The FMEA technique gave us a rating of the failure modes in accordance to the calculated RPN, but in some cases solving one failure mode having a high value of RPN will be less efficient than solving a set of failure modes having a sum of RPN greater than the one with the high RPN, with minimum cost and time, but the question is which failure modes should be eliminated first if we take the efficiency into consideration. One of the proposed solutions is the integration of the time and the cost notions; it means we will consume time and cost in order to decrease the

RPN, by taking in account the occurrence, the severity and the detection as well. To do so, we will consider a DEA model where we will minimize time, cost, O, S, and D, thereon the RPN will decrease. On the other hand, solving a failure mode (FM) is efficient if this FM has a high RPN and consumes less time and costs. In other words, the highest RPN is, the more efficient the corrective actions will be. Since the inputs consist of what we have on hand, and the outputs concern what we will obtain in the future, the RPN should be an input, cost and time are outputs. We know that the efficiency function will increase the outputs and increase the inputs; that is why we will have to consider the reciprocal of time, cost and RPN. Moreover, our aim is to decrease the RPN after the application of corrective actions, this is translated by decreasing the occurrence, severity and detection that we have on hand, thus O, S, and D should be considered as inputs.

To summarize what have been said above, our inputs will be O, S, D, and the reciprocal RPN; and our outputs will be the inverse of the cost and time; and the decision making units (DMUs) are the failures modes and the sub-failure modes. The following figure illustrates our DMU, inputs and outputs:

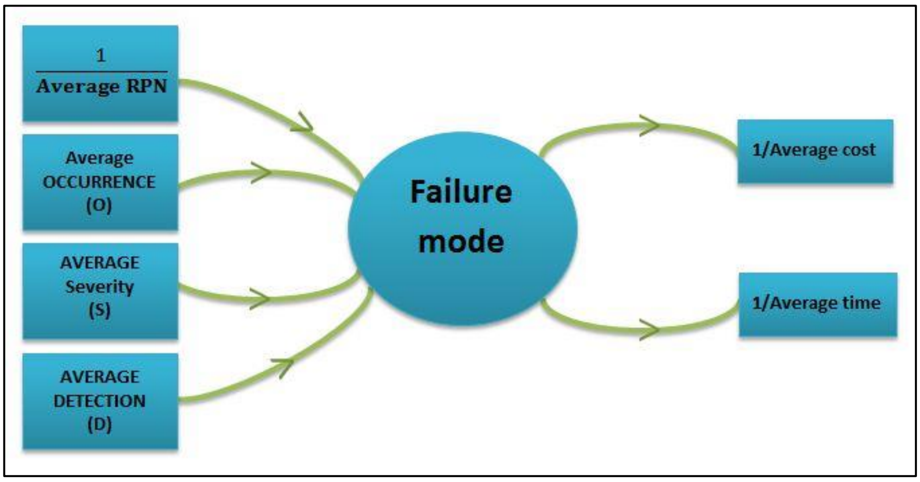

Figure 24: DEA Inputs and Outpus Model

3.5 Data collection

The collection of data was the most difficult part in this research, we had to find experts who are using or have used the RFID on LinkedIn, Facebook, the websites of the companies specialized in the RFID production, teachers and engineers, most of them did not have any data about RFID failure modes, some of them sent us the data that they already have, but it didn't include all the failure modes that we dressed. After gathering all these data, we took the average of each criterion, cost and time, and we could realize our analysis at the end. This operation took approximately two months. The experts who gave us their feed-back are:

Expert1: Academic staff in an electronic and electrical engineering department, with more than thirty years of experience (Famagusta-Cyprus).

Expert2: Informatics engineer, with a master of data management (MDM) degree, who is working in a big construction society for more than 10 years (Casablanca-Morocco).

Expert3: Mechatronic engineer and postgraduate student, who work in a big sewing society (Tangier-Morocco).

Expert4: A Data science engineer, and PHD candidate (Paris-France).

Expert5: An electrical engineer, who is responsible for customer services and care center, from technical support division (Germany).

Chapter 4

RESULTS

4.1 Conventional FMEA results

4.1.1 Computation of the Risk Priority Number (RPN)

This section will be a direct application of the conventional FMEA method steps mentioned in figure 5. The table 6 summarizes the first two steps (Initialization and Failure analysis). The remaining tasks are then the evaluation of the failures (Risk prioritization) and the choice of the corrective actions. As mentioned in table 6, some failure modes (FM) can have sub-failure modes (SFM) that are the different causes of the FM. We are going to compute the RPNs for each of these SFM, according to the following steps:

1- Collection of data related to O, S, and D from the k experts. (j=1, 2... k) and fill the table for the n SFMs ($\mathrm{i} = 1,2,3, \dots, \mathrm{n};\ \text{where } \mathrm{n} = 67$).

2- Calculate the average of occurrence: Ave O_i= average$(O_j), \mathrm{j} = 1,2,3,4,5$.

3- Compute the average of severity : Ave S_i= average$(S_j), \mathrm{j} = 1,2,3,4,5$.

4- Compute the average of detection : Ave D_i= average$(D_j), \mathrm{j} = 1,2,3,4,5$.

5- Compute the RPN for each sub-failure mode SFM is :

$\mathrm{RPN}_i = \text{Ave } \mathrm{O}_i \times \text{Ave } \mathrm{S}_i \times \text{Ave } \mathrm{D}_i \text{ , } i = 1,2,3 \dots ,67$

6- Rank the RPNs obtained from the step 5.

The Tables 8 and 9 combine the results obtained after the computation of the variables defined in the previous steps, using Microsoft Excel.

Table 8: Conventional RPNs Computation

FM number	RFID SYSTEM	Sub systems	Failure modes	SFM	Cause of failure (Sub Failure modes)	Average OCCURRENCE (Ave O)	AVERAGE Severity (Ave S)	AVERAGE DETECTION (Ave D)	RPN
1	TAG	Tag power supply	inefficient conversion of RF to DC energy	1	insufficient power provided by the antenna	3	3.6	2.8	30.24
				2	threshold voltage due to the diode connected MOS	2.5	3.5	2.75	24.0625
2			conversion of enough electrical power when it should not be	3	The reader emits too much energy	2	2	2.2	8.8
3		Integrated Circuit and connections	short between bumps	4	over cured adhesive with age	2.75	2.5	3	20.625
4			short between antenna pads	5	under cured adhesive due to high temperature	3	2.25	3.5	23.625
5			insufficient impedance between bumps	6	corrosion of antenna in low temperature	1.75	2.75	2.5	12.0312
6			insufficient impedance between antenna pads	7	corrosion of bumps due to humidity	2.25	2.5	2.75	15.4687
7			open bump and antenna pad	8	corrosion of filter particle because of temperature and humidity	2	2.75	2.75	15.125
8			excessive impedance between antenna pad and bump at bond line	9	adhesive swelling due to temperature cycling	2.25	3.25	2.25	16.4531
9			antenna lead is partially fractured and the impedance in antenna is excessive	10	Die lift because of humidity cycling	2.25	3.5	2.75	21.6562
10			Antenna is open and its impedance is excessive	11	The chip is separated from the adhesive due to temperature and humidity change	2.5	3.75	2.75	25.7812
11			the contact between bump and antenna pad is not continuous	12	The adhesive and the antenna are separated because of ESD	1.75	3.75	2.25	14.7656
12			short in IC	13	adhesive void due to excessive bond force	2	4	2.75	22
13			open in IC	14	insufficient compression of filler due to insufficient bond force	2.5	3.5	3	26.25
14			Damaged IC	15	excessive bond temperature	1.75	4	2.75	19.25
				16	current leakage caused by electrical overstress(EOS)	1.75	4.25	3	22.3125

Table 8 (continued)

FM number	RFID SYSTEM	Sub systems	Failure modes	SFM	Cause of failure (Sub Failure modes)	Average OCCURRENCE (Ave O)	AVERAGE Severity (Ave S)	AVERAGE DETECTION (Ave D)	RPN
15	TAG	Integrated Circuit and connections	The gap separating the antenna and the chip is not sufficient	17	The bond temperature is deficient	1.75	3	3	15.75
				18	bond time more than required	2	2.5	3	15
				19	bond time less than required	1.5	2.25	3	10.125
				20	mechanical crop	2	3	3.5	21
				21	mechanical curving	2	3.25	3.75	24.375
				22	mechanical squeezing	1.75	2.75	3.25	15.640
16		EEPROM	insufficient memory	23	limited storage memory	2	3.8	2	15.2
17			The EPC number is same for two tags or more. (EPC memory bank of the tag)	24	the Electronic product code is random repeating number used by the manufacturer	2	4	3	24
18			Contactless cards are more exposed than regular credit cards.	25	a suitable reader can interrogate the Tag if it is not secured	2.25	4.25	3.5	33.4687
19			decryption of the user data in the User memory bank	26	insufficient or inefficient tag encryption	2.25	4.25	3	28.6875
20			non authorized access to the tag data in the reserved memory bank	27	access and lock password not secured enough	1.8	4.2	3	22.68
21		Positioning	incorrect tag orientation	28	miss much between tag antenna orientation and reader antenna orientation	2.8	3.2	3	26.88
22			steep angle of the tag	29	the front of the tag is not facing the antenna	2.8	1.6	2.6	11.648
23		Application surface	incompatible type of surface material with the type of tag	30	due to the way the antenna sends and receives signals, it is very sensitive to t type of material where it is put	2.2	2.4	2.6	13.728
24		Tag attachment	the tag fall off the item	31	Damaged attachment because of dust, water, UV light, chemicals, temperatures, lifespan…	2.2	2.6	3	17.16
25		Encasement	Fails to protect the tag IC and antenna	32	damaged encasement in harsh environment like water and temperature or metallic surface	1.8	4.2	3.4	25.704
26	Reader	Reader API communications event management	Reader collision issue (reader-reader collision)	33	the reader communicates with tags covered by another reader	1.6	3.8	2.2	13.376
				34	The coverage areas of two readers overlap	1.6	3.8	2.6	15.808
27			Tag collision issue (Tag-Tag collision)	35	Multiple tags are trying to send data simultaneously	2	4	1.75	14

Table 8 (continued)

FM number	RFID SYSTEM	Sub systems	Failure modes	SFM	Cause of failure (Sub Failure modes)	Average OCCURRENCE (Ave O)	AVERAGE Severity (Ave S)	AVERAGE DETECTION (Ave D)	RPN
28	Reader	Reader API communications event management	Interference between multiple readers (Reader-Tag collision)	36	insufficient distance between two readers	2	4	2.2	17.6
				37	wrong settings of The operating frequency of two adjacent readers	2.2	3.8	2.2	18.392
29			Short reading distance	38	the reader frequency settings are not correct	2.4	3.6	3.8	32.832
				39	label and antenna polarization	3.2	3.6	2.8	32.256
				40	label surface is covered with other materials like metal	2.8	3.6	2.4	24.192
				41	The RF cable is not connected to reader and antenna.	1.8	2.6	2	9.36
				42	RFID label's properties	1.8	2.75	3.2	15.84
30			Cannot read card	43	the serial cable or the network cable is not properly connected	1.8	2.8	2.8	14.112
				44	the RFID antenna SMA connector is tightened	1.4	2.8	3	11.76
				45	miss matching ISO standard between tag and reader	1.8	3.6	3.2	20.736
				46	the construction size of the tag and the reader don't match	1.2	3.8	3.2	14.592
				47	miss matching frequency between the tag and the head	1.8	3.4	3.2	19.584
				48	label is damaged	2.4	4.4	3	31.68
31			Read EPC instead of TID	49	reader setting are not accommodate	1.2	4.4	3	15.84
32			Self-jammer	50	continuous waves signal sent to the tag	1.4	3.2	3	13.44
33			The rectifier converts small sinusoidal voltage to DC voltage	51	incorrect power matching between the antenna and the rectifier input	1.75	3.25	2.5	14.2187
34	The "between" tag and reader	Antenna MODEM	signals are not received by tag or reader	52	Tag or reader sensibility detection defect	1.8	4.2	2.4	18.144
				53	EM disturbance	2.8	4.8	2.4	32.256
				54	External aggression in the tag or reader antennas	1.8	4.8	3	25.92
				55	Interior failure in the reader	2	4.6	3	27.6
35			Signals are not transmitted to the tag or the reader	56	Interior failure in the Tag	2	4.6	3.6	33.12
				57	Interior failure in the reader	2.4	4	3.2	30.72
36			The transmission in continuous	58	Interior failure in the Tag	2	3.8	3.8	28.88
				59	Interior failure in the reader	2	3.8	3.4	25.84
				60	Repetitive trials to communicate by the software	1.6	3.6	3	17.28
37		EM field	The EM waves emitted by the tag can't reach the reader and vice versa	61	Harsh environment (metal –liquid…)	3.2	4.2	2.2	29.568

Table 8 (Continued)

FM number	RFID SYSTEM	Sub systems	Failure modes	SFM	Cause of failure (Sub Failure modes)	Average OCCURRENCE (Ave O)	AVERAGE Severity (Ave S)	AVERAGE DETECTION (Ave D)	RPN
38	HOST	Computer middleware data base , SD card …	hack	62	insufficient or inefficient protection tools	1.5	5	3.25	24.375
39			Software bugs	63	Ignorance ,big data ,slow system	2.6	3.2	2	16.64
40			data transfer	64	Poor connection between the reader and the host (Wi-Fi/serial interface/Bluetooth …)	3.2	4.4	2.6	36.608
41			virus attack	65	inappropriate antivirus	2.5	4	2	20
42	Health	RF waves	- thermal effects: can damage the lens of the eye, and heats cells and biological tissues -possibly carcinogenic	66	The distance between the reader and the human body is less than 10 cm	1.8	3	3.8	20.52
43	green IT	Heavy metals, silicon, aluminum, plastics…	The number of RFID tags is increasing drastically, consuming metals and toxic materials	67	chemical reactions with environment	2	2	2.4	9.6

4.1.2 Failure modes prioritization

4.1.2.1 Ranking the SFM according to their RPNs

After computing the RPN of each SFM, we will rank them according to the descendent order of the RPNs using sort function of Microsoft Excel. The table 9 illustrates the ranks of the SFMs.

Table 9: Ranks of the Conventional RPNS

FM number	RFID SYSTEM	Sub systems	Failure modes	SFM	Cause of failure	RPN	RPN RANK
1	TAG	Tag power supply	inefficient conversion of RF to DC energy	1	insufficient power provided by the antenna	30.24	9
				2	threshold voltage due to the diode connected MOS	24.0625	23
2			conversion of enough electrical power when it should not be	3	The reader emits too much energy	8.8	67
3		Integrated Circuit and connections	short between bumps	4	over cured adhesive with age	20.625	32
4			short between antenna pads	5	under cured adhesive due to high temperature	23.625	25
5			insufficient impedance between bumps	6	corrosion of antenna in low temperature	12.03125	61
6			insufficient impedance between antenna pads	7	corrosion of bumps due to humidity	15.46875	49
7			open bump and antenna pad	8	corrosion of filter particle because of temperature and humidity	15.125	51
8			excessive impedance between antenna pad and bump at bond line	9	adhesive swelling due to temperature cycling	16.45312	43
9			excessive impedance in antenna (e.g. partially fractured antenna lead)	10	Die lift because of humidity cycling	21.65625	29
10			open in antenna (e.g. partially fractured antenna lead)	11	die separation from adhesive due to temperature and humidity cycling	25.78125	18
11			intermittent contact between bump and antenna pad	12	adhesive separation from antenna due to ESD	14.76562	53
12			short in IC	13	adhesive void due to excessive bond force	22	28
13			open in IC	14	insufficient compression of filler due to insufficient bond force	26.25	15
14			Damaged IC	15	excessive bond temperature	19.25	36
				16	current leakage caused by electrical overstress(EOS)	22.3125	27
15			insufficient gap between die and antenna	17	insufficient bond temperature	15.75	47
				18	excessive bond time	15	52
				19	insufficient bond time	10.125	64
				20	mechanical shear stress	21	30
				21	mechanical bending stress	24.375	20
				22	mechanical compression	15.64062	48

Table 9 (Continued)

FM number	RFID SYSTEM	Sub systems	Failure modes	SFM	Cause of failure		RPN	RPN RANK
16	TAG	EEPROM	insufficient memory	23	limited storage memory		15.2	50
17			The EPC number is same for two tags or more. (EPC memory bank of the tag)	24	the Electronic product code is random repeating number used by the manufacturer		24	24
18			Contactless cards are more exposed than regular credit cards.	25	a suitable reader can interrogate the Tag if it is not secured		33.46875	2
19			decryption of the user data in the User memory bank	26	insufficient or inefficient tag encryption		28.6875	12
20			non authorized access to the tag data in the reserved memory bank	27	access and lock password not secured enough		22.68	26
21		Positioning	incorrect tag orientation	28	miss much between tag antenna orientation and reader antenna orientation		26.88	14
22			steep angle of the tag	29	the front of the tag is not facing the antenna		11.648	63
23		Application surface	incompatible type of surface material with the type of tag	30	the tag's antenna is sensitive to the type of material it is placed on due to the way it sends and receive signals		13.728	58
24		Tag attachment	the tag fall off the item	31	damaged attachment because of dust, water, UV light, chemicals, temperatures, lifespan…		17.16	41
25		Encasement	Fails to protect the tag IC and antenna	32	damaged encasement in harsh environment like water and temperature or metallic surface		25.704	19
26	Reader	Reader API communications event management	Reader collision problem (reader-reader collision)	33	the reader makes communication with tags that are in the coverage area of another reader		13.376	60
				34	The coverage areas of two readers overlap		15.808	46
27			Tag collision problem (Tag-Tag collision)	35	Several tags attempt to send information at the same time		14	57
28			Interference between multiple readers (Reader-Tag collision)	36	insufficient distance between two readers		17.6	39
				37	wrong settings of The operating frequency of two adjacent readers		18.392	37
29			Short reading distance	38	the reader frequency settings are not correct		32.832	4
				39	label and antenna polarization		32.256	5
				40	label surface is covered with other materials like metal		24.192	22
				41	The RF cable is not connected to reader and antenna.		9.36	66
				42	RFID label's properties		15.84	44

Table 9 (Continued)

FM number	RFID SYSTEM	Sub systems	Failure modes	SFM	Cause of failure	RPN	RPN RANK
30	Reader	Reader API communications event management	Cannot read card	43	the serial cable or the network cable is not properly connected	14.112	**56**
				44	the RFID antenna SMA connector is tightened	11.76	**62**
				45	miss matching ISO standard between tag and reader	20.736	**31**
				46	the construction size of the tag and the reader don't match	14.592	**54**
				47	miss matching frequency between the tag and the head	19.584	**35**
				48	label is damaged	31.68	**7**
31			Read EPC instead of TID	49	reader setting are not accommodate	15.84	**45**
32			Self-jammer	50	continuous waves signal sent to the tag	13.44	**59**
33			The rectifier converts small sinusoidal voltage to DC voltage	51	incorrect power matching between the antenna and the rectifier input	14.21875	**55**
34	The "between" tag and reader	Physical layer (antenna /modulator / demodulator)	Non reception of signals by tag or reader	52	Tag or reader sensibility detection defect	18.144	**38**
				53	EM disturbance	32.256	**6**
				54	External aggression in the tag or reader antennas	25.92	**16**
				55	Reader internal failure	27.6	**13**
35			Non transmission of signals by tag or reader	56	Tag internal failure	33.12	**3**
				57	Reader internal failure	30.72	**8**
36			continuous transmission	58	Tag internal failure	28.88	**11**
				59	Reader internal failure	25.84	**17**
				60	continuous repetition of attempts issue (software failure)	17.28	**40**
37		EM field	The EM waves emitted by the tag can't reach the reader and vice versa	61	Harsh environment (metal – liquid…)	29.568	**10**
38	HOST	Computer middleware data base , SD card …	hack	62	insufficient or inefficient protection tools	24.375	**21**
39			Software bugs	63	Ignorance ,big data ,slow system	16.64	**42**
40			data transfer	64	Poor connection between the reader and the host (Wi-Fi/serial interface/Bluetooth …)	36.608	**1**
41			virus attack	65	inappropriate antivirus	20	**34**
42	Health	RF waves	- thermal effects: can damage the lens of the eye, and heats cells and biological tissues	66	The distance between the reader and the human body is less than 10 cm	20.52	**33**
43	green IT	Heavy metals, silicon, aluminum, plastics…	The number of RFID tags is increasing drastically, consuming metals and toxic materials	67	chemical reactions with environment	9.6	**65**

4.1.2.2 Criticality analysis

The following table illustrates the results of the criticality analysis (Farmer Diagram); the computations are performed by Microsoft Excel.

Table 10: Criticality Analysis

		Criticality analysis		RPNs Ranking	
FM	**SFM**	**Farmer Diagram (C = O×S)**	**ACTION**	**RPN**	**RPN RANK**
1	1	10.8	**Unacceptable**	30.24	9
1	2	8.75	**Tolerable under control**	24.0625	23
2	3	4	Acceptable	8.8	67
3	4	6.875	**Tolerable under control**	20.625	32
4	5	6.75	**Tolerable under control**	23.625	25
5	6	4.8125	Acceptable	12.03125	61
6	7	5.625	**Tolerable under control**	15.46875	49
7	8	5.5	**Tolerable under control**	15.125	51
8	9	7.3125	**Tolerable under control**	16.453125	43
9	10	7.875	**Tolerable under control**	21.65625	29
10	11	9.375	**Tolerable under control**	25.78125	18
11	12	6.5625	**Tolerable under control**	14.765625	53
12	13	8	**Tolerable under control**	22	28
13	14	8.75	**Tolerable under control**	26.25	15
14	15	7	**Tolerable under control**	19.25	36
14	16	7.4375	**Tolerable under control**	22.3125	27
15	17	5.25	**Tolerable under control**	15.75	47
15	18	5	Acceptable	15	52
15	19	3.375	Acceptable	10.125	64
15	20	6	**Tolerable under control**	21	30
15	21	6.5	**Tolerable under control**	24.375	20
15	22	4.8125	Acceptable	15.640625	48
16	23	7.6	**Tolerable under control**	15.2	50
17	24	8	**Tolerable under control**	24	24
18	25	9.5625	**Tolerable under control**	33.46875	2
19	26	9.5625	**Tolerable under control**	28.6875	12
20	27	7.56	**Tolerable under control**	22.68	26
21	28	8.96	**Tolerable under control**	26.88	14
22	29	4.48	Acceptable	11.648	63
23	30	5.28	**Tolerable under control**	13.728	58
24	31	5.72	**Tolerable under control**	17.16	41
25	32	7.56	**Tolerable under control**	25.704	19

Table 10 (Continued)

		Criticality analysis		RPNs Ranking	
FM	SFM	Farmer Diagram (C = O×S)	ACTION	RPN	RPN RANK
26	33	6.08	Tolerable under control	13.376	60
26	34	6.08	Tolerable under control	15.808	46
27	35	8	Tolerable under control	14	57
28	36	8	Tolerable under control	17.6	39
28	37	8.36	Tolerable under control	18.392	37
29	38	8.64	Tolerable under control	32.832	4
29	39	11.52	Unacceptable	32.256	5
29	40	10.08	Unacceptable	24.192	22
29	41	4.68	Acceptable	9.36	66
29	42	4.95	Acceptable	15.84	44
30	43	5.04	Tolerable under control	14.112	56
30	44	3.92	Acceptable	11.76	62
30	45	6.48	Tolerable under control	20.736	31
30	46	4.56	Acceptable	14.592	54
30	47	6.12	Tolerable under control	19.584	35
30	48	10.56	Unacceptable	31.68	7
31	49	5.28	Tolerable under control	15.84	45
32	50	4.48	Acceptable	13.44	59
33	51	5.6875	Tolerable under control	14.21875	55
34	52	7.56	Tolerable under control	18.144	38
34	53	13.44	Unacceptable	32.256	6
34	54	8.64	Tolerable under control	25.92	16
34	55	9.2	Tolerable under control	27.6	13
35	56	9.2	Tolerable under control	33.12	3
35	57	9.6	Tolerable under control	30.72	8
36	58	7.6	Tolerable under control	28.88	11
36	59	7.6	Tolerable under control	25.84	17
36	60	5.76	Tolerable under control	17.28	40
37	61	13.44	Unacceptable	29.568	10
38	62	7.5	Tolerable under control	24.375	21
39	63	8.32	Tolerable under control	16.64	42
40	64	14.08	Unacceptable	36.608	1
41	65	10	Tolerable under control	20	34
42	66	5.4	Tolerable under control	20.52	33
43	67	4	Acceptable	9.6	65

4.1.2.3 Interpretation of the results

Table 11: Ranking of FMS according to Descendent RPNS

		Criticality analysis		RPNs Ranking	
FM	**SFM**	**Farmer Diagram (C = O×S)**	**ACTION**	**RPN**	**RPN RANK**
40	64	14.08	**Unacceptable**	36.608	1
18	25	9.5625	**Tolerable under control**	33.46875	2
35	56	9.2	**Tolerable under control**	33.12	3
29	38	8.64	**Tolerable under control**	32.832	4
29	39	11.52	**Unacceptable**	32.256	5
34	53	13.44	**Unacceptable**	32.256	6
30	48	10.56	**Unacceptable**	31.68	7
35	57	9.6	**Tolerable under control**	30.72	8
1	1	10.8	**Unacceptable**	30.24	9
37	61	13.44	**Unacceptable**	29.568	10
36	58	7.6	**Tolerable under control**	28.88	11
19	26	9.5625	**Tolerable under control**	28.6875	12
34	55	9.2	**Tolerable under control**	27.6	13
21	28	8.96	**Tolerable under control**	26.88	14
13	14	8.75	**Tolerable under control**	26.25	15
34	54	8.64	**Tolerable under control**	25.92	16
36	59	7.6	**Tolerable under control**	25.84	17
10	11	9.375	**Tolerable under control**	25.78125	18
25	32	7.56	**Tolerable under control**	25.704	19
15	21	6.5	**Tolerable under control**	24.375	20
38	62	7.5	**Tolerable under control**	24.375	21
29	40	10.08	**Unacceptable**	24.192	22
1	2	8.75	**Tolerable under control**	24.0625	23
17	24	8	**Tolerable under control**	24	24
4	5	6.75	**Tolerable under control**	23.625	25
20	27	7.56	**Tolerable under control**	22.68	26
14	16	7.4375	**Tolerable under control**	22.3125	27
12	13	8	**Tolerable under control**	22	28
9	10	7.875	**Tolerable under control**	21.65625	29
15	20	6	**Tolerable under control**	21	30
30	45	6.48	**Tolerable under control**	20.736	31
3	4	6.875	**Tolerable under control**	20.625	32
42	66	5.4	**Tolerable under control**	20.52	33
41	65	10	**Tolerable under control**	20	34

Table 11 (Continued)

		Criticality analysis		RPNs Ranking	
FM	**SFM**	**Farmer Diagram (C = O×S)**	**ACTION**	**RPN**	**RPN RANK**
30	47	6.12	Tolerable under control	19.584	35
14	15	7	Tolerable under control	19.25	36
28	37	8.36	Tolerable under control	18.392	37
34	52	7.56	Tolerable under control	18.144	38
28	36	8	Tolerable under control	17.6	39
36	60	5.76	Tolerable under control	17.28	40
24	31	5.72	Tolerable under control	17.16	41
39	63	8.32	Tolerable under control	16.64	42
8	9	7.3125	Tolerable under control	16.453125	43
29	42	4.95	Acceptable	15.84	44
31	49	5.28	Tolerable under control	15.84	45
26	34	6.08	Tolerable under control	15.808	46
15	17	5.25	Tolerable under control	15.75	47
15	22	4.8125	Acceptable	15.640625	48
6	7	5.625	Tolerable under control	15.46875	49
16	23	7.6	Tolerable under control	15.2	50
7	8	5.5	Tolerable under control	15.125	51
15	18	5	Acceptable	15	52
11	12	6.5625	Tolerable under control	14.765625	53
30	46	4.56	Acceptable	14.592	54
33	51	5.6875	Tolerable under control	14.21875	55
30	43	5.04	Tolerable under control	14.112	56
27	35	8	Tolerable under control	14	57
23	30	5.28	Tolerable under control	13.728	58
32	50	4.48	Acceptable	13.44	59
26	33	6.08	Tolerable under control	13.376	60
5	6	4.8125	Acceptable	12.03125	61
30	44	3.92	Acceptable	11.76	62
22	29	4.48	Acceptable	11.648	63
15	19	3.375	Acceptable	10.125	64
43	67	4	Acceptable	9.6	65
29	41	4.68	Acceptable	9.36	66
2	3	4	Acceptable	8.8	67

The results obtained in Tables 10 and 11 show that the ranks of the RPN are not coherent with the criticality analysis, and the effects of the sub-failure modes (SFM) are not taken into consideration, and we know that if a sub-failure mode is risky, then the associated failure mode is risky too, the Table 12 shows the gaps between the ranks of the SFM of each FM.

Table 12: Gaps between the Extreme Ranks of the SFMs

FM	1	14	15	26	28	29	30	34	35	36
Min SFM rank	9	27	20	46	37	4	7	6	3	11
Max SFM rank	23	36	64	60	39	66	62	38	8	40
GAP	14	9	44	34	2	62	55	32	5	29

Thus, it is crucial to give an importance the sub-failure modes with maximum ranks in risk prioritization. In other words, we ought to find a way to aggregate the SFMs of a given FM; in the following section we are going to explain this regrouping procedure in details.

4.2 Aggregated FMEA approach

4.2.1 Aggregated RPNs

In order to aggregate the sub failure modes of each “parent” failure mode, we are going to compute an aggregate RPN for each failure mode, which is equivalent to the weighted average of the sub-failure modes RPNs; this average will prioritize the sub failure mode with the highest RPN number (or the smallest RPN rank). The aggregate RPN for each SFM will be found using the RPNs belonging to each sub-failure mode SFM and their ranks from the previous step (conventional FMEA), as follows:

1- The new rank b_{ij} for each sub failure modes will be $b_{ij} = n + 1 - a_{ij}$ where a_{ij} is the rank of SFM_j related to the FM_i, according to the descending order of RPN_j (conventional RPNs), and n is the number of the SFMs.

(In our case $n = 67$, $i = 1,2,3, \dots, 43$ and $j = 1,2,3, \dots, 67$)

2- Compute the aggregate RPN ($AGRPN_i$) for each FM_i, having n_i sub failure modes SFM_j, according to the following formula:

$$AGRPN_i = \frac{\sum_{j=1}^{n_i} b_{ij} \times RPN_j}{\sum_{j=1}^{n_i} b_{ij}}$$

3- Give a rank (c_{ij}) to the failure modes by accordance to the dropping order of the $AGRPN_i$.

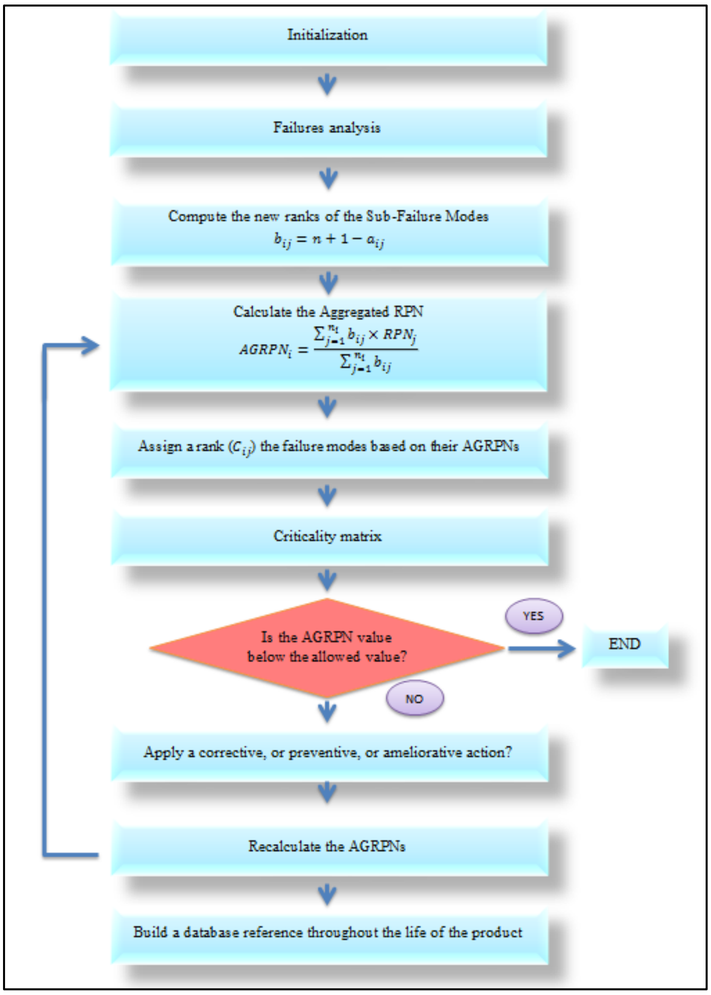

Figure 25: Aggregate FMEA Steps

The Table 13 summarizes the outcomes of the calculations above using Microsoft Excel.

Table 13: Aggregate RPNS and their Ranks

FM	SFM	Conventional RPN	Rank a_{ij}	Aggregate RPNs	Aggregate RPNs rank c_{ij}
1	1	30.24	9	27.5670433	7
	2	24.0625	23		
2	3	8.8	67	8.8	43
3	4	20.625	32	20.625	22
4	5	23.625	25	23.625	16
5	6	12.03125	61	12.03125	40
6	7	15.46875	49	15.46875	31
7	8	15.125	51	15.125	34
8	9	16.453125	43	16.453125	29
9	10	21.65625	29	21.65625	20
10	11	25.78125	18	25.78125	11
11	12	14.765625	53	14.765625	35
12	13	22	28	22	19
13	14	26.25	15	26.25	10
14	15	19.25	36	20.9700342	21
	16	22.3125	27		
15	17	15.75	47	19.6738946	25
	18	15	52		
	19	10.125	64		
	20	21	30		
	21	24.375	20		
	22	15.640625	48		
16	23	15.2	50	15.2	32
17	24	24	24	24	15
18	25	33.46875	2	33.46875	2
19	26	28.6875	12	28.6875	5
20	27	22.68	26	22.68	18
21	28	26.88	14	26.88	9
22	29	11.648	63	11.648	41
23	30	13.728	58	13.728	38
24	31	17.16	41	17.16	27
25	32	25.704	19	25.704	12
26	33	13.376	60	15.1594667	33
	34	15.808	46		
27	35	14	57	14	37
28	36	17.6	39	18.0092	26
	37	18.392	37		

Table 13 (Continued)

FM	SFM	Conventional RPN	Rank a_{ij}	Aggregate RPNs	Aggregate RPNs rank c_{ij}
29	38	32.832	4	28.3672764	6
	39	32.256	5		
	40	24.192	22		
	41	9.36	66		
	42	15.84	44		
30	43	14.112	56	23.2526135	17
	44	11.76	62		
	45	20.736	31		
	46	14.592	54		
	47	19.584	35		
	48	31.68	7		
31	49	15.84	45	15.84	30
32	50	13.44	59	13.44	39
33	51	14.21875	55	14.21875	36
34	52	18.144	38	27.1860905	8
	53	32.256	6		
	54	25.92	16		
	55	27.6	13		
35	56	33.12	3	31.968	3
	57	30.72	8		
36	58	28.88	11	25.3517647	13
	59	25.84	17		
	60	17.28	40		
37	61	29.568	10	29.568	4
38	62	24.375	21	24.375	14
39	63	16.64	42	16.64	28
40	64	36.608	1	36.608	1
41	65	20	34	20	24
42	66	20.52	33	20.52	23
43	67	9.6	65	9.6	42

4.2.2 Normalization of the Ranks

The ranks in the conventional FMEA were between 1 and 67 (67 SFMs), and when we considered the aggregated failure modes, these ranks became between 1 and 43 (43 FMs). Thus, in order to compare and interpret the results we should normalize the ranks for the both methods.

Instead of the previous ranks, we will consider the percentage of priority, for example if a sub failure mode rank is 1 out of 67, then it is prioritized more than all the other SFMs, so the number of the SFMs that have a rank smaller than it is 0%, and the SFMs that have a rank less than it is 98.5%. In the same way, if a given SFMs is ranked the last, then it is prioritized more than 0% of the total SFMs, and it is prioritized less than 100%. The same logic is done for the ranks of the FMs. Each SFM represents 1.5% (100/67) of the total SFMs, and each FM represents 2.3% (100/43) of the total FMs. By this way all the ranks will be between 0% and 100%. The Figure 26 illustrates the normalization principle.

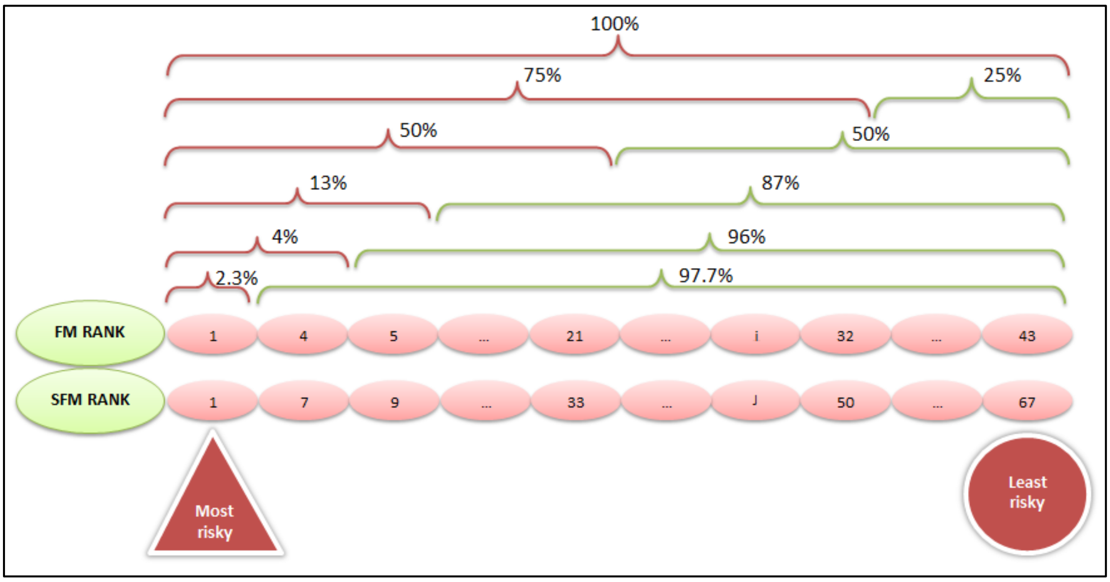

Figure 26: Normalization of the Ranks

The normalization process will be as follows:

Percentage of priority of SFM_j(it is prior more than P_1% SFMs):

$$P_{1j} = 100 - (\frac{a_{ij}}{67} \times 100)$$

Percentage of priority of overall FM_i (it is prior more than P_2% FMs):

$$P_{2i} = 100 - (\frac{c_{ij}}{43} \times 100)$$

Progress (won or lost ranks): $P = P_{2extended} - P_1$

$P_{2extended}$ is a vector containing 67 entries, it can be extracted from P_2 by considering the percentage of priority of each FM for its SFMs. The variables are already defined in the section 4.1.2. The table 14 summarizes the ranks normalization computations performed by Microsoft Excel.

Table 14: Normalized SFMs and FMs Ranks

FM	SFM	Conventional RPN RANK a_{ij}	Aggregate RPNs RANK c_{ij}	percentage of SFM priority P_1	percentage of FM priority $P_{2extended}$	Progress P
1	1	9	7	86.57	83.72	-2.85
	2	23	7	65.67	83.72	18.05
2	3	67	43	0.00	0.00	0.00
3	4	32	22	52.24	48.84	-3.40
4	5	25	16	62.69	62.79	0.10
5	6	61	40	8.96	6.98	-1.98
6	7	49	31	26.87	27.91	1.04
7	8	51	34	23.88	20.93	-2.95
8	9	43	29	35.82	32.56	-3.26
9	10	29	20	56.72	53.49	-3.23
10	11	18	11	73.13	74.42	1.28
11	12	53	35	20.90	18.60	-2.29
12	13	28	19	58.21	55.81	-2.40
13	14	15	10	77.61	76.74	-0.87
14	15	36	21	46.27	51.16	4.89
	16	27	21	59.70	51.16	-8.54
15	17	47	25	29.85	41.86	12.01
	18	52	25	22.39	41.86	19.47
	19	64	25	4.48	41.86	37.38
	20	30	25	55.22	41.86	-13.36
	21	20	25	70.15	41.86	-28.29
	22	48	25	28.36	41.86	13.50
16	23	50	32	25.37	25.58	0.21
17	24	24	15	64.18	65.12	0.94
18	25	2	2	97.01	95.35	-1.67
19	26	12	5	82.09	88.37	6.28
20	27	26	18	61.19	58.14	-3.05
21	28	14	9	79.10	79.07	-0.03
22	29	63	41	5.97	4.65	-1.32
23	30	58	38	13.43	11.63	-1.80
24	31	41	27	38.81	37.21	-1.60
25	32	19	12	71.64	72.09	0.45
26	33	60	33	10.45	23.26	12.81
	34	46	33	31.34	23.26	-8.09

Table 14 (Continued)

FM	SFM	Conventional RPN RANK a_{ij}	Aggregate RPNs RANK c_{ij}	percentage of SFM priority P_1	percentage of FM priority $P_{2extended}$	Progress P
27	35	57	37	14.93	13.95	-0.97
28	36	39	26	41.79	39.53	-2.26
	37	37	26	44.78	39.53	-5.24
29	38	4	6	94.03	86.05	-7.98
	39	5	6	92.54	86.05	-6.49
	40	22	6	67.16	86.05	18.88
	41	66	6	1.49	86.05	84.55
	42	44	6	34.33	86.05	51.72
30	43	56	17	16.42	60.47	44.05
	44	62	17	7.46	60.47	53.00
	45	31	17	53.73	60.47	6.73
	46	54	17	19.40	60.47	41.06
	47	35	17	47.76	60.47	12.70
	48	7	17	89.55	60.47	-29.09
31	49	45	30	32.84	30.23	-2.60
32	50	59	39	11.94	9.30	-2.64
33	51	55	36	17.91	16.28	-1.63
34	52	38	8	43.28	81.40	38.11
	53	6	8	91.04	81.40	-9.65
	54	16	8	76.12	81.40	5.28
	55	13	8	80.60	81.40	0.80
35	56	3	3	95.52	93.02	-2.50
	57	8	3	88.06	93.02	4.96
36	58	11	13	83.58	69.77	-13.81
	59	17	13	74.63	69.77	-4.86
	60	40	13	40.30	69.77	29.47
37	61	10	4	85.07	90.70	5.62
38	62	21	14	68.66	67.44	-1.21
39	63	42	28	37.31	34.88	-2.43
40	64	1	1	98.51	97.67	-0.83
41	65	34	24	49.25	44.19	-5.07
42	66	33	23	50.75	46.51	-4.23
43	67	65	42	2.99	2.33	-0.66

4.2.3 Interpretation of the results

The Table 15 combines the computations found in Table 14 and the failure modes details explained in Table 6.

Table 15: Normalization of Results

FM	SFM	percentage of SFM priority P_1	percentage of FM priority P_2	Progress P	SFM Details
29	41	1.49	86.05	84.55	short reading distance because of non-connected rf cable reader antenna
30	44	7.46	60.47	53.00	reader antenna tightened
29	42	34.33	86.05	51.72	tag properties-short reading range
30	43	16.42	60.47	44.05	cable or wifi problem
30	46	19.40	60.47	41.06	size of reader and tag missmatch
34	52	43.28	81.40	38.11	tag/reader sensitibility degraded
15	19	4.48	41.86	37.38	insufficient bond time
36	60	40.30	69.77	29.47	contunuous software attemptions
15	18	22.39	41.86	19.47	excessive bond time for ic tag
29	40	67.16	86.05	18.88	tag dirty or covered
1	2	65.67	83.72	18.05	treshold because of the diode
15	22	28.36	41.86	13.50	mechanical compression
26	33	10.45	23.26	12.81	reader reader collision (settings)
30	47	47.76	60.47	12.70	miss matching frequency of tag-reader
15	17	29.85	41.86	12.01	insufficient bond remperature in tag IC
30	45	53.73	60.47	6.73	miss matching iso standard
19	26	82.09	88.37	6.28	tag decryption
37	61	85.07	90.70	5.62	metal-liquid
34	54	76.12	81.40	5.28	antennas problems (reception)
35	57	88.06	93.02	4.96	non transmission of signal by reader
14	15	46.27	51.16	4.89	bond temperature

Sub Failure modes that won ranks

Table 15 (Continued)

FM	SFM	percentage of SFM priority P_1	percentage of FM priority P_2	Progress P	SFM Details	
10	11	73.13	74.42	1.28	chip separation from the adhesive due to humidity cycling	Sub Failure modes that kept the same priority
6	7	26.87	27.91	1.04	tag antenna corrosion(humidity)	
17	24	64.18	65.12	0.94	duplicate EPS by the manufacturer	
34	55	80.60	81.40	0.80	reader antenna failure (reception)	
25	32	71.64	72.09	0.45	Encasement	
16	23	25.37	25.58	0.21	memory	
4	5	62.69	62.79	0.10	tag antenna shortage because of high temperature	
2	3	0.00	0.00	0.00	too much energy emitted by the reader	
21	28	79.10	79.07	-0.03	tag antenna orientation mismatch with the reader antenna	
43	67	2.99	2.33	-0.66	pollution	
40	64	98.51	97.67	-0.83	data transfer	
13	14	77.61	76.74	-0.87	tag IC filter open	
27	35	14.93	13.95	-0.97	tag-tag collision	
38	62	68.66	67.44	-1.21	hacks	
22	29	5.97	4.65	-1.32	tag position	
24	31	38.81	37.21	-1.60	tag attachment	
33	51	17.91	16.28	-1.63	wrong power matching in the reader	
18	25	97.01	95.35	-1.67	encasement	
23	30	13.43	11.63	-1.80	application surface	
5	6	8.96	6.98	-1.98	tag antenna corrosion	
28	36	41.79	39.53	-2.26	distance between readers	
11	12	20.90	18.60	-2.29	tag adhesive damaged	
12	13	58.21	55.81	-2.40	tag adhesive damaged	Sub Failure modes that lost ranks
39	63	37.31	34.88	-2.43	software bugs	
35	56	95.52	93.02	-2.50	tag antenna failure	
31	49	32.84	30.23	-2.60	reader settings	
32	50	11.94	9.30	-2.64	continuous wave sent-self jammer	
1	1	86.57	83.72	-2.85	insufficient power supply	
7	8	23.88	20.93	-2.95	corrosion because of humidity	
20	27	61.19	58.14	-3.05	password security	
9	10	56.72	53.49	-3.23	humidity cycling	
8	9	35.82	32.56	-3.26	temperature cycling	
3	4	52.24	48.84	-3.40	high temperature	
42	66	50.75	46.51	-4.23	health	
36	59	74.63	69.77	-4.86	reader antenna damaged	
41	65	49.25	44.19	-5.07	virus attack	
28	37	44.78	39.53	-5.24	reader tag collision	

Table 15 (Continued)

FM	SFM	percentage of SFM priority P_1	percentage of FM priority P_2	Progress P	SFM Details
29	39	92.54	86.05	-6.49	antenna polarization
29	38	94.03	86.05	-7.98	reader settings
26	34	31.34	23.26	-8.09	Reader-reader collision (interference)
14	16	59.70	51.16	-8.54	damaged tag IC by EOS
34	53	91.04	81.40	-9.65	EM disturbance
15	20	55.22	41.86	-13.36	mechanical stress tag
36	58	83.58	69.77	-13.81	tag antenna damaged
15	21	70.15	41.86	-28.29	tag orientation
30	48	89.55	60.47	-29.09	damaged tag

The aggregation of the sub failure modes is more reliable than the conventional FMEA method, as the results show, when the sub failure modes ranks are taken in consideration for the ranking of the overall failure mode, the priority order change significantly, and the new prioritization ranks are more reliable and logic.

The first category represents the SFMs who won ranks using the weighted average RPN, this category had less priority in the conventional FMEA, but in reality these sub failure modes can affect the mission of the system drastically, and can even break the system's functioning. For example the SFM_{41} was prioritized more than 1.49% of the total SFMs, which means it was not considered as a dangerous failure; but in fact, if the reading distance is very short then the tag will not be detected at all, consequently the system will not work. the Table 14 shows these facts in details.

Concerning the second category, the priority rank remained the same for both conventional and weighted FMEA approaches.

The SFMs of the third category, who lost in terms of priority, don't cause the malfunctioning of the system, but they can lead to a degraded operation of the RFID components. Thus, they can be avoided by applying some simple preventive actions, as we can see from the Table 6, these SFMs are related to the settings and the choice of the type of the RFID system components, which means that they would be prior if we were in the planning phase.

Until now, we discussed the risk priority of the failures of the RFID system, but the question is which failure modes would be more efficient to solve?

In the next section we are going to see a method for the measurement of the efficiency of solving each of the FM and the SFMs discussed before.

4.3 Measurement of the efficiency of solutions of the failure modes using DEA

In this section we are going to apply the method explained in chapter 3, we are going to consider the aggregated FMs instead of the SFMs.

4.3.1 Aggregation of the sub failure modes

A- Solving a failure mode means solving all the related sub failure modes. Thus, the cost of each failure mode will be equal to the summation of the related SFMs. And its cost will be equal to the summation of its sub failure modes.

$$AGGCOST_i = \sum_{j=1}^{n_i} cost_{ij}$$

$$AGGTIME_i = \sum_{j=1}^{n_i} time_{ij}$$

B- The aggregated severity, the aggregated occurrence, and the aggregated detection will be equal to the weighted S, O, and D. We can use the rank b_{ij} obtained by the aggregate FMEA method, this rank will prioritize the sub failure mode having the highest RPN number; furthermore, the DEA model will consider the highest numbers of RPNs as well; in order to make a balance between aggregated FMEA, conventional FMEA and DEA, we will use the ranks a_{ij} obtained by the conventional FMEA method.

$$AGGS_i = \frac{\sum_{j=1}^{n_i} S_{ij} \times a_{ij}}{\sum_{j=1}^{n_i} a_{ij}}$$

$$AGGO_i = \frac{\sum_{j=1}^{n_i} O_{ij} \times a_{ij}}{\sum_{j=1}^{n_i} a_{ij}}$$

$$AGGD_i = \frac{\sum_{j=1}^{n_i} D_{ij} \times a_{ij}}{\sum_{j=1}^{n_i} a_{ij}}$$

C- The RPN will be equal to the multiplication of the aggregated criteria obtained in the previous step.

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

(For all $i = 1,2,3, \dots ,43$ and $j = 1,2,3, \dots ,67$)

Where a_{ij} is the rank of SFM_j related to the FM_i, in function of the dropping order of RPN_j (conventional RPNs), n_i is the number of sub-failure modes SFM_j for each failure mode FM_i.

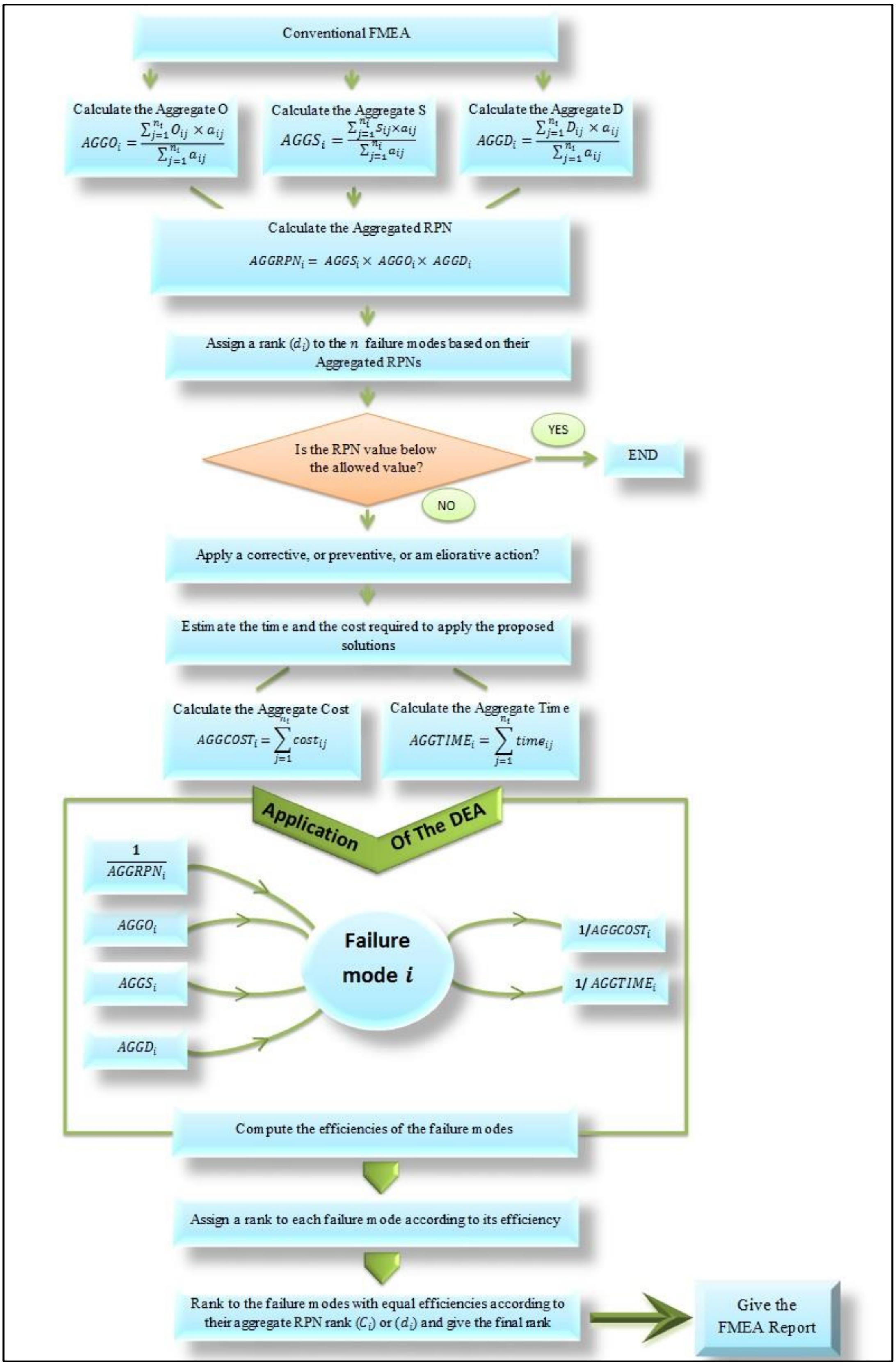

Figure 27: DEA Based FMEA Steps

The outcomes of the aggregation procedure are performed by Microsoft Excel and grouped in the Table 16.

Table 16: Aggregated Data

Failure mode FM_i	**Aggregated cost (minutes)** $AGGCOST_i$	**Aggregated time (dollars)** $AGGTIME_i$	**Aggregated OCCURRENCE** $AGGO_i$	**Aggregated SEVERITY** $AGGS_i$	**Aggregated DETECTION** $AGGD_i$	**Aggregated RPN** $AGGRPN_i$
1	0.50	90.00	2.640625	3.528125	2.764	25.7512
2	0.25	45.00	2	2	2.2	8.8
3	35.25	95.00	2.75	2.5	3	20.625
4	25.25	85.00	3	2.25	3.5	23.625
5	0.25	75.00	1.75	2.75	2.5	12.03125
6	25.25	85.00	2.25	2.5	2.75	15.46875
7	25.25	85.00	2	2.75	2.75	15.125
8	25.25	85.00	2.25	3.25	2.25	16.453125
9	35.25	95.00	2.25	3.5	2.75	21.65625
10	35.25	95.00	2.5	3.75	2.75	25.78125
11	25.25	85.00	1.75	3.75	2.25	14.765625
12	25.25	85.00	2	4	2.75	22
13	35.25	95.00	2.5	3.5	3	26.25
14	26.00	55.00	1.75	4.107	2.857	20.535
15	161.50	520.00	1.786	2.689	3.16	15.187
16	0.50	45.00	2	3.8	2	15.2
17	35.25	42.50	2	4	3	24
18	35.50	95.00	2.25	4.25	3.5	33.46875
19	35.50	95.00	2.25	4.25	3	28.6875
20	35.50	95.00	1.8	4.2	3	22.68
21	25.25	37.50	2.8	3.2	3	26.88
22	25.25	27.50	2.8	1.6	2.6	11.648
23	35.50	50.00	2.2	2.4	2.6	13.728
24	35.50	42.50	2.2	2.6	3	17.16
25	25.50	55.00	1.8	4.2	3.4	25.704
26	110.00	180.00	1.6	3.8	2.373584	14.4313962
27	50.00	85.00	2	4	1.75	14
28	120.00	190.00	2.097368	3.90263	2.2	18.0075637

Table 16 (Continued)

Failure mode FM_i	**Aggregated cost (minutes)** $AGGCOST_i$	**Aggregated time (dollars)** $AGGTIME_i$	**Aggregated OCCURRENCE** $AGGO_i$	**Aggregated SEVERITY** $AGGS_i$	**Aggregated DETECTION** $AGGD_i$	**Aggregated RPN** $AGGRPN_i$
29	176.25	260.00	2.02269	2.866	2.51631205	14.5905648
30	161.50	340.00	1.5836	3.25306	3.05224489	15.7245148
31	35.25	50.00	1.2	4.4	3	15.84
32	35.25	50.00	1.4	3.2	3	13.44
33	25.25	40.00	1.75	3.25	2.5	14.21875
34	260.50	500.00	1.91780	4.45205	2.63835616	22.526779
35	101.00	95.00	2.290909	4.1636	3.30909090	31.5638047
36	96.00	155.00	1.7647058	3.682352	3.22941176	20.9855893
37	27.50	55.00	3.2	4.2	2.2	29.568
38	40.00	85.00	1.5	5	3.25	24.375
39	25.25	55.00	2.6	3.2	2	16.64
40	30.00	32.50	3.2	4.4	2.6	36.608
41	45.00	55.00	2.5	4	2	20
42	37.50	95.00	1.8	3	3.8	20.52
43	10.00	265.00	2	2	2.4	9.6

4.3.2 Efficiency measurement by DEA

The Table 17 summarized the DEA model inputs, outputs and efficiencies of each DMU (failure mode) found by PIM DEA version 3.2.

We assumed that the set of data has constant return to scale that is why we used the CCR-input oriented model in the envelopment form. Obviously other standard DEA models can be used instead of the proposed model.

Table 17: DEA Model Inputs, Outputs and Efficiencies

	INPUTS				OUTPUTS		RESULTS
DMU (FM)	**weighted OCCURRENCE (O) of the FM**	**weighted severity (S) of the FM**	**weighted DETECTION(D) of the FM**	**1/RPN**	**1/cost**	**1/time**	**Efficiency**
1	2.6406	3.5281	2.7641	0.0388	2.0000	0.0111	100
2	2.0000	2.0000	2.2000	0.1136	4.0000	0.0222	100
3	2.7500	2.5000	3.0000	0.0485	0.0284	0.0105	37.43
4	3.0000	2.2500	3.5000	0.0423	0.0396	0.0118	47.48
5	1.7500	2.7500	2.5000	0.0831	4.0000	0.0133	100
6	2.2500	2.5000	2.7500	0.0646	0.0396	0.0118	41.12
7	2.0000	2.7500	2.7500	0.0661	0.0396	0.0118	43.94
8	2.2500	3.2500	2.2500	0.0608	0.0396	0.0118	42.14
9	2.2500	3.5000	2.7500	0.0462	0.0284	0.0105	40.49
10	2.5000	3.7500	2.7500	0.0388	0.0284	0.0105	39.23
11	1.7500	3.7500	2.2500	0.0677	0.0396	0.0118	48.42
12	2.0000	4.0000	2.7500	0.0455	0.0396	0.0118	49.29
13	2.5000	3.5000	3.0000	0.0381	0.0284	0.0105	39.49
14	1.7500	4.1071	2.8571	0.0487	0.0385	0.0182	81.24
15	1.7864	2.6897	3.1609	0.0658	0.0062	0.0019	7.71
16	2.0000	3.8000	2.0000	0.0658	2.0000	0.0222	100
17	2.0000	4.0000	3.0000	0.0417	0.0284	0.0235	100
18	2.2500	4.2500	3.5000	0.0299	0.0282	0.0105	44.99
19	2.2500	4.2500	3.0000	0.0349	0.0282	0.0105	43.38
20	1.8000	4.2000	3.0000	0.0441	0.0282	0.0105	47.6
21	2.8000	3.2000	3.0000	0.0372	0.0396	0.0267	95.05
22	2.8000	1.6000	2.6000	0.0859	0.0396	0.0364	100
23	2.2000	2.4000	2.6000	0.0728	0.0282	0.0200	67.76
24	2.2000	2.6000	3.0000	0.0583	0.0282	0.0235	85.79
25	1.8000	4.2000	3.4000	0.0389	0.0392	0.0182	85.19
26	1.6000	3.8000	2.3736	0.0693	0.0091	0.0056	24.1
27	2.0000	4.0000	1.7500	0.0714	0.0200	0.0118	48.13

Table 17 (Continued)

	INPUTS				OUTPUTS		RESULTS
DMU (FM)	weighted OCCURRENCE (O) of the FM	weighted severity (S) of the FM	weighted DETECTION(D) of the FM	1/RPN	1/cost	1/time	Efficiency
28	2.0974	3.9026	2.2000	0.0555	0.0083	0.0053	20.24
29	2.0227	2.8667	2.5163	0.0685	0.0057	0.0038	14.04
30	1.5837	3.2531	3.0522	0.0636	0.0062	0.0029	12.75
31	1.2000	4.4000	3.0000	0.0631	0.0284	0.0200	100
32	1.4000	3.2000	3.0000	0.0744	0.0284	0.0200	95.09
33	1.7500	3.2500	2.5000	0.0703	0.0396	0.0250	100
34	1.9178	4.4521	2.6384	0.0444	0.0038	0.0020	8.66
35	2.2909	4.1636	3.3091	0.0317	0.0099	0.0105	43.59
36	1.7647	3.6824	3.2294	0.0477	0.0104	0.0065	28.86
37	3.2000	4.2000	2.2000	0.0338	0.0364	0.0182	67.37
38	1.5000	5.0000	3.2500	0.0410	0.0250	0.0118	61.55
39	2.6000	3.2000	2.0000	0.0601	0.0396	0.0182	66.56
40	3.2000	4.4000	2.6000	0.0273	0.0333	0.0308	100
41	2.5000	4.0000	2.0000	0.0500	0.0222	0.0182	68.8
42	1.8000	3.0000	3.8000	0.0487	0.0267	0.0105	46.46
43	2.0000	2.0000	2.4000	0.1042	0.1000	0.0038	14.41

We can see that some DMUs have the same efficiency value, thus they have the same rank; in order to settle this issue, the DMUs having the same efficiency will be ranked according to their aggregated RPN obtained in the section 4.2.1. The Table 18 contains the new ranks.

Table 18: Efficiency Ranks According to the Aggregate RPN

Name	Efficiency	efficiency ranks (duplicates)	Aggregated RPN RANK	New Efficiency RANKS
DMU01	100	1	7	2
DMU02	100	1	43	9
DMU05	100	1	40	7
DMU16	100	1	32	5
DMU17	100	1	15	3
DMU22	100	1	41	8
DMU31	100	1	30	4
DMU33	100	1	36	6
DMU40	100	1	1	1
DMU32	95.09	2	39	10
DMU21	95.05	3	9	11
DMU24	85.79	4	27	12
DMU25	85.19	5	12	13
DMU14	81.24	6	21	14
DMU41	68.8	7	24	15
DMU23	67.76	8	38	16
DMU37	67.37	9	4	17
DMU39	66.56	10	28	18
DMU38	61.55	11	14	19
DMU12	49.29	12	19	20
DMU11	48.42	13	35	21
DMU27	48.13	14	37	22
DMU20	47.6	15	18	23
DMU04	47.48	16	16	24
DMU42	46.46	17	23	25
DMU18	44.99	18	2	26
DMU07	43.94	19	34	27
DMU35	43.59	20	3	28
DMU19	43.38	21	5	29
DMU08	42.14	22	29	30
DMU06	41.12	23	31	31
DMU09	40.49	24	20	32
DMU13	39.49	25	10	33
DMU10	39.23	26	11	34
DMU03	37.43	27	22	35
DMU36	28.86	28	13	36
DMU26	24.1	29	33	37
DMU28	20.24	30	26	38
DMU43	14.41	31	42	39
DMU29	14.04	32	6	40
DMU30	12.75	33	17	41
DMU34	8.66	34	8	42
DMU15	7.71	35	25	43

4.3.3 Interpretation of the results

The ranks are normalized as explained in section 4.2.

Let the percentage of risk priority of FM be P_2=P_r obtained in table 14.

With the same way we will normalize the ranks of table 17; so the percentage of efficiency priority of FM will be

$$P_e = 100 - ((^{new\ efficiency\ rank}/_{43}) \times 100)$$

Let the progress or the difference between the aggregate FMEA and the efficiency ranks be $P = P_e - P_r$

We will symbolize by the red color the failure modes that won ranks, with the green those who lost ranks, and in yellow those who kept the same rank.

Results are compared and interpreted in Table 19.

Table 19: Results interpretation

		FMEA		DEA		
FM	**SFM**	P_r	**SFM Description**	P_e	P	**Interpretation and explanation**
1	1	83.72	insufficient power supply	95.35	11.63	It won ranks in terms of risk and of efficiency as well.
1	2	83.72	threshold because of the diode	95.35	11.63	It won ranks in terms of risk and of efficiency as well.
2	3	0.00	too much energy emitted by the reader	79.07	79.07	It was indifferent in the point vue of the risk, ranked the last, but because its cost and time are negligible (settings), it won a lot of ranks in terms of efficiency.
3	4	48.84	high temperature	18.60	-30.23	Related to the choice of the tag, hard tags are expensive, they lost in ranks in terms of efficiency
4	5	62.79	tag antenna shorting because of high temperature	44.19	-18.60	Related to the choice of the tag, hard tags are expensive, they lost in ranks in terms of efficiency

Table 19 (Continued)

		FMEA		DEA		
FM	**SFM**	P_r	**SFM Description**	P_e	P	**Interpretation and explanation**
5	6	6.98	tag antenna corrosion (low temperature)	83.72	76.74	Indifferent or with decreased priority ranks, but they are efficient in terms of cost and time, because the tags are ususally used in low temperate places and with big numbers, if they are damaged it will be costly.
6	7	27.91	tag antenna corrosion(humidity)	27.91	0.00	
7	8	20.93	corrosion because of humidity	37.21	16.28	
8	9	32.56	temperature cycling	30.23	-2.33	
9	10	53.49	humidity cycling	25.58	-27.91	Related to the choice of the tag, which is expensive, it would be efficient in the design phase
10	11	74.42	chip separation from the adhesive due to humidity cycling	20.93	-53.49	
11	12	18.60	tag adhesive damaged	51.16	32.56	If the tag adhesive is damaged it cannot carry the IC and the antenna efficiently, thus this kind of failure is potential and their cost and time are medium.
12	13	55.81	tag adhesive damaged	53.49	-2.33	
13	14	76.74	tag IC filter open	23.26	-53.49	The tag IC is very small and requires advanced technologies to be repaired. Thus changing the entire tag is more efficient than repairing it in this case.
14	15	51.16	bond temperature	67.44	16.28	Damaged IC means damaged tag, changing the tag is efficient and cheap in most of the cases. These problems are not frequent, they depend on the frequency of usage and the behavior of tag user, usually they are related to the age of the label, and thus it is efficient to think about hard tags for specific applications in the design phase.
14	16	51.16	damaged tag IC by EOS	67.44	16.28	
15	17	41.86	insufficient bond temperature in tag IC	0.00	-41.86	
15	18	41.86	excessive bond time for IC tag	0.00	-41.86	
15	19	41.86	insufficient bond time	0.00	-41.86	
15	20	41.86	mechanical stress tag	0.00	-41.86	
15	21	41.86	mechanical stress	0.00	-41.86	
15	22	41.86	mechanical compression	0.00	-41.86	

Table 19 (Continued)

		FMEA		DEA		
FM	**SFM**	P_r	**SFM Description**	P_e	P	**Interpretation and explanation**
16	23	25.58	memory	88.37	62.79	The tag memory is very important, thus it is necessary to think about the suitable tag memory capacity for the desired application.
17	24	65.12	duplicate EPS by the manufacturer	93.02	27.91	It depends on the manufacturer, can be avoided by checking the tags before use.
18	25	95.35	Security (exposed tags)	39.53	-55.81	Security is important, but nowadays the tags are secured with strong passwords, and if the owner uses a suitable RFID protected portfolio Etc. But their cost is relatively high (with big quantities), spreading awareness may take time and can be costly.
19	26	88.37	tag decryption	32.56	-55.81	Security is important, but nowadays the tags are secured with strong passwords, and if the owner uses a suitable RFID protected portfolio Etc. But their cost is relatively high (with big quantities), spreading awareness may take time and can be costly.
20	27	58.14	password security	46.51	-11.63	Security is important, but nowadays the tags are secured with strong passwords, and if the owner uses a suitable RFID protected portfolio Etc. But their cost is relatively high (with big quantities), spreading awareness may take time and can be costly.
21	28	79.07	tag antenna orientation mismatch with the reader antenna	74.42	-4.65	Can be avoided if the system is set up by an expert
22	29	4.65	tag position	81.40	76.74	They are related to the right positioning of the tag and where it should be put, they can be solved by a small action that does not require any effort or time or cost, and thus it is efficient to solve them. But if they are not solved the system can go wrong.
23	30	11.63	application surface	62.79	51.16	They are related to the right positioning of the tag and where it should be put, they can be solved by a small action that does not require any effort or time or cost, and thus it is efficient to solve them. But if they are not solved the system can go wrong.
24	31	37.21	tag attachment	72.09	34.88	They are related to the right positioning of the tag and where it should be put, they can be solved by a small action that does not require any effort or time or cost, and thus it is efficient to solve them. But if they are not solved the system can go wrong.
25	32	72.09	Encasement	69.77	-2.33	Usually the encasement is compatible with the tag type and use.

Table 19 (Continued)

		FMEA		DEA		
FM	**SFM**	P_r	**SFM Description**	P_e	***P***	**Interpretation and explanation**
26	33	23.26	Collision between readers (settings)	13.95	-9.30	These failure are not frequent because once the system is set up by a professional, the settings and distances are corrects, and this is the case of the big companies and markets. But when it comes to individuals, they can face such problems. This can occur when a portable reader is used as well.
26	34	23.26	Collision of readers (interference)	13.95	-9.30	
27	35	13.95	Collision between tags	48.84	34.88	It has a high frequency of occurrence, and it can be solved by a simple anti-collision protocol.
28	36	39.53	distance between readers	11.63	-27.91	It is not prioritized and not very efficient, because the distances are already set up by professionals.
28	37	39.53	reader tag collision	11.63	-27.91	
29	38	86.05	reader settings	6.98	-79.07	
29	39	86.05	antenna polarization	6.98	-79.07	
29	40	86.05	tag dirty or covered with plastic or metal	6.98	-79.07	They had high priority in terms of risk, but If the preventive precautions are considered while implementing the RFID system, these problems would not occur, solving these failures requires changing the whole system, which is costly and requires a lot of time, and thus it is not efficient. In this case the aggregate FMEA explained before would be efficient for preventive actions.
29	41	86.05	short reading distance because of non-connected RF cable reader antenna	6.98	-79.07	
29	42	86.05	tag properties-short reading range	6.98	-79.07	
30	43	60.47	cable or wifi problem	4.65	-55.81	
30	44	60.47	reader antenna tightened	4.65	-55.81	
30	45	60.47	miss matching ISO standard	4.65	-55.81	
30	46	60.47	size of reader and tag missmatch	4.65	-55.81	
30	47	60.47	miss matching frequency of tag-reader	4.65	-55.81	
30	48	60.47	damaged tag	4.65	-55.81	

Table 19 (Continued)

		FMEA		DEA		
FM	**SFM**	P_r	**SFM Description**	P_e	P	**Interpretation and explanation**
31	49	30.23	reader settings	90.70	60.47	If by mistake, the reader settings changed, or an internal failure happened, the card will not be detected leading to malfunctioning of the system, which makes solving this problem efficient.
32	50	9.30	continuous wave sent-self jammer	76.74	67.44	
33	51	16.28	wrong power matching in the reader	86.05	69.77	
34	52	81.40	tag/reader sensibility degraded (non-reception)	2.33	-79.07	The sensitivity degradation with age, the electromagnetic waves received from other devices, and antennas problems are not very prioritized or efficient, because if the previous failures are solved, then these latters would be fixed automatically, by choosing the right tag for each specific application and the proper reader, and setting the correct distances.
34	53	81.40	EM disturbance	2.33	-79.07	
34	54	81.40	antennas problems (reception)	2.33	-79.07	
34	55	81.40	reader antenna failure (reception)	2.33	-79.07	
35	56	93.02	tag antenna failure	34.88	-58.14	
35	57	93.02	non transmission of signal by reader	34.88	-58.14	
36	58	69.77	tag antenna damaged	16.28	-53.49	
36	59	69.77	reader antenna damaged	16.28	-53.49	
36	60	69.77	continuous software attemptions	16.28	-53.49	
37	61	90.70	metal-liquid	60.47	-30.23	
38	62	67.44	hacks	55.81	-11.63	These failures are relatively the most risky, because the host is the master of the RFID system, if it fails to fulfill its mission, then all the system will fall down, millions would be lost, and they are moderately expensive to solve, which explains why they are situated in the middle, except the data transfer which is the most risky and efficient mode.
39	63	34.88	software bugs	58.14	23.26	
40	64	97.67	data transfer	97.67	0.00	
41	65	44.19	virus attack	65.12	20.93	

Table 19 (Continued)

		FMEA		DEA		
FM	**SFM**	P_r	**SFM Description**	P_e	P	**Interpretation and explanation**
42	66	46.51	health	41.86	-4.65	If the precautions are taken, the RFID would not affect the health; usually this problem does not occur.
43	67	2.33	pollution	9.30	6.98	It is almost the last, because recycling can be expensive, especially with the huge number of the RFID used.

We can see in the Table 19 that the most of the efficient failure modes were indifferent to the FMEA method, they kept almost the same percentage of priority in both conventional and aggregate FMEA, but when we applied the DEA method, they changed the ranks drastically. For example the failure mode number 2 was ranked the last in both FMEA methods, now it became prioritized more than 79% of the failure modes, it it logic because it is related to the settings and can be fixed in two minutes without any dispenses, furthermore, if it is not solved it will cause a degraded functioning or break down of the system. The Table 20 gathers the most efficient failure modes in the descending order of the percentage of priority.

Table 20: The Most Efficient Failure Modes

		FMEA		DEA		
FM	**SFM**	P_r	**SFM Description**	P_e	P	**Interpretation and explanation**
40	64	97.67	Data Transfer	97.67	0.00	The most risky, because the host is the master of the RFID system, if it fails to fulfill its mission: editing and exchanging data in the real time.
1	1	83.72	Insufficient Power Supply	95.35	11.63	If the tag is not powered, it will not be "woken up" and the sustem will not work.
	2	83.72	Threshold Because Of The Diode	95.35	11.63	
17	24	65.12	Duplicate EPS by the manufacturer	93.02	27.91	It can be avoided by checking the tags before use.
31	49	30.23	Reader Settings	90.70	60.47	The card will not be detected or it will be detected with errors leading to malfunctioning of the system.
16	23	25.58	Memory	88.37	62.79	The tag memory is very important, thus it is necessary to think about the suitable tag memory capacity for the desired application.
33	51	16.28	wWong power matching in the reader	86.05	69.77	If not well powered, the reader cannot be on, and it will affect the tag as well, the system will not work
5	6	6.98	Tag antenna corrosion (low temperature)	83.72	76.74	Indifferent or with decreased priority ranks, but they are efficient in terms of cost and time, because the tags are ususally used in low temperate places and with big numbers, if they are damaged it will be costly.
22	29	4.65	Tag position	81.40	76.74	It can be solved by a small action that does not require any effort or time or cost.
2	3	0.00	Too much energy emitted by the reader	79.07	79.07	It was indifferent in the point vue of the risk, ranked the last, but because its cost and time are negligible (settings), it won a lot of ranks in terms of efficiency.

Chapter 5

CONCLUSION AND FUTURE STUDY

5.1 Conclusion

Through this research, we could gather interesting knowledge about the functioning of the RFID system, its components and sub components in details, we could put the light on a major set of RFID system failure modes and sub failure modes; we presented their causes and effects as well. We tried to explain them in a simple and easy way, so even if an individual is not a specialist can understand; the idea is to make the users aware of the potential failures and the precautions to take and how to use their RFID tags, since we are surrounded by these small devices everywhere.

In a second part, we applied the FMEA procedure in the purpose of ranking the failure and the sub-failure modes of the system, by using data from experts and the published books and papers. We compared several ways of computing the risk priority number, and we found that taking the weighted average and prioritizing the sub failure mode having the highest risk can be the most fair and reliable approach. Based on the risk priority ranks, we could define which action should be taken, corrective or preventive actions.

In a third part, we noticed that the FMEA approach can give a rank of risk priority, but it doesn't give a prioritization in terms of efficiency, that is why we combined it with the DEA method, that aims to compute the efficiency rates. In order to do this, we aggregated the sub failure modes in the first step, by computing the aggregated (or weighted) occurrence, detection, severity, time and cost; and we computed the related aggregated RPN numbers. In a second step, we gave a rank for each of these failure modes based on the aggregate RPN. After that, we used a DEA model, specifically the CCR input oriented model, with a view to compute the efficiency of solving each of the failure modes, the outputs were the reversed times and the reversed costs; and the inputs were the reversed aggregated RPN, the aggregated occurrence, the aggregated severity, and the aggregated detection. Some of the failure modes had equal efficiencies; the solution was to rank them according to their aggregated RPN numbers. The final ranks of the efficiency, or as we called the efficiency priority ranks, were more fair, logic and reliable than the FMEA approach alone. We found that the most efficient modes are related to data transfer, power supply, reader settings, memory, the surrounding conditions (humidity, temperature…) and the positioning of the tag and the reader.

The choice of the inputs and outputs was very important, we tried and compared a set of methods and we figured out that this one gave as the best results.

The method presented in this research takes in consideration the risk of the sub failure modes, which is very important, as well as the notion of time and cost. The RFID system example proved its effectiveness and usefulness; therefore, it can be applied to assign a risk priority rate for failures of a different system or organization as well.

5.2 Future study

There is no method that is ideal, so in a future study we can improve this approach and consider more details, like more sub failure modes, or we can suggest more possible solutions to deal with the failures and try to minimize the price and costs.

We can suggest other methods to aggregate the sub failure modes, like considering the rank b_{ij} instead of a_{ij} to calculate the aggregate O, S, and D.

We can also use other DEA and FMEA models and approaches like the fuzzy FMEA approach, or use the modified BCC models, another option is to use the output oriented models, or try different inputs and outputs. Actually there are a large set of possible studies that can be done and compared.

We can use other features of the DEA approach for ranking the failures having the same efficiencies, like the model of Andersen and Petersen, cross-efficiency, benchmarking and others (Hosseinzadeh Lotfi et al., 2013).

The RFID field is spreading every day, and it is still needs to be studied and ameliorated, because of its importance and its impacts on our daily life.

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APPENDICES

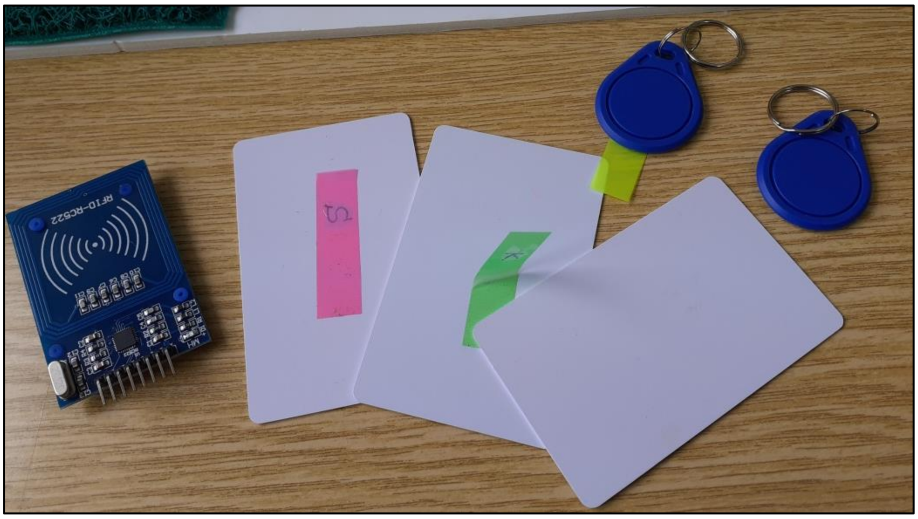
Appendix A: The CCR Model Properties Used in PIM DEA Solver

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	Index4
Output Variables	Index5	Index6		
Selected Periods	Sheet2			
DMU Selections	NO			
Categorical Selections	NO			
Weight Restrictions	Disabled			

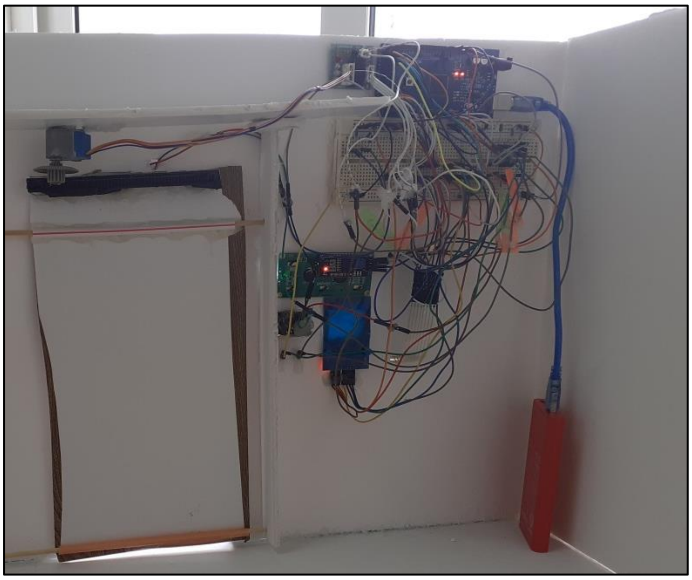
Appendix B: The Outputs of the CCR Model

Name	Efficiency
DMU01	100
DMU02	100
DMU03	37.43
DMU04	47.48
DMU05	100
DMU06	41.12
DMU07	43.94
DMU08	42.14
DMU09	40.49
DMU10	39.23
DMU11	48.42
DMU12	49.29
DMU13	39.49
DMU14	81.24
DMU15	7.71
DMU16	100
DMU17	100
DMU18	44.99
DMU19	43.38
DMU20	47.6
DMU21	95.05
DMU22	100
DMU23	67.76
DMU24	85.79
DMU25	85.19
DMU26	24.1
DMU27	48.13
DMU28	20.24
DMU29	14.04
DMU30	12.75
DMU31	100
DMU32	95.09
DMU33	100
DMU34	8.66
DMU35	43.59
DMU36	28.86
DMU37	67.37
DMU38	61.55
DMU39	66.56
DMU40	100
DMU41	68.8
DMU42	46.46
DMU43	14.41

Appendix C: The RFID Experiment

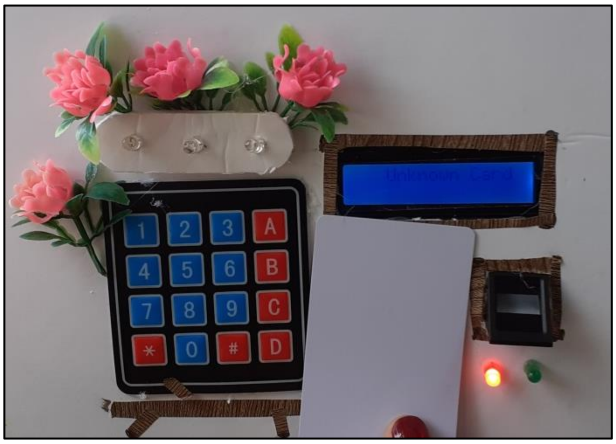


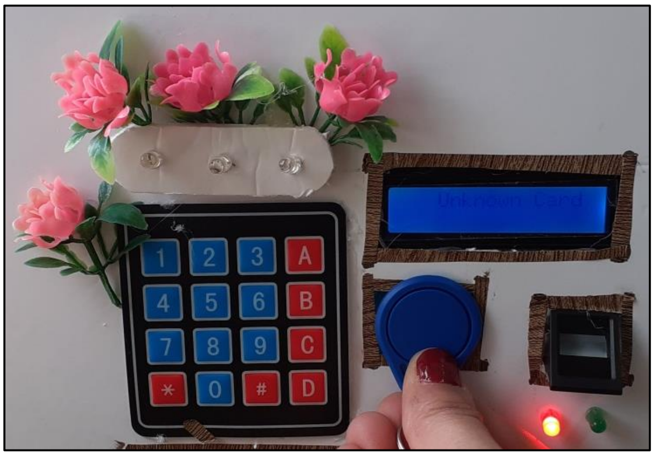
Tags and Reader



The Host (Arduino Card)

Master Card





Unknown Cards

Registered Cards