

The articulation of advanced tools for product development

The Lean Design-for-X framework supported by Fuzzy QFD

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Abstract

Project Design can be a slow and problematic process. Also, it influences cost in an enormous way. To reduce cost, time and problems, a schematic approach to the designing process can be taken. To aid this process, INEGI (Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial) in 2015 started developing a methodology called LeanDfX so designing process can be facilitated and more systematic.

LeanDfX, inspired by Lean Thinking and Design-for-eXcellence or Design-for-X, tries to asses various domains such as optimization, manufacturing, assembly, maintenance, modularity or adaptability. This approach brings a systematic applicability for design engineers and technical managers assessing effectiveness and efficiency of a given product design.

In the present dissertation, several existent methodologies are tested, such as QFD and FMEA, in order to complement the framework and aid in its development. These methodologies were adapted to LeanDfX "software" with several adaptations, such as the implementation of Fuzzy Set theory so it is possible to take advantage of every methodology and possibly bridge some disadvantages in these and in the framework.

As a case study to test the implemented and developed methodologies, in collaboration with JPM Industry(a Portuguese company described by excellence and dedicated to the logistics and automation market), within the initiative PRODUTECH-SIF (an initiative with the mission of promoting the sustainable development and internationalization of the Portuguese industry of manufacturing technologies), an internal project of an AGV, Autonomous Guided Vehicle, chassis was used. This AGV is an existing project within JPM Industry and with the motivation to develop this same framework, JPM Industry allowed a great level of freedom to the project, so they can see the results of implementing a systematic approach (DfX) and focusing on what is necessary to add value (Lean Thinking) to the designing process. Only the metallic structure was the focus of this dissertation and structural dynamic, fatigue and static studies were done in order to assure the use of this same chassis.

In the end, it was concluded that this methodology upgraded the LeanDfX framework and allowed an easier deployment of it. Thanks to it, the focus in the designing process was established from the start in what is important for the customer, this is, focusing only on what may add value to the project. Finally, this also reduced time spent in the designing process, allowing the improvement loop step to be bigger and as a conclusion, have a better product in the end with the same time available.

Keywords: Design-for-X, DfX, Quality Function Deployment, QFD, Failure Mode and Effect Analysis, FMEA, Product Design, Product Development, Lean, Automated Guided Vehicles, AGV

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Resumo

Projetar pode ser um processo lento e problemático. Adicionalmente, influencia imenso custos. Para reduzir custos, tempo e problemas, deve-se ter uma abordagem esquemática e sistemática ao processo de projeto. Para ajudar nesta fase, o INEGI (Instituto De Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial) começou a desenvolver em 2015, uma metodologia com o nome de LeanDfX, de forma que o processo de projeto seja facilitado e mais sistemático.

LeanDfX, inspirado por pensamento Lean e por Design-for-eXcellence ou Design-for-X, tenta estimar e combinar vários domínios como otimização, manufatura, montagem, manutenção, modularidade e adaptabilidade. Esta abordagem permite uma avaliação sistemática a engenheiros de projeto e gestores técnicos, onde a eficiência e a eficácia de um design de um produto pode ser avaliada.

No presente documento, várias metodologias existentes são testadas, como QFD ou FMEA, com o intuito de complementar o *framework* e ajudar o desenvolvimeneto deste. Estas metodologias foram adaptadas para o *software* LeanDfX com vários ajustes, como a implementação da teoria *Fuzzy Set* para permitir tirar o maior número de vantagens de todas as metodolgias e colmatar algumas desvantagens existentes nestas e no *framework*.

Como cabaia para testar as metodologias desenvolvidas e implementadas, em colaboração com a JPM Industry (uma empresa portuguesa caracterizada por excelência e dedicação ao mercado de automação e intralogística), dentro da iniciativa PRODUTECH-SIF (uma iniciativa com a missão de promover o desenvolvimento sustentável e o desenvolvimento e interconexão da indústria portuguesa nas tecnologias de manufatura), foi utilizado um projeto interno de um *chassis* de um AGV, veículo guiado automaticamente. Este AGV é um projeto existente na JPM Industry e com a mesma motivação para ajudar o desenvolvimento deste *framework*, a JPM Industry permitiu grande liberdade ao projeto, de forma que seja possível ver os resultados da implementação de uma abordagem sistemática (DfX) e com o foco no que apenas adiciona valor ao produto (Pensamento Lean) no processo de projeto. O cerne da dissertação é apenas a estrutura metálica do AGV e foi feito o cálculo estrutural, dinâmico, estático e de fadiga para assegurar a funcionalidade deste mesmo *chassis*.

No final, pode-se concluir que as metodologias desenvolvidas melhoraram o *framework* e facilitaram o uso deste. Graças a isto, o foco do projeto foi desde início estabelecido no que era importante para o cliente, ou seja, concentrar a atenção no que realmente adicionará valor ao produto. Finalmente, isto também permitiu a redução do tempo perdido no processo de projeto mecânico, o que permitiu que o ciclo de melhoramento fosse maior e como conclusão, terminar com um produto melhor com o mesmo tempo disponível.

Palavra-Chave: Design-for-X, DfX, QFD, Desdobramento da Função de Qualidade, Modos de Falha e Análise de efeitos, FMEA, Projeto de produto, Desenvolvimento de Produto, Lean, Veículo Guiado Automaticamente, AGV

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Dedication

I want to dedicate this work to the most important people in the world, my family, as a culmination of all that was invested for me without deserving. To Mafalda Gomes, my girlfriend, to Lurdes Meireles, my mother, to Valentim Carneiro, my father and to my brothers and sister, Sara Carneiro, Bernardo Carneiro and Duarte Carneiro. They were the ones that made all of this possible, made me go to college and gave me reasons to stay alive through it.

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‘All those moments will be lost in time, like tears in rain. Time to die.’

Roy Batty, played by Rutger Hauer in Blade Runner

‘A failure in planning is a plan for failure.’

Jedi Fortune Cookie, in Star Wars: The Clone Wars

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List of Abbreviations and Symbols

A	
A	Cross Section Area
A	Generic Trapezoidal number
a	Braking acceleration
a_{emer}	Emergency Braking acceleration
a_n	Generic Trapezoidal number parameter
$AFTI_c$	Aggregated Fuzzy Technical Importance on column c
AGV	Automated Guided Vehicle
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
B	
B	Generic Trapezoidal number
b_n	Generic Trapezoidal number parameter
C	
C	Stability Coefficient
c	Generic column
C_1	Total Number of Columns
$CFFV_r$	Combined final fuzzy term for variable, V on row r
CG	Centre of Gravity
CRAR	Customer Requirements and Additional Requirements
CR_r	Customer Requirements on row r
D	
D	Probability of Detection of Failure
d	Generic diameter
DEGI	Department of Industrial Engineering and Management
DEMec	Department of Mechanical Engineering
DFMEA	Design Failure Mode and Effect Analysis
DfA	Design-for-Assembly
DfAa	Design-for-Automation
DfC	Design-for-Cost
DfD	Design-for-Disassembly
DfDr	Design-for-Durability
DfE	Design-for-Environment
DfL	Design-for-Logistics
DfM	Design-for-Manufacture
DfMA	Design-for-Manufacture and Assembly
DfMod	Design-for-Modularity
DfMt	Design-for-Maintenance
DfQ	Design-for-Quality
DfRb	Design-for-Reliability

DfRem	Design-for-Remanufacture
DfRu	Design-for-Reuse
DfS	Design-for-Safety
DfSC	Design-for-Supply Chain
DfSR	Design-for-Social Responsibility
DfSS	Design-for-Six Sigma
DfV	Design-for-Variety
DfWMR	Design-for-Waste Minimization and Recovery
DfX	Design-for-eXcellence
E	
EN	European Standard
F	
F	Set of linguistic variables
F_{cw}	Force created by the counterweights
F_f	Force created by the forklift
F_{fw}	Force created by the full structure and components
F_l	Force created by the transported load
F_w	Force created by the structure weight
F_{fw}^h	Horizontal Force created by the full structure and components
F_l^h	Horizontal Force created by the transported load
FAT	Fatigue Class
FBS	Function Behaviour Structure
FEM	Finite Element Method
FEUP	Faculty of Engineering of the University of Porto
FFV_r	Final fuzzy term for variable, V on row r
FI_r	Fuzzy Importance for Customer Requirements on row r
FMEA	Failure Mode and Effect Analysis
FR_c	Functional Requirements on column c
FTI_c	Fuzzy Technical Importance on column c
FV_r	Fuzzy term for variable, V on row r
G	
GPa	Gigapascal
H	
H	High
h	Generic Height
HoQ	House of Quality
I	
I	Moment of Inertia
I_u^x	Importance for X-Domain, x for user, u
IC_r	Importance for Customer Requirements on row r
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
J	
JE_u	Job Experience for user u
K	
kg	Kilogram
kgf	Kilogram-Force
km/h	Kilometre per hour
KPI	Key Performance Indicator

L	
L	Low
l	Generic length
LeanDfX or LDfX	Lean Design-for-eXcellence
M	
M	Generic Bending Moment
M	Moderate
m	metre
m^3	Cubic metre
m/s	Metre per second
m/s^2	Metre per second squared
m_{fw}	Full Structure mass
m_l	Load mass
MCDM	Multi Criteria Decision Making
mm	millimetre
MNV	Maximum normalized value for Variable, V
MPa	Megapascal
$MRCR_r$	Max Relationship for Customer Requirement on row r
$MRFR_c$	Max Relationship for Functional Requirement on column c
MULTIMOORA	Multi Objective Optimization by Ratio Analysis
MV	Maximum value for Variable, V
N	
N	Newton
N	Number of Cycles
NA	Not applicable
norm FEM	European Material Handling Federation norm
NV_r	Normalized value for variable, V on row r
O	
O	Probability of Occurrence
P	
P	Generic Axial Force
PFMEA	Process Failure Mode and Effect Analysis
PRODUTECH-SIF	PRODUTECH Solutions for the Industry of the Future
Q	
QFD	Quality Function Deployment
R	
r	Generic row
R_1	Total Number of Rows
R_a	Reaction forces in point a
R_b	Reaction forces in point b
R(P)N	Risk (Priority) Number
RS_{rc}	Relationship Strength on row r and on column c
RTO	Research and Technology Organization
RWC_r	Relative Weight for Customer Requirement on row r
RWF_c	Relative Weight for Functional Requirement on column c
$RWTID^x$	Relative Weight for Total Importance for X-Domain, x
S	
S	Severity of effects
S_f	Fuzzy set of Objects

LIST OF TABLES

S	Strong
SM	Strongly Moderate
ST	Strongest
T	
TI_c	Technical Importance on column c
TID^x	Total Importance for X-Domain, x
TQM	Total Quality Management
TRIZ	Theory of Inventive Problem Solving
U	
u	Generic user
U	Total Number of users
USD	United State Dollars
V	
V	Generic Shearing Force
V_r	Value for variable, V on row r
VH	Very High
VL	Very Low
VS	Very Strong
VW	Very Weak
W	
W	Weak
w	Generic Width
WM	Weakly Moderate
WT	Weakest
X	
X	Total Number of X-Domains
x	x-axis
XFI_u^x	Fuzzy Importance for X-Domain x , for user u
Y	
y	y-axis
Z	
z	z-axis
Others	
$\Delta\sigma_R$	Applied Stress Range
μ	Generic Membership Function
σ_{max}	Maximum Stress
σ_{min}	Minimum Stress

Chapter 1

Introduction

Recently, new product creation became more complex and it demanded an interconnection of conception and project of multidisciplinary natures. The increasing global market competition, the directives, normative and social requirements (*Exempli gratia*, global warming), introduced in companies and their product design teams a new status quo and new difficulties to the development of new products that can aggregate an enormous amount of objectives-functions-requirements-restrictions-specifications. This also demands a life-cycle management approach to the product and the confluence of several engineering and management disciplines, just like Mechanical, Electronic, Ambient, Computers, Industrial and Operation Management engineering, etc..

With this new status quo, there is an increasing need to the industry and companies to increase the research on the creation and development of tools that can be applied to complex product management and support product development. Since 2015, INEGI (Institute of Science and Innovation in Mechanical and Industrial Engineering) has created and has been developing the Lean Design-for-eXcellence framework or simply LeanDfX and it focus on the evaluation and product development management behind the Lean thinking and Lean Product Development axioms, Modular Design and with a great degree of product systematization and organization and its multi-dimensional (and discipline) conception [1].

With the inherent growth of the framework, it becomes mandatory interconnect its application and its holistic capacity to manage requirements and life-cycle information for the project with the application of specific and/or complementary product development tools (e.g., Failure Mode and Effect Analysis (FMEA), Quality Function Matrix (QFD), etc.).

In this thesis, the connection of some of these complementary product development tools such as QFD and its application in the LeanDfX framework is studied and evaluated. There's also a case study to this, where the framework it is applied in the development of a Automated Guided Vehicle (AGV) chassis with the objective of material transport. This project is inserted in the mobilizing project PRODUTECH SIF - PPS5.

1.1 PRODUTECH

Production Technologies Cluster, or PRODUTECH, is an initiative promoted by the Portuguese Industry Manufacturing Technologies. "This Cluster comprises companies that are capable of addressing competitiveness and sustainability challenges by delivering innovative, flexible, integrated and competitive solutions in response to the manufacturing industry's needs" [2].

The main mission of this initiative is "to promote the sustainable development and internationalization of the Portuguese industry of manufacturing technologies - such as providers of capital goods, machine-tools, industrial equipment and systems, system inte-

grator, software houses, and developers of industry-oriented computer applications, engineering and consultancy companies - in close collaboration with key sectors of the manufacturing industry, the Portuguese Science and Technology System (SCT) and other stakeholders” [2]. More information about the initiative is *ibid*.

1.1.1 PRODUTECH SIF - PPS5 project

As an existing umbrella project of PRODUTECH, the mobilizing plan PRODUTECH-SIF (i.e. Solutions for the Industry of the Future) has the focus on the ”development and implementation of new production systems, embedding advanced production technologies that will equip the manufacturing industry to meet the challenges and opportunities of the 4th industrial revolution” [3]. The PPS5 comes from the goal for this section of the PRODUTECH initiative and this is the dissemination, coordination and management [4].

”It incorporates a strategic, coherent and integrative set of R&D activities in key domains that foresees the development of new production technologies for multi-sectorial application, and with impacts in terms of the reinforcement of the competitiveness and sustainability of the industry at international level, encompassing:

- Networked production systems;
- Innovative technologies for new cyber-physical production systems;
- Development, management and improvement of cyber-physical production systems;
- Key enabling production technologies, automation and advance robotic systems;
- Integral sustainability and efficiency of production systems;
- Energy technologies;
- Advanced tools for the development of products and services” [3]

1.2 Companies

This work was made in INEGI installations since the project is part of the company and the case study was from the company, JPM.

1.2.1 INEGI

INEGI, or Institute of Science and Innovation in Mechanical and Industrial Engineering is a Research and Technology Organization (RTO) that helps narrowing the gap existing between University and Industry and its main focus is Research and Development, Innovation and Technology Transfer activities for the industry. ”It was founded in 1986, among what are now the Departments of Mechanical Engineering (DEMec) and of Industrial Engineering and Management (DEGI) of the Faculty of Engineering of the University of Porto (FEUP)” having the main building in Porto [5].

It is important to notice that it is a non-profit private association but it is recognized as of public utility and the team is composed with 200 collaborators. The importance and weight of INEGI in the development and consolidation of a competitive model based on knowledge, on high product and process technological content and innovation can not and it must not be ignored [5]. In figure 1.1 it is possible to see all the work done in 2016 by the association. More information about the association is *ibid*.

This dissertation was done, before the COVID-19 outbreak in the installations of INEGI, allowing a great and direct contact with the industry and engineers. This allowed the and easier adaptation process and a softer start to the project.



Figure 1.1: 2019 INEGI Scientific Output [5]

1.2.2 JPM Industry

Founded in 1994, by José Paulo Martins in Vale de Cambra, Portugal, JPM main motivation was to deliver, using a continuous improvement culture, the best services for electrification and automation for industries and partners. Through the years, the company grown and expanded their areas of work and reach. Some of the industries where the company works nowadays are i.e. airports, post and parcel, manufacturing, process and warehouse. At this stage, JPM Industry is a part of the JPM Group, where JPM Renewables and Joinsteel also are part of this group. This great growth allowed JPM Industry to be a worldwide player in the intralogistics market [6]. It is possible to highlight the services that JPM Industry gives, such as engineering projects, installation and commissioning, modernization and upgrade, after-sales service and contract maintenance and manufacturing. Finally, the solution portfolio of JPM Industry goes from conveyors, robotics, software and automation to industrial equipment [6]. More information about the company is *ibid*.

1.3 Motivation

The industry present *status quo* is mass production with very strict quality requirements [7], which means that goes in encounter to the mass production of highly customized products but with still the economy of scale [1].

One of the main goals of nowadays industries is to reduce as much as possible the time spent in the design and production process, because spending more time means spending more money and consequentially, the product becomes more expensive [8]. There is, so, a need to cut as much as possible the time spent in the production phase but still checking every customer requirement for the product that is being developed. To make this possible, the Design-for-eXcellence (DfX) can be used [9]. The Lean DfX tool developed by INEGI has the objective to help in this time reduction goal without jeopardizing the final product quality [1].

Ergo, the main motivation behind this dissertation is built with the purpose to help the development of the LeanDfX tool so that companies, specially small and middle-sized ones can start building a more systematic approach to the designing process and therefore, promote their and the Portuguese industry growth. This development will be tested with the study on how some auxiliary project and product development tools interlink with

DfX and the LeanDfX made by INEGI, such as QFD (Quality Function Deployment) or FMEA (Failure Mode and Effect Analysis).

1.4 Objectives

The main objectives to this project are:

- State of the art study of product design development tools;
- Evaluation of tools like QFD and how they can complement and connect with the Lean DfX framework;
- Establishment of rules or orientations to the combined application of tools (LeanDfX, QFD, etc.) so it is possible to turn the product development process more effective and efficient without jeopardizing the quality of the product;
- Practical application of the framework and tools in a complex mechatronic project for a national company under the umbrella of the project "Mobilizador PRODUTECH SIF - PPS5";

1.5 Research methodology

The research methodology that served as inspiration on the current dissertation was Design Science Research. Applied mainly in Engineering and Computer Science [10], the main goal of design science research is to promote and blossom knowledge in the area of investigation that can help in the design of solutions for problems in the field in analysis [10]. As stated in the work of Hevner, "knowledge and understanding of a problem and its solutions are achieved in the building and application of the designed artifact" [11].

However, according to Hevner et al [11], Information Systems research is characterized by two paradigms, behavioral science and design science. The former paradigm tries "to develop and justify theories that explain or predict organizational and human phenomena surrounding the analysis, design, implementation, management, and use of information systems" [11]. It aims at truth, at the exploration and validation of generic cause-effect relations [12]. The latter paradigm began in engineering and sciences of the artificial [11]. As a problem-solving paradigm, it aims at the creation of innovation "that define the ideas, practices, technical capabilities, and products through which the analysis, design, implementation, management, and use of information systems can be effectively and efficiently accomplished" [11]. Design science research aims at "utility", at the construction and evaluation of generic means-ends relations [12].

The fact that Design science research is defined as a paradigm that allows the quantitative evaluation of an artifact through optimization, analytical simulation and quantitative comparisons with alternative designs, made it the one to apply in this dissertation. Design science research has seven guidelines that serves as pillars to support the implementation of such methodology. To a better understanding of each one, table 1.1 has a small explanation for each guideline that should be considered in the implementation of it.

In his work, Hevner et al.[11] shows in which research *wicked problems* design-science research tries to solve. Those problems are [11]:

- Unstable requirements and constraints based upon ill-defined environmental contexts;
- Complex interactions among subcomponents of the problem and its solution;
- Inherent flexibility to change design processes as well as design artifacts (i.e., malleable processes and artifacts);

Guideline	Description
I: <i>Design as an Artifact</i>	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
II: <i>Problem Relevance</i>	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
III: <i>Design Evaluation</i>	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
IV: <i>Research Contributions</i>	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
V: <i>Research Rigor</i>	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
VI: <i>Design as a Search Process</i>	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
VII: <i>Communication of research</i>	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Table 1.1: Design-Science Research Guideline [11]

- A critical dependence upon human cognitive abilities (e.g., creativity) to produce effective solutions;
- A critical dependence upon human social abilities (e.g., teamwork) to produce effective solutions;

To show how it was applied in this dissertation, each guideline will be shown and explained in the background of this dissertation.

Guideline I: Design as an Artifact

The tool that is being developed is a tool inspired in Lean Thinking and Design-for-X (DfX) methodologies and how supplementary tools like Quality Function Deployment (QFD) or Failure Mode Effect and Analysis (FMEA) can integrate the framework to help the designing process. QFD is inserted as a preliminary tool to help to define the customer requirements so it is possible to clearly define which ones they are and how to integrate them in LeanDfX. A new approach to QFD, known as Extended Lean Fuzzy QFD is implemented as a tool to help the previous definition of X domains. FMEA is also implemented as a tool to aid and serve as guidelines to follow in the Design for Reliability, Safety and Quality domains.

Guideline II: Problem Relevance

Reducing time and costs are some of the most important goals of almost any company. At the designing process, even if its direct costs are about 20% [13], the real impact of the decisions that are taken during these initial stages influence about 70% to 85% of the total cost [13]. To allow a systematic framework that may be applied to any designing

process, so time and cost can be reduced by having a systematic and organized approach, LeanDfX tries to answer that problem. LeanDfX can also evaluate efficiency, meaning that the use of excessive means (materials, component capacity, among others) is assessed which allows the evaluation of over-costs in the design process. The integration of "foreign" tools outside the direct realm of Design-for-X, like QFD that help the definition of customer requirements in a much more efficient way or FMEA, that allows the correction and prediction of some failures in the designing process, can help the development of the tool and meet its main goal of reducing time and cost in overall process by taking a holistic and systematic framework from the early stages of the process.

Guideline III: Design Evaluation

Experimental, Analytical and Feedback are the types of evaluation for this point. The integration of such tools will be tested through the designing process of an existing Autonomous Guided Vehicle for JPM Industry and the design obtained compared with an already existing one with the same requirements. A comparison of the potentialities of the framework at the beginning of this dissertation and at the end of it will be done so it is possible to acknowledge development made in the available time.

Guideline IV: Research Contributions

The maturation and development of a systematic framework for product development and design process, the LeanDfX framework, through the articulation and implementation of advanced tools, QFD and FMEA.

Guideline V: Research Rigor

Past relevant research in the fields of product development processes and its tools. Relevant bibliography on the connection of Design-for-X methodology and complementary tools. Past research done to develop QFD, DfX and FMEA. Literature with a summary of the existing and most common AGVs in market, its components and the norms that should be taken in consideration in the design process of an AGV.

Guideline VI: Design as a Search Process

The study of the needed concepts to understand what was already developed in the first place, such as Lean Design and Design-for-X basis. Identification of existing tools to aid the designing process was the start of the search. Afterwards, new developments for each existing tool so the application that may be done it is the most recent and connected to the existing world as possible so that the framework would not lose value through its life. Identify the main issues with each tool and methodology and how some may cover each others flaws through the search of keywords common to every single one.

Guideline VII: Communication of research

Even if it is primarily aimed to people with interest in the areas of product development and mechanical engineering, this dissertation was elaborated with the aim at that any person can understand every chapter and the work that was done. This justifies the small introductory theoretical explanation for almost everything that is mentioned in this dissertation. To test it, at the same time this dissertation was written, the section was analysed and read by someone outside the area that is being analysed. A clear and simple language was used with at least one example for every acronym and abbreviation used. The tool and framework developed through the dissertation was also done with a user-friendly

mind-set and interface, allowing the implementation of LeanDfX with the steps required. The designing process and result is also presented in a simple way, so its understanding and analysis is easy and clear.

1.6 Gantt chart

As a first step and a good measure to have a systematic approach to the dissertation planning, a Gantt chart was made in a reunion with both supervisors. Gantt charts allow, in the same way as the methodology that is trying to be developed in this dissertation, project planning and scheduling. The tasks considered are vague because when beginning the dissertation, several unknowns existed. From the company which the project would be done, to obviously, the project itself. Finally, the COVID-19 pandemic made an unpredictable change of landscape to the whole process. These are the tasks:

- Literature Review;
- State Of the Art;
- Case Study Selection;
- Thesis Redaction;
- Project Development;
- Final Thesis Redaction;

The Gantt Chart is available in Appendix A.

1.7 Outline

The general outline of this document and the main characteristics of each chapter are here described. The order of the chapters have a thought process behind. Firstly, the concepts needed to understand what was done are described. After, it was made an exposition on how the project started. Then, the developed methodologies to aid the framework and how they work are illustrated. Finally, to show how the results from these methodologies reflected in the design process and the case study design, a sole chapter is dedicated to it.

Chapter 2

Here a brief review of important concepts to understand what is done in this document is presented. In first place, product life cycle and more specifically, design process are explained. Next, several methodologies are analysed in order to understand why were they tested in this document and what is the current state of such methodologies. Then, Lean Thinking and Design is explained due to their weight in the framework.

Chapter 3

Due to the weight in the overall project, a single chapter is dedicated to Automated Guided Vehicles or AGVs. Here, they are briefly explained and its components. Then, the physics concepts important to the analysis done in this document are explained, as their use in Finite Element Method.

Chapter 4

The framework object of analysis in this dissertation, the LeanDfX framework is described, its goals and the steps needed to deploy it.

Chapter 5

An exposition on the start of the project and the information given as the requirements from the project happens in this chapter. Also, the starting deployment process of LeanDfX is here explained.

Chapter 6

The first developed methodology for this project, LeanDfX Fuzzy QFD, is here totally explained, step by step and stage by stage, as all the thought process behind the development. In the end of the chapter, the results from their use in this project are shown and analysed on how they may reflect on the overall design.

Chapter 7

As in the previous chapter, a step by step and a stage by stage explanation for another developed and adapted methodology, FMEA, for the framework under analysis, is done. Similarly, after the filling process, the results obtained from it and their influence on the final design are here analysed also.

Chapter 8

With the results of every methodology used and the existent requirements, in this chapter, the designing process, the results influence and the final design are assessed. Structural calculation necessary for the structure are here shown, as the scorecards generated from the framework are explained and how they helped the improvement loop. Then, final regards about the design are exposed.

Chapter 9

Here, a final conclusion on what was obtained in the end and what can be done afterwards regarding this project, being it the AGV or the framework, is shown.

Chapter 2

Literature Review and State of the Art

Products and the way that they are produced are evolving in a fast pace for the last decades due to many factors. The increasing competitive global market, fast moving markets and the technological development are some of the most obvious ones [14]. But there are others that also influenced the product life cycle and even more now, such as the depletion of natural resources and an increasing attention given to the environmental effects of a product during its life. These are just some of the factors that must be taken into account during the product life cycle and that changed the way that they are produced. All of this puts some pressure in manufacturers and in industries, e.g., to improve flexibility, lead times and recyclability without increasing costs or reducing quality, pretty much the opposite, a higher quality is expected even more from manufacturers [15].

2.1 Product life cycle management

A product has many steps during his life, figure 2.1 has a representation of the product life cycle and the many steps that have to be taken in account in the designing process. As shown in figure 2.1, a new cycle is triggered by a market demand or a new idea and only ends with recycling of the environmental disposal of the product. The life cycle of a product is not a linear process. This cycle represents the ability to convert raw materials into economic products of high added value [17]. The high value is given or obtained by having:

- Satisfied clients;
- Minimum cost and highest profitability;
- Short time-to-market;
- Low product development cost;
- High quality;
- High factory throughput with minimum work-in-progress;
- Minimum space, handling and inventory of raw materials and finished goods;
- The fewest redesigns and engineering changes as possible, none being the best case;
- Early supplier involvement;
- Reuse and recyclability;

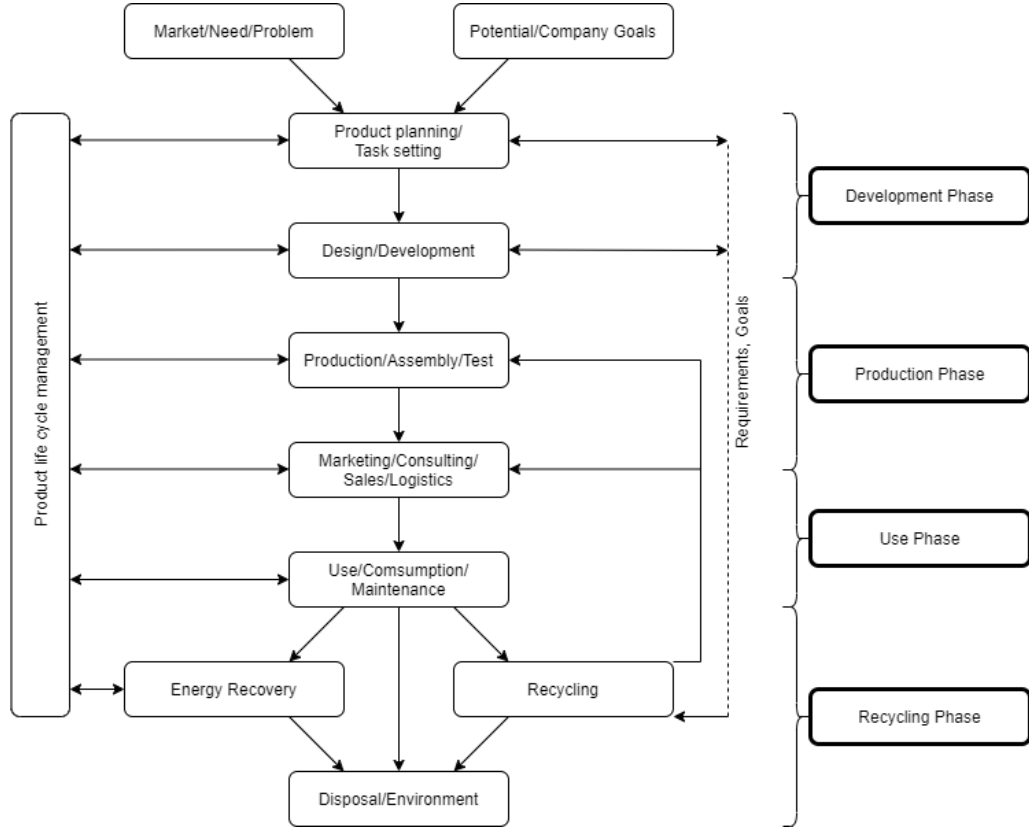


Figure 2.1: Life Cycle of a Product [16, 17]

- Customization;

Just to name a few, being producibility the overall theme of the requirements or goals [13].

In most of the available literature, there are four main phases in the life cycle of a product (Design, Assembly, Usage/service and Disassembly/Recycling [18] or Product Identification, Concept Development, Design and Manufacturing and Launch [13]) but they can be decomposed in many other smaller phases and these are the ones that are pretty much same throughout all literature. Figure 2.1 is a simple representation of the life cycle because there are much more smaller phases that are not represented and every single phase is interconnected. Every phase has a big influence in the life cycle of a product, but as shown by some studies [19], the designing process of a product is responsible for most of the decisions for the total product life cycle [13] and this process also influences between 70% to 85% of the total cost of the product even if the direct cost of the designing phase it is about 20% of the overall process [13]. Regarding the total influence of this stage in the overall life cycle, it is needed a more focused analysis.

2.2 Product Development Design Process

To achieve every or most requirements from the aforementioned list as possible, it is necessary a systematic approach to the product development design process [20], in other words, it is important to use and to organize an effective product development process [21].

The biggest proof that the use of a product development process is needed are the high failure rates associated with the lack of use of tools and technologies to aid and improve this process, specially to create new products [22]. There are a few reasons to why these technologies are still under-used, such as the lack of companies that aid in new

product development problems solving, the fact that project managers do not know these technologies and processes or when they know them, the lack of faith in the effectiveness of these tools [23].

A life cycle engineering approach in the designing process must be made to help to achieve most of the aforementioned requirements [9]. Life-cycle engineering is a process that emphasizes early in the product development various aspects of a product journey from creation to disposal and/or recycling. Some of the products aspects are [13]:

- Failure modes and reliability issues;
- Availability of spare parts;
- Diagnostic tools and personnel;
- Customer service and maintainability;
- Product installation requirements;
- Among others;

The useful life of a product is a measure of how long it will meet performance standards when maintained properly and when not subject to uses beyond its stated limits [13].

The product development design process are all the steps, decision and activities associated in the development of the product itself, this is, from the task clarification and planning to the product launch and after [17]. There are many ways to divide the designing process, one of them comes from Pahl et al. [17], where there is a division in four main stages, Planning and Task Clarification, Conceptual Design, Embodiment Design and Detail Design [17]. A small explanation for each stage will be given.

At the Planning and Task Clarification, there is a design task that contains all the possible information about the product that will be developed, such as functionality, performance, deadlines and even cost targets. With the available information about the product, it must be done a requirements list. These requirements are sometimes explicitly given, such as limit values for tensile strength or limit dimensions for the product as examples or can be implicitly given, where things obvious as the fact that a gearbox has to be able to change gear or the fuel consumption should be the lowest possible respecting the others requirements are some examples [17]. One of the most useful methods to support the preparation of the requirements list is Quality Function Deployment (QFD) [17]. Since this is one of the main focus of this project there is a single section dedicated to this matter (Section 2.3). Even with the fact that this is done in the beginning of the process, it should be kept in mind, as already stated, this is not a linear process, there is always new requirements that will appear due to many factors during the whole process, so this list should be updated when possible.

The next phase is the Conceptual Design [17]. From the requirements list available at this stage, the basic solution concept is laid down, this means that the basis principle solution is specified here. At this stage, the requirements list is also refined. This happens because it is the first stage where the requirements are turned into first ambiguous designs and some flaws can be seen in them. The principle solution serves as the guideline for the next step, the embodiment design.

This is the part of the design and development process, using the concept or the basis solution previously obtained, the design is developed with the motivation to meet the criteria and requirements previously established [17]. Regarding once again the requirements for the product, at this stage the first drawings are made, the layouts and form designs for the main functions are chosen, the solutions for the auxiliary functions are also developed. At the beginning, only a preliminary design is made for each one but as they are chosen,

the more detailed the drawings and the solutions become [17]. At this moment of the process design, there is a need for a systematic approach and guidelines and frameworks that pays attention to standards, regulations, limit values or compatibility. This is where the Design-For-X or Design-for-eXcellence methodology can shine as an example, even if its effect is felt through all designing process, most of its use can be aggregated in this phase. At this stage, many guidelines are followed for each requirement at the requirements list.

At last, the final stage can be named as Detail Design. At this phase all the arrangement, forms, dimensions and surface properties of every individual parts are specified, as the materials, production, costs and every other thing. This stage results in the specification of information in the form of production documentation [17].

As mentioned, the designing process is responsible by most of the cost in the overall process and also responsible by most part of the faults that happen during a product life [24]. So, the demand for quality is essential. Quality is influenced in a big way in the designing process and a systematic approach to the overall development procedure supports a holistic approach to the product quality.

There are several tools and techniques that can help the designing process and ensuring the quality of the product, some of them were already mentioned in this chapter but there are many more. They can be applied at different stages of the process and in more than one phase and also several times. Some of them are:

- Quality function deployment (QFD)(Section 2.3);
- Design-for-X (DfX)(Section 2.5);
- Failure Mode and Effect Analysis (FMEA) (Section 2.6);
- Theory of Inventive problem solving (TRIZ)(Section 2.7.1);
- Design-for-Six Sigma (DfSS)(Section 2.5.1);

In this thesis, the emphasis will be on QFD and DfX and how they interconnect. However, a small explanation and state-of-art investigation is given for some other interesting tools and techniques that may have some influence and room to grow in the future [23].

2.3 Quality Function Deployment (QFD)

Originated in Japan [25], the Quality Function Deployment (QFD, from now on), was born with the intent to solve or at least aid in the problem of converting customer requirements into specifications or technical requirements [26]. It can also be explained as almost a translator, when possible, of customer requirements into specifications. It is also a methodology that aids the planning and assurance of quality [17].

QFD, even with the fact that was idealized as product development, quality management and customer needs analysis tool [27], it can be used also in many more fields, such as design, planning, teamwork, engineering, timing or even cost, showing that it is a very versatile tool [27]. This happens due to the ability of the tool, since it can use an interlocking structure to link many stages. This happens in order to trace customer requirements from the planning to the most detailed instructions at the operating level [28]. A graphic representation is in figure 2.2 for an easier understanding of the process.

The main design tool used, or the diagram(s) in QFD is named the House of Quality (HoQ). The diagram can be supported by the "How"'s and "What's" of the project. To help the understanding of the House of Quality, a graphical representation of one is available in figure 2.3. In the left part of the chart, are the customer requirements, what the customer needs and wants ("What's") for the product, usually are or were vague at this point. As an answer to those "What's", there's the "How's", the engineering characteristics that the product should have, in order to meet what the customer wants. These

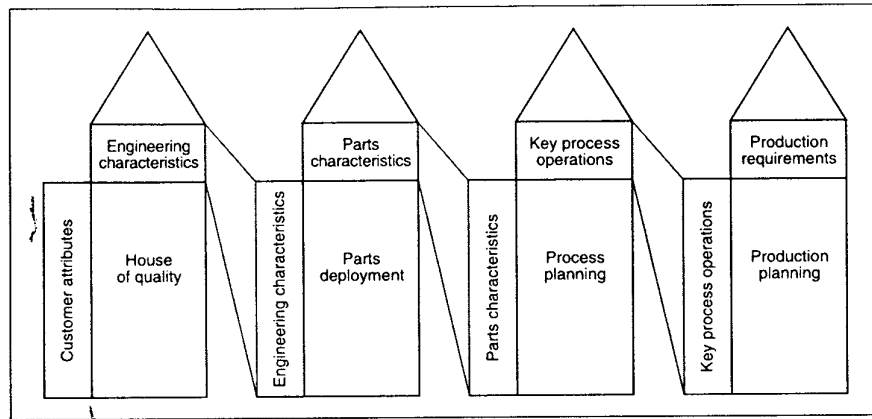


Figure 2.2: QFD through the customer requirements to the design [28]

engineering characteristics or technical requirements are the "How's" of the house. In the middle of both there's the relationship matrix, and this matrix shows the interrelationships between each customer requirement and each technical requirement. The relationship between them is represented as the team responsible for the HoQ process wants and the values/symbols in the matrix should translate the level of connection between the customer requirement and the engineering characteristic. At the roof of the house, the triangle at the top, it is the roof matrix or correlation matrix. This matrix shows how the engineering characteristics interrelate with each other and also the strength of their relationship. Just like the relationships in the relationship matrix, the roof matrix is filled with values/symbols representing the relationship between engineering characteristics, if they exist or if they are positive or negative. Underneath the relationship matrix, for each technical requirement, there is a target value for it and along with it are plotted technical assessment of competing products, technical competitive benchmark. For each customer requirement, there may be a weighting factor, determining the relative importance of each requirement. This can be also done to the technical requirements [17, 28, 29, 13].

At this point, the main characteristics for the HoQ are explained. Of course that it can be added much more things to the overall diagram. Things such as customer perspectives of each customer requirement, in the case of already existing products, and how they compare with competition can be added at the right of the relationship matrix. It can also be added below the relationship matrix, the technical difficulty for each engineering characteristic and much more, depending of the endgame for the HoQ [28, 29, 17].

As already stated previously in this report, usually the QFD process has more than one HoQ associated and all of them are interlinked. There are usually four phases to the QFD method and they are displayed in figure 2.2 and in table 2.1 in a way that the left column are translated as "What's" and the top row are translated as "How's".

HoQ	What	How
1	Customer Requirements	Engineering characteristics
2	Engineering characteristics	Parts characteristics
3	Parts characteristics	Key process operations
4	Key process operations	Product requirements

Table 2.1: Different HoQ applied in QFD methodology

The figure and table show that the "How's" turn into the "What's" of the subsequent HoQ.

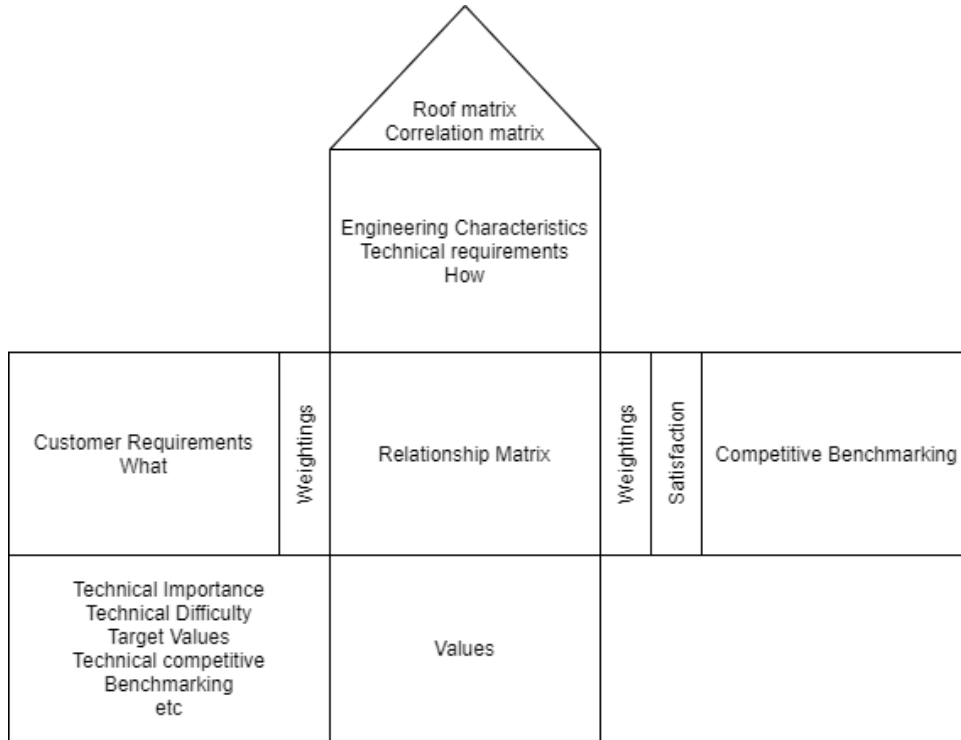


Figure 2.3: Conceptual House of Quality [29, 28]

2.3.1 Current approaches

The QFD methodology has many advantages and disadvantages. Some advantages are:

- Better understanding of the client [30];
- Focus on teamwork [30];
- Continuous improvement [30];
- Reduction of production costs and purchasing costs [31];
- Better knowledge of the product [30];
- A structured, systematic approach [30];
- Increased organizational knowledge [30];
- Improving the product development process [31];
- Shorter time to market a new product [31];

It is possible to say that the advantages of QFD are seen in many aspects of a company, from the economical standpoint to the socio-psychological, showing the versatility of the method.

In the same way, there are some problems and limitations when applying this method. Some of the more important disadvantages linked to this method are:

- Slowness of performing QFD analysis [30];
- Difficulties in maintaining the integrity of the interdisciplinary team [30];
- A small understanding of the QFD method [30];

- Lack of sufficient financial resources [30];
- Vagueness of the categories used [30];
- Difficulty in relating the relationship strength between characteristics and requirements and among them [31];

To overcome these disadvantages and to improve the advantages of the method, there are many works available in the literature with some of these works.

Adiano et al [28] worked to turn the QFD method into a dynamic method that will be updated through the life of the product.

A popular methodology to fight the uncertainty and the fuzziness of the process is the Fuzzy set theory [32]. Developed and popularized by Zadeh [33], the Fuzzy set theory is usually combined with QFD with several different approaches. Section 2.4 is dedicated to Fuzzy Set Theory explanation. There are studies that have a direct combination of conventional QFD with the Fuzzy theory and their application in various products and services [34, 35, 36]. However, to overcome most of the problems with the process, the QFD and Fuzzy-QFD are combined with one or more complementary methodologies. Many of the methods are Muticriteria Decision Making (MCDM) methods. Some join analytic network process (ANP) with the Fuzzy-QFD [37, 32, 35] with the work of Asadabadi et al [37] also combining the Markov chain. Both to help with the necessary weighting phase of the process, to help the decision making. Fuzzy-QFD also can be completed with the use of analytical hierarchy process (AHP) in many available literature [35, 38, 39, 40, 41, 42, 43] with many different approaches in how to complement the combined process, also to have a more systematic approach to the weighting problem. In the work of Yazdani et al [44], to eliminate the uncertainty of many criteria, it is done a combination of the Fuzzy-QFD with the decision-making trial and evaluation laboratory (DEMATEL) [44]. Other methodology that was recently developed by Yazdani et al [45] called SWARA to aid in the weighting method of the customer requirements. Another recently developed to help the ranking process in QFD is the use of the ranking method ORESTE, as used by Wu et al [46]. Multi-Objective optimization by ratio analysis (MULTIMOORA) method is also a commonly used method to help to determine the ranking order of the engineering characteristics and many approaches to its implementation to QFD and Fuzzy-QFD is developed in many articles through the literature [47, 48]. Other methods than can be named to apply to the weighting process and decision making process are Delphi [39] or TOPSIS [48].

Wan et al [49], using the function behaviour structure (FBS), a methodology employed to guide the designer and to express the knowledge and formalize the synthesis, analysis and evaluation methods [49], with QFD, tried to create an innovative device to transport electron gun automatically in nuclear power plant [49]. There are numerous different approaches to QFD and complementary methods to use, an almost overwhelming account, so it is important to keep in mind that the ones mentioned are just some and not by any means every single one of them.

2.4 Fuzzy Set Theory

Due to the weight that this technique has in the methodology further developed, a single section is dedicated to the logic and how it works.

Developed in 1965 by Zadeh [33], the fuzzy set theory provides a natural way of dealing with problems where imprecision has its origin on the uncertainty or lack of clarity regarding previously defined criteria of class membership [33]. In other words, is a theory that tries to deal with imprecision and vagueness in data. The same theory allows mathematical operators and programming to apply to the fuzzy domain [35]. To define the sets, membership function, μ is used. Even if the most typical application of the fuzzy

set theory in QFD relies on triangular fuzzy numbers, as it was possible to conclude from the work aforementioned. In this approach, it was used trapezoidal fuzzy numbers. The membership function may have any value between 0 and 1 and with this, unclear data is represented in more accurate way. Being S a set of objects which is represented by y , the fuzzy set A in S_f is defined by [33].

$$A = \{y, \mu_A(y) | y \in S_f\} \quad (2.1)$$

A trapezoidal fuzzy number, A is represented by four parameters (a_1, a_2, a_3, a_4) , where $a_1 \leq a_2 \leq a_3 \leq a_4$ and are in the membership group under fuzzy set S_f , instead of a more typical triangular three values approach. With a trapezoidal number, the theory can provide solutions with grater detail [35]. To ease the understanding of equation 2.2, there is an illustration on figure 2.4.

$$\mu_B(y) = \begin{cases} \frac{y-a_1}{a_2-a_1}, & \text{if } y \in [a_1, a_2] \\ 1, & \text{if } y \in [a_2, a_3] \\ \frac{a_4-y}{a_4-a_3}, & \text{if } y \in [a_3, a_4] \\ 0, & \text{otherwise} \end{cases} \quad (2.2)$$

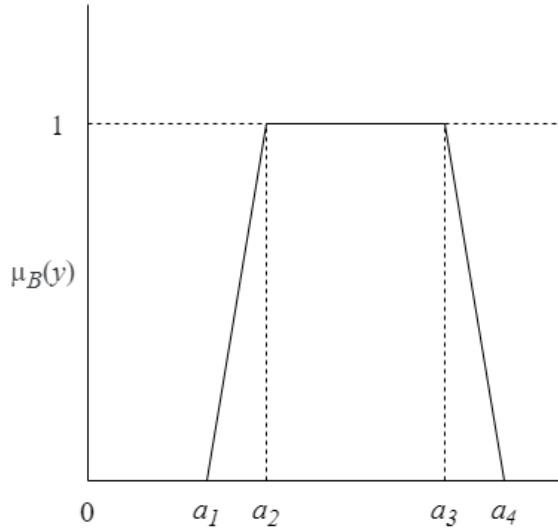


Figure 2.4: Graphic of a trapezoidal fuzzy number

Mathematical operations with fuzzy numbers also have particular characteristics. If $\bar{A} = (\bar{a}_1, \bar{a}_2, \bar{a}_3, \bar{a}_4)$ and $\bar{B} = (\bar{b}_1, \bar{b}_2, \bar{b}_3, \bar{b}_4)$ are the fuzzy trapezoidal number, then their operations are given by [50]:

- Addition of two fuzzy numbers, $\oplus$

$$\bar{A} \oplus \bar{B} = (\bar{a}_1 + \bar{b}_1, \bar{a}_2 + \bar{b}_2, \bar{a}_3 + \bar{b}_3, \bar{a}_4 + \bar{b}_4) \quad (2.3)$$

- Multiplication of two fuzzy numbers, $\otimes$

$$\bar{A} \otimes \bar{B} = (\bar{a}_1 * \bar{b}_1, \bar{a}_2 * \bar{b}_2, \bar{a}_3 * \bar{b}_3, \bar{a}_4 * \bar{b}_4) \quad (2.4)$$

- Multiplication of a fuzzy number with a real number, n

$$\bar{A} \otimes n = (\bar{a}_1 * n, \bar{a}_2 * n, \bar{a}_3 * n, \bar{a}_4 * n) \quad (2.5)$$

- Division of two fuzzy numbers, Δ

$$\bar{A}\Delta\bar{B} = \left(\frac{\bar{a}_1}{\bar{b}_1}, \frac{\bar{a}_2}{\bar{b}_2}, \frac{\bar{a}_3}{\bar{b}_3}, \frac{\bar{a}_4}{\bar{b}_4} \right) \quad (2.6)$$

- Division of a fuzzy number with a real number, n

$$\bar{A}\Delta n = \left(\frac{\bar{a}_1}{n}, \frac{\bar{a}_2}{n}, \frac{\bar{a}_3}{n}, \frac{\bar{a}_4}{n} \right) \quad (2.7)$$

- Defuzzification of one fuzzy number to a crisp number, CN

$$CN_{\bar{A}} = \frac{1}{4} * (\bar{a}_1 + \bar{a}_2 + \bar{a}_3 + \bar{a}_4) \quad (2.8)$$

Many works are available in literature connecting QFD and fuzzy language [38, 35, 39, 51, 52] due to their intricate connection where fuzzy language helps covering one of the main problems with QFD methodology, the indecision and lack of clearness already mentioned in previous chapters.

2.5 Design-for-X (DfX)

Obviously, the Design-for-X methodologies are usually in the aftermath of the QFD methodology, even if there are some direct application of QFD in DfX. To help to transform what is desired for a product in the development and design process, there are guidelines and strategies that were developed through the years to help. Created in AT&T Bell Laboratories [53], these methods can be called DfX or Design-For-X [9], where the X represents the many fields of work in which a methodology can be applied, such as manufacturability, assembly, quality, disassembly, recyclability or logistics [9]. Even though it began as only as a design for manufacturing [54], through the years, the concept of Design-for-X (something) became much more broader and as mentioned already, applicable in many fields so it is possible to provide to designers a framework and guidelines that can help them reach all the desirable features for a product.

The main objectives of DFX are the following:

- Higher or satisfactory functional performance [9];
- Minimum cost [9];
- Minimum maintenance and repair [9];
- High levels of quality and reliability and durability [9];
- Fastest time to market [9];
- Environmentally friendly products and processes [9];
- Retrofitting and upgrading as much as possible [9];
- Rationalization of decisions in the designing process [17];
- Safety [9];
- Aesthetic and feeling [17];

There are many X's that can be referenced throughout the literature and the number of publications and guidelines for each X can be overwhelming. It would be needed much more time to fully understand the total dimension of DfX and the various fields that it is associated with. The more common and more used ones will be analysed within the possible time and some few others will be at least mentioned. In table 2.3 there is a list with many of the X's used and their categorization is within the methodology used in the work of Arnette et al. [55] where the DfX taxonomy is in the following dimensions: economics, ecology and social equity. There was also a second categorization of the DfX dimensions inspired in the work of Chiu et al [56] where the DfX methods are aggregated in two ranges of perception, they are the product scope and system scope. One that it is not considered in the table is the Design-for-Cost (DFC) because of their versatility and its presence in any scope and dimension. Design-for-Quality could also be considered but it is possible a small aggregation to this.

Even if a small state-of-art review is done in this dissertation, there are several literature reviews on many DfX approaches since it has an enormous amount of information due to the specter of themes that the DfX techniques are applied. Benabdellah et al [57], Fagnoli and Sakao [58] or Chiu and Kremer [56] are just some of the many literature reviews that were used to write the following sections.

It is possible to conclude from the various available dimensions in the DfX method that the Design-for-X provides an holistic view in the overall process and this shows that it can be a powerful and important tool to use in the Product development process. In the following tables, a small sample of some X domains and their explanation is presented as also in the other, a small sample of Design-for-X methodologies.

Design for	Guidelines	Reference
Assembly	Design symmetrical components when possible; If symmetry cannot be achieved, make sure marked asymmetry is present; Provide location features on parts to facilitate assembly	Miles and Swift (1998) [59]
Manufacturing	Use the widest possible tolerances and finishes on components Avoid the use of undercuts where possible; Fillet should be used at corners wherever possible; Develop the design to contain as many identical components as possible;	Edwards (2002) [60]
Maintenance	Part reference designations shall be located next to each part legibly and permanently; Minimise the need for special tools; Mount heavy units as low as possible; Provide clarity around connectors to provide adequate viewing and hand access;	Kuo <i>et al.</i> (2001) [61]
Recycling	Select material properties to permit material recycling; Reduce the number of components; Reduce the number different materials; Design disassembly-friendly connections; Facilitate separation of incompatible materials;	VDI 2221 [62]

Table 2.2: Sample of some DfX methodologies

Dimension	Scope	Abbreviation	Full Name	Description
Economy	Product	DfM	Manufacturing	Design with the focus on integrating the manufacturing stage [63]
		DfA	Assembly	Design with the focus on integrating the assembly stage [56]
		DfMA	Assembly and Manufacturing	Combination of DfA and DfM
		DfV	Variety	Design to meet the market demand for product variety with the most balance of design modularity, component standardization and product offerings [56].
		DfDr	Durability	Design to meet the stress requirements [17]
		DfQ	Quality	Design to meet customer requirements and process defects [17]
		DfRb	Reliability	Design to the product not to fail or malfunction within their expected working conditions [13]
		DfMt	Maintainability	Design concerning the ease with which a product can be maintained and his life extended [55]
		DfSS	Six-Sigma	Design to minimize defects and to meet customer requirements [13]
		DfMod	Modularity	Design with the focus to have modules in products
Economy and Ecology	Product	DfS	Safety	Design regarding the safety of people, materials and processes involved [13]
		DfAa	Automation	Design with the focus on the automation of the process and product [64]
		DfSC	Supply Chain	Design regarding the supply chain process in the manufacturing and logistic process [55]
		DfL	Logistics	Design with the focus on distribution and packaging stage [55]
		DfD	Disassembly	Design considering the disassembly and separation of parts, components and materials
		DfCr	Circularity	Design with the attention to the upgradability of product and to the design of both the upstream and the downstream phases of the process [65]
		DfE	Environment	Design with the focus on a full product life cycle environmentally friendly approach [55]
		DfRem	Remanufacture	Design to have the possibility to reuse the material in manufacture after his life[55]
		DfR	Recycling	Design to save and reuse raw materials to reach a more sustainable development [17]
		DfWMR	Waste Minimization and Recovery	Design to minimize and if possible, eliminate waste by giving a second life to the so-called before waste [55]
Ecology	Product	DfRu	Reuse	Design to promote the reuse of the product, usually as harvesting working parts [55]
		DfSR	Social Responsibility	Design products that support humanity, are produced in good conditions and with social responsibility to do not harm communities [55]
Equity	Product	DfSR	Social Responsibility	Design products that support humanity, are produced in good conditions and with social responsibility to do not harm communities [55]

Table 2.3: Various DfX dimensions and their aggregation

2.5.1 Current approaches

As it can be expected, there are many guidelines proposed for various X's, so the focus on this section will be to give some of the most applied current guidelines in the design dimensions that are the most valuable ones in this theme.

Design for Manufacturing and Assembly

DfA, or Design for Assembly has the design focus to reach the lowest assembly cost achievable still having an appropriate assembly system [61]. Mainly developed by Boothroyd and Dewhurst in some of their work [66], through the years there were many proposed guidelines. The general guidelines are already in the previous section and they were also developed in many works [67, 68, 69, 70, 71, 59]. The main consideration on all approaches is to design to reduce the number of parts, tasks and motions.

Since there is a inherent connection between Design for Assembly and Design for Manufacturing, some of the guidelines are available in works that combine both.

Expanding on the most general guidelines previously mentioned in table 2.2, a review by Chiu and Kremer [56] cited seventeen varied guidelines and methods for the implementation of DfM and DfA. Even if in this literature review, they appear in different subsection, these two approaches may appear in one domain only as DfMA (Design for Manufacturing and Assembly), by authors like Boothroyd [72]. These are also the first to be mentioned because they are the most developed ones. Starting in 1988, Stoll [73] developed thirteen DfM guidelines with three main focus: Modular Design; Multi-use parts with standardization; Ease of assembly to increase manufacturability. In fact, the focus on modularity is common in many works of reference [74, 75, 76]. Other works focus on methods on how to obtain the cost for different kind of parts depending on its origin [66, 77, 78, 79]. The overall theme of all the cited papers is to minimize reorientation of parts, standarize parts, encourage modular design, design for component symmetry, design parts with self-aligning and fastening features, among others. Some works, to promote good design practices, developed some guidelines[80, 81] with some combining them with other techniques such as decision analysis[82, 83] or axiomatic design [84, 85]. Baptista et al [86] also proposed a design management technique to support Design for Manufacturing, where the decomposition of products is made, based on the manufacturing features of each component, where the complexity of a part depends on the number of operations and in the directions of material alteration.

As stated, DfMA almost become the approach that is now taken by DfX methodologies and its general idea is, as expected, design product that allow easy manufacturing and assembly. Their main guidelines have usually the focus on the minimization of component number, simplification and reduction of the number of manufacturing operations, maximization of standard parts and materials, to design for efficient joining, for ease of part fabrication, for ease of packaging and for ease of assembly and to use modular design [72]. This should be a focus for companies that wish to remain competitive in the future, since it allows the application of cost quantification tools at the earliest product design stages.

Design for Quality

Quality, a much repeated term so far, means not only the classical definition of fulfilling the required technical functions, but also careful attention has to be paid to the requirements of safety, use, ergonomics, etc [17]. Knowing this, DfQ objectives are to meet customer requirements but also to design a product by maximizing robustness but also improving product reliability, performance, robustness and reducing the effects of variation in manufacture and product environment [17]. This is obvious because even when all requirements are met, if the product is unsafe or unreliable, it has poor quality. The same can be said if

it has no conditions for transportation, for logistics. This means that even when customer requirements are met, quality is not confirmed. Many research and benchmarking tools were developed by several authors for DfQ [87, 88, 89, 90].

Design for Six Sigma (DFSS)

First of all, it is important to define what is Six Sigma. It was originally developed in the 1980's and it was part of total quality management (TQM). The overall meaning of Six Sigma is a statistical term to describe the quality goal to have no more than 3.4 defects out of every million opportunities. There is also an underlying mean in the improvement philosophy and program [91].

The Design approach that the DfSS focuses on is one that tries to design the right thing right, give an insurance in designing for improvement and quality [13]. Therefore, it can be said that DfSS is closer than ever to the overall meaning of DfQ.

Design for Safety

Safety is essential, a failure of malfunction in some systems or products may result in serious injuries to people or even worse, death. And even if it may not come as a first when thinking about safety issues, these deaths and injuries usually, if they happen, translates in significant costs for the companies. Great scale disasters like the Bhopal disaster [92] or Texas City disaster [93] are large scale examples to illustrate it in the worst possible scenario. Design for safety attempts to integrate safety knowledge into the design process [94].

There are several drawbacks when designing for safety, mainly because of how hard it is to identify all scenarios early in the design process and how to prioritize them [95].

In the work of Ghemraoui et al [95], a Innovative Risk Assessment Design (IRAD) method was developed so it is possible to cover other of the biggest problems in safety design, a systematic approach for the application of safety design. Sadeghi et al [94] developed a safety indicator to measure the safety level during design for safety, where hazards should be eliminated and risk reduced in early product design phases.

Both this and the work of Ghemraoui et al [95] take inspiration on the division of the design process in the research of Pahl et al [17], where there are three main stages: conceptual design, embodiment design and detailed design. Both also consider three types of risks (accident risks, ergonomics risks and residual risks). Several tools and methodologies are combined for research in the design for service. Theory of Inventive problem solving (TRIZ) is used in some works with the motif to help the designer to find solutions behind the analysis of the design problem [96, 97]. One of the focus of this project, FMEA (Failure Mode and effect analysis) is also used to address product quality and human safety and how to implement in a design for safety/reliability approach [98].

Design for Environment

The Environment is becoming one of the main concerns in any process and in every other industry. There is a increasing concern to the effects that a certain design and process may have in the environment and the Design for Environment domain covers the various methodologies that are available to avoid harming the planet.

As mentioned, the main motivation is to create an environmentally friendly product and to have a sustainable economic growth without increasing the consumption of resources [13]. And even if it may seem as a hard objective to get, especially regarding the economical part, there are some businesses that showed that reducing emissions, energy usage, using non-toxic processes and minimizing waste improves profitability [13]. To help

to understand the basis behind this massive domain, three things can be said as universal in this [13]:

- The environment is considered a customer in the life-cycle design;
- A product with a negative impact for the environment is a defective product;
- The product total environmental impact must be reflected in the product cost;

In the many approaches the overall goal of the design and product team it is to evaluate the product through all its life and how the materials, processes used to manufacture and assembly as also the disassembly process affect the environment and if there is a possibility to substitute any part of the overall process to a more environmentally friendly approach [13].

One of the most important things that it can be done is the material choice process, as mentioned. This has a huge weight in the environmental evaluation of a product because it will affect everything, from the recyclability of the product and material to the processes chosen. Some of the recyclable materials are the following [13]:

- **Metals:** iron, steel, copper, brass, aluminum, lead;
- **Thermoplastics:** polypropylene, ABS, polyethylene, nylon, acrylic, PVC, polycarbonate;
- **Other common materials:** nonlaminated glass, wood products and paper, including cartons;

Some of the materials that should be avoidable are laminated materials, e.g. plastic and glass, plastic foam, galvanized steel, ceramics, thermosetting plastics and parts that are glued or riveted together [13].

2.6 Failure Model and Effect Analysis (FMEA)

FMEA or Failure Model and Effect Analysis is an analytical method that aids to identify the possible failures and to give a prediction of possible risk through a systematic approach to the product [17]. It is usually applied through the development of new products and it is connected to the total quality management (TQM) approach [99]. This method can be separated in 2 distinct methods regarding the phase where is applied. It can be Design FMEA (DFMEA) or Production FMEA (PFMEA). But as a first step, it is necessary to identify the possible hazards and failures to the product that is being or already was designed. Hunter [100] proposes the following 5-step methodology to this process [100]:

- Review existing standards;
- Identify Known Hazards;
- Identify Unknown Hazards;
- Determine Characteristics of Hazards;
- Minimize or Eliminate Hazards;

The explanation to each step is available in the work done by Hunter [100].

2.6.1 DFMEA

In order to reach their reliability requirements, in 1963, NASA proposed for the first time the DFMEA [101]. This was developed in the future by many companies, with the Ford Motor Company being one of them [101]. As expected, DFMEA has the goal to verify if the reliability requirements are met during the design and production stage [17].

The first stage to build a DFMEA chart is to identify each failure mode that may happen to what is in study [17], in other words, this means to make a risk analysis. Then, for each one of the possible failures, their consequences and causes must be also written [17]. The next step is to propose test measures. Afterwards, it is necessary to have a Risk Number (RN) for each of the failure mode. This RN is calculated through other three estimated parameters:

- Probability of Occurrence (O) [17];
- Significance or severity of the effects of the failure (S) [17];
- Probability of detection of the failure before it fails (D) [17];

For each of these parameters, the most conventional methodology is to give a rating between 1 and 10 for each one, where 1 being the best case scenario and 10 the worst. After this, it is possible to obtain the Risk Number (RN) through equation 2.9 [17]:

$$RN = O * S * D \quad (2.9)$$

If the RN is bigger than 125, then the failure is considered critical [17]. Finally, for each of the possible failures to the component, a solution or improvement should be given and for this new solution, estimate the parameters and compare both RN results [101].

2.6.2 PFMEA

Just like DFMEA, this method was primarily developed in the 1960's by NASA [102] and in the same way, it was continuously developed by the automotive industry through the years.

The process failure mode and effect analysis (PFMEA) is a technique that measures the potential failures of the planned production process [17]. As a methodology, it has the same steps as DFMEA [103] but in PFMEA, the pre-production control plans, nonconforming products, costumer complaints are also items that should be considered [104]. Sometimes this process is indirectly contained in the DFMEA because the production problems should already been taken into account in the design process [17].

2.6.3 Current approaches

Firstly, to better understand the process, a FMEA chart is available in figure 2.5. As expected from being a qualitative method, there are some problems that are connected with both FMEA. The biggest disadvantages for this method are:

- Measurement scale for parameters [101];
- The lack of interconnection between the three parameters [101];
- Loss of information as lack of precision due to the dilution of expert knowledge in the overall responsible team [101];
- Lack of connection to cost [103];

To overcome these and more negatives from the FMEA method, many authors proposed several approaches to the method. Wang et al [105] use the fuzzy linguistic terms in order to turn the Risk Number, or Risk Priority Number into a fuzzy Risk Priority Number

 TU-Berlin		Failure Mode and Effect Analysis Design (product)-FMEA ☒ Process-FMEA ☐				Component name Cylindrical cam								
Name/ Department/ Supplier/ Telephone Institute for Machine Design-Engineering Design						By (Name/ Department/ Telephone) Mr Wende								
Failure location/characteristic	Failure type	Failure consequence	Failure cause	Current situation				Suggested remedial measures	Improved situation					
				Proposed test steps	O	S	D		RN	Applied steps	O	S	D	RN
Shaft	Shaft fracture	Complete breakdown	Type of loading not identified correctly		3	10	10	300	Determine loading using suitable calculations	Proof of strength of the shaft	1	10	10	100
	Play in bearing assembly	Imprecise function fulfilment	Slackening of shaft nut during operation (impulse loading)		3	8	10	240	Additional locking of the shaft nut		1	8	10	80
Bearing	Sealing leakage	Early wear of bearing	Sealing not as required		2	5	10	100	Use of radial shaft seals recommended by DIN		1	5	10	50
	Insufficient frictional fit	Shear stress in bolts	Layout error (friction values neglected)		2	6	10	120	Application of a sufficiently high safety factor		1	6	10	60
Shaft-hub-connection (flange-bolt connection)	Precision of fittings	Joining not possible or centering insufficient	Design fault		2	5	1	10	Check tolerance calculation		1	5	1	5
	Failure of bolts	Complete breakdown	Type of loading not identified correctly		3	10	10	300	Suitable calculation for loading situation	Appropriate bolt dimensions	1	10	10	100
Cylindrical cam	Surface pressure too high	Pitting in the running surface	Lever pressure on surface too high		7	8	10	560	Suitable combination of materials and adapted geometry		2	8	10	160

O: Occurrence
Probability of occurrence
(failure can exist)

very low = 1
medium low = 2-3
medium = 4-6
medium high = 7-8
high = 9-10

S: Significance
Effect on customers

effects hardly noticeable = 1
failures not important (little trouble to the customer) = 2-3
reasonably serious failure = 4-6
serious failure (annoying for the customer) = 7-8
failure with large negative effects = 9-10

D: Detection
Probability of detection
(before delivery to customers)

high = 1
medium high = 2-5
medium = 6-8
medium low = 9
low = 10

RN: Risk number

high = 1000
medium = 125
no risk = 1

Figure 2.5: FMEA chart available in the work of Pahl et al [17]

(FRPN) so it is possible to eliminate part of the inaccuracy related to the evaluation process [105]. In their work, Pillay, A. and Wang, J. [106] approach the FMEA chart and try to eliminate much of the problems aforementioned by combining FMEA with fuzzy linguistic terms also but adding a grey relation analysis [106]. QFD is also combined in some of the available works in the literature, just like in the case of the work of Liu et al. [107] where the method is tested in the quality improvement of packaging designs in the TFT-LCD industry [107]. With the motivation to also improve the method of RPN evaluation, Chang and Wen [105] combine 2-tuple and the Ordered Weighted Averaging (OWA) operator to improve the failure prioritization process [105]. Rivera Torres et al. [108] applied a probabilistic Boolean Network modeling as an approach for DFMEA. Also to overcome the measurement scale problem associated with FMEA, Chang [109] compared the results obtained by the RPN traditional result and the DEMATEL method and also proposed a new method based in Xtal unit [109]. Other MCDM are used in combinations in some articles and works available, such as AHP [51], ANP [110] or TOPSIS [111]. A Six Sigma approach also included a FMEA method, in the work of Prashar [112], showing that this is a quality evaluation tool. Kolich [113] applied DFMEA to design a comfortable automotive driver seat, giving a second dimension to FMEA where the ergonomic aspect of the product is also considered in the method.

In a different perspective, Krasich [114] concluded in his work that FMEA cannot be taken as enough to assure the reliability of a product but must be considered as a complementary one [114].

2.7 Other methods

Even if the focus of the thesis is the ones that were already analysed, there are many more methods and procedures to help the designing process. Due to the possible importance of the following methods, a small explanation of each one will be given.

2.7.1 Theory of Inventive problem solving (TRIZ)

TRIZ, or Theory of Inventive problem solving (the abbreviation comes from the original Russian name) is a knowledge-based systematic methodology of inventive problem solving [115]. In the work of Fey and Rivin [116], TRIZ is described as an effective methodology to the development of new technical systems and also being a set of principles that describe

the evolution of systems and technologies. The overall concept behind TRIZ is that technology evolution and their development is not a random process but a predictable one and it is dominated by certain laws [115].

2.7.2 Fault-Tree Analysis

The Fault-Tree analysis is a method that makes an estimate of faults, their consequences and causes through a Boolean algebra approach. Is based on causality, i.e., every event demands one cause minimum [17]. Knowing the overall functions and sub functions, they are assumed to be unfulfilled and then designer try to seek out the possible causes of that failure. Finally, through OR or AND relationships, the effect of each fault is analysed [17].

2.8 Lean Design

As clear as it seems, Lean Design is heavily influenced by the idea Lean Thinking, so, the ultimate objective is to create value from the perspective of the final customer and to minimize or eliminate when possible all the waste, this is, all the processes and activities that add no value to the final product [117]. The optimal process in Lean Thinking is the one that only has activities that add value to the end product and the search for the optimal process design has been done through the years through Lean Product Development.

The customer value is translated by the sum of product properties that the customer is willing to pay for [117]. By opposition, all activities and processes executed but not necessary to generate the properties that are important to the customer are seen as waste [117].

Lean Design has the main focus on the customer value by an optimized product design [117]. As already mentioned, product design means amount of individual components, their properties and relationships. Obviously, to achieve this objective, a good definition of the customer requirements and what the customer values in the product they desire and how these translates in product properties has extreme importance [118]. From one side, these properties that are relevant to the customer are dependent of the defined product design and from the other side, the necessary processes and activities to the overall product life-cycle are implied by the product design [119]. As a recap, lean design focuses at maximizing customer value and to avoid and prevent waste that may happen in the downstream life-cycle processes through the optimization of product design, even when it may not be a direct connection [119]. Once again, an holistic approach is necessary with Lean Design because that is the main focus of the Design-For-X methodologies. This means when thinking and designing the product, the design must ensure that the waste minimization and product value addition must be prioritized from the concept to the recycling and dispatch of product [119].

2.8.1 Current approaches

In this section, the focus is to highlight some approaches of Lean Design and works that combines it with some methodologies mentioned in the current thesis. In the work of Hoppmann et al. [120], through the analysis of many works, it collected eleven components in common in all of the works to the Lean Product Development. Those eleven components are [120]:

- Strong Project Manager;
- Specialist Career Path;
- Workload Leveling;
- Responsibility-based Planning and Control;
- Cross-project Knowledge Transfer;

- Simultaneous Engineering;
- Supplier Integration;
- Product Variety Management;
- Rapid Prototyping, Simulation and Testing;
- Process Standardization;
- Set-based Engineering;

Dombrowski et al [121] develops in its work the interdependencies between the Industry 4.0 and Lean Production Systems, a pretty much actual work regarding the importance and the overtake that the 4.0 approach in industries had in the last years. The same author also developed some possible connections between the Design-for-X approaches and their analysis under a Lean Design type of thinking in which a theoretical model that integrates Design-for-X approaches in the context of Lean Design was developed [119]. Also, in the work of Baptista et al. [122], an important work in the development of this thesis, a framework called Lean Design-for-X is used. In chapter 4, a more detailed view about the framework was done. As expected, QFD and lean design connections are developed in literature because of some obvious connections between both. This theme is developed further in the current project. Setijono and Dahlgaard [123] show in their work how to measure customer value, an important measure in lean design and QFD. Brady [124] also developed on how an effective cost and waste reduction is important to product development and how it may integrate QFD and Six Sigma. Also as expected, many works connect the Design-for-Six Sigma methodologies, QFD and lean design. Al-Aomar [125] developed a simulation based approach for lean Design-for-Six Sigma, where one of the first stages focuses on the deployment of QFD and Ni et al [126] validated a methodology based on value engineering-driven lean product development with the use of QFD, regarding the value analysis that is made in QFD process.

Many more works are available in the available literature because of the direct connection that is possible to make between lean design and the tools used in product development.

Chapter 3

AGV and Physical Concepts

3.1 Automated Guided Vehicle (AGV)

Regarding that the project on which the framework was applied was a Automated Guided Vehicle (AGV), it is important to focus on what is an AGV and some of the most important parts and components that may influence the chassis design of the AGV.

Automated Guided Vehicle, or AGV is a vehicle capable of performing its function without the need of a human direct intervention. As a result, many repetitive jobs have been now responsibility of these vehicles, allowing the specialization of the workers in other jobs. Beyond that, another main goal is to reduce as much as possible human intervention in the vehicle functions, so that it is possible to appropriate of the almost flawless decision making and precision. This reduces the possibility for error in this type of jobs [127]. Invented in the 1950's in EUA and expanding years later to Europe, it was based on the idea of replacing the drivers of a tractor trailer for transporting goods using automation [127].

Nowadays, there are several applications to AGVs, them being in land, water or air. Drones and military satellites in the case of in-air applications or deep sea landscape recognition in the case of use in water. The most versatile are the ones used in land as expected, from military uses to dismantle explosives to logistics to transport goods from one place to the other. In this project, the focus is on transportation vehicles so that will be the object in analysis from this point. There are also many different types of AGV for transportation. The existing categories are the Forklift AGV specially designed, Forklift AGV as automated serial vehicle, Piggyback AGV, Towing vehicle (Pulls multiple trailers [127]), Underride AGV(Standard hospital logistics AGV [127]), Assembly AGV(Use in serial assembly [127]), Heavy Load AGV(To transport heavy loads [127]), Mini-AGV(use in large fleets, e.g., for commissioning [127]), People Mover(For conveying passengers [127]), Diesel AGV(Outdoor vehicles [127]) and Special AGV(Special solutions for special tasks [127]) [127]. An illustration of each one are below and only the first three types of AGVs has an explanation due to the lack of interest to cover the other ones since they were not in consideration from the beginning to the project. More information is given to the others in the available literature [127, 128, 129].

The Forklift AGV has a large range of uses and it is one of the most common type of AGV. It centers on the pallet or forklift compatible containers [127]. Their tasks are usually centered in the transportation and pickup of floor-level loads to various heights through the help of forklifts [127]. There are several models of forklifts depending on the end goal for each one. The most common uses have a load capacity between 1000 and 16000 kilograms and their lifting capacity varies between 2 and 14 meters. The difference between AGV specially designed and as automated serial vehicle is that in the former, the AGVs manufacturer uses a serial product from a forklift manufacturer and automates it with the necessary AGV equipment and the other is conceived and produced totally by



(a) Forklift AGV (*Source E&K*)



(b) Piggyback AGV (*Source Frog*)

Figure 3.1: Examples of Forklift and Piggyback AGVs



(a) Towing AGV (*Source dpm*)



(b) Underride AGV (*Source Swisslog*)

Figure 3.2: Examples of Towing and Underride AGVs

AGVs manufacturers [127].

The next category is the Piggyback AGV, and the load are the same as in the forklifts AGVs, Pallets. As it may be deduced by the name, it transports the load on its frame and it cannot lift the loads directly from the floor. The main advantage to justify the use of these lies in the fact that the lateral pickup makes possible to drive directly along the stationary load transfer station without maneuvering due to the lack of forklifts. It can also be quicker and requires less space [127].

Regarding the current AGV market, companies like JBT, ROCLA or ELETTRIC are some of the strongest ones. There are many works with several different focus concerning the theme of AGVs. from the optimization of trajectory that an AGV does [130] to the optimization of production through the help of an AGV in the logistics department and the various aspects around it, like means of production, throughput, unit load, flow path design or fleet size [131]. In the work of T.Ferreira and I.A. Gorchach [132], the concept of an AGV is developed. AGVs connection to the Future of Things, e.g., Industry 4.0 or Internet of things, both very common developments to the foreseeable future are discussed in some works through the available literature [133, 134]. e-commerce is also considered in some since its intricate connection with logistics and industry development [135].



(a) Assembly and supply AGV (*Source* CREFORM)



(b) Heavy Load AGV (*Source* Frog/Siemag)

Figure 3.3: Examples of Assembly and Heavy Load AGVs



(a) Mini AGV (*Source* Götting)



(b) PeopleMover AGV (*Source* Frog)

Figure 3.4: Examples of Mini and PeopleMover AGVs



(a) Diesel AGV (*Source* Götting)



(b) Special AGV (*Source* Snox)

Figure 3.5: Examples of Diesel and Special AGVs

3.1.1 AGVs navigation system

An AGV can be guided in many different ways. To understand, a small explanation for each navigation system and an illustration is used.

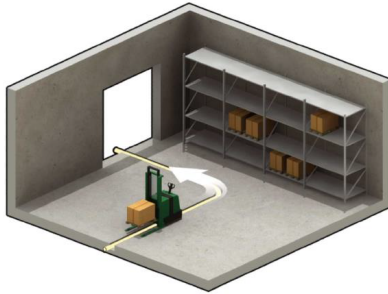
Inductive Wire Navigation is one of the most common and oldest technologies [127]. A current-bearing conductor is set into the floor, creating a path for the AGV to follow [127]. It is precise but demands a high-cost path manufacturing due to the floor work that must be done [127]. See figure 3.6a.

Instead of an inductive wire, a magnetic tape may also be stuck to the floor. This type of navigation is known as Magnetic Tape Navigation. See figure 3.6b.

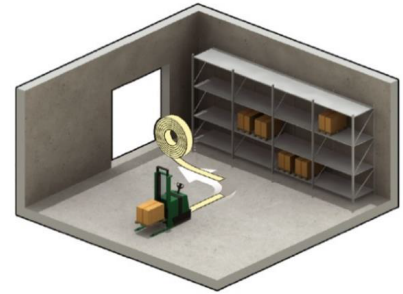
Another physical navigation type is Spot Navigation where several magnetic points are strategically displayed in the floor and serve as reference for the vehicle drive [127]. See figure 3.7a.

Laser Navigation is also another solution. It is based on triangulation where reflectors are distributed in an analysed way in walls and pillars. The laser is usually mounted in a navigation stick and emits a beam that reflects on the reflectors and allows to know the position of the vehicle. As expected, this kind of navigation eases any kind of future changes of the factory layout, making this also one of the most common navigation types [127]. See figure 3.7b

A method that does not need any kind of tape or reflectors is Range Navigation. In this, scanners are mounted on the vehicle and walls and obstacle recognizing is made. It is extremely useful and simple paths and corridors and also due to the fact that it is not necessary the use of reflectors or tapes or wires. However it is sensitive to floor inclination [127]. See figure 3.8.



(a) Inductive Wire Navigation AGV [136]

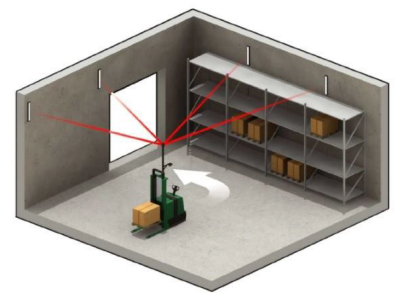


(b) Magnetic Tape Navigation AGV [136]

Figure 3.6: Illustration of Inductive Wire Navigation AGV and Magnetic Tape Navigation AGV



(a) Spot Navigation AGV [136]



(b) Laser Navigation AGV [136]

Figure 3.7: Illustration of Spot Navigation AGV and Laser Navigation AGV

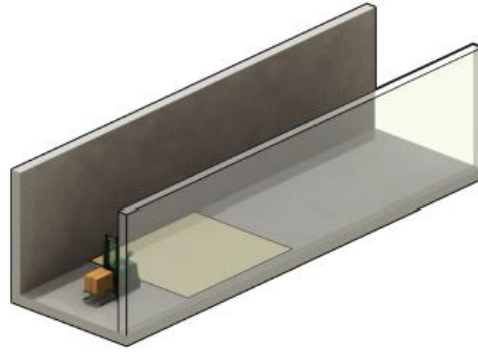


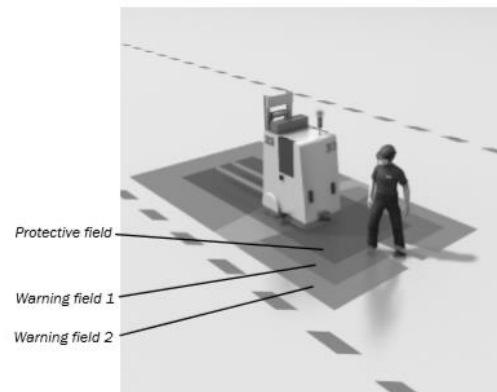
Figure 3.8: Range Navigation AGV [136]

3.1.2 AGV safety systems

Just like many other characteristic in AGVs, there are many choices and possibilities to a security system that must be in AGVs. The most common ones are the SICK laser scanners [137]. The safety field depends on vehicle speed meaning that speed and stopping distance evolve in the same direction. This is because, the higher the speed, the bigger is the distance needed to avoid collision [137]. There are two different zones to the safety scanner, a warning zone, that reduces AGVs speed when a possible collision is detected within the field and a protective field where the vehicle effectively stops [137].



(a) SICK safety laser scanners [137]



(b) Protection fields [137]

Another safety system are safety edges [138], where safety rubbers are deployed at a advised height, regarded in the safety standard NP EN 1525 - Safety of industrial trucks [139]. In this system, when there is a collision, the safety edges deform and stop immediately the vehicle.

3.1.3 Batteries

Batteries are the electric source of an AGV. The charging method of the batteries does not demand the removal of the batteries or the movement of these, however, in certain situations, just like overhear or battery malfunction demands the substitution of the batteries [140]. There is no need to go deeper in the battery knowledge instead on lead-acid batteries since it is the battery that will be used on this AGV.

3.1.4 Lead-Acid Battery

This low-cost rechargeable battery has a very low energy to volume ratio and energy to weight ratio, however they have a relatively large power to weight ratio [141]. As a quick recap of their characteristics are that they: are low cost, can be used for capacitive oper-

ations, have long charging times and their heavy weight is advantageous as counterweight or for stability [127].

Regarding the hazards that may come with the use of this kind of batteries, one may cite the risk of explosion due to excessive charging in a process known as gassing [140]. Other reason to explosion may be accumulated hydrogen and oxygen internally. Finally, a short circuit in an individual cell may cause an explosion [140]. Other possible hazard that may happen is leakage due to corrosion of the external metal parts of the lead-acid batteries.

Other factor to consider when using lead-acid batteries and one that has a growing concern throughout the years, are the environmental concerns regarding the use of these batteries. Although it is necessary to reduce the use of lead, because of the several toxic lead compounds and their consequences and effects to humans [142], lead-acid batteries are ones of the most successful recycling batteries in the world. This compensates the issues previously mentioned [142].

3.1.5 Mecanum Wheels

Created by the Swedish engineer Bengt Ilon in 1973 [143], the Mecanum Wheel allows omnidirectional movement on level ground for the vehicle where it is located. What this means is that a vehicle can move along a prescribed path and at the same time rotate as it is wished around its center [144]. The basis behind the wheels is a set of k congruent rolls placed symmetrically around the wheel body [144]. Due to the excellent explanation of A. Gferrer, the explanation of how the wheels work and figure 3.10 are directly from the mentioned work [144]. "The face of each roll is part of a surface of revolution $\mathfrak{R}$ whose axis b is skew to the wheel axis a . Usually an angle δ between a and b of $\pm 45^\circ$ is chosen." [144]. To allow the independent movement of each wheel, a motor drives only one wheel giving the possibility of movement in the three degrees of freedom necessary for omnidirectional movement in the ground level. Since the focus of the project is not on these wheels, there is no further development on the explanation of the wheels, however, for a more detailed analysis on the kinematics, geometry or control of them, there are available works to consider [144, 145, 146]

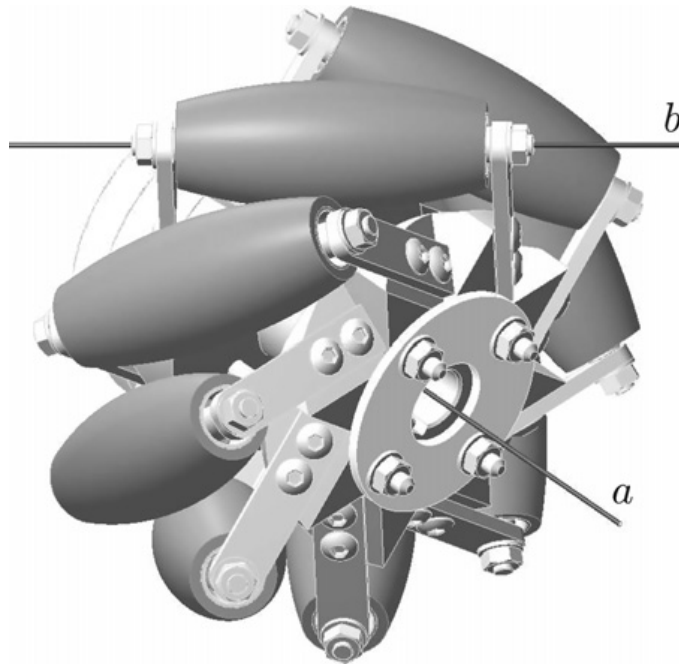


Figure 3.10: Mecanum Wheel representation [144]

3.1.6 Standards and Directives

In the design process of an AGV chassis, there are a few standards that must be considered, in cooperation with every other guidelines that are consequence of the use of DfX. The standards that were considered in the designing process are the following:

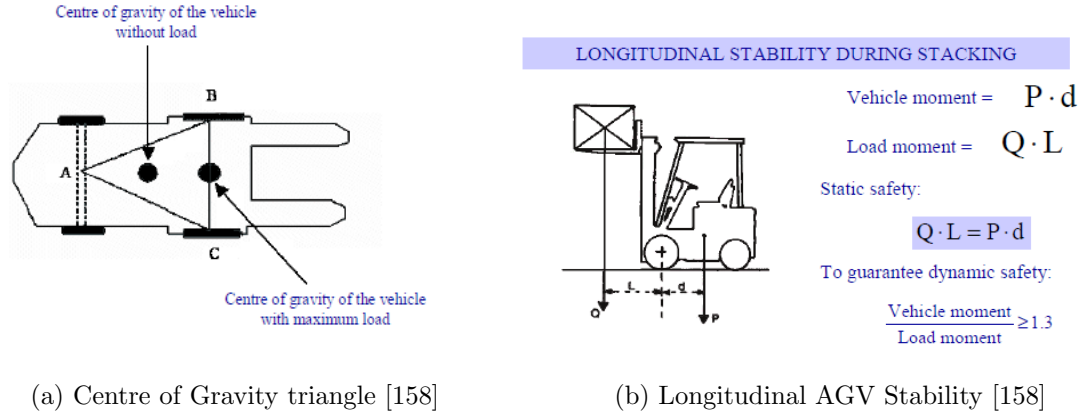
- Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC(recast) [147];
- EN 280:2001+A2 - Mobile elevating work platforms - Design calculations - Stability criteria - Construction - Safety - Examinations and tests [148](Even if it is only for working platforms, it has given useful information about design calculation);
- EN 1175-1: 1998 - Safety of industrial trucks - Electrical requirements - Part 1: General requirements for battery powered trucks [149]
- EN 1495:1997+A2 - Lifting platforms - Mast climbing work platforms [150];
- EN 1525:1997 - Safety of Industrial Trucks - Driverless trucks and their systems [139];
- FEM 9.311:02 1978 - Rules for the design of storage and retrieval machines - Structures [151].
- ISO 3691-5:2014 - Industrial trucks — Safety requirements and verification [152];
- ISO 12100-1:2003 - Safety of machinery - Basic concepts, general principles for design - Part 1: Basic terminology, methodology [153];
- ISO 12100-2:2003 - Safety of machinery - Basic concepts, general principles for design - Part 2: Technical principles [154];
- ISO 13857:2008 - Safety distances to prevent hazard zones being reached by upper and lower limbs [155];
- NP EN 1726-2 2002 - Safety of industrial trucks - Self-propelled trucks up to and including 10000 kg capacity and tractors with a drawbar pull up to and including 20000 N Part 2: Additional requirements for trucks with elevating operator position and trucks specifically designed to travel with elevated load [156];

3.1.7 AGV Stability

In standard FEM 9.311 [151], some rules and equations to calculate the structure and frame of a counterbalanced AGV stability in static and dynamic status are presented. In standard FEM 9.311 [151] and in standard EN280:2001 [148], the factor of safety for several types of load cases are also shown, however these may lead to a overengineering situation, which is not desirable. Further research was done as complement and documents to define the factor of safety to use for several load cases were found [157, 158].

In figure 3.11a, an illustration of the Centre of Gravity of the AGV to be safe with maximum load is shown and in figure 3.11b, longitudinal stability during stacking has a guideline to follow in order to assure its safety. Both figures are extracted from their original document [158].

The calculation in figure 3.11b assures AGV stability, static or dynamic. In static stability, horizontal loads are not considered. However, in dynamic calculation, horizontal loads are influential and part of the load moment and must be taken into account.



3.2 Beams, Beam Theory and Finite Element Method

3.2.1 Beams and Beam Theory

In order to understand the basis of what was done in the simulation and Finite Element Method (FEM) procedure, a small exposition about beams and beam theory is done here.

Beam elements are resistant to bending, shear and torsional loads. To allow the program to calculate the moments of inertia, neutral axes and displacements, its cross section is necessary. In the following figure (figure 3.12), a representation of a beam element subjected to simplified 2D forces (axial force P , shearing force V and bending moment M and A is the cross section area) is shown [159].

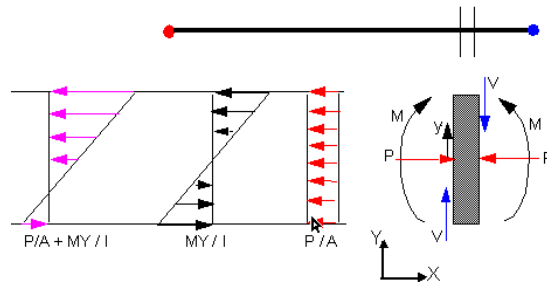


Figure 3.12: Beam element subjected to simplified 2D forces [159]

In the most general case, there are three acting forces and moments on each segment. The stresses are Uniform Axial Stress ($\frac{P}{A}$), Uniform Shearing Stress ($\frac{V}{A}$) and Bending stress, caused by the bending moment M ($\frac{My}{I}$). This bending stress varies linearly with the vertical distance, y , from the neutral axis and with the moment of Inertia, I [159].

3.2.2 Beams in SOLIDWORKS FEM

In SOLIDWORKS simulation, joints (the free ends of structural members or the intersections of two or more structural members) are created with a node at the center of the cross section of each joint member [159]. The program creates a rigid connection. Since there are six degrees of freedom, it is possible to apply restraints to each joint applying prescribed translations and rotations [159].

SOLIDWORKS allows the appliance of several loads. These can be [159]:

- Concentrated forces and moments at joints and reference points;
- Distributed loads along the whole length of a beam;
- Gravitational loads, when material density is defined;

- Uniform or selected base excitation for dynamic studies;
- Initial conditions for dynamic studies;

The meshing is applied to each structural member and meshed with beam elements, where the number of elements divided by can be selected.

For each element are presented results in its local directions. It is possible to analyze uniform axial stresses, torsional, bending and shear stresses in two orthogonal directions and the highest stresses generated by combining axial and bending stresses [159].

3.3 Fatigue study of Welded Structures

The fatigue study of structural details and welded joints is based on the nominal stress range [160]. Nominal stress is the stress calculated in the sectional area under consideration, where the local stress raising effects of the welded joints are ignored, but the stress raising effects of macrogeometric shape of the component in the vicinity of the joint is included [161]. In most cases, structural details are assessed on the basis of the maximum principal stress range in the section where there is a possibility of fatigue cracking. It is also possible for shear loaded details, based on the maximum shear stress range [160]. S-N curves are provided for consideration of normal or shear stress in the work of Hobbacher [160]. A S-N curve is a graphical presentation of the dependence of fatigue life N on applied stress range $S(\Delta\sigma_R \text{ or } \Delta\tau_R)$ [160]. Residual stresses are in the same order of the tensile strength and because of that, there is no effect from the average load in S-N curves. The applied stress range is given by:

$$\Delta\sigma_R = \sigma_{max} - \sigma_{min} \quad (3.1)$$

where σ_{max} is the max stress in Pa and σ_{min} is the minimum stress in Pa.

The used fatigue curves have their basis on representative experimental investigations and include the effects of [160]:

- Structural hot spot stress concentrations due to the detail shown;
- Local stress concentrations due to the weld geometry;
- Weld imperfections consistent with normal fabrication standards;
- Direction of loading;
- High residual stresses;
- Metallurgical conditions;
- Welding process;
- Inspection procedure;
- Post weld treatment;

The fatigue curves of welded joints are independent of the tensile strength of the material and each S-N curve is identified by the characteristic fatigue strength of the detail in MPa at 2 million cycles, classified as fatigue class or FAT. The knee point, where an infinite life can be assumed for the detail is for $N = 10^7$ [160]. An example of the S-N curve used is presented in figure 3.13. To know what is the FAT category to apply, from the available table in the work and the type of load and weld, the FAT category of the detail can be obtained.

All fatigue study and analysis is done with the work of Hobbacher [160] on welded structure as a basis and the methodology is the one presented in the same work.

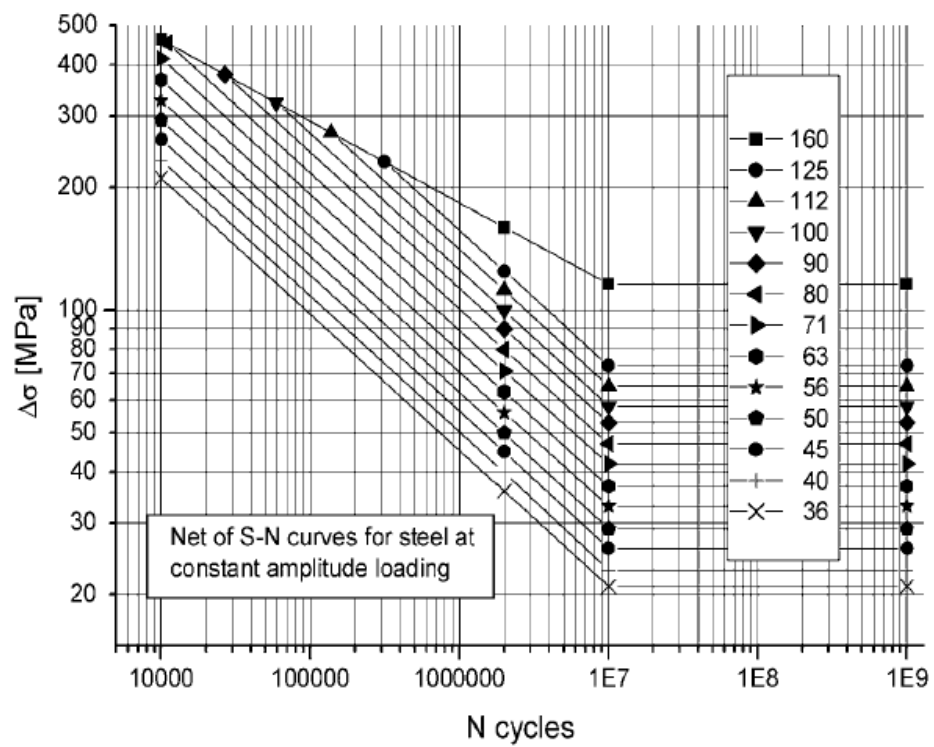


Figure 3.13: Fatigue resistance S-N curves for steel, normal stress, standard applications [160]

Chapter 4

Lean Design-for-X tool

Through the years, there is an increasing focus on reducing the time spent in design processes without sacrificing product quality and increasing costs [162]. This increases the importance of approaches like Design-for-X and their use, since they allow the systematization of the designing process and support design management in complex products, guiding also towards sustainable development [122]. With the same purpose, Lean practices are taken so it is possible to keep up with the market, narrowing budgets [162].

Inspired by both concepts, INEGI (Institute of Science and Innovation in Mechanical and Industrial Engineering) started developing an approach called Lean Design-for-eXcellence (LeanDfX) methodology since 2015, with the motif of combining Lean Thinking and Design-for-X project support, where multiple domains are assessed such as optimization, manufacturing, assembly, maintenance, eco-design, modularity or adaptability [122]. It allows a systematic approach towards effectiveness design goals assessment, evaluating the product design through multiple "X" domains, a multidimensional evaluation, incorporating Lean Thinking principles, focusing in decreasing waste resources in all product life cycle phases through a visual management concept [122]. In this chapter, LeanDfX is explained and how it works so it is possible to understand where the research of this project may lead.

4.1 LeanDfX framework

LeanDfX is a useful framework to aid design teams and give them the necessary tools to reach a new performance stage, managing in a very structured form, products or system designs with high levels of complexity and regarding all product life cycle [122]. It was developed taking into account the MSM - Multi-Layer Stream Mapping [163] concept framework and, as already mentioned, based on "Design-for-eXcellence" methods [164].

As already stated, industry is pushing the boundaries in the complexity of mass products, this means that, usually, a product has a large number of requirements and technical specifications. The need for a structured approach and framework increases, so it is possible to manage a high number of different requirements and specifications and relate them with the associated stage of its life cycle, such as, manufacturing, assembly, maintenance, retrofitting, disposal, etc [122]. To help the understanding of the tool and the structure, in figure 4.1 there are some domains and where the tool uses them.

To assure that timelines are respected and time is reduced as possible, the number of iterations in the design process must be the lowest possible. LeanDfX framework also aids and works towards this goal. And also inspired by lean thinking, it is extremely important to apply just the necessary resources to obtain design targets and product goals [119]. To ensure that this is reached, effectiveness and efficiency must be measured. Effectiveness works towards the verification of product design targets, it measures if all requirements and specifications are fulfilled. Efficiency comprehends the resources quan-

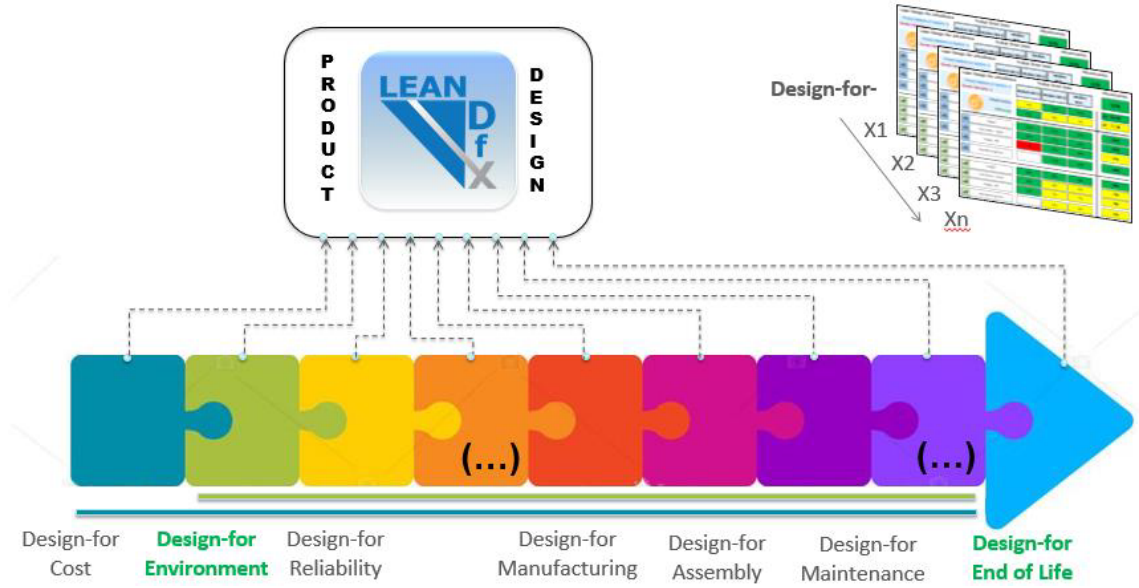


Figure 4.1: Examples of design domains and their relation within LeanDfX approach [122]

tification and consequently the cost assessment of the product designed [122]. This is inherently present in Lean Thinking in which the inefficiency is measured by the evaluation of "over-engineering" (waste generation) that is in the product [122] (Inefficiency either of excess of material, energy, capacity, etc.) [122].

4.1.1 LeanDfX Pillars

The structure of LeanDfX or LDfX, is supported in 4 main Pillars and it is the basis of this holistic approach [164].

- Pillar 1 - *Product breakdown*;
- Pillar 2 - *Selection of 'X' domains and their specific design indicators*;
- Pillar 3 - *Simple Visual Management attributes*;
- Pillar 4 - *Aggregation of efficiency and effectiveness through product modular hierarchy and 'X' Design Domains*.

Pillar 1 - *Product breakdown*

To ensure a correct implementation of the framework, a product breakdown must be the first step. Modular Design principles are the ones that must be applied in this stage. In this, functional components of a product are organized as physical units and the interaction among them, known as modularization, allows the management of high complexity level products and this approach is the cornerstone of this tool (Fig. 4.2). Modularization also makes the measuring of effectiveness and efficiency much more accurate and focused on modules, sub-modules, product, etc [122].

Pillar 2 - *Selection of 'X' domains and their specific design indicators*

Taking once again Modular design and a systematic approach to the process, at this stage, the design manager should analyse and choose which are the relevant project domains. Each "X" domain represents a group of design influent variables to be analysed within the LDfX [122]. This has an enormous weight in the overall process and framework because this is the basis behind of what will be designed and what it is needed to be done to meet

the product goals, requirements and specifications. Taking this into account, it means that all aspects must be considered when establishing domains. Thereafter, it is necessary to list the design variable or KPI (Key Performance Indicator) involved in each domain [122].

Pillar 3 - *Simple Visual Management attributes*

Visual Management systems contribute positively in several ways in a process, from enabling a straightforward analysis of data and results to enhancing collaboration and strategic thinking [165, 166]. LeanDfX uses a four-color grading type systems analysis (from worst to best: red, orange, yellow and green) depending on the efficiency/effectiveness level [164].

Pillar 4 - *Aggregation of efficiency and effectiveness through product modular hierarchy and 'X' Design Domains*

Behind a bottom-up analysis, meaning that it starts with each sub-module and then it evolves to module, system and finally product, efficiency and effectiveness are calculated and aggregated to resume the results obtained. It begins with the calculation of effectiveness and efficiency ratios for each "X" domain that was previously selected for the bottom level, namely elementary modules of the product breakdown. Afterwards those results are integrated to the upper levels until the top level, simply put, the entire product [164]. Thus it is possible to have the overall effectiveness and efficiency of the product/system design and every modules. Consequently, both ratios are always between 0-100% to avoid possible distortion effects on the LDfX scorecards aggregated values and misleading information. This happens for consistency reasons regarding the hierarchical aggregation of dimensionless ratios [164]. Also to avoid the same situation, so far, each module has the same relative weight in the modular breakdown structure. LDfX only calculates efficiency when efficacy is met, so the first to be analysed is Effectiveness.

Effectiveness

Briefly aforementioned, effectiveness means doing the right things to create the most value [167] and applying this to LDfX perspective, means if a particular requirement is met by the variable. Therefore, in this case, the color scheme is binary in which the green corresponds to ratios of 100% and for ratios below 100%, red is applied. The use of colors is justified by an approval system, where green means the value that is being analysed is approved and red for the ones that does not.

For the tool to work, two things are necessary. The first one is to define the threshold value. In other words, the target value or minimum/maximum acceptable value for the variable/module couple must be defined. The second one is to define in what way that threshold or target value must be met. That is to say, if the objective is to maximize, equal or minimize the variable under analysis. E.g. minimize weight, maximize speed or meet width requirement [122]. Even if the easier examples are quantitative and continuous variables based in physical quantities like the aforementioned ones, LeanDfX also allows the effectiveness calculus to qualitative and discrete variables. To give an example, the accessibility to critical components that it is important in Design for Maintenance guidelines can be also be measured, where the shown effectiveness ratio is reached by comparing the maximum level, "Very Good" that corresponds to a 5 in a 5 value scale to the input value. If the input is "Very Good", effectiveness will be 100% and if the input is "Very Poor", that corresponds to a 1, effectiveness value will be 20%. Regarding the needed evaluation, the user must choose one of the available options for the calculation: NA (not applicable), < (minimization), > (maximization) or T (Tolerance range). This choice will define the

condition of the mathematical operation. In some cases, usually depending on the item being analysed (system/module/submodule), variables may not be applicable. When this happens, the user must choose "NA" and an hyphen is displayed in the scorecard [122].

Efficiency

Where all requirements are met, meaning that every effectiveness reaches 100%, Efficiency is calculated, otherwise the corresponding efficiency cell displays an hyphen, representing "efficiency not calculated". The core meaning of efficiency is a ratio of the actual output of a process relative to some standard and doing something at the lowest possible cost [167]. In its essence, the meaning of it in LDfX is the same, where is a quantification of the effort to achieve a certain goal/target [122].

In this measure, a more varied color-scheme makes more sense and it is what it is done. 5 colors are used and they related to a respective closed interval: intense green (100%); soft green (90-99%); yellow (70-89%); orange (40-69%); red (<40%).

At a first stage, a reference value should be defined as "optimal", which would guarantee the excellence of the design. Obviously, the efficiency optimal value can be the same or not as the effectiveness reference target value. This may happen because some design variables, there may be a minimum admissible threshold number, in other words, a target value that would make the design fulfill its function but would not be the best case scenario [122]. This measure helps to identify cases of "over-engineering", identifying waste generation, a counter productive aspect through the lens of Lean Thinking. As also previously mentioned, the cost of the design phase has a small direct impact in the overall cost, however the decisions taken at this stage affects about 70% of the total cost of the product [168]. Therefore, LeanDfX can provide and help product design decisions and a more clear insight by the analysis of both ratios and the impacts of design decisions in the product life cycle [122]. This information is displayed and summarized in scorecards generated by the tool. Dashboards like the ones generated are useful for the organization and visual analysis of information and data important for the project design.

4.1.2 Deployment

Even if the available resources are more developed, that does not mean that every single company and industry will follow through, far from it, a resistance to change is a common difficulty in the industrial world [122]. Ergo, a deployment mechanism to help the implementation to LeanDfX tool is almost a need for it to be successful. So, the implementation of the following six steps are necessary for the deployment of LeanDfX. These are not only linked to the pillars definition but also to a mind-set of continuous improvement [122].

- Step 1 - *Workshop*;
- Step 2 - *Modularization*;
- Step 3 - *Selection of Design Domains*;
- Step 4 - *Selection Indicators and Parameter values*;
- Step 5 - *Analysis of results*;
- Step 6 - *Improvement of the design (iteration loop)*;

Step 1 - *Workshop*

To avoid an erroneous use from the beginning, first, an introductory workshop must be performed, so the alignment of all team members with the methodology principles is

guaranteed. When the design team has a high number of members, a pilot group must be chosen to test and validate the methodology and afterwards, extended to the entire design team [122].

Step 2 - *Modularization*

Directly connected to Product Breakdown, when starting the analysis of design of a particular product, equipment or system, the starting point for the implementation should be its decomposition into functional parts, or modules. It is a fundamental step to reduce product and tool implementation complexity and besides, to allow the evaluation of effectiveness and efficiency for the smaller component to the overall product. Thus, the second step consists in decomposing the product along its hierarchy of relations in product breakdown (Fig. 4.2).

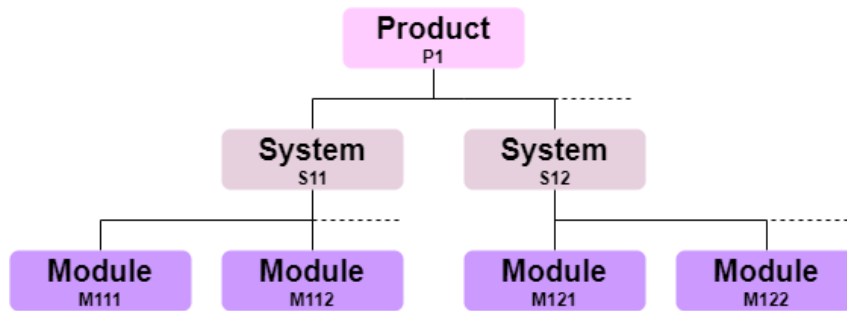


Figure 4.2: General modular breakdown structure

Step 3 - *Selection of Design Domains*

The third step of the process demands a study and evaluation in the development so it is possible the correct definition of the various "X" domains (Design-for-Structural Integrity, Design-for-Manufacturing, eco-design, Design-for-Modularity, etc.) [164]. A life cycle oriented analysis to the selection for the domains and a very clear alignment with product requirements, specifications and standards must be considered [122].

Step 4 - *Selection Indicators and Parameter values*

Afterwards, for each domain, the indicators and design variables associated must be identified. Then, for each design variable, the parameter value must be decided by the design team. Id est, this step consists in listing the design variables of the concerned domain based on the complete product specifications [164].

The results are calculated and as aforementioned, a visually intuitive system (scorecards) to facilitate the analysis is used. The color scheme helps to a quick determination of which values must be developed and worked on. An example of a scorecard is in figure 4.3.

Step 5 - *Analysis of results*

With the help of the scorecards, the team must analyse the obtained results. For it to be possible, the aggregation tree must be used and every previously chosen domain, considered. In a bottom-up analysis, one should start the examination of the lower level (Module, subsystem, system, etc) and gradually progressing upwards. In the upper levels, the aggregation results in two ratios of the product design. To help understanding this step, figure 4.4 has a visual representation of the process (Simple average was applied/



Figure 4.3: LDfX scorecard general example

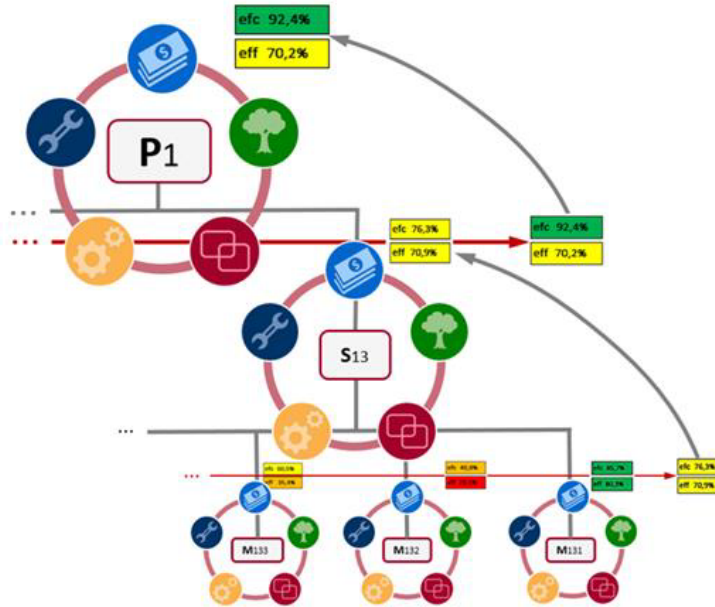


Figure 4.4: Bottom-up aggregation of efficiency and effectiveness values (modules, system and product) [164]

average effectiveness (efc) and efficiency (eff)). This aggregation method can be adapted as the user wants depending on the company or product, using different mathematical operators.

The team can at this step see if it is possible to lessen the design effort on some module and apply it to another without compromising the budgetary constraints and overall design [122].

Step 6 - *Improvement of the design (iteration loop)*

Finally, driven by a mind-set of continuous improvement and iterative process, at this step, correction of non effective results of current design variable and improvement of poor efficiency results must be done. In a given concept to be improved, the iterative step is done to improve modules with the variables in the most critical state. It allows the evaluation and selection of the best design concepts through the analysis of the LeanDfX scorecards [122].

Chapter 5

Project Start and Case Study

Before the real start of the basis project, to help the understanding of the framework and the several tools that may be used for the project, a previous project was used as a first test and approach. Even if the details are not be exposed in this work in order to not extend this chapter, they are in appendix E. This happens because it is important to have a small explanation of what was done.

The project used was a gearbox designed from scratch for a previous curricular unit dedicated to machine design called "Project Initiation". A classical QFD approach was taken for a familiarization process. With the same purpose, the same gearbox was also deployed in the LeanDfX methodology. With it was possible to identify some problems and difficulties with the framework for a first time user. Those are identified later in this introduction, however they became the focus to cover in the making of this dissertation, in order to develop and give the tool what it needs to become as complete as it is possible.

To begin the development process of LeanDfX framework, a case study must be selected, allowing to experiment and test every single research done in this dissertation. The selected case study must be one associated with the PRODUTECH project and with a company with the availability and the commitment to give orientation during the project. Considering the situation and requirements for the case study, JPM Industry, already mentioned in chapter 1.2.2 was the considered and chosen company due to their excellency, availability to evolve and involvement in PRODUTECH, INEGI and most importantly, LeanDfX framework.

In the several projects that could be considered, the one chosen was the mechanical frame of a Autonomous Guided Vehicle to be produced in the company, only for their use. This was the selected case due to the time that it could last, the difficulty of requirement fulfillment and the overall mechanical and project difficulty.

Also, after literature review was done, LeanDfX framework investigation and the implementation of the gearbox in it also, it was clear which were some of the weakest points or at least, hardest steps that hindered the framework application for a new company. The identified issues were mainly in steps 3 and 4 of the deployment process. The vagueness of both for someone outside the project are obvious and should addressed.

A company with 0 experience on a structured approach to design process and to DfX methodologies see the implementation of frameworks like this a waste of time, as previously mentioned in chapter 2. Also, their lack of clarification, organization and translation of requirements to functional requirements hinders an already hard task of first implementation of a new framework. Also, to turn the tool as complete as possible, the development of several tools to cover possible domains were points in consideration in the start of the project development. Fortunately, JPM Industry has forward thinking view in the designing process and experience to schematic and systematic approach to the designing process, making them the perfect company to work with.

5.1 Requirements

At the start, a meeting was taken in order to meet the company and its facilities and choose the project. In this meeting, a small Workshop took place in order to re-introduce JPM to the LeanDfX framework.

After some time, a set of requirements for the AGV project was sent so the project could start. Due to privacy, the requirements here listed are not the actual sent but a similar meaning without compromising the project is here shown. The requirements are:

Client/Customer Requirements

- Capacity to transport the desired load (1500 kg);
- Capacity to list the loads to desired height (1.5 m);
- Safe moving speed (3 km/h);
- Allowed height (800mm Max);
- Allowed Width (1200mm Max);
- Allowed Length (2000mm Max);
- Have a system to elevate loads;
- Omnidirectional movement;
- Autonomous Movement;
- Speed Reduction;
- Capacity to Control;
- Possibility to allocate 2 scanners;
- Possibility to allocate 3 Electrical Cabinets;
- Autonomy (Battery);

After obtaining the requirements, the following step is transforming them to actual technical requirements. Of course, some of them are already as technical requirements, however, a step back was made so it is possible to have every single requirement at the same stage and ease the functional requirements transformation. This step was made because as a first test to develop the framework it is the insertion of a QFD methodology to facilitate the deployment of LeanDfX framework.

Their translation to technical requirements are (d-diameter; w-width; l-length; h-height):

Technical/Functional Requirements

- Loading Capacity - 1500 kg;
- Lifting Capacity - 1.5 m;
- AGV Speed - 3 km/h;
- Chassis Height - Max - 800 mm;
- Chassis Width - Between 800 – 1200 mm;
- Chassis Length - Between 1500 – 2000 mm;
- Elevation Tower - Forklifts with 364 kg;
- Placement for Mecanum Wheels - $d = 356$ mm, $w = 200$ mm;
- Placement for 4 DC Motors - $d = 200$ mm, $l = 400$ mm;
- Placement for 4 Gearboxes - $d = 115$ mm, $l = 320$ mm;
- Placement for 4 Controllers - $(l)x(h)x(w)$, $204x140x60$ mm;
- Placement for 2 Scanners - $d = 130$ mm, $h = 150$ mm;
- Placement for 3 Electrical Cabinets (EC) - $(l)x(h)x(w)$;
 - 2 ES - $800x470x250$ mm;
 - 1 ES - $555x430x275$ mm;

- Placement for Battery - $(l)x(w)x(h)$, 1106x604x400 mm;
- Minimum Height for Scanner - 150 mm;
- Sustain Battery Weight - 600 kg;

The dimensions and characteristics of the several components are obtained by their choice and need. The components used can not be specified due to privacy from companies. The battery is a lead battery.

5.2 Optional Requirements

As explained, there are also another requirements that, even if they were not explicitly mentioned by the company or were not seen as demanding, are important to fulfill in order to have an acceptable design in several dimensions.

To know and decide which requirements these could be, a set of interviews were done. Eng. João Oliveira and supervisors Eng. Paulo Tavares de Castro and Eng. António Baptista were addressed to this and complementing those with information found in literature review and the experience gained through the degree, a set of optional requirements were reached.

Optional/Additional Requirements

- Avoid excessive Wear;
- Avoid excessive Fracture;
- Avoid excessive Bending;
- Easy to Manufacture;
- Easy to Assembly;
- Be easy to use;
- Use Standard pieces;
- Stop when necessary;
- Respect safety norms and directives;
- Reduce possible failure occurrences;
- Ergonomic when in the need to operate;
- Allow easy Maintenance;
- Allow possibility to change AGV type;
- Allow Retrofitting;
- Reduce cost;
- "Be as green as possible";

Afterwards, the functional requirements, the "How's" for the optional requirements were decided and reached.

Technical/Functional Requirements

- Tensile Strength;
- Fracture Toughness;
- Young's Modulus;
- Simple parts;
- Symmetry when possible;
- Modules;
- Identical Components;
- Number of Standard pieces;
- Emergency Stop Button;
- Machine Directory;
- EN 1525-1997;
- ISO 3691-1-5-2014;
- ISO 12000;
- Risk Analysis (FMEA);

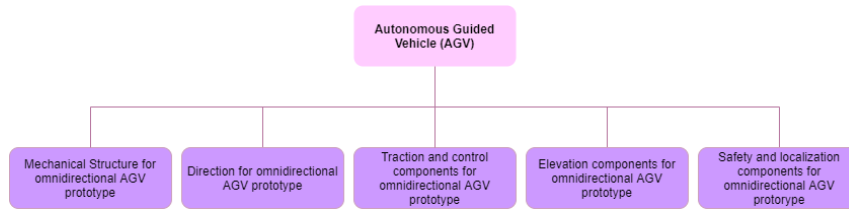


Figure 5.1: AGV modular breakdown

- Ergonomics;
- Easy accessibility to dangerous components;
- Top transportation made possible;
- Easy accessibility to upgradable parts;
- Use recyclable material;

5.3 Modularization

As seen in chapter 4, the first step after explaining the process, *Workshop*, is *Modularization*, step 2. In this step, QFD can be already done but it can also be done after or even at the same time. The reason for this is explained in chapter 6.

The modularization on the regarded AGV was done in collaboration with JPM Industry and supervisor Engineer João Oliveira. The first level, equivalent to the product is the most obvious one, is the AGV. Then, it is necessary to identify the various systems. After consideration, the systems obtained were the following:

- Mechanical Structure for omnidirectional AGV prototype;
- Direction for omnidirectional AGV prototype;
- Traction and control components for omnidirectional AGV prototype;
- Elevation components for omnidirectional AGV prototype;
- Safety and localization components for omnidirectional AGV prototype;

After some consideration, it was concluded that further modularization was unnecessary, because for the Mechanical Structure, its modules would appear later in the design process. For the other modules, no consideration would be made in the execution of this project, so it is not necessary to divide each system even more and it would be unnecessary use of time. It happens because the case study it is only the frame, the chassis of the AGV. Its components are already defined at this stage and the design process would not benefit from the development of smaller modules. The modular breakdown of the AGV is in figure 5.1.

5.4 Selection of Design Domains and Selection Indicators and Parameter values

For the implementation of steps 3 and 4, QFD appears to be an important and useful tool to use and with these first measures taken, it is possible to test the use of a QFD in the framework since what is necessary for its deployment was obtained. Also, as seen in the last set of technical requirements, another tool that is selected to the design process and LeanDfX framework is FMEA. Its intricate connection with quality, reliability and safety makes it possible to expect a positive contribution to LeanDfX in those domains. In chapter 6, the methodology used and developed is explained. Chapter 7 explores in the same way, the contribution made by FMEA in the project.

Chapter 6

LeanDfX Fuzzy QFD

6.1 Introduction

LeanDfX Fuzzy QFD is an introductory methodology developed in this dissertation, inspired in Fuzzy QFD. As mentioned in literature review, it is a very common approach in QFD to incorporate Fuzzy set theory to reduce as much as possible any uncertainty in the decision process. It has several goals, where the main one is to help the deployment process of LeanDfX framework and a systematic approach to the organization and clarification of client and customer requirements and also, if needed, additional requirements for good design principles or goals. In the filling process, it is a three procedure methodology (possibly four) and its 6 main goals are the following:

- Clarification of customer and client requirements and its functional requirements;
- Ranking of the most important technical requirements to implement in the design of the product under analysis;
- Identification of trade-offs between technical requirements;
- Choice and identification of which domains shall be used in LeanDfX;
- Choice and identification of the indicators and parameter values that shall be deployed in Lean DfX;
- Start the deployment process of LeanDfX;

The existence of three documents to fill is the origin of the three stage procedure. However, there is an additional document, that if it is desired also to have its information, transforms this into a four stage procedure. In the following sections, a space by space explanation is done and a step by step instruction to help the implementation of the methodology. The 3 documents and the optional document to fill are:

- Client/Customer requirements HoQ;
- Additional Requirements HoQ;
- CRAR(Customer Requirements and Additional Requirements) QFD-LeanDfX;
- (Optional) LeanDfX Domains Weighting;

There are also three additional sheets to recap results, one for each of the first two sheets and one aggregating both results. Those tables are:

- Customer Requirements Order;

- Additional Requirements Order;
- Total Requirements Order;

Following sections with focuses on explaining the processes behind each space and a step by step instructions to deploy the framework. Appendix B is a document with a light explanation of the process that was given as an auxiliary document to help the user on the filling process. In other words, if the reader desires to read more compact explanation of the process, it may consult appendix B.

6.2 LeanDfX Fuzzy QFD explanation

A systematic approach was also taken to explain the process and a sheet by sheet, space by space explanation is given in order to fully understand it. The first to analyse is the Client/Customer Requirements HoQ.

6.2.1 Client/Customer requirements HoQ

This House of Quality is the most classic House of Quality with Fuzzy set theory, however, to help the deployment phase of LeanDfX framework, there are some twists made to this sheet. Figure 6.1 is a conceptual illustration of it and each space, in other words, column, row or matrix, there is a number so a space by space description can be made. Figure 6.2 is a small figure representing the obtained results in the filling of one Client/Customer requirements HoQ. The same House of Quality is available in appendix C.

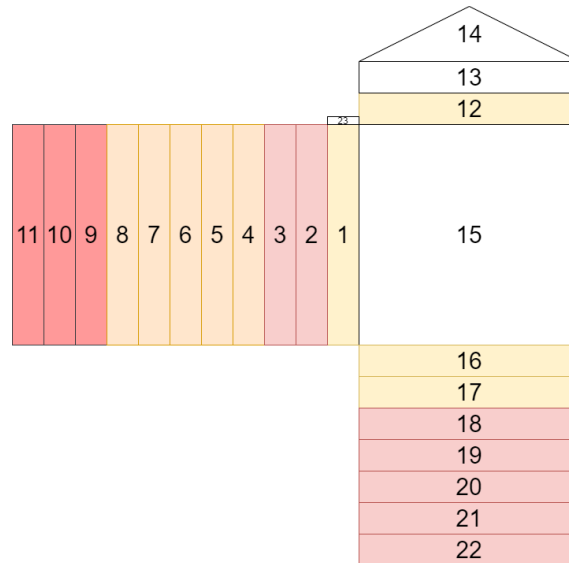


Figure 6.1: Concept figure of Client Requirement HoQ

Space 1 - Customer Requirements

The first space is the Customer Requirements column as they are given by the client/customer. This space should be filled by the team responsible by the project. It represents the main "What's" for the project under analysis. The customer requirement on a given row r can be translated as CR_r , where $\{r \in \mathbb{N}, r \in [1, R_1]\}$, with R_1 being the total number of rows with customer requirements

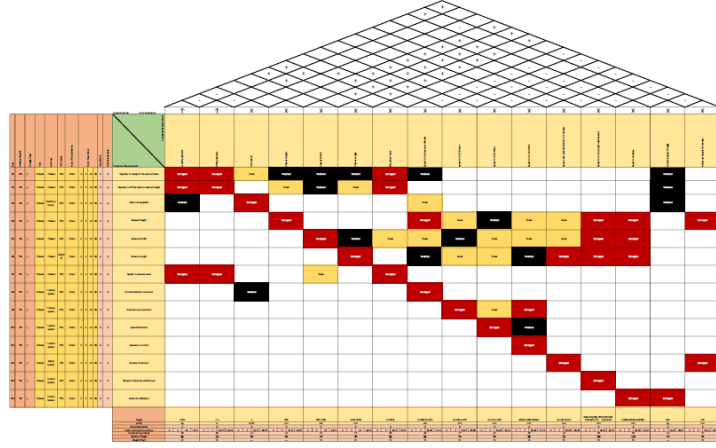


Figure 6.2: Miniature figure of one Client Requirement HoQ

Space 2 - Max Relationship

This is an automatic column that represents in a number, the maximum value of relationship of the customer requirement on row r , CR_r for every functional requirement. It can assume any value between 0 and 9, depending on the matrix 15, the relationship matrix. Even if the numbers that translates the relationship between functional and customer requirements are fuzzy numbers, to help the user easily understand what it is represented here, the number that appears is the crisp relationship number. The desirable value should be 9, meaning that there is at least one functional requirement dedicated to meet the customer requirement under analysis. Of course that if the value is 0, it means that none functional requirements relates to the customer/client requirement in the row, in other words, it would not be met. If this happens, a functional requirement must be added to meet it. The value may be translated as $MRCR_r$.

Space 3 - Importance

Importance column is where the user tries to give a weight to the customer requirement, regarding on how important it is, from a scale from 1 to 9. In the first stage, almost every if not every customer requirements should have a 9 value importance because, meeting the real customer requirements is a measure of quality, which means that meeting every one of these requirements is essential to add value to the customer in the final product. This must be filled by the selected people and the value for the given row, r , is translated as IC_r .

Space 4 - Fuzzy Importance

Inspired in a Trapezoidal Fuzzy Number, this column translates the importance given in space 3 in fuzzy logic and may be translated as FI_r , where r represents the row under analysis. It changes with the Job/Experience chosen in space 23, JE . It is automatically filled and its value are calculated from $FI_r = JE \otimes IC_r$.

Space 5 - Type of Requirement

Here, the team should specify what type of requirement is the customer requirement on the given row, that is, CR_r . In this first stage, almost or every requirement will be a

"Client" requirement and that is the value that should be filled by the team. This space is important for an organizational point of view.

Space 6 - X-Domain

If a team already wants to specify a certain domain to a customer requirement so at least one domain can be given to ease the third stage, this column offers that possibility. Due to the fact that in this first HoQ the requirements are client requirements, it can be filled with simply "Quality" or "DfQ", because meeting customer requirements is deeply connected to product quality, meaning that these are quality requirements.

Space 7 - Sub-Part

This column must indicate which sub-part or module the customer requirement is about. It helps for further deployment of LeanDfX in the modularization step, because being this a previous tool to LeanDfX, when deploying LeanDfX framework, part of the modularization is already done here.

Space 8 - Part

The "parent" module of the sub-part in the Sub-Part column shall be the value in this column. It must be filled by the team and it also helps for further deployment of LeanDfX in the modularization step.

Space 9 - Weight Chart

In this column a chart with the relative weight calculated in 10 is represented. Automatic and no need to fill.

Space 10 - Relative Weight

Relative weight in percentage is what is presented in this column. Also automatic, what means that it is not to fill; This is calculated from the division of the "Importance" of the customer requirement of the row by the sum of all "Importance" rating given for each customer requirement.

If IC_r is the importance of the customer requirement on the row r and R_1 the total number of rows, then the relative weight of customer requirement on the row r , RWC_r , is given by:

$$RWC_r = \frac{IC_r}{\sum_{r=1}^{R_1} IC_r}, \quad r = 1, 2, \dots, R_1 \quad (6.1)$$

Space 11 - Row

This space is simply, row number. Automatic as well.

Space 12 - Functional Requirements

In this row, the team must specify the "How's", this means, how to translate the customer requirements in technical requirements for the team. It must be filled by the team and its filling process has extreme importance for the overall process. This value may be translated as FR_c , meaning Functional Requirement for column c where c can have any natural value between 1 and C_1 and C_1 is the total number of columns with functional requirements in the first sheet. Once again, it is important to emphasize the weight of this space and step

because a good definition of functional requirements helps the whole process, from the implementation and filling of this HoQ to the deployment of LeanDfX framework, because these are the requirements that are used on *Step 4 - Selection Indicators and Parameter Values*. This is one the major strengths of the methodology, because it helps in one of the hardest steps in the LeanDfX deployment thought a very logical and systematic approach.

Space 13 - Direction of improvement

Regarding the Functional Requirement on a given column, the direction of improvement should be decided by the team. It has 4 possible values in this space:

- $\uparrow$, meaning that the value in the technical or functional requirement shall be maximized;
- X, meaning that the value is the target value;
- $\downarrow$, meaning that the value in the technical or functional requirement shall be minimized;
- *blank space*, meaning that no information is useful for the direction of improvement;

This also helps the same step in LeanDfX deployment because as mentioned in chapter 4, it is also needed to indicate if the parameter is meant to be maximized, minimized or met. The space dedicated to direction of improvement clearly accelerates that step.

Space 14 - Roof Matrix

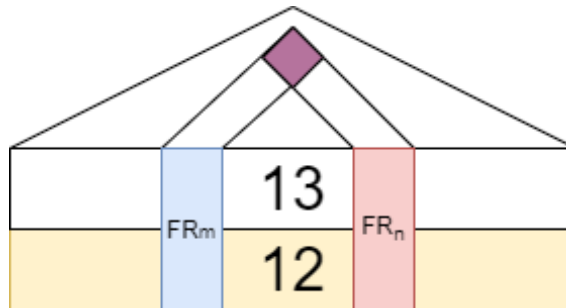


Figure 6.3: Auxiliary figure to Roof Matrix

This matrix must be filled also by the team and it has extreme importance for future decisions in trade-offs. Regarding the two functional requirements that originate the space under analysis, their possible existing relationship shall be defined. This space may be filled with 5 values but a simpler 3 value approach is also possible. The possible values are:

- ++, meaning that the dependence between functional requirements is strongly positive;
- +, meaning that the dependence between functional requirements is positive;
- NO or *blank space*, meaning that there is not an existing dependence between functional requirements;
- -, meaning that the dependence between functional requirements is negative;

- - -, meaning that the dependence between functional requirements is strongly negative;

For a 3 value approach, the values should be: +, NO or *blank space* and -.

To help understand the space in consideration, the purple space in figure 6.3 is the one that relates the dependence between functional requirements FR_n and FR_m .

Space 15 - Relationship matrix

This is the main focus of QFD, the relationship matrix. The goal of this space is to identify how the customer requirement on row r , CR_r relates to the functional requirement on column c , FR_c . In the most developed version of the methodology, a 9 value scale is available to fill the space under analysis. The chosen value should measure the "strength" of relationship between the requirements. In the case that no relationship exists between requirements, a blank space should be left. The values are the following:

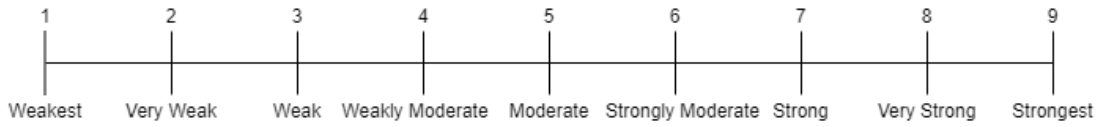


Figure 6.4: Graphic representation of the 9 value scale and its crisp weights

It is also possible to have a 5 value scale or a 3 value scale and that it is a choice that is made by the team. The advised 5 value scale is: Weakest < Weak < Moderate < Strong < Strongest; and the advised 3 value scale is: Weakest < Weak (It corresponds to Moderate) < Strongest.

In figure 6.4, the weights represented are the crisp weights, however the weights considered are in a Fuzzy Logic. In figure 6.5, each decision maker assigns value based on linguistic scale is represented and their relationship strength in fuzzy language is translated by RS_{rc} , where once again, r is row number and c is column number.

This set of linguistic variables is denoted by $F = \{WT, VW, W, WM, M, SM, S, VS, ST\}$ and are quantified in trapezoidal fuzzy numbers.

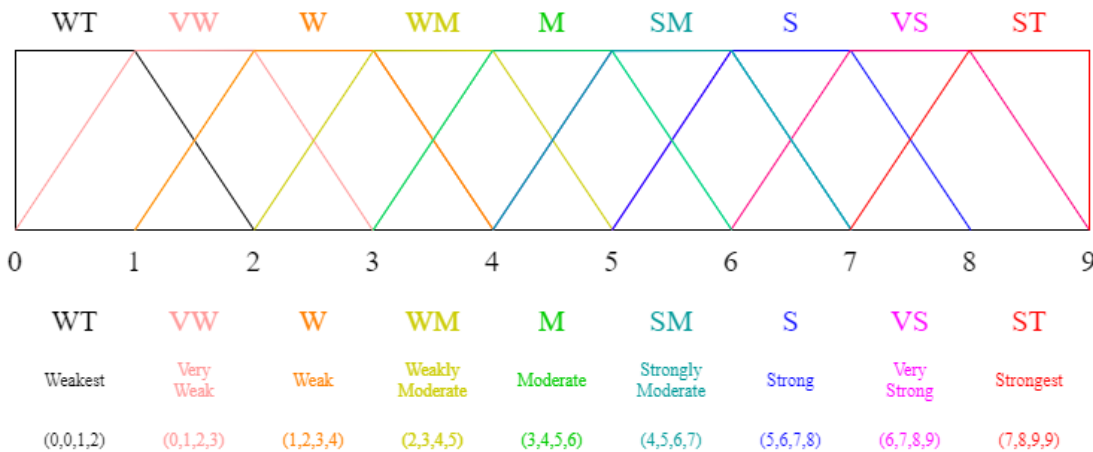


Figure 6.5: Linguistic Scale

Space 16 - Target

Here the user must fill with the target value of the functional requirements in the column under analysis. It can be a number or an information. Once again, this is data that will

help LeanDfX deployment.

Space 17 - Unit

This row is where the user must specify what is the unit for the target value of the column under analysis. Same as before, it helps in future deployment also.

Space 18 - Max Relationship

The same as in space 2 but this is the maximum value of relationship of the functional requirement on column c . Once again, it will be a value between 0 and 9, desirably 9 and it can be translated as $MRFR_c$.

Space 19 - Fuzzy Technical Importance

Here, for a functional requirement FR_c , its technical importance is calculated through a relationship equation depending on the Job/Experience, JE , Importance of each customer/client requirement, IC_r , total number of rows, R_1 and the relationship between the functional requirement under analysis and all customer/client requirements, RS_{rc} . With this value, it is possible to connect results between everyone that fills the process and have it in fuzzy language. This value translates how important a functional requirement is and it allows to rank functional requirements from the most important to the less important to meet. To have the Fuzzy Technical Importance in a column c , FTI_c , the expression is the following:

$$FTI_c = JE \otimes \frac{\sum_{r=1}^{R_1} RS_{rc} \otimes IC_r}{R_1}, \quad c = 1, 2, \dots, C_1 \quad (6.2)$$

FTI_c is in this way, a trapezoidal fuzzy number that represents the technical importance of the functional requirement in a given column c .

Space 20 - Technical Importance

This column is the average value of the 4 Fuzzy Technical Importance values of the functional requirement under analysis. It represents how important the functional requirement is to meet the most customer requirements, and allows the ranking of the various functional requirements, helping the decision process in designing stages. If for each functional requirement on column c , FR_c , 4 fuzzy technical importance values are used, FTI_{ci} , where i is a number between 1 and 4, the Technical importance for column c , TI_c , can be obtained by:

$$TI_c = \frac{\sum_{i=1}^4 FTI_{ci}}{4} \quad (6.3)$$

This space exists to give a first conclusion for which are the main requirements for the user.

Space 21 - Relative Weight

In this column, the relative weight of the Technical Importance on column c under analysis is given in percentage. This helps the understanding and decision making of implementation for each functional requirement.

If TI_c is the technical importance of column c , and C_1 is the total number of functional requirements, then the relative weight for each functional requirement can be calculated by:

$$RWF_c = \frac{TI_c}{\sum_{c=1}^{C_1} TI_c}, \quad c = 1, 2, \dots, C_1 \quad (6.4)$$

Space 22 - Weight Chart

A graphic chart of the relative weight of the functional requirement under analysis is represented in the space 23.

Space 23 - Job/Experience

In this space, depending on the Job or experience of the user, a certain option shall be chosen. At the stage of development of the methodology, three levels are available and each one has a different weight on the final calculus of the combined QFD from the different users. This allows that people with less experience on the project, if wanted, have less influence on the final decision and values given by the QFD when combining results of everyone that has access and filled what is necessary.

This is just an example of three available options, these intervals can be any that the team wants. An example can be the following:

- Poor Experience, if the user has between none to 2 years of experience in the field;
- Medium Experience, if the user has between 2 and 6 years of experience in the field;
- Good Experience, if the user has 6 or more years of experience in the field;

This was made so it can be implemented in LeanDfX framework because it allows to have many type of users, from project manager to technical engineer, so this can be also an addition that is easily implemented in the framework. Experience and its value using fuzzy linguistic scale is represented in figure 6.6 and as JE .

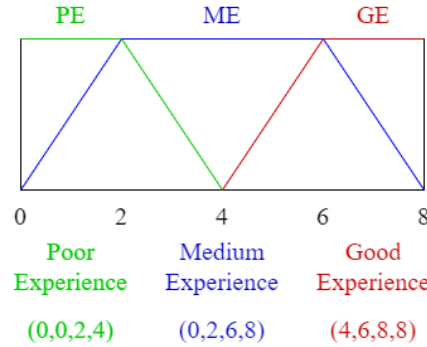


Figure 6.6: Linguistic scale used for experience

6.2.2 Additional requirements HoQ

This House of Quality is very similar to the previous explained with a small differences in some spaces. To avoid overextending this chapter, only the differences between both are analysed here. The concept figure is in figure 6.7 and it is the same as the first one. Figure 6.8 is a small figure representing the obtained results in the filling of one Additional requirements HoQ. The same House of Quality is available in appendix C.

These differences between both appear due to the fact that this is a HoQ dedicated to the requirements that may not be mentioned by the client or they do not even know

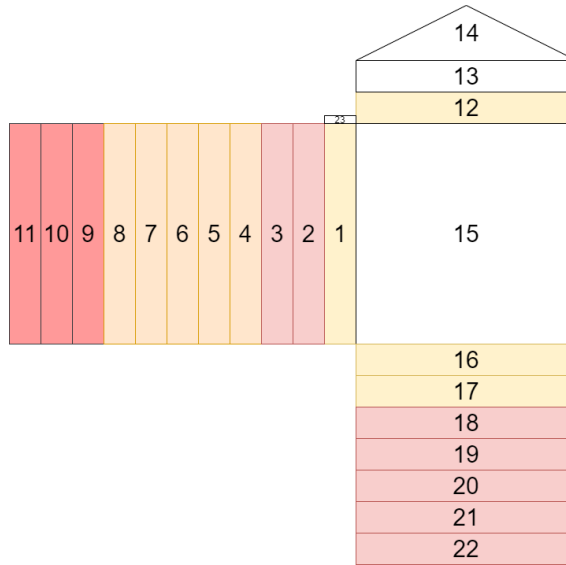


Figure 6.7: Concept figure of Additional Requirements HoQ

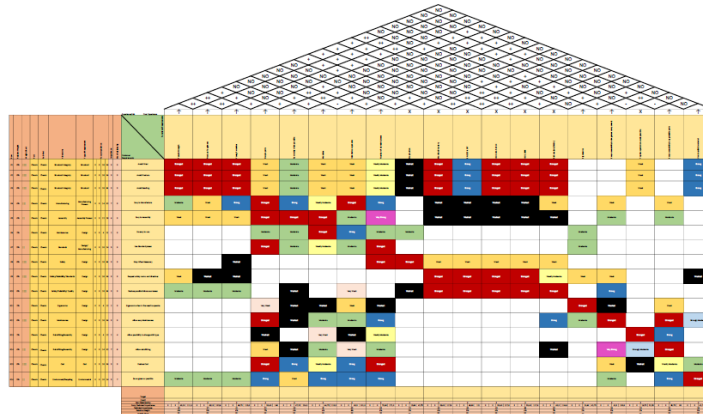


Figure 6.8: Miniature figure of one Additional Requirement HoQ

the existence of, however, they exist or they should be taken into account. E.g., a client may not require an eco-friendly approach to the design process, however it is important to have it into account when designing so, in here, the team makes the decision to add another requirement. This also allows appear new X-Domains to fill, because not every or almost every requirement here will be at least quality requirements.

Space 1 - Additional Requirements

It is almost the same as Client/Customer Requirements, however, these are usually not directly transmitted to the team as essential, or at all. This is also a column that should be filled by the whole team, and it is in this House of Quality that requirements that maybe are not directly mentioned as "Easy to Assembly" or "Respect safety norms" may appear.

Space 5 - Type of Requirement

It is exactly the same as in Client/Customer Requirements QFD, however it is mentioned because here a larger range of type of requirements may appear. "Structural" or "Envi-

ronmental” are some examples of what can be filled here instead of mainly ”Client” or ”Customer”.

6.2.3 CRAR(Customer Requirements and Additional Requirements) QFD-LeanDfX

The next under analysis is the CRAR QFD-LeanDfX. This is the one that makes the most direct bridge between this methodology and LeanDfX framework because in here, LeanDfX framework *Step 3 - Selection of Design Domains* can happen with a systematic approach and ease, once again, the deployment process of the framework. As the previous, the concept graphic representation is available in figure 6.9 and it is more simpler that the previous 2. Figure 6.10 is a small figure representing the obtained results in the filling of one CRAR QFD-LeanDfX. The same matrix is available in appendix C.

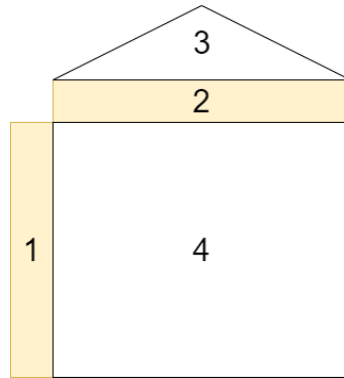


Figure 6.9: Concept figure of CRAR QFD-LeanDfX

Space 1 - X-Domains

In this column, all X-Domains that are regarded in LeanDfX framework are displayed in an alphabetical order. If possible, this would be connected to the framework and would update with all X-Domains available to work with in LeanDfX.

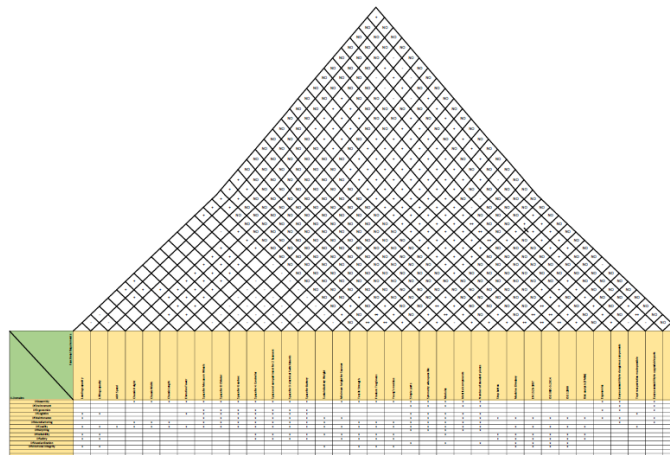


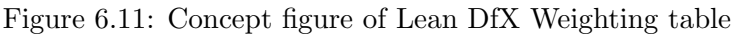
Figure 6.10: Miniature figure of one CRAR QFD-LeanDfX

Here, all requirements from the previous two stages are displayed, having in this case, a much larger matrix than the previous. So far, this step must also be done by the team by copying the information from the other 2 House of Quality's.

Like in the previous stages, this has the same motivation behind, where the team must fill in to know how two requirements relate and influence each other. However, in this CRAR QFD-LeanDfX, if the team wants it, a relationship between additional functional requirements and functional requirements may be also done to help further developments.

This final space relates to the connection between the X-Domain on the row r and the requirement on column c . From 2 possible options (X or *blank space*), the user must put an X in the X-Domains in which the requirement has to be related with. This matrix helps the decision of which domains shall be selected in the deployment phase of LeanDfX.

In this optional step, the users should give a weight to each domain, where the Job Experience of the user is taken into account also. The conceptual figure of the sheet is in figure 6.11. Figure 6.12 is a small figure representing the obtained results in the filling of one LeanDfX Domains Weighting. The same matrix is available in appendix C.



A Domains	Years	Totals	Prof Skills / Areas of Compet										Total	Prof Skills Total						
			Prof Experience		4 Good Experience		Highly experienced		Prof Action Studies		Highly experienced				Prof Action Studies		Highly experienced			
Job Experience		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Observation		10	15	20	25	30	35	40	45	50	55	60	65							

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Space 1 - X-Domains

As in the previous stage, in this column, the several X-Domains available in LeanDfX framework are considered.

Space 2 - Users and Fuzzy Importance

In this space, five columns are dedicated to each user. The first is dedicated to the name of the user and the remaining, dedicated to the fuzzy importance, that is automatically calculated in space 6.

Space 3 - Total

Column number three has the responsibility of showing the final importance for each X-Domain. This is obtained by the sum of the defuzzified importance value of every user for each X-Domain. To understand the mathematical process behind this, a dedicated section is available in the dissertation dedicated. If the fuzzy importance value for each domain, x , with X being the total number of domains, for each user, u , where U is the total number of users, is given by XFI_{ui}^x and i is a value between 1 and 4, the fuzzy values, the total, TID^x is given by:

$$TID^x = \sum_{u=1}^U \frac{\sum_{i=1}^4 XFI_{ui}^x}{4}, \quad x = 1, 2, \dots, X \quad (6.5)$$

Space 4 - Relative Weight

Here, total values are converted in relative weights, so it is possible to have an easier analysis to know which X-Domains are more important. With the same abbreviations as in the previous space, $RWTID^x$ being the relative weight for each total importance of each domain, x :

$$RWTID^x = \frac{TID^x}{\sum_{x=1}^X TID^x}, \quad x = 1, 2, \dots, X \quad (6.6)$$

Space 5 - Job Experience

In the same as the first two stages, here, for each user, the correspondent Job Experience should be chosen so a fuzzyfied importance can be calculated. Once again, this value can be translated in JE_u .

Space 6 - Importance Matrix

Here, each user should give, also in a 9 value scale, an importance should be given to each X-Domain, where 9 is the value correspondent to the most important. This allows a ranking system also in the X-Domains, allowing the team to know in which ones they should focus first. In the following 4 columns, its fuzzy number correspondent importance is calculated. If I_u^x is the importance given by each user, u for each domain x , its fuzzy value XFI_u^x is calculated by:

$$XFI_u^x = JE \otimes I_u^x, \quad u = 1, 2, \dots, U; \quad x = 1, 2, \dots, X \quad (6.7)$$

6.2.5 Additional Sheets

To summarize and some analysis of results and possible ranking of requirements, some tables were created in the file. Those are, as mentioned: Customer Requirements Order; Additional Requirements Order; Total Requirements Order;

Customer Requirements Order Sheet

In this sheet, functional requirements from Client/Customer Requirements HoQ are sorted by their technical importance, from highest to lowest, helping the decision process and organization.

Additional Requirements Order Sheet

Here, functional requirements from Additional Requirements HoQ are sorted by their technical importance, from highest to lowest, also helping the decision process and organization.

Total Requirements Order Sheet

In this final sheet, functional requirements from both House of Quality's are sorted by their technical importance, also from highest to lowest. However, this results should not be taken much into consideration because the scales for each requirement is not the same, even when they are divided by the number of columns on each HoQ, but that does not take the value that it can have.

6.2.6 Methodology Steps

To see which steps the user must do to complete this methodology, Appendix B has a full section dedicated to it since it is the main reason it was created.

6.2.7 Combining Results

One of the strengths of all methodology, is the possibility of combining obtained results of all people that may have done this methodology and reach a combined result with useful information for the team. Here, several variables were regarded, as it can be seen from the analysis made, from the experience of each user to their opinion on how each requirement connects and relates to each other.

To combine results, if U is the number of users that followed the steps and filled the file, u being a natural number that represents a user and FTI_{cu} , the fuzzy technical importance of a user u of a functional requirement on a column c , to obtain the aggregated Fuzzy Technical Importance value, $AFTI_c$:

$$AFTI_c = \frac{\sum_{u=1}^U FTI_{cu}}{U}, \quad c = 1, \dots, C_1 \quad (6.8)$$

The same must be done with the functional requirements in the Additional Requirements HoQ. After this, a simple defuzzification of the result is done and a single value technical importance is obtained combining the contributions from every single user. Once again, this allows a ranking of multiple requirements with the opinion of many people from various jobs, connecting in one file and analysis several levels of knowledge.

6.3 Results

After the contributions of both supervisors, Eng. António Baptista and Eng. Paulo Tavares de Castro and the engineer responsible to help and guide the project in JPM Industry, João Oliveira, the combined results are obtained. It is possible through the use of the methodology previously explained. Due to the fact that it would require several appendixes of a considerable size to show the contributions of each user, only an example it is shown in this document in appendix C, one for each step in a A3 format paper. With the results obtained, it is possible to evaluate if the proposed goals for LeanDfX Fuzzy QFD are checked.

LeanDfX Fuzzy QFD versatility can be already highlighted by the fact that more than one method can be and was used for the contributors to fill the documents. The first one is through the instructions document available in appendix B and the Excel file. The feedback was positive and its results also. The other possible way is through an interview and a sequence of questions in order to fill the documents. It was also made and its feedback was also positive. Both proved to be effective in the filling process.

The results are divided by the different stages and analysed in the next sections.

Supervisor Engineer Paulo Tavares de Castro and Supervisor Engineer António Baptista were categorized as "Good Experience" making their contribution the most relevant and with more weight. Engineer João Oliveira was attributed the option of "Medium Experience" and finally, the contribution of the writer was weighed as "Poor Experience".

6.3.1 Client/Customer requirements HoQ results

The results are in table 6.1 where they are organized by their relative weight after everything considered.

Technical Requirements	Relative Weight
Placement for 3 Electrical Cabinets	10.09%
Placement for Battery	10.09%
Elevation Tower	8.45%
Loading Capacity	7.90%
Lifting Capacity	7.57%
Placement for 4 Mecanum Wheels	7.48%
Placement for 4 Controller	7.47%
Placement and Compartment for 2 Scanners	6.82%
Placement for 4 Gearboxes	5.35%
Minimum Height for Scanner	5.04%
Placement for 4 DC Motors	4.63%
Chassis Length	4.07%
Chassis Width	4.07%
AGV Speed	3.74%
Chassis Height	3.74%
Sustain Battery Weight	3.51%

Table 6.1: Client/Customer Requirements combined results

Analysis

It is important to focus that in this stage, every requirement is demanding, meaning that it is necessary to confirm that this is fulfilled.

From the results, it is possible to conclude that due to the fact of the size of the electrical Cabinets and the battery, consideration for their place in the overall design first it is the most important. The way that they relate to requirements such as allowed dimensions and possibility to allocate every single component makes them essential to consider in the first place. The Elevation Tower placement and its influence on the overall structure must be considered after. Its high ranking among the requirements can be explained by their strong connection to the capacity to meet loading and lifting capacities and also in some way with sizing capacity. Next and also in a same way, a logical requirement with some weight it is both capacities, the loading and lifting capacity. These will also heavily influence the overall design because these are the main loads on the structure.

Then, with almost same percentages, placement of the 4 wheels and controllers must be analysed and thought. This can also be explained by their relative big size and influence

on the structure. In the same way, the placement requirements for the gearboxes, scanners and motors are the ones that follow. Of course, the disposal of all these components are a major issue due to the structure dimensions limitations, even if they appear in the lowest rankings when considering relative weights. However, the fact that the placement for all components are so high in the requirements show that dimensions are a problem and are inherently connected to the dimension limitations. This justifies why length, width and height limitations are so low. Finally, the battery weight appears as the least important and this can be explained by the fact that its weight it is important to chassis stability, so it is clear that the battery will always be sustained due to the advantages that it brings. In other words, consideration of sustaining the battery weight first than the Placement for the 4 DC Motors, as an example, does not makes sense. This is because the battery placement will almost certainly guarantee its sustainability because it is easy to make that possible in the designing process. Also can be justified by the fact that it is connected only to battery requirements and loading capacity, and not with a strong connection.

In order to test the need of QFD, these requirements are regarded in their order in the design process.

6.3.2 Additional Requirements HoQ results

Results are shown in the same way as in for the previous House of Quality, in table 6.2.

Technical Requirements	Relative Weight
Number of Standard Pieces	8.74%
Simple parts	7.38%
Identical Components	6.57%
Risk Analysis (FMEA)	6.16%
Modules	6.08%
Symmetry when possible	5.99%
Machine Directory	5.67%
ISO 12000	5.67%
ISO 3691-5:2014	5.67%
Young's modulus	5.43%
Tensile Strength	5.34%
EN 1525-1997	5.11%
Fracture Toughness	4.90%
Use recyclable material	4.85%
Easy accessibility to upgradable parts	4.59%
Easy accessibility to dangerous components	4.55%
Ergonomics	2.74%
Top transportation made possible	2.45%
Emergency stop button	2.12%

Table 6.2: Additional Requirements combined results

Analysis

Here, not every requirement is necessary to fulfil, but obviously, the more the merrier. The first three can be analysed as a group since they are interconnected. Number of Standard Pieces, Simple Parts and Identical Components influences many of the additional requirements, such has Easy to Manufacture, Easy to Assembly, be easy to use, reduce costs and many more. Their intricate connection to several requirements, important requirements

makes them the most important requirements to meet. This is important to notice because in this case study, these three may not seem as important. This happens because it is one of a kind project, however, the need to be easy to manufacture, reduce cost, accessibility problems and many more, makes them extremely important to meet. Then, the methodology taken in further steps of the project, FMEA, appears as a necessary requirement. This is also expected from the fact that it is a Risk Analysis methodology that allows to cover many requirements. Every single safety and even cost requirements are connected to it, what makes it also an essential to meet.

Modules and Symmetry when possible are both connected to several requirements related to manufacture, maintenance and assembly processes. They are also related to safety requirements in some way from the fact that it allows the spreading of loads in the overall structure, making them high in the ranking of the functional requirements.

In the same way, Machine Directory, ISO 3691-1-5-2014 and ISO 12000 appear with similar percentages and followed by each other. This can be explained by the fact that they are norms and directories connected to good design and safety principles, justifying why they appear so high. Then, physical properties and another norm are the following requirements and the same logic as in the previous can be applied to these.

The use of recyclable material appears next. Even if they may not seem connected strongly to almost any requirement, this is not true, because the choice of material influences most requirements, strongly or not. On a more maintenance, assembly and retrofitting dimension, easy accessibility to parts are the following requirements and it is expected because of their relationship to good design principles.

The final ones are probably expected to appear in the bottom of the rankings, due to the fact that they are not essential to meet and only are necessary as an improvement and may be important in the iteration loop to improve the design.

6.3.3 LeanDfX Domains Weighting results

Since this was filled by the contributors, it is possible to focus on the results of this step instead of CRAR QFD-LeanDfX because the information taken from this is more valuable to the overall process. The results are in table 6.3.

Domain	Relative Weight
Safety	9.49%
Standardization	9.49%
Structural Integrity	9.49%
Reliability	8.79%
Maintenance	8.57%
Quality	8.57%
Assembly	8.22%
Manufacturing	8.22%
Ergonomics	8.13%
Environment	7.30%
Recycling	7.16%
Logistics	6.55%

Table 6.3: X-Domains Weighting combined results

A more direct analysis is possible to this step. As a connection to the previous two results, safety, cost and structural domains are the ones that are seen as more important. Design for Safety, Design for Standardization , Design for Structural Integrity and Design for Reliability are the first four domains that must be considered in the time of designing process. After, Maintenance and Quality show same percentages and also their importance

is logical. Maintenance domain is also related to safety, cost and structural realms and this mirrors in its ranking. Design for Quality, as previously mentioned, represents meeting requirements and working towards improvement. It is also important to mention how connected Design for Assembly and Manufacturing are and how their weightings show that connection in a non forced way. Both environmental domains are low in the rankings due to the small environmental impact that the project has, result of being probably a one of a kind. This also justifies why Design for Logistics is in the bottom, since logistical and supply chain issues are only for one product.

A more deep analysis and influence of the domains in the designing process is made in chapters 7 and 8, where it is explained its connection with several domains and in section 8.1.2, where it is briefly elucidated how every domain changed the design process.

6.3.4 Final Thoughts

In conclusion, there are a few more relevant facts and aspects to recognize and mention. The connection that this methodology has with LeanDfX framework is not only limited to Design-for-X methods but also to Lean Thinking, the other part that individualizes and makes LeanDfX potential shine. Focusing on meeting the functional and technical requirements that allows to fulfill the highest number of client, customer and additional requirements makes the designer or the design team wasted time reduced and doing only on what adds value and on what it is asked, meeting Lean thinking guidelines.

Also, this systematic and simple approach allows a more smooth transition to LeanDfX framework. Some vagueness associated to some requirements or steps needed to deploy LeanDfX are eliminated by QFD and in comparison to what was done with the gearbox as a first case study, it was much simpler the deployment process.

Finally, it can also be referred that with the special conditions on which this project was done to the COVID-19 pandemic, everything had to be done by distance without a physical meeting on how to explain the process and giving the workshop. Even with this, no issue in filling the documents or understanding the purpose and the instruction guides, were encountered by the people responsible for filling QFD, proving to be, at least in a small sample, an easy and approachable methodology. A characteristic that was seen as important from the start of the development process of this methodology. As mentioned, it is hoped that small and middle enterprises can understand and adapt LeanDfX FuzzyQFD. Even if the sample is small and JPM is an exceptional company that already has a mature approach to systematic designing processes, the feedback from the deployment of this QFD methodology was positive. There were no major drawbacks or difficulties in understanding the importance of this methodology as its deployment.

If the complexity of the methodology is a major drawback to some companies, there is also a possibility to transform LeanDfX FuzzyQFD as a modular tool where only one or two of the stages are filled. For instance, in the case of seeing the House of Quality as a hard and difficult process, only the LeanDfX Domains Weighting can be done and even with only that, value is added to the designing process. This is originated from the implementation of modularization forward thinking into the full designing process outside of the main LeanDfX framework.

Chapter 7

FMEA

Another additional tool used to complement and integrate in LeanDfX framework was FMEA, Failure Mode and Effect Analysis. A direct connection with Design-for-Safety and Design-for-Reliability domains can be concluded from a first analysis. The existing connection between FMEA and both domains is clear, because FMEA is a risk analysis tool, and design for safety and design for reliability guidelines have a strong connection to risk and failure reduction as already mentioned.

A classical approach was made, with small changes. One being the fact that it was considered the opinion of several people, inside and outside the project, so in the same way as in QFD where the experience of the person that filled the file was taken in consideration, here it was done the same. This demanded that the results of every FMEA were converted to Fuzzy set language so then they could be combined in one single file and conclusion. In appendix D, there are three examples of what was done, where figure D.1 is the table delivered to the people responsible to fill the FMEA. Figure D.2 has an example of one of the FMEA tables filled and already converted to Fuzzy set Language, with the job of the person with that table in consideration. Finally, in figure D.3, the combined results and normalization of the scale are represented.

In this chapter, the process done is explained in detail so it can be comprehended how the scales, fuzzyfication and defuzzyfication of the grades and the normalization happened. How failure modes and possible failures were thought and considered is also explained.

7.1 Fuzzy FMEA

7.1.1 Introduction

Even if FMEA is usually a risk analysis process mainly done after the product is produced or at least one sample is available [17], this process can be done in previous stages, like design stages in order to avoid possible normal failures in the type of product in consideration. However, if this is done, it is much harder to obtain estimation values for some failures, like the occurrence probability, where instead of having real data regarding the product, this value must be estimated through experience and existing data on similar products.

To have a coherent approach in the explaining process, a conceptual representation of the spaces and FMEA is in figure 7.1. A space by space explanation is available below, however there is no need to be as detailed as in QFD.

For each filled FMEA, two Excel sheets can be individualized. One has the direct information given or filled by the user from a 5 options linguistic scale. This one is figure D.1 in appendix D. The other has an additional column for every value in order to transform the chosen value in a fuzzy number. In this, there is also an additional space to identify the experience of the person that filled FMEA. Figure D.2 in appendix D is an example of this sheet. Finally, there is another that it has the responsibility to join every

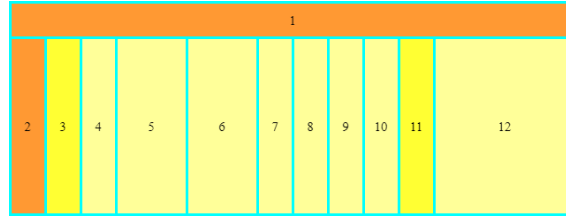


Figure 7.1: Concept of the given FMEA

fuzzy result for each failure and then, normalize back to a 10 value, single number scale, so it is possible to use 125 as RPN threshold to determine a failure as critical. To see an example, figure D.3 can serve as one, in appendix D.

7.1.2 Spaces

Space 1 and 2 are just dedicated fields to mention what is the component in main analysis.

In the same way, space 3 is a field where which additional component may be associated to the considered failure or extra information or detail on the place where the failure may happen in the component.

Like the example given in the work of Pahl et al [17], there are spaces then dedicated to explain failures, from type of failure, the consequence associated to it and what is the cause to why the failure may happen. These are, respectively spaces 4, 5 and 6.

Space 7 is dedicated to possible test that can be done to prevent or to detect possible failures so accurate values can be reached when filling FMEA.

To the people that only needed to fill the file, spaces 8, 9 and 10 are also the classical fields where the probability of Occurrence (O), severity of failure (S) and Detectability (D), where all of them are in a linguistic scale of 5 terms, instead of a typical scale of 1 to 10. This 5 linguistic terms scale is inspired in the work of Pillay and Wang [106]. This was done so it is easier to fill the process and to be able to use it without having to conceptualize values in a case. Finally, they were transformed to values, where the linguistic scale and its values to put in FMEA are the following:

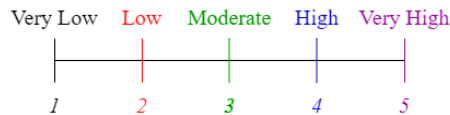


Figure 7.2: Linguistic Scale in FMEA

The scale used and the meaning of each value is in tables 7.1:

Fuzzification Process

Afterwards, in other sheet, to do not confuse the user, these three terms are translated to a Fuzzy linguistic scale where here, the lowest term is 0 and the highest is 10, converting it to now a more classical 1 to 10 scale and allowing the possibility to use again the 125 RPN threshold number. The fuzzy scale used for the linguistic scale is also represented in a graphic and a trapezoidal fuzzy number was also the method used, only to have a same and similar approach in both additional tools. The linguistic scale to Fuzzy language is represented in figure 7.3.

Values used for the experience of user were the same as in the QFD methodology, where the three classes were:

- Poor Experience - (0, 0, 2, 4);

Term	Occurrence	Severity	Detectability
VL	Unlikely to observe even once	Has no effect on the system performance	Easily detected, without a specific visual inspection
L	May occur once, but not many more times	It would not defect the system but it can reduce quality of certain functions	Easily detected with a routine visual inspection
M	Likely to occur more than once	A defect that may slightly reduce system performance or cause high degree of dissatisfaction to the operator	Undetected until system performance is affected
H	Near certain to occur at least once	A failure that may lead to minor injuries and significant deterioration of system performance	Undetected until specific inspection or test is carried out
VH	Near certain to occur several times	A failure that would affect seriously the ability to complete the task or that can cause major injuries or even death	Failure undetected until very specific sets of tests or system fail even

Table 7.1: Meaning of each term in the levels of evaluation in FMEA

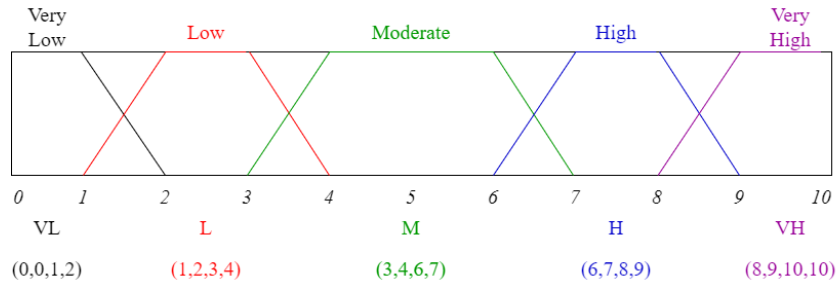


Figure 7.3: Linguistic Scale in fuzzy terms

- Medium Experience - (0, 2, 6, 8);
- Good Experience - (4, 6, 8, 8);

The fuzzyfication process is obtained by the following expression:

$$FFV_r = FV_r \otimes JE \quad (7.1)$$

Where JE is a fuzzy number regarding the user experience, FV_r translates the value given in the 5 linguistic scale in the fuzzy scale for one of the 3 evaluation variables (Meaning that the V can be one of these 3: O, S, D), for a failure in row r and FFV_r is the final fuzzy value for the variable calculated (O, S, D) for the same row r .

After, in space 11, depending on the sheet that is being analysed, in other words, it can be the one that only has the values from 1 to 5 where the scale is in Fig 7.2 or one where those values are also translated to Fuzzy numbers, in the scale represented in figure 7.3. Space 7, 8 and 9 also can be one of the options aforementioned, depending only on the Excel sheet. In this space, a classical approach to Risk Priority Number, or RPN was

taken, meaning that to calculate RPN, the expression is the following:

$$RPN = O * S * D \quad (7.2)$$

If RPN is calculated from the 5 value scale, it has direct meaning where the user can have a direct analysis of which are the most critical failures to him or her. If RPN is represented in Fuzzy Language, it has little meaning and it is only used to possible future uses.

Finally, space 12 is left for one of the following purposes:

- If it is possible to do it in the design process, suggested measures and tips can be written on how to prevent the failure in the same row and try to see how the alteration may impact Occurrence (O), Severity (S) and Detectability (D);
- If it is not possible to do it in the design process, when the team has a physical sample of the product, it can proceed to improve the design using this space to analyse the new design after the problems were detected in the physical sample;

7.1.3 Combining results

Defuzzyfication process

After every FMEA is filled, in another Excel sheet with the same format as the previous, all fuzzy values for each indicator for each failure are summed up. To understand it, with FFV_r^u , where u is the number of a user and U is the total number of users that filled FMEA, R is the total number of failures, which will correspond to the total number of rows with failures and $CFFV_r$ is the combined final fuzzy value for each failure of one specific variable or indicator (O, S, D), the first step after everyone has finalized it is the following:

$$CFFV_r = \frac{\sum_{u=1}^U FFV_r^u}{U}, \quad r = 1, 2, \dots, R \quad (7.3)$$

It is only divided by the number of users at this stage just to present lower number. This allows a possible analysis with smaller numbers than if it was not divided by the number of users. Then, the next step is defuzzyfication process of values. With $CFFV_r = (C_1, C_2, C_3, C_4)$, to have V_r , where V is one of these 3 option of variables (O, S, D), the following expression is needed:

$$V_r = \frac{\sum_{i=1}^4 C_i}{4}, \quad r = 1, 2, \dots, R \quad (7.4)$$

Normalization and RPN

Finally, after having a single value for each variable, they should be normalized to a 10 value scale being possible, afterwards, calculate RPN and know which failures can be critical. To obtain NV_r , normalized variable for row r , once again, with V assuming one of the 3 indicators or variables of evaluation, occurrence O , severity S or detectability D , a 2-step process is made.

First, the maximum weight given by everyone should be searched. In an ideal case, there is at least one variable where everyone gives a 5 when filling FMEA. If that is the case, then the V_r of that same variable becomes the maximum, MV . Otherwise, by making a simple average of every single indicator, regarding the users, the highest obtained number for an indicator becomes the maximum normalized value, MNV and the value for which its defuzzyfied value is correspondent, V_r , becomes the maximum, MV .

To ease the understanding, an example is given in this paragraph. From several possible failures of an AGV, one that must be considered can be Overheating and possible fire of the battery. To the 3 individuals that are responsible of filling FMEA, the severity of this failure is Very High, a 5. If this is the case, the average of the severity of overheating on the battery is exactly 5, as expected, making it MNV , the maximum normalized value. In the case of there is no indicator where the average is 5, the highest average number becomes MNV . Then, the correspondent value defuzzyfied number, V_r becomes the MV .

The second step is normalizing every value to a classical scale. NV_r , or variable normalized on row r , where, V , once again it is one of the 3 indicators. To obtain that number:

$$NV_r = \frac{V_r}{MV} * MNV * 2, \quad r = 1, 2, \dots, R \quad (7.5)$$

Finally, RPN for each failure can be calculated through the normalized values for each indicator for a single failure. If ON_r , SN_r and DN_r are normalized Occurrence, Severity and Detectability, respectively and RPN_r , the normalized Risk Priority Number, all of them for a given row, r are related on the following equation:

$$RPN_r = ON_r * SN_r * DN_r, \quad r = 1, 2, \dots, R \quad (7.6)$$

With this, if RPN is equal or higher than 125, than the failure is considered a critical failure.

7.2 Failures

In this section it is explained how and where failures were considered.

7.2.1 Chassis Failures

The first failure place considered were chassis failures, obviously, since the project is the chassis of AGV, all of the failures are related to the chassis, but this first are failures that happen in the chassis itself, not only caused by it.

Analyzing the Machinery Directive [147], more specifically in Annex I, 1.3 - Protection Against Mechanical Hazards and EN 280:2001+A2 - Mobile elevating work platforms [148] a conclusion about the most common hazards that may occur in this type of vehicles can be had. Complementary research was done through the analysis of NP EN 1726-2 2002 - Safety of industrial Trucks [156] and both ISO 121000-1:2003 [153, 154]. Finally, additional advisory done by both supervisors helped reach which were the possible failures. They are:

- Corrosion - Causes: corrosive working conditions;
- Fatigue - Causes: bad design, use or excessive payload can be some of many possible causes;
- Looseness - Causes: bad design, use or excessive payload can be some of many possible causes;
- Weld Failure - Causes: defective welding or bad utilization;
- Wear - Causes: bad design, use or excessive payload can be some of many possible causes;

7.2.2 Wheels Failure

Wheels can also be the reason or place of a failure and those failures may be reduced, at least in some way, through chassis design. Wheel failure is not usual because they are usually checked at least one time per year and at least corrected or even replaced in the same time period. However, also through Machinery Directive [147] and ISO 3691-5:2014 - Industrial Trucks [152], it was concluded that one kind of failure may happen:

- Wear - Causes: defective soil or many other causes;

7.2.3 Elevation Tower Failure

Even if designing the elevation tower is not necessary to the project, chassis design may impact or cause failures in elevation towers, mainly in the connecting parts. Consulting EN 1495:1997+A2 [150], an estimation of possible failures impacted by chassis design was reached. These are:

- Fatigue - Causes: bad design, use or excessive payload can be some of many possible causes;
- Looseness - Causes: bad design, use or excessive payload can be some of many possible causes;
- Wear - Causes: bad design, use or excessive payload can be some of many possible causes;

7.2.4 DC Motor Failure

Every motor can fail and its fails can be augmented by chassis design. Once again, Machine Directive [147] and supervisors advisory was extremely important to reach the fails. Additionally, EN 1175-1: 1998 [149] and EN 1525:1997 [139] were also 2 more standards investigated to this topic. The fails are:

- Unit Fail - Causes: Bad maintenance or Faulty Unit;
- Overheat - Causes: Bad maintenance, Overuse or Overheat;

7.2.5 Gearbox Failure

Gearbox failures can also be avoided with good chassis design. Consulting the same fonts as in DC Motor Failure, the possible failures are:

- Wear - Causes: Broken Gears;

7.2.6 Motor Controllers and Scanners Failure

Another components that are affected by chassis design and its possibility of fail also are motor controllers and scanners. These were combined in the same section due to their similarities. Adding to the fonts used in the previous sections, manual guides of each component were consulted where safety standards are considered. The most common failures to these components and their causes may be:

- Unit Fail - Causes: Broken Unit or Faulty Unit;

7.2.7 Batteries Failure

One of the most important components to consider in safety issues is the battery due to the possible unstable nature of these. Also, chassis design has major impact in it. Machinery Directive [147] has a single section dedicated to battery safety and through its analysis and supervisors and engineers advisory, the possible failures associated to the battery are:

- Leakage - Causes: Bad use or lack of maintenance;
- Overheat - Causes: Lack of maintenance, overheat or confined space;
- Performance Degeneration - Causes: Bad use or lack of maintenance;

7.2.8 Electric Cabinet Failure

Finally, with a research about Electric Cabinets studies and their behaviours and also consultation of engineer João Oliveira of JPM, engineer Susana Fernandes and both dissertation supervisors, engineer Paulo Tavares de Castro and engineer António Baptista, failures with the electric Cabinets were possible to obtain. They are:

- Overheat - Causes: Lack of cleaning, dust;
- Unit Fail - Broken Unit or Faulty Unit;

7.3 Results

FMEA used was only filled by 2 users. One with poor experience, so the weight attributed to his results were (0,0,2,4) and one with good experience, (4,6,8,8), with more than 6 years of experience in the field of AGV. The latter was engineer Susana Fernandes and the contribution made was essential.

The combined results FMEA is in appendix D in figure D.3 and critical RPN threshold number selected was 125. The failures considered critical were:

- Chassis:
 - Fatigue;
 - Wear;
- Elevation Tower:
 - Wear;
- Battery;
 - Performance Degeneration;

To solve these critical failures, there were measures considered in chassis design to reduce RPN value. These solution and measures were obtained and suggested through analysing several documents, standards and engineers.

7.3.1 Chassis

To avoid Fatigue failures, in design process, the structure fatigue strength should be calculated. This measure was suggested and reached through the analysis of EN 280:2001+A2 [148], a standard dedicated to design calculations, NP EN 1726-2 2002 [156] and supervisors advisory. This would reduce possible occurrence. Another suggested measure taken into consideration is to, if there is a necessity to have places with high stress concentration factor, try to locate them in places where chassis stability can be detected previously or in less important zones, so detectability or severity indicators can have lower values.

In the Wear category failure, the measure suggested is to design a structure that allowed easy maintenance and substitution. Reading the same standards and advisory from dissertation supervisors, this was the applied measure. It would allow to reduce occurrence and detectability factors because it would be easy to locate possible structure Wear and, if possible, future substitution of that part. This can be done by avoiding interior critical components of the chassis, trying to locate the most critical components in the exterior of the chassis.

Even if not critical, another measures were considered in order to avoid failure. In chassis failures, designing for easy accessibility to weldable places, so welding process could be easier and therefore, less prone to failure.

7.3.2 Elevation Tower

Here, standard EN 1494:1997+A2 [150] and Machinery Directive [147] were considered and to avoid Wear and fatigue of elevation tower and copulation system with chassis, certain measures were taken into consideration. From suggesting a weight detector in the elevation tower to avoid lifting loads above the one considered the maximum to designing the chassis thinking in order to ease elevation tower substitution when it appears to be Wear or its stability is at risk. This would reduce occurrence of both events. This means that direct access could be done at any point with the connection between the elevation tower and chassis.

7.3.3 Battery

Once again, the Machinery Directive has a full section dedicated to batteries. In the same way, standard EN 1175-1: 1998 [149] and EN 1525:1997 [139] also consider battery failures and safety. The measures that were accounted when designing in order to reduce performance degeneration failure and also other possible failures, even if not critical, was to design the chassis in a way that battery substitution would not be jeopardized by chassis design. Since this batteries are substituted with a help of a small crane (information given by the company JPM) due to its weight, it is important for the battery to be located in the top of the AGV and without many pieces to transport when this is needed. Also it is important to design in a way that it is easy to connect the battery with the structure or with the crane.

Overheat problems is not seen as critical with FMEA, however, it can be reduced by just having more space in the compartment dedicated to the battery. This was also taken into consideration in chassis design.

7.3.4 Additional Measures

Critical failures were already reduced at this point, however, even if the other failures are not critical, if there is a possibility to reduce the risk of a failure without compromising any other more important aspect of the chassis, than it should be done.

Once again, with the help of the existing standards for AGVs or Machinery in general and several components manual, a measure that would reduce every failure risk of components relating chassis design was detected. Designing with the focus of every component being easily accessed so its substitution and maintenance could be facilitated and therefore, its failure risk reduced. Of course, all of this was considered in designing phase.

Chapter 8

Designing Process

At this stage, it is possible to start the designing process of the AGV. In order to test the efficiency of the proposed methodology, their results will be used and taken into consideration. From chapter 6 it is possible to take what must be taken into account in first place from the various requirements and which Design domains should also be pondered. Chapter 7 gives an idea of which failures must be prevented in the designing process, when possible. In this chapter, the background and thought process behind the designing process is explained and as well, the results that were obtained.

8.1 Schematic design

8.1.1 Schematic Design Process

From the results on table 6.1 it is possible to conclude that the most important characteristic to consider is the disposal of the several components on the limited space. In order to treat this problem, the first step in the designing process was the schematic design, where the main focus of it, is to choose where each component is disposed in the chassis.

The first components to consider are the Electrical Cabinets. These must be accessible to the several users and their dimensions must be respected in order to allow their ventilation system to work. From the additional requirements, table 6.2, it can be concluded that Symmetry and identical components are important to meet the several additional requirements. Easy accessibility to the Cabinets and the possibility to make modules are also considered in this step.

Then, consideration for the battery place in the chassis is regarded. Several factors influenced its placement. AGV stability, Modularity, Symmetry, accessibility and its failure possibility were all considered. In order to guarantee AGV stability, the placement for the battery should be at least in the center of the AGV, so its center of gravity stays closer to the geometrical center. In order to avoid its failure, it is necessary easy accessibility to the battery and a larger space than its dimensions, so the possibility of a fire can be reduced. Battery substitution must also be weighted in, since its performance degeneration it is a possible failure. Batteries with this dimensions are usually replaced with the aid of a crane, so it is important to have top accessibility to the battery, even if for AGV stability, a lower placement would benefit more.

The elevation tower placement is simple, even being essential and influential in the overall design. The possibility for symmetry, modularity and standards regarding forklifts were considered and they can be seen in the schematic design. The lifting and loading capacity are requirements that must be taken into consideration in the structural designing, making them not as essential in this schematic designing stage. However, as seen in the placement for battery requirement, they were taken into consideration since the lifting and loading capacity inherently depend on the vehicle stability.

The following requirement to consider is the placement for the 4 mecanum wheels.

Wheels have usually a natural place in vehicles and there are several standards considering wheel safety. From a safety distance to the ground to a possibility to install a physical protection to the wheel and the possibility for symmetry, identical components and easy accessibility, many results and measures were considered for the schematic design of the AGV.

Next, the placement for the four controllers was the requirement to ponder about. Since it is necessary to contemplate the need to easy accessibility in order to replace them when it may be necessary, these should be in a visible place .

One tricky technical requirement to be considered after is the placement of both safety scanners and many aspects are connected to it. First, the fact that they should be protected in a compartment so they will not break in case of crash. Then, they have to be in two opposites places in the AGV, due to the fact that they read 270°, being necessary a full read of the place. They also need to be placed in a minimum height and finally, it is also important for them to be in a reachable position so their maintenance and cleaning is possible. The need or desire at least for symmetry also heavily influenced its placement.

The necessary placement for the gearboxes and the DC Motors can be analysed side by side. In the same way as others components, the possible need for their replacement or maintenance weighted in their placement. The necessity for symmetry, modules, simple parts also weighted in it.

Finally, AGV's dimensions limitation were always a concern and always regarded because they are inherently connected to placement of the components. Speed and battery sustainability are concerned in future steps of the process, mainly the structure. The drawing is available in appendix F.

8.1.2 X-Domains Influence

Design-for-Safety is met in the designing process through several additional functional requirements. Simple parts, identical components, modules and symmetry when possible allow the spreading of loads through all structure, reducing its impact at the loading point. FMEA is a critical and a safety tool that allows meeting several guidelines in Design-for-Safety domain. Safety standards are naturally connected to safety requirements and guidelines and also the calculus and consideration for physical properties. Structural Integrity and Reliability are also met from the same reasons, from the same measures, showing that Safety, Structural Integrity and Reliability are deeply connected and there is one single tool that helps meeting several guidelines for the three domains, FMEA. Another safety measure that may not be seen as such, is the easy accessibility to components, allowing their replacement and maintenance in a safe way.

Standardization forward thinking design is easy to see how it can be translated to the designing process, where number of standard pieces, simple parts, identical components, modules and symmetry when possible all aid in meeting this domain guidelines.

Design-for-Maintenance is followed by allowing easy maintenance for parts and obviously, easy accessibility measures if possible. Also, number of standard pieces, simple parts, identical components, modularity and possibility of symmetry also aid this, due to the fact that using identical parts and standardized parts makes their replacement and behaviour prediction a lot easier.

As previously mentioned in section 2.5.1, DfQ has several dimensions. Using FMEA, also a quality tool [17], and meeting customer requirements are the most basic ways to be considering this domain. The iteration loop of LeanDfX is also a design process that makes designing for quality possible.

DfMA is deeply analysed in section 2.5 and can be met through, once again, the first six functional requirements from the additional requirements, table 6.2. Obeying several standards also facilitate manufacturability and assembly processes.

Ergonomics may seem not important in the first place because, since it is an AGV,

there is no direct operator, however, accessibility to components that may be maintained or operated or cleaned must be considered. As an example, ergonomic principles would not be respected if the electrical cabinets were placed in a low position in the AGV. This would oblige the operator to get in a non-ergonomic position in order to operate the machine.

One important overall knowledge domain is the environment and the X-Domains dedicated to it, such as Design-for-Environment and Recycling. Naturally, the use of recyclable material is a direct measure of these, however it is not the only one. Once again and showing why they have such a high ranking in the results table, the first six technical requirements from table 6.2 also allow it. Recycling is easier when parts are standardized parts with recycling guidelines. When they are simple or at least identical parts, they can have the same treatment, from the beginning of its life to the very end. Modularity makes replacement easier and retrofitting actions are deeply connected with environmental domains.

8.1.3 Result

In appendix F is the final iteration of the schematic design. In the structural design, some changes were done due to structural integrity. This was a longstanding process because of its difficulty and communication problems between parts. The disposal of the parts have their origin on the reason aforementioned. After this, the structural design as materials choice is possible, allowing the start of the real deployment of LeanDfX software.

8.2 LeanDfX deployment

It is also possible to submit project specifications in LeanDfX framework in order to prepare it to future utilization. The main project requirements were the ones submitted and are available for analysis in Appendix G.

8.3 Structural Design

The starting point to the structural design, it is through the adaptation of the schematic design with beam profiles and the application of a material. The goal is to design the metallic frame and its simulation.

Through the time, applying the LeanDfX framework, mainly the iteration loop step, the frame design evolved in order to meet the requirements in the best possible way with the available time. This improvement happened due to the deployment of the framework, where the scorecards allowed recognizing where the design could be improved.

8.3.1 Material

Regarding the material, there are some aspects to have in consideration. Since there is no need to have a lightweight structure, in reality, the opposite is more desirable in order to have a better stability, materials density is not an issue. However, attention to the recycling possibility must be had. As previously mentioned in section 2.5, steel is highly recyclable, being one of the most recycled materials in the world [169]. This makes steel a good choice to the material of the structure. Another point in consideration must be the also the cost. With steel being one of the most used materials in the world and one of the most common, structural steel even more, its price are usually low. They also have good mechanical properties, high tensile strength and high yield strength, making them the perfect material to apply. There were several structural steels in consideration, but the chosen was the E360. The information in table 8.1 were obtained through SOLIDWORKS database.

8.3.2 Profile

Normalised profiles are desired from the start due to the fact that this eases the manufacturing process, reduces the cost and machining of the profiles, because they are normalized. The profiles in consideration were the available ones in SOLIDWORKS.

Steel	Yield Strength MPa	Young's Modulus GPa	Density kg/m ³	Cost USD/kg
E360	360	190	7800	0.372

Table 8.1: E360 Steel properties

JPM advised profiles were squared tubes or "L" shaped. In a first approach, "L" shaped profiles were used but these hardened the design process because of their reduced contact area, making them less able to handle the necessary loads. Then, square profiles became the primordial profiles in use. In the first iteration of the project, the dimensions of all squared tubes were 40x40x4 mm. Through the improvement process, it was possible to reduce the size of the profile in some places of the frame to 30x30x2.6 mm, reducing the overengineering, applying Lean Thinking. These dimensions are ISO dimensions, meaning that they are standard dimensions, an important requirement to meet as seen in table 6.1 and 6.2.

The landmark designs that were also deployed in LeanDfX are in Appendix H in chronological order of development. The first will be called iteration 1.1, the second 1.2, the third 1.3 and the last one 1.4. They are shown in a A3 sheet to ease its analysis and were obtained through the drawing possibility option in SOLIDWORKS. As previously mentioned, the design was made with several standards into consideration, from a good practices, safety and design basis.

8.4 Final design and modules

The last design designed has several features that allows the fulfillment of the necessary requirements and engineering characteristics. First, a module per module analysis is done and the remaining features necessary to explain, are in an whole module analysis.

8.4.1 Top Module

In the top Module, some requirements are checked. It is in the Top Module that the battery is allocated, in the biggest space available. It is also here that the 3 Electrical Cabinets are located and the Elevation tower is connected. This is also responsible for sustaining battery weight. Specifically in the Top Module, excessive space for the battery is also taken in consideration in order to reduce the possibility of overheating of the battery and to facilitate the maintenance and possible substitution of the battery, with the help of a crane. The top Module also allows top transportation and every component allocated in it, is easily accessed since all of them are turned to the outside of the frame. Another point also regarded here is the symmetry of the module and overall structure.

Most of the parts are simple with just a few examples with the need of more difficult cuts to the beams.

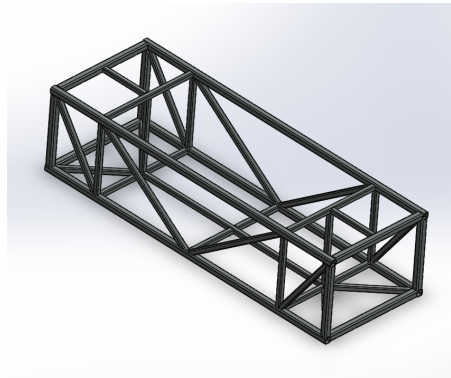


Figure 8.1: Top Module

8.4.2 Back Module

Here, the placement for two Mecanum Wheels, two controllers, one scanner, two gear-boxes and 2 DC Motors are taken into consideration. Also, symmetry is also taken into account. All components are also easily accessed because they are all connected to the outside of the structure, only the gearbox is covered by the wheels, all the other components are covered by metal sheets or nothing at all. Wheel protection mentioned in safety standards is also assessed from one side. This design creates 2 spaces on each bottom module for the scanner, allowing many more possibilities of substitution and maintenance to them. In the case of the module that it is decided to be the back module, there is existing space to add counterweights so that vehicle stability it is obtainable.

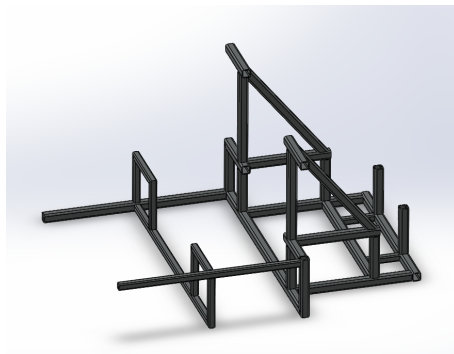


Figure 8.2: Back Module

8.4.3 Front Module

The other half of the components in the back module are here, in the same position. In this way, symmetry is assured between the full structure. This is also the module responsible to connect with the elevation tower in pair with the top module. In the same way, every requirement regarded in the back module is also taken into consideration here. The fact that the back and front module are symmetrical facilitates the manufacturing and assembly process and assures symmetry of the overall structure.

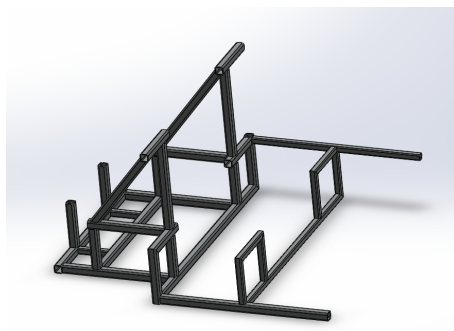


Figure 8.3: Front Module

8.4.4 Full Structure

Modularity and symmetry is verified by the whole structure because of the previous sections. With this design, every safety, reliability and structural integrity requirement and measure to have is verified and proofed in the following sections, where the structural calculation are made. The overall structure also fulfills the maximum dimensions imposed by JPM Industry as the minimum height of the scanner, since the structure would be 50 mm from the ground and an additional 100 mm are from the self size of the scanner. Ergonomics is also assessed in this design from an operating standpoint. As mentioned,

every component is easily accessed so vehicles and its components maintenance or substitution is possible and easy. This has high importance because maintenance highly reduces failures, as seen in chapter 7.

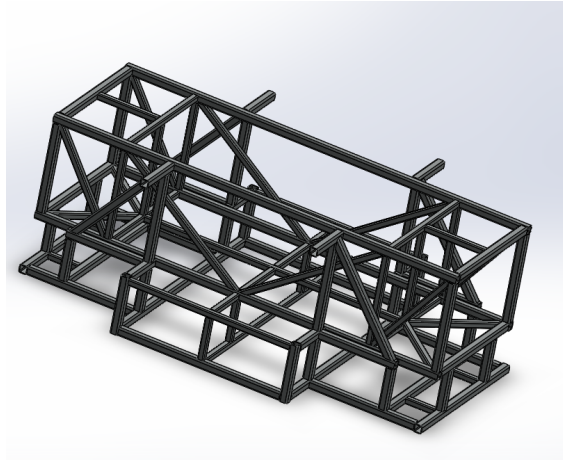


Figure 8.4: Whole Structure

8.5 Structural calculations and simulation

With the help of the simulation feature in SOLIDWORKS and analytical analysis, multiple tests regarding the effect of the loads, the stiffness of the structure and its stability were done for each iteration in order to know if the structure could resist the worst case scenario. It is important to mention that even if the worst load case scenario is not probable, there is a chance that they may happen. For instance, when lifting the load to maximum height and leaving the load in the right place, when in the separation phase, where the AGV is departing from the load, the load may connect once again with the forks and being in the tip of the forklifts. An illustration of the applied loads and their distances are in figure 8.5.

In the weight of the structure, F_w , the weight of the multiple components, just as the battery, are already in consideration. Even with this, the total structure weight is low and the need of counterweights may happen. As mentioned, the worst case was considered for every structural calculation. The value for every variable is in table 8.2, only for the last iteration, since there is no value in adding the information for every other iteration since the calculus is the same. The load is the max load allowed, 1500kg, the distance is the maximum possible and the value is obtained by the length of the forks and pallet plus the length of the elevation tower and chassis and this value is 1100 mm. The height is also the maximum height possible, where the forks are at 1500 mm height. An additional load was added in the need of it, the counterweights, F_{cw} . These may be necessary to assure AGV stability. In the designing process it was taken into account also a space to possible counterweights. Since they will only make the loading worse and demanding more from the structure, it was considered in the calculus 4000 kg in order to cover the several components and counterweights to be added in. R_a and R_b are the reactions on each support, in this case, the wheels.

The values for the Center of Gravity for the structure were obtained in SOLIDWORKS. The Forklift elevation tower center of gravity it was given by JPM, as its weight.

8.5.1 AGV Stability and reactions

For each version, calculation about AGV stability and reactions were done with classical mechanics as resource material. From the mentioned literature in section 3.3, several stability coefficients for several cases were obtained.

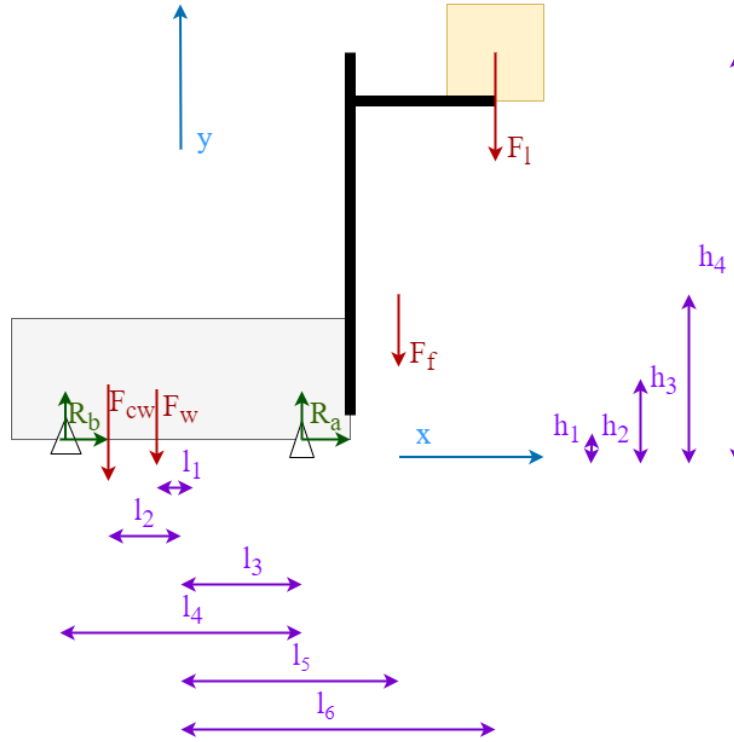


Figure 8.5: Illustration of the case study and their loads

Dimensions	[mm]	Dimensions	[mm]
l_1	90	l_2	160
l_3	600	l_4	1200
l_5	1100	l_6	2300
h_1	200	h_2	320
h_3	1100	h_4	1700
Loads	[kgf]	Loads	[kgf]
F_w	1271	F_{cw}	4000
F_f	364	F_l	1500

Table 8.2: Variables and their values

For Static calculation, where horizontal loads (loads as result from dynamic) are not considered, the worst case scenario should present a stability coefficient of at least 1.8;

For dynamic calculus in braking at normal acceleration, with the load at the transportation height, should present a stability coefficient of at least 1.5;

For emergency braking situation, with the load at maximum height, the stability coefficient should be at least 1.1;

Static Calculation

$$\sum F_y = 0 \quad (8.1)$$

$$\sum M_a = 0 \quad (8.2)$$

For the vertical forces, the equation is:

$$F_w + F_{cw} + F_f + F_l + R_a + R_b = 0 \quad (8.3)$$

For the sum of moments in a , the results can be obtained through:

$$F_w(l_1 + l_3) + F_{cw}(l_2 + l_3) + R_b l_4 = F_f(l_5 - l_3) + F_l(l_6 - l_3) \quad (8.4)$$

As a result, the reactions in the wheels are: $R_a = 55419$ N and $R_b = 14584$ N. Then, it is necessary to reach C , the longitudinal Stability coefficient. As a first step, the centre of gravity for the full structure, with its weights, the counterweights and the forklift, should be calculated. The obtained position for the CG is: $(x = -200, y = 120, z = 0)$ mm. If l_{cg} is the distance of the centre of gravity to the origin, and F_{fw} , the load made by the full weight of the structure and counterweights and forklift ($F_{fw} = -55319$ N) then C may be reached by:

$$C = \frac{F_{fw}(l_{cg} + l_3)}{F_l(l_6 - l_3)} \quad (8.5)$$

This results in a stability factor of 1.8, proving to be in safety and with the necessity of some counterweights in the back of the structure.

Dynamic Calculation

Here, horizontal loads must be considered and the braking acceleration is given by $a = 0.5$ m/s², which is a braking acceleration over what is the truth, since the top AGV's speed is 3 km/h, or 0.833 m/s and through standard research, for a vehicle of this type, it is needed that the vehicle stops in 2 meters. A 0.5 m/s² braking acceleration would always accomplish that.

In this case, also, as mentioned, horizontal loads are important and should be calculated. For the full structure load, F_{fw}^h , with m_{fw} being the mass of the structure, this can be calculated by:

$$F_{fw}^h = m_{fw} * a \quad (8.6)$$

In the same way, the horizontal load for the load transported, F_l^h , can be reached by:

$$F_l^h = m_l * a \quad (8.7)$$

The transportation height assumed here is 600 mm, which is an acceptable height regarding the elevation tower in use, with this distance being h_t . Now, it is possible to calculate C , stability coefficient:

$$C = \frac{F_{fw} * (l_{cg} + l_3)}{F_l * (l_6 - l_3) + F_l^h * l_t + F_{fw}^h * h_{cg}} \quad (8.8)$$

Here, the stability factor shows a value of 1.5, right on the acceptable value. The reactions in both wheels also shows different values. Here, $R_a = 49717$ N and $R_b = 8652$ N.

Emergency calculation - Limit situation

Here, the braking acceleration is given by $a_{emer} = 0.96$ m/s². This result was reached as result of research about AGV's braking systems [127, 128] and it is an overestimated value, in order to assure that safety is reached. Here the same approach as in the previous point is used, however the acceleration is the emergency braking acceleration.

$$F_{fwEmer}^h = m_{fw} * a_{emer} \quad (8.9)$$

$$F_{lEmer}^h = m_l * a_{emer} \quad (8.10)$$

$$C = \frac{F_{fw} * (l_{cg} + l_3)}{F_l * (l_6 - l_3) + F_{l_{Emer}}^h * l_t + F_{fw_{Emer}}^h * h_{cg}} \quad (8.11)$$

The resulting stability coefficient here is 1.15, being once again in the threshold of safety, avoiding overengineering. Also, the resulting reactions of this situation is $R_a = 81919$ N and $R_b = 3151$ N.

Finite Element Method

In order to simulate the situation illustrated in figure 8.5 with the available means, all profiles were treated as beams. Beam theory and its application in Finite Element Methods reduces drastically the size of the problem as the resources needed to simulate the situation. The use of beams is acceptable for static, buckling, frequency and non-linear studies. To produce acceptable results, they should be in length 10 times the largest dimension of its cross section and this was also taken into account. To obtain acceptable results, each beam was divided into 100 elements, creating in this way its mesh. A small explanation of beam theory and beams in SOLIDWORKS is available in section 3.2. The number of total elements for this iteration is 10949 and the number of total nodes is 10977. The global contact selected is "bonded".

Only the results for the last iteration are shown due to their relevance amongst the other previous versions. However, in order to understand the improvement process, the scorecards for every iteration are shown but only for some domains.

The overall structure meshing is available in figure 8.6.

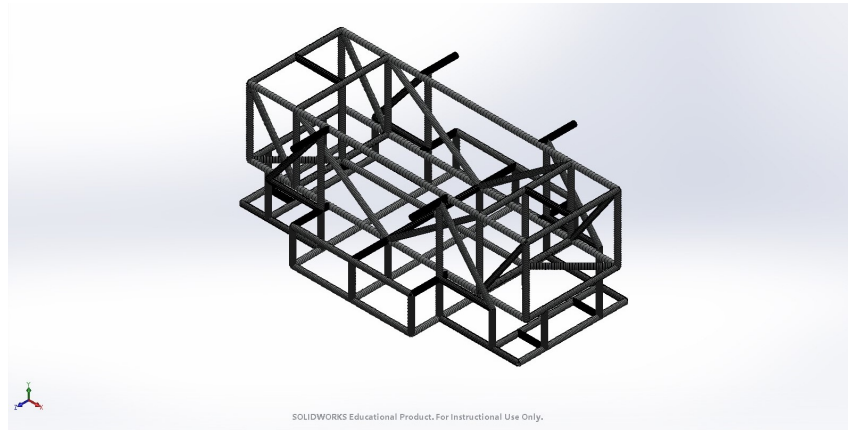


Figure 8.6: AGV's frame meshing

Static

For Static study and calculation, the worst case scenario was once again assumed, where the load is moved in the edge of the forklifts and it is the heaviest load possible at the highest possible height, of course, inside the threshold values. The Factor of Safety recommended in standards about Moving Platforms and forklifts, as an example, EN 1945:1997+A2 - Lifting Platforms standard in the worst case scenario is 1.5 [150].

The maximum load obtained for the worst load case is 193 MPa, resulting in a factor of safety of 1.8, a value close enough to the minimum threshold of 1.5 and not overengineered and the maximum displacement in the overall structure is 1.5 mm, however in only one beam, where the remaining structure shows displacements lower than 1 mm.

Figure 8.7, figure 8.8 and figure 8.9 have a graphical representation of stress distribution and the frames displacement with a deformation scale of 139.

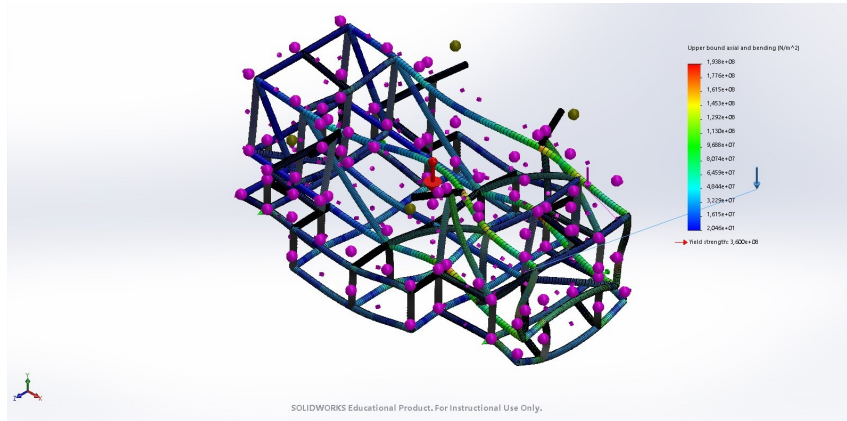


Figure 8.7: AGV's frame stress distribution

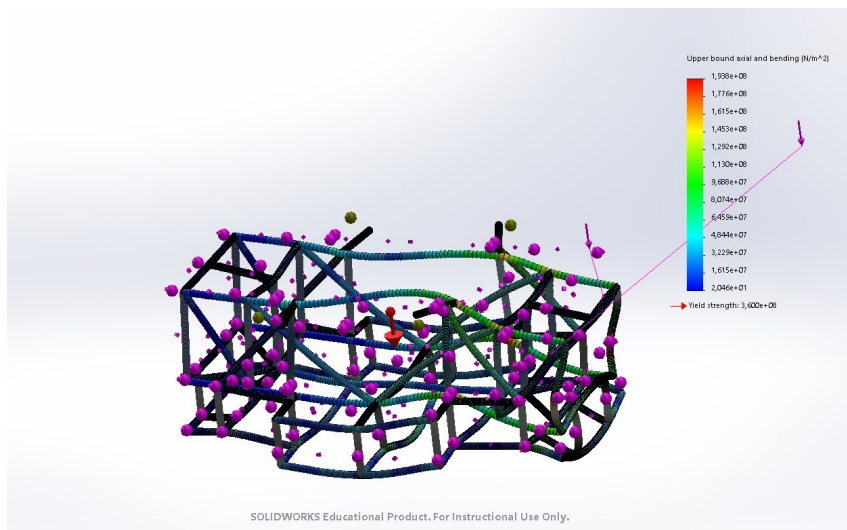


Figure 8.8: AGV's frame stress distribution

The loads were applied to the beams that are going to be connected to the forklifts with both the weight of the load and the forklift considered. These results considers that the maximum load is in those same beams. The others high loads can be verified in the beams next to the fixtures, the wheels, the front of the AGV, the part of the frame responsible to be connected to the forklift and the longest beams, the beams in the top plane of the AGV. This explains why these are larger profiles than the remaining ones.

Fatigue

Fatigue was also tested, since it is extremely important in these kind of structures. These vehicles are under stresses in a cyclic way. The loading cycles are varied since the loads are not the same every time. In order to test fatigue strength of the present frame, it was assumed also the worst case scenario and a loading cycle with the biggest amplitude possible, since the stress range is what will impact the weld details, as explained and verified in section 3.3 and in the work of Hobbacher [160]. Meaning a loading cycle between the maximum load at the forklift at the maximum height and no load carried in the forklifts is the assumed loading cycle.

To know the stress state and distribution in a no loading case, simulation in SOLIDWORKS was once again done and several details were analyzed. It is important to mention this because not always the detail with the highest stress represents the detail with the

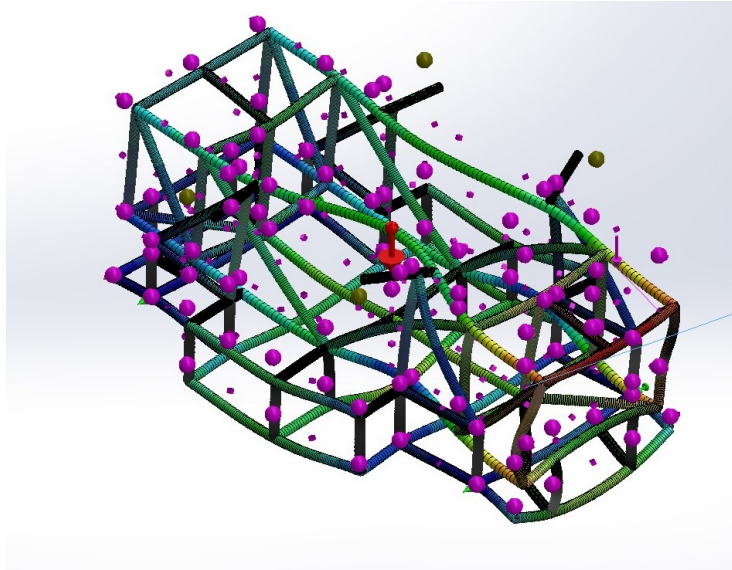


Figure 8.9: AGV's frame displacements

biggest stress range. Also the type of detail must be considered.

The threshold number of cycles to assume for AGV's frame in order to assure its safety in their expected life, is about $4 * 10^4$ cycles for normal duty machines or 10^5 cycles for heavy duty machines, assuring a 10 year lifespan for the vehicle. This value is result of analysis and research of literature and standards [148, 150].

In the last design, the critical detail with the least lifespan, in other words, with the fewer number of cycles can resist about $5 * 10^5$ cycles, assuring the frame's safety and durability for the needed life.

8.5.2 Iteration

To reach this final design, several iterations were done through time and in order to understand what was overdone or what was still to fulfill, LeanDfX framework was deployed. This is the strength of the framework and the overall purpose, so a systematic and organized approach to designing and improvement can be had.

In order to test the structure, QFD and FMEA methodology developed and LeanDfX framework, it was selected some X-Domains for DfX. Also, to allow an easy analysis and to reduce the number of scorecards with redundant information, some domains were combined due to their connection and similarity in some fields. The used domains were the following:

- Cost;
- Manufacturing;
- Recyclability/Environment;
- Standardization;
- Structural/Safety/Reliability;

For Structural/Safety/Reliability domain, a modular analysis was also done. This can give additional information about the life of each module and allowing upgradability and retrofitting due to the possible life expectancy calculation.

Cost

Cost has only a symbolic meaning, since the lack of knowledge of the writer of real industry costs. However, considering the usual cost of each material by its weight, provided by SOLIDWORKS and the usual cost of machining and weldment of the designed structure, also provided by SOLIDWORKS, it is possible to have a symbolic estimation of total cost. The value, even if there is a possibility to have a wrong estimation of the value, it is a useful value and feature when comparing between various iterations.

Manufacturing

Availing one tool available in SOLIDWORKS, DFMXpress, it is possible to calculate how easy to manufacture is the current structure. DFMXpress is an analysis tool that validates the manufacturability of parts, identifying which parts may be cost increasing or trouble causing in manufacturing [170]. The feature has 10 rules for milling and drilling processes and if every part of the structure passes the rule, then and only then the rule is seen and evaluated as passed.

Recyclability/Environment

Recyclability and Environment were tested from considering the percentage of recyclable material used for the frame and the number of components necessary for the structure. The threshold value selected was one, since a single block would represent the easiest recyclability, however, it is known that this is an unreachable value. Once again, this is only to aid the analysis and comparison between the several designs.

Standardization

Here, the only requirement tested is the number of standard components in percentage. Using normalized sizes and cuts represents a total use of standardized parts.

Structural/Safety/Reliability

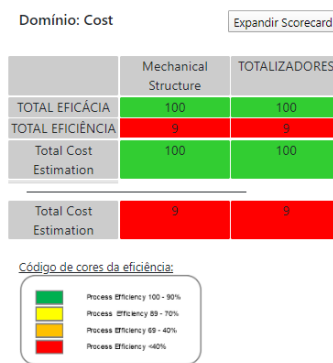
In what is the most critical domain overall, as seen in table 6.3, these were tested for the overall structure and for each module. To ensure this, already some measures were taken, like applying Fuzzy FMEA and some requirements in the technical requirements list. To complete this and to be possible to calculate if structure fulfills structural integrity variables and to know how far is the design to the best case scenario, the design variables chosen to apply to the framework were Number of Cycles (Fatigue) and Max Stress. The threshold values for this are already previously mentioned. Even if the threshold value for Factor of Safety assumed is 1.5, it was assumed that a Factor of Safety about 2 would be the ideal value. In the same way, 10^5 was the number of cycles assumed to be ideal because it would translate to failure through fatigue almost nonexistent.

Scorecards

Some additional scorecards generated for every iteration is in appendix I. Here, scorecards for iteration 1.1 and 1.4 for the mentioned domains are shown, in order to show the full improvement loop results. Then, an analysis to the scorecards results is done to see which were the done improvements. These are the main outtakes for LeanDfX framework and where the methodology shines the most.

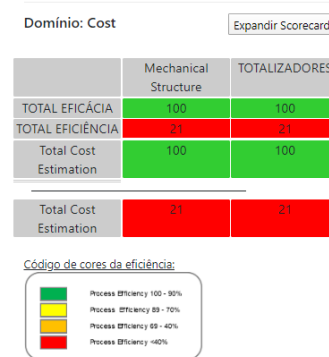
Cost domain

Scorecard do Módulo: Mechanical Structure



(a) Cost scorecard for iteration 1.1

Scorecard do Módulo: Mechanical Structure

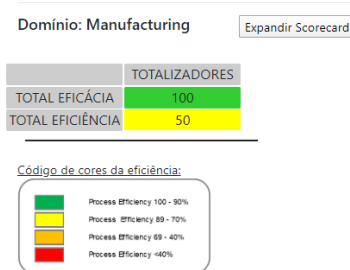


(b) Cost scorecard for iteration 1.4

Figure 8.10: Cost scorecards for first and last iteration in LeanDfX

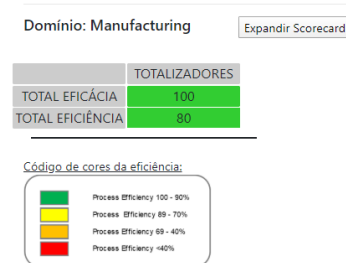
Manufacturing Domain

Scorecard do Módulo: Mechanical Structure



(a) Manufacturing scorecard for iteration 1.1

Scorecard do Módulo: Mechanical Structure

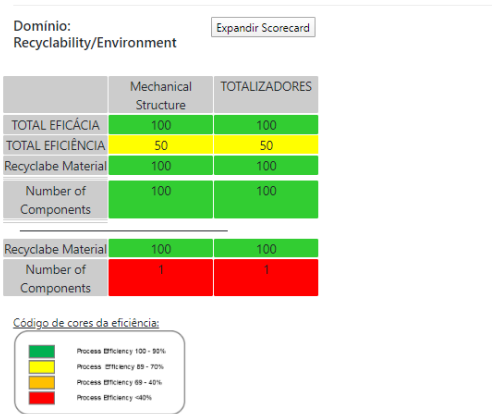


(b) Manufacturing scorecard for iteration 1.4

Figure 8.11: Manufacturing scorecards for first and last iteration in LeanDfX

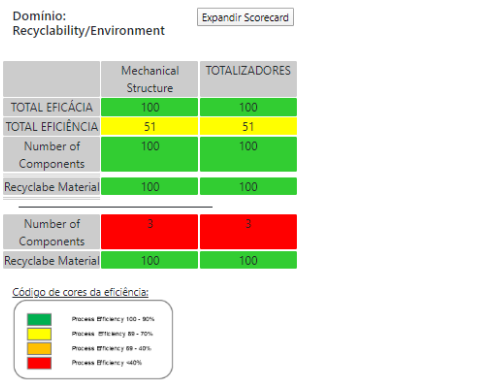
Recyclability/Environment Domain

Scorecard do Módulo: Mechanical Structure



(a) Recyclability/Environment scorecard for iteration 1.1

Scorecard do Módulo: Mechanical Structure

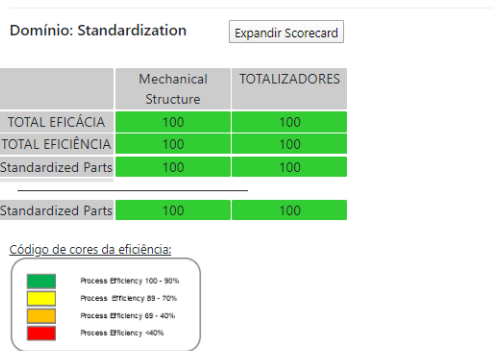


(b) Recyclability/Environment scorecard for iteration 1.4

Figure 8.12: Recyclability/Environment scorecards for first and last iteration in LeanDfX

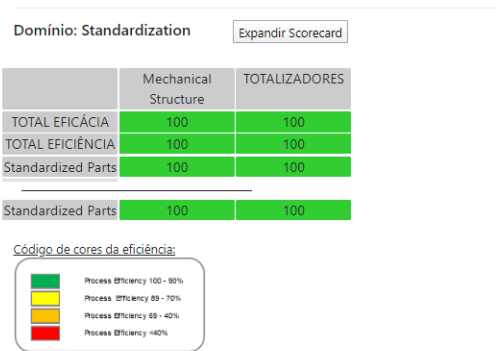
Standardization Domain

Scorecard do Módulo: Mechanical Structure



(a) Standardization scorecard for iteration 1.1

Scorecard do Módulo: Mechanical Structure

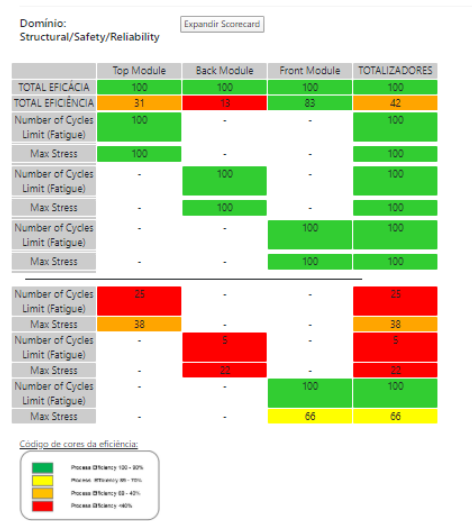


(b) Standardization scorecard for iteration 1.4

Figure 8.13: Standardization scorecards for first and last iteration in LeanDfX

Structural/Safety/Reliability Domain

Scorecard do Módulo: Mechanical Structure



(a) Structural/Safety/Reliability scorecard for iteration 1.1 overall structure

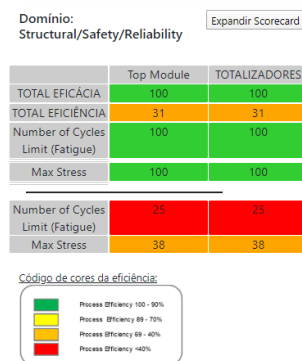
Scorecard do Módulo: Mechanical Structure



(b) Structural/Safety/Reliability scorecard for iteration 1.4 overall structure

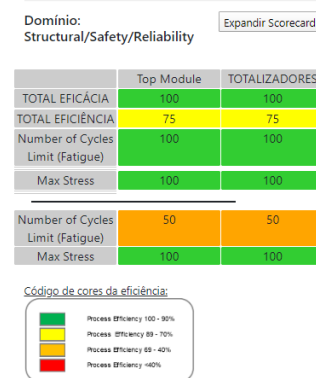
Figure 8.14: Structural/Safety/Reliability scorecards for iteration 1.1 and 1.4

Scorecard do Módulo: Top Module



(a) Structural/Safety/Reliability scorecard for iteration 1.1 Top Module

Scorecard do Módulo: Top Module



(b) Structural/Safety/Reliability scorecard for iteration 1.4 Top Module

Figure 8.15: Structural/Safety/Reliability scorecard Top Modules

Scorecard do Módulo: Back Module



(a) Structural/Safety/Reliability scorecard for iteration 1.1 Back Module

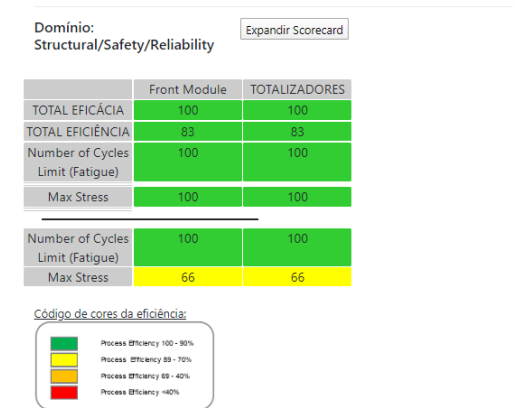
Scorecard do Módulo: Back Module



(b) Structural/Safety/Reliability scorecard for iteration 1.4 Back Module

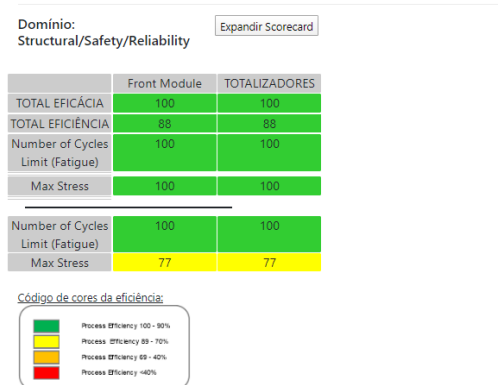
Figure 8.16: Structural/Safety/Reliability scorecard Back Modules

Scorecard do Módulo: Front Module



(a) Structural/Safety/Reliability scorecard for iteration 1.1 Front Module

Scorecard do Módulo: Front Module



(b) Structural/Safety/Reliability scorecard for iteration 1.4 Front Module

Figure 8.17: Structural/Safety/Reliability scorecard Front Modules

8.5.3 Scorecards Analysis

Due to the visual representation possible by the framework, the scorecards comparison and analysis is easier. Before the full results analysis, it is important to acknowledge that every iteration fulfills the clients requirements, this is, the initial requirements demanded by JPM Industry. This means that the information in appendix G applies to every iteration, where the column "Estado", in English, State, is true. This happened due to the use of Lean DfX Fuzzy QFD methodology, allowing to recognize where the focus must be from the start of the project. This already can prove some value in the developed methodology since it allowed that from the first iteration, every single requirement was fulfilled and made the improvement process much quicker and earlier in the designing process. This makes it possible to reach much better results from the added time to the improvement loop process.

Cost

In the cost domain it is important to have a relative analysis to it. Since the ideal value was decided in being basically five times less the cost assessed for the last iteration, the jump from a total efficiency of 9 to 21 means more than the color red in the field. In its essence, this is a cost reduction to more than a half from the first to the last version of the design, almost two and a half times less, showing that the iteration process worked in an efficient manner in this domain.

Manufacturing

Relying in the information given by SOLIDWORKS in DFMXpress analysis, the design has improved greatly from the first iteration to the last, where from the 10 rules established by SOLIDWORKS [170], the first version only passes half of them. However, the last version passes 8 of the 10 good practices rules, making it much better for manufacturing. As it can be seen in figures 8.11a and 8.11b, efficiency grows from 50% to 80%, once again, having an efficiency in the green color.

Recyclability/Environment

From the two selected design variables for this domain, the use of recyclable materials have the same result because both use the same material, steel, a recyclable material. However, in the design variable of the number of components, significant changes were made, resulting in considerable improvements. Once again, it is important to apply a relative analysis to the value. Since the used ideal value was one, assuming to be a one component block, it is normal that efficiencies for this variable are low. However, when comparing one to the other, it is possible to verify that the number of components from the first version to the last that was done, was reduced by 3 times. This means a great upgrade from one version to the other.

Standardization

Since every component used in the frame from the start were standardized components, due to the results obtained in Lean DfX Fuzzy QFD, this was regarded from the beginning.

Structural/Safety/Reliability

This is probably the most important domain, as it can be seen from the results in table 6.3. This is a combination of several domains and 3 of the top 4 with the highest weight. As expected from Appendix H, the first version is much more complex than the last version.

As a result, overengineering and overdo is shown in the scorecards figure 8.14a, 8.15a, 8.16a and 8.17a. Even if it presents an effectiveness of 100%, it has a low efficiency due to the overengineering in several variables. As it can be analysed, only the front module has a good efficiency because it is the one with the higher stresses and load cycle. It is the module connected to the elevation tower, explaining why this is. However, the other two modules show a high level of "oversafety", which is against lean thinking and what is desired. The total efficiency presented for the whole structure is 42%.

For the last version it can be seen that efficiency rose to much more acceptable values, evolving from 42% to 65% and showing that only the back module is much more robust than what is necessary. However, this is not a problem because of how this design was designed. Allowing the possibility to connect the elevation tower to both sides makes that this back module becomes only robust enough if it is necessary to connect the elevation tower to it. Taking this into consideration, real efficiency value is higher than what is presented in the scoreboard figure 8.14b and 8.16b. The only module that suffers real overengineering is the top module, however its efficiency has good enough value to allow its manufacturing, 75%.

8.6 Final and total analysis

In this final section, the results for the four considered iterations are discussed and also the last design pros and cons in relation to the previous versions.

All scorecards are presented in Appendix I. In the cost domain, iteration 1.4 does not present the best result, with this being iteration 1.3, as it can be seen in figure I.2a and figure I.2b. However, considering the other domains, version 1.3 was far from perfect and a possible increase in the manufacturing cost department is justified due to the improvement in the other domains. The cost for version 1.2 (figure I.1b) and 1.4 are similar, but, once again, version 1.4 presents much better efficiency in the other domains. In figure 8.18 is a representative graphic of the evolution of efficiency through the four iterations.

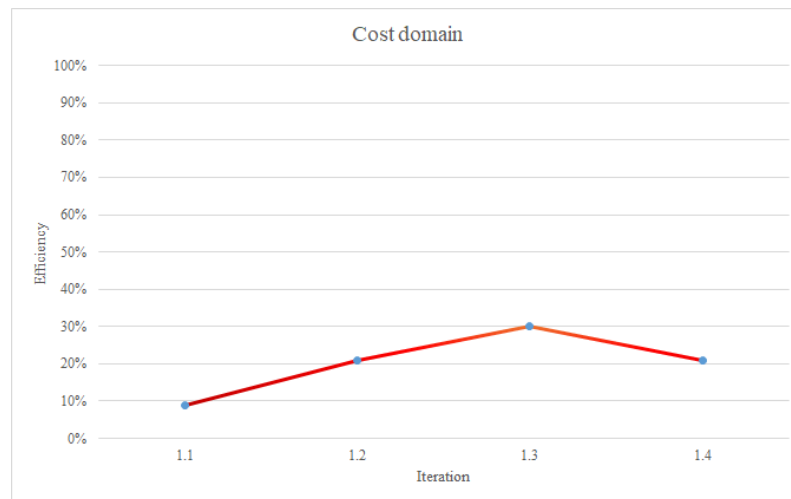


Figure 8.18: Evolution of efficiency in cost domain

Manufacturability has a grow for every version, where each iteration has a better manufacturing evaluation according to DFMXpress. This is due to the fact of the decreasing number of components and difficult cuts to each part from the various versions. Sharp internal corners, fillets in outside edges and inaccessible features are drastically reduced from the first version, even to the point of being non-existent in the last version, making it the most manufacturing friendly. In figure 8.19 is a representative graphic of the evolution of efficiency through the four iterations.

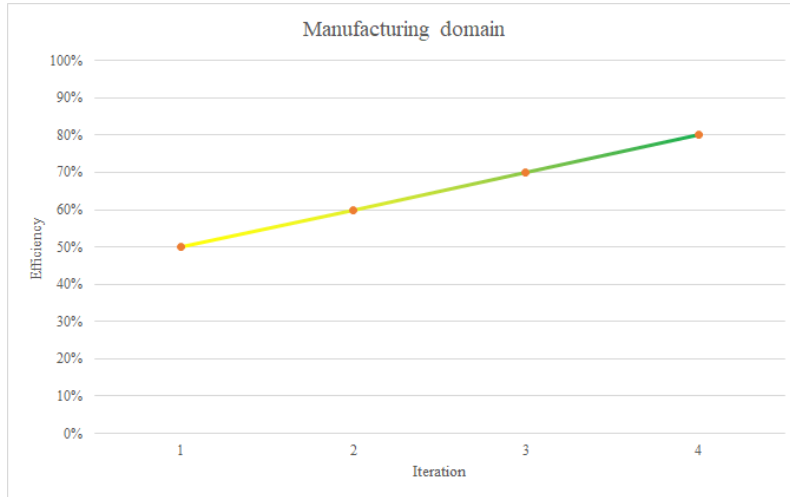


Figure 8.19: Evolution of efficiency in manufacturing domain

Another domain that improved through all iterations is recyclability, mainly the design domain of Number of Components. Through the time, the number of parts was reduced so it was possible to ease assembly and manufacturing and as a consequence, a good consequence, the domain dedicated to environment has a better performance. In figure 8.20 is a representative graphic of the evolution of efficiency through the four iterations and in figure 8.21 is about the standardization domain.

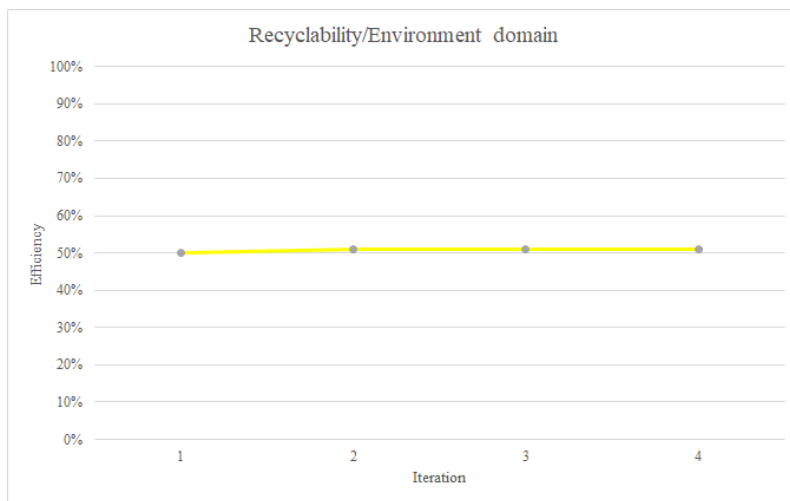


Figure 8.20: Evolution of efficiency in recyclability/environment domain

In the structural/safety/reliability Domain is where several improvements were done. In the top Module, efficiency grows, where there is a total improvement from 31% (figure I.9a) to 75% (figure I.10b). It is also possible to see that stresses are better distributed through all structure, reducing the overengineering in the top modules of versions 1.1, 1.2 and 1.3. The same does not apparently happens with the back module of the last version, where loads are distributed in a more efficient way in version 1.2 (figure I.11b) and version 1.3 (figure I.12a). However, when considering the hypothesis to connect the elevation tower to both sides of the vehicle and allocating the electrical cabinet in either opposite side, the values for this back module are not completely representative of its true potential. The true efficiency for the back module for version 1.4 (figure I.12b) can almost be seen as what is shown for the front module (figure I.14b). Finally, for the front module, the first iteration, 1.1 (figure I.13a) presents the second best efficiency of all, but is overengineered,

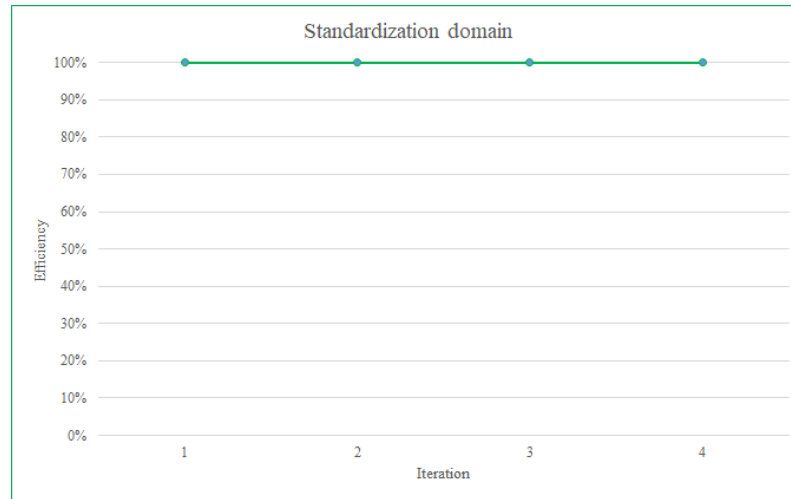


Figure 8.21: Evolution of efficiency in standardization domain

more expensive and with more parts than any other version. Versions 1.2 (figure I.13b) and 1.3 (figure I.14a) are good enough for the minimum required, however they do not present the most desirable values, mainly the risk of fatigue failure in version 1.3. However, the front module in version 1.4 (figure I.14b) show almost perfect efficiency, with only a higher stress in the structure than the perfect stress recommended. As a result of these three modules, LeanDfX calculates the total efficiency of the vehicle through the combination of the efficiency of those. Even without considering the possibility to connect the forklift to any side, version 1.4 (figure I.16b) shows the best overall efficiency in comparison to the other three versions (figures I.15a, I.15b and I.16a). In figure 8.22 is a representative graphic of the evolution of efficiency through the four iterations for the whole structure, figure 8.23 for the top module, figure 8.24 for the back module and figure 8.25 for the front module.

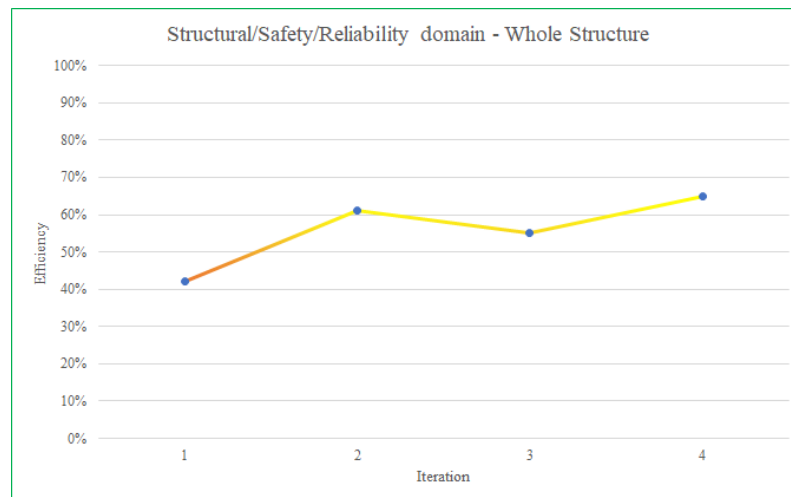


Figure 8.22: Evolution of efficiency in structural/safety/reliability domain for the whole structure

Now, it is important to analyse the design from requirements and FMEA standpoint. Starting from QFD results (tables 6.1 and 6.2), the placement for every component needed is accomplished within the proposed design, so every placement needing requirement is fulfilled. Elevation Tower connection is assessed and in an upgraded way, where there are two possible connections for the forklifts, making maintenance a lot easier, retrofitting

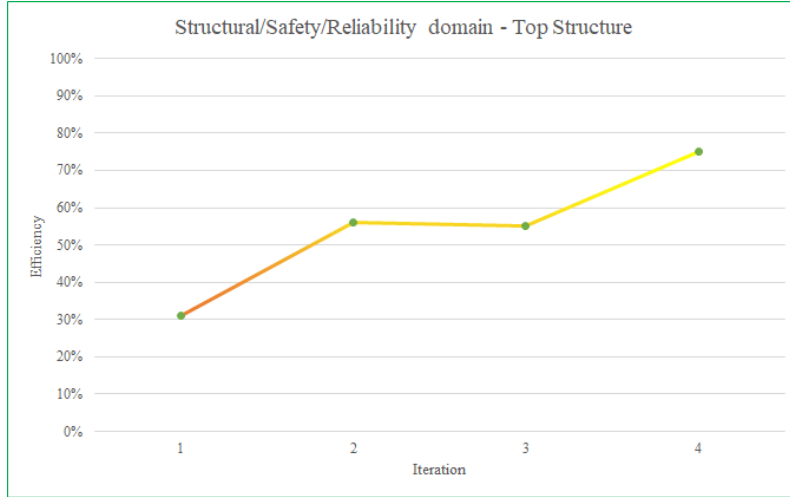


Figure 8.23: Evolution of efficiency in structural/safety/reliability domain for the top module

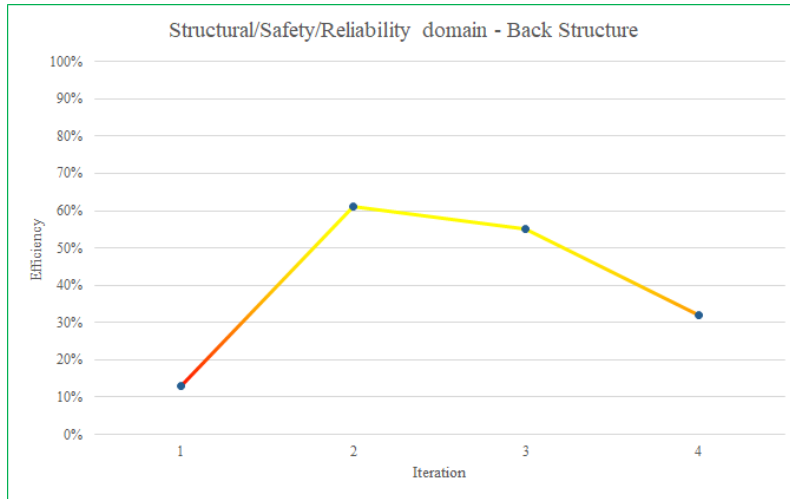


Figure 8.24: Evolution of efficiency in structural/safety/reliability domain for the back module

possible and failure much less likely, because of exactly what is referenced. Regarding scanners requirements, they are also taken into consideration in the last design. Additionally to the needed space, minimum height for scanners is considered, where taking into account the height of the AGV from the floor, 50 mm, assures that it is in the needed height. Then, the compartment made for them assures their security and protection with the aid of sheet metals. The scanners would be 100 mm "inside" the frame. This design also makes it possible, in the case of some defect or need to maintenance to some scanner, to connect the scanner to any corner where a space for a scanner is existent. Finally, loading, lifting capacity, AGV Speed and battery weight sustainability is accomplished through the structural calculations made in this same chapter. Finally, limit dimensions also are fulfilled, where the last design has $2000 * 1190 * 750$ ($l * w * h$) as dimensions.

Considering the technical requirements resulting on the additional requirements, the number of standard pieces, simple parts and identical components are all fulfilled because every part is a standardized squared beam, with only two different cross section areas only and simple cuts in most of the cases. Modularity is completely assessed also. As it can be seen in appendix H, this version is symmetrical in 2 planes. Safety standards and

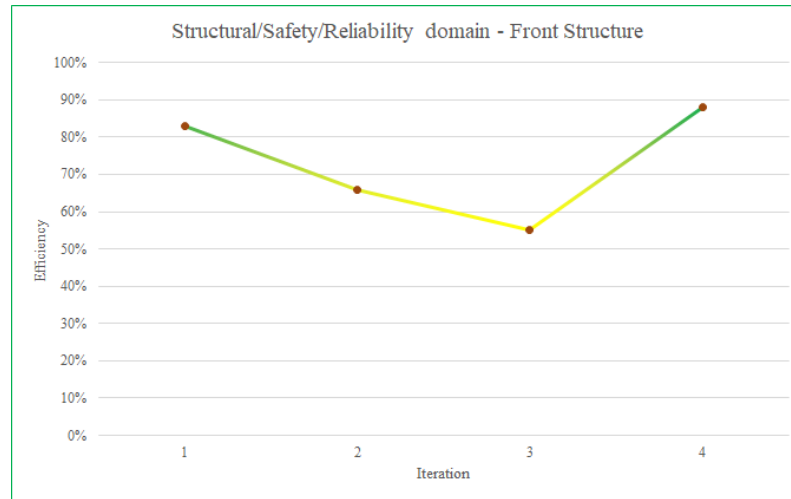


Figure 8.25: Evolution of efficiency in structural/safety/reliability domain for the front module

directories are mainly considered in the design. As an example, a few points considered in the design from Machine Directory can be mentioned. They are points 1.1.2., 1.3, 1.4, 1.5, 3.4 and 4.1.2, to name a few. To illustrate also, in standard ISO 12000, minimum gap between moving parts and avoiding sharp corners are another points considered, existing many more points in consideration. Once again, mechanical characteristics are all considered in this same chapter, in previous sections dedicated to structural and fatigue calculations. Accessibility to any component is easy, as already explained in the module analysis (section 8.4).

From FMEA, the measures taken in order to reduce failures were the following:

- Structural and Fatigue calculation in order to reduce chassis and forklift failure;
- Easy accessibility to welding points through modularity;
- Easy accessibility to wheels to allow easy maintenance and substitution;
- Easy accessibility to motor to allow easy maintenance and substitution;
- Easy accessibility to gearbox to allow easy maintenance and substitution;
- Easy accessibility to controllers and scanners to allow easy maintenance and substitution;
- Easy accessibility to Battery to allow easy maintenance and substitution;
- Above needed space for Battery to reduce overheating;
- Easy accessibility to Electric Cabinets to allow easy cleaning, maintenance and substitution;

Chapter 9

Future Works and Conclusion

9.1 Conclusion

This project had its focus on the articulation of advanced tools for product development, more specifically, on trying to complement Lean Design-for-X framework, a framework developed by INEGI, a non-profit private association committed to Research and Development in the industry that narrows the gap between Industry and University. Several different methodologies and/or tools were applied and developed in order to meet that goal, such as QFD, Quality Function Deployment. To test the results and the efficiency of the developed methodology and framework, an Automated Guided Vehicle frame, or AGV chassis was selected as the case study from an existing project inside JPM Industry, a Portuguese company based in Vale de Cambra focused on being a worldwide player in the intralogistics market, marking its position by its excellence. This project was also done under the umbrella of the project "PRODUTECH SIF - PPS5", a plan focusing on the development and implementation of new production systems to meet the challenges and opportunities of the 4th industrial revolution.

In the first place, to enable a critical and complex analysis to the framework and how some existing tools could help the product design development process, an extensive state of the art review was done, meeting at the same time, one of the objectives proposed from the start of this dissertation. This was essential to identify that even if several tools are being developed to facilitate the designing process and to reduce costs, some are still somewhat unpolished or too uncomfortable for small companies to use them. There is also some hesitations from several companies, mainly the smaller ones in employing this methodologies, because they are usually seen as a waste of time and not advantageous enough. From the research that was done, it was also possible to conclude that the incorporation of Design-for-X methodologies is increasingly growing and their combination with other tools also. From the several tools that are combined with Design-for-X methodologies or useful frameworks to apply in project design and development process, some were taken into consideration as a possible option to LeanDfX framework complement.

To aid the choice of which tools could be implemented in order to overcome some problems in general product design development tools and specifically, LeanDfX framework, an already finished project was deployed in this same framework. From the identified hurdles for a first-time user, it can be mentioned:

- Hard definition of project requirements;
- Project modularity;
- Difficult selection of Design Domains;
- Some vagueness in the selection of indicators and parameter values;

- Lack of guidelines or processes to apply for several domains;

Some methodologies were selected to apply to this project from the aforementioned obstacles. Towards covering the first three points and starting the deployment process of the framework, QFD was chosen and adapted. The reason behind this choice is that QFD works almost as a translator of customer requirements into engineering and technical specifications and helps the planning and assurance of quality, focusing on only what is necessary as in Lean thinking. To reduce even more the vagueness of the several project requirements and to have a systematic and correct approach to the designing process, Fuzzy Set Theory was applied to QFD. It is a theory already combined a few times with QFD and it reproduced good results from the several methodologies available in the existent literature.

In order to cover mainly the last two problems identified, FMEA was also applied and adapted to LeanDfX framework. FMEA is a quality tool and can help the creation of parameter values, indicators or guidelines for some domains, such as safety, reliability or structural integrity. Fuzzy Set Theory was also implemented in FMEA due to the associated uncertainty to the values given to the variables in the tool. Both QFD and FMEA were totally modified and upgraded from their classical approach so they are adapted as possible to the framework, taking advantages from what they can offer.

Also, the AGVs frame was also a case of research and the several norms that are usually applied to the designing process and structural calculation of the frame were analysed so it was possible to have the best approach to the design process.

After the implementation and development of the now named, LeanDfX Fuzzy QFD, FMEA and the design of the AGV, it is possible to have several conclusions regarding on how these complement and connect with Lean DfX framework. The main conclusion that can be taken from the implementation of both developed methodologies is the overall time reduction that resulted from their implementation. This is analysed later in this same chapter.

The implementation of QFD to the framework led to various conclusions. LeanDfX Fuzzy QFD can be a preceding methodology to the framework because its use has many advantages. These are:

- A smooth transition for the LeanDfX framework;
 - Easy definition of requirements, its values and direction of improvement;
 - Easy selection of Domains;
 - Modularity is facilitated;
 - Some parameters and indicators are already here chosen and defined;
- Ranking of the requirements from the most important to account in the designing process to the least, allowing to focus on what adds more value;
- An evaluation on designing trade-offs through the roof matrix;
- An experience or job ranking system that allows that more experienced works in the area of analysis have bigger influence in the overall result;
- A possible direct connection to the software since everything can be automated and the job choice is also available in QFD;
- Elimination of some uncertainty connected to the requirements and their value, as their ranking due to the use of Fuzzy Set Theory;
- An existent, made in this project, instructions document to aid the filling process of the document (easily understandable from the brief application of it);

- A defined starting point to any designing product design and development process;

The other tool directly implemented and tested for LeanDfX framework was Failure Mode and Effect Analysis or FMEA. From its deployment, some advantages are:

- The range of domains directly covered in such tool;
 - Durability;
 - Maintainability;
 - Quality;
 - Reliability;
 - Safety;
 - Structural Integrity;
- Definition of guidelines for some domains through the filling process of FMEA;
- An experience or job ranking system that allows that more experienced works in the area of analysis have bigger influence in the overall result;
- A possible direct connection to the software since everything can be automated and the job choice is also available in FMEA;
- Early identification of possible failures of the design, avoiding them or at least reducing their risk;

Even if these are some great advantages for both tools, the most important one and coincident in both, is how their implementation on par with LeanDfX leads to a clear reduction of time spent in the designing process. Having from the start of the designing process what should be the focus in order to fulfill what the customer asks for, allows to have an acceptable design and one that met every requirement from the first iteration.

This also allowed that the time spent on the improvement loop step, improving the product was much bigger, ending with a better product with the same time. Of course, the deployment of these three tools, obliges that the true designing phase starts a little later than without all the planing and systematic approach. However, in the end, the time spent earlier in planning, allowed the project to reach its demands much earlier than expected, meeting what the customer wanted from the start, even with possible difficulties associated to the COVID-19 outbreak. This extended the period of time dedicated to improvement of the design, reducing overengineering situations, reducing costs, directly and indirectly. Directly from reducing means and material due to the overengineering reduction and indirectly, from predicting possible causes of problems in the life-cycle of the product, thanks to the heuristic analysis that LeanDfX framework allows and reducing their occurrence risk.

Obviously, none of this would be possible without the professional type of work and excellence associated to both companies that participated in this project. The great receptiveness of JPM Industry in having even a more structured approach to design processes and their commitment to excellence and the freedom given by INEGI, allowed the project to reach a higher result than the designed one.

Directly to LeanDfX framework only, from the several advantages already mentioned through the document and in chapter 4, one that deserves a special notice is the capacity to compare the several iterations or versions for the project. Through the scorecards generated in the framework, a very straight analysis to the results and their comparison to previous or future versions can be made, opening many improvement opportunities. With this, it is possible to know how some changes affected the overall results and where the

focus should be from the point of analysis through the color scale available for effectiveness and efficiency. Finally, in appendix G is presented a pdf file generated with a checklist confirming that every requirement asked for was met.

Regarding the final design of the AGV, in addition to what was mentioned in chapter 8, it is important to recognize that not only without the implementation and deployment of these tools and framework, but also the fact that the design would not be so advanced, the certification of met requirements for the project would not be as easy as it was. The ranking of engineering certifications, their deployment on LeanDfX framework and the generation of scorecards allowed a quick certification that the initial needs were met.

9.2 Future Works

Much more work can be done towards the improvement of LeanDfX, QFD, FMEA and even the AGV. Approaching this final section in the same logic of the basis of the document, a structured analysis to each one is done.

From LeanDfX point of view, some features can be added in the future to complement and increase the potential of such framework. These may be:

- Association of weight to each requirement, allowing their ranking and connection to LeanDfX Fuzzy QFD;
- Possibility of definition on how requirements connect with each other so trade-offs are easily identified in later stages of the project;
- Possibility to have non mandatory requirements;
- Priority analysis, in other words, make possible to see what are the most important requirements in order to increase product value;
- Connect requirements and specifications to domains when possible;
- In the design-for-standardization or for norms, have a database of norms applicable to the module under analysis;
- Analysis of the data in each scorecard;
- Possibility of Machine Learning regarding the available data in the scorecards and the interactions between "X" domains and design variables;

In the case of the LeanDfX Fuzzy QFD, there is still work that can be done:

- Possibility to create line/column automatically, adding also the needed spaces in the roof matrix;
- Direct and automatic connection between Client/Customer requirements HoQ and Additional requirements HoQ with CRAR QFD-LeanDfX;
- Addition of this methodology to LeanDfX framework;

FMEA can also be improved, simply by connecting FMEA with LeanDfX framework and implementing FMEA as a Design-for-Safety/Reliability/Structural Integrity guideline or variable.

Finally, considering the AGV, the improvement loop is not finished in this point and it can be improved even more by:

- Applying the same methodology to the other modules(Direction, Traction, Elevation and Safety components);
- Reducing even more the number of components and cost;
- Reducing structures complexity due to the harder cuts;
- Pass the remaining two rules regarding DfMA;
- Better scanner protection compartment;

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Appendix A

Gantt Chart



Figure A.1: Gantt Chart made in GanttProject

Appendix B

How to use LeanDfX Fuzzy QFD

B.1 Introduction

Lean DfX Fuzzy QFD is a Fuzzy QFD inspired methodology to help the implementation of LeanDfX framework and a systematic approach to the organization and clarification of client and customer requirements and also, if needed, additional requirements for good design principles or goals.

It is a three procedure methodology and in the end, it has 6 main goals:

- Clarification of customer and client requirements and its functional requirements;
- Ranking of the most important technical requirements to implement in the design of the product in analysis;
- Identification of trade-offs between technical requirements;
- Choice and identification of which domains shall be used in LeanDfX;
- Choice and identification of the indicators and parameter values that shall be deployed in Lean DfX;
- Start the deployment process of LeanDfX;

LeanDfX Fuzzy QFD, or LeanDFQ involves filling 3 documents in order to complete the methodology (there is an optional stage if desired); To help the procedure for each one, a step by step instruction is available in this document. The 3 stages plus the optional are:

- Client/Customer requirements HoQ;
- Additional Requirements HoQ;
- CRAR(Customer Requirements and Additional Requirements) QFD-LeanDfX;
- (Optional) LeanDfX Domains Weighting;

There is a possibility, if the team wants, to also have a fourth stage, dedicated to the weighing of the various domains available in Lean DfX framework. Since it is optional stage, it is only explained in the end of the document. For a better understanding of the full process, a deeper explanation of the process is available in the methodology project. The next section focuses on a small explanation on each space. If a full understanding of the basis of the methodology is not necessary for contributing to the process, it is recommended to read the present document.

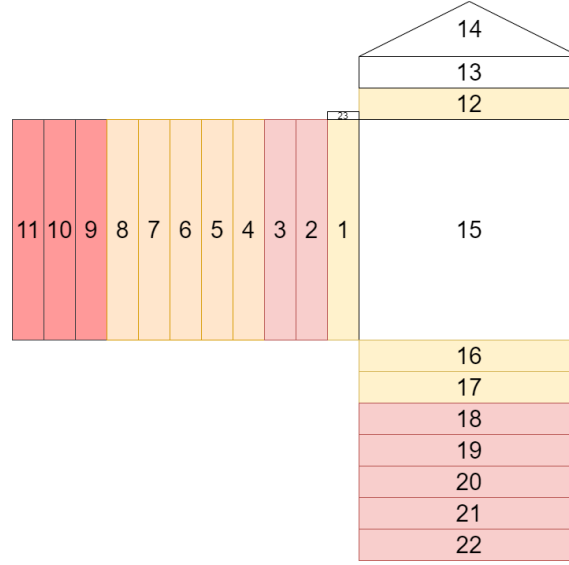


Figure B.1: Concept figure of Client Requirement HoQ

B.2 Stages

B.2.1 Stage 1: Client/Customer requirements HoQ

The first stage is based on a classic HoQ from QFD. Each space is explained and a concept of the House of Quality is illustrated in figure B.1.

Space 1 - Customer Requirements

The first space is the Customer Requirements column as they are given by the client/customer. This space should be filled by the team responsible for the project. It represents the "What's" for the project in analysis.

Space 2 - Max Relationship

This is an automatic column that represents in a number, the maximum value of relationship of the customer requirement on row r , CR_r for every functional requirement. It can assume any value between 0 and 9, depending on the matrix 15, the relationship matrix. The desirable value should be 9, meaning that there is at least one functional requirement dedicated to the customer requirement under analysis. The value may be translated as $MRCR_r$.

Space 3 - Importance

Importance column is where the user tries to give a weight to the customer requirement, regarding on how important it is, from a scale from 1 to 9. This must be filled by the selected people and the value for the given row, r , is translated as IC_r .

Space 4 - Fuzzy Importance

This column translates the importance given by the user in a Fuzzy logic, where different values for the same importance may be reached due to the Job field that will be filled. This is an automatic space.

Space 5 - Type of Requirement

Here, the team should specify what type of requirement is the customer requirement on the given row, that is, CR_r . In this first stage, almost or every requirement will be a "Client" requirement and that is the value that should be filled by the team. This space is important for an organizational point of view.

Space 6 - X-Domain

If a team already wants to specify a certain domain to a customer requirement, so at least one domain can be given to facilitate the third stage; That step may be done in this column.

Space 7 - Sub-Part

This column must indicate which sub-part or module the customer requirement is about. It helps for further deployment of LeanDfX in the modularization step.

Space 8 - Part

The "parent" module of the sub-part in the Sub-Part column shall be the value in this column. It must be filled by the team and it also helps for further deployment of LeanDfX in the modularization step.

Space 9 - Weight Chart

In this column a chart with the relative weight calculated in space 10 is represented; Automatic and no need to fill.

Space 10 - Relative Weight

Relative weight in percentage is what is presented in this column. Also automatic, meaning that it is not to be filled; This is calculated from the division of the "Importance" of the customer requirement of the row by the sum of all "Importance" ratings given for each customer requirement.

If IC_r is the importance of the customer requirement on the row r and R the total number of rows, then the relative weight of customer requirement on the row r , RWC_r , is given by:

$$RWC_r = \frac{IC_r}{\sum_{r=1}^R IC_r}, \quad r = 1, 2, \dots, R \quad (\text{B.1})$$

Space 11 - Row

This space is simply, row number; Automatic as well.

Space 12 - Functional Requirements

In this row, the team must specify the "How's", this means, how to translate the customer requirements in technical requirements for the team. It must be filled by the team and this has extreme importance for the overall process. This value may be translated as FR_c , meaning Functional Requirement for column c .

Space 13 - Direction of improvement

Regarding the Functional Requirement on a given column, the direction of improvement should be decided by the team. It has 4 possible values in this space:

- $\uparrow$, meaning that the value in the technical or functional requirement shall be maximized;
- X, meaning that the value is the target value;
- $\downarrow$, meaning that the value in the technical or functional requirement shall be minimized;
- *blank space*, meaning that no information is useful for the direction of improvement;

Space 14 - Roof Matrix

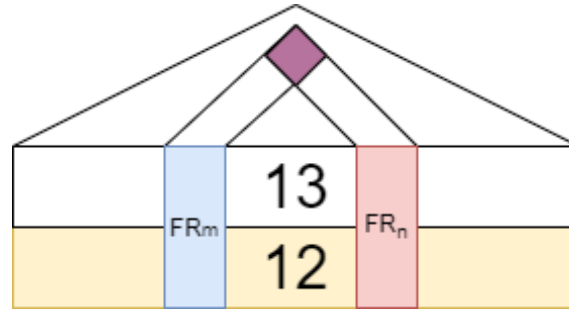


Figure B.2: Auxiliary figure to Roof Matrix

This matrix must be filled also by the team and it has extreme importance for future decisions in trade-offs. Regarding the two functional requirements that originate the space under analysis, their possible existing relationship shall be defined. This space may be filled with 5 values but a simpler 3 value approach is also possible. The possible values are:

- ++, meaning that the dependence between functional requirements is strongly positive;
- +, meaning that the dependence between functional requirements is positive;
- NO or *blank space*, meaning that there is not an existing dependence between functional requirements;
- -, meaning that the dependence between functional requirements is negative;
- --, meaning that the dependence between functional requirements is strongly negative;

For a 3 value approach, the values should be: +, NO or *blank space* and -.

To help understand the space under consideration, the purple space in figure B.2 is the one that relates the dependence between functional requirements FR_n and FR_m .

Space 15 - Relationship matrix

This is the main focus of QFD, the relationship matrix. The goal of this space is to identify how the customer requirement on row r , CR_r relates to the functional requirement on column c , FR_c . In the most developed version of the methodology, a 9 value scale is available to fill the space under analysis. The chosen value should measure the "strength" of relationship between the requirements. In the case that no relationship exists between requirements, a blank space should be left. The values are the following:

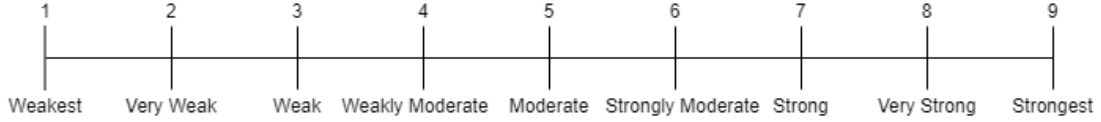


Figure B.3: Graphic representation of the 9 value scale and its crisp weights

It is also possible to have a 5 value scale or a 3 value scale and that it is a choice to be made by the team. The advised 5 value scale is: Weakest < Weak < Moderate < Strong < Strongest; and the advised 3 value scale is: Weakest < Weak(It corresponds to Moderate) < Strongest.

In figure B.3, the weights represented are the crisp weights, however the weights considered are in a Fuzzy Logic. The process behind the transformation is explained in greater detail in the main report.

Space 16 - Target

Here the user must fill with the target value of the functional requirements in the column under analysis. It can be a number or an information.

Space 17 - Unit

This row is where the user must specify what is the unit for the target value of the column under analysis.

Space 18 - Max Relationship

The same as in space 2 but this is the maximum value of relationship of the functional requirement on column c . Once again, it will be a value between 0 and 9, desirably 9 and it can be translated as $MRFR_c$.

Space 19 - Fuzzy Technical Importance

Also behind the same logic as space 4, this row is automatic and has the values of the technical importance in a Fuzzy Logic. This depends on the relationships of the functional requirement, the Job field and the importance rating given to each customer requirements. To fully understand the calculus behind this field, the dedicated chapter in the project regarding the methodology should be read.

Space 20 - Technical Importance

This column is the average value of the 4 Fuzzy Technical Importance values of the functional requirement under analysis. It represents how important the functional requirement is to meet most of the customer requirements, and allows the ranking of the various functional requirements, helping the decision process in designing stages. If for each functional requirement on column c , FR_c , 4 fuzzy technical importance values are used, FTI_{ci} , where

i is a number between 1 and 4, the Technical importance for column c , TI_c , can be obtained by:

$$TI_c = \frac{\sum_{i=1}^4 FTI_{ci}}{4} \quad (B.2)$$

Space 21 - Relative Weight

In this column, the relative weight of the Technical Importance on the column c under analysis is given in percentage. This helps the understanding and decision making of implementation for each functional requirement.

If TI_c is the technical importance of column c , and C is the total number of functional requirements, then the relative weight for each functional requirement can be calculated by:

$$RWF_r = \frac{TI_c}{\sum_{c=1}^C TI_c}, \quad c = 1, 2, \dots, C \quad (B.3)$$

Space 22 - Weight Chart

A graphic chart of the relative weight of the functional requirement under analysis is represented in the space 23.

Space 23 - Job/Experience

In this space, depending on the Job or experience of the user, a certain option shall be chosen. At the stage of development of the methodology, 3 levels are available and each one has a different weight on the final calculus of the combined QFD from the different users. This allows that people with less experience on the project, if wanted, have less influence on the final decision and values given by the QFD.

The 3 available options are the following:

- Poor Experience, if the user has between none to 2 years of experience in the field;
- Medium Experience, if the user has between 2 and 6 years of experience in the field;
- Good Experience, if the user has 6 or more years of experience in the field;

Of course, this can be chosen as the design team wants and its final use is also decided by the design team.

B.2.2 Stage 2 - Additional Requirements HoQ

This stage is very much similar to the previous one however, there are small tweaks that makes it different. The concept is the same as in the previous stage, regardless, it is available once again in figure B.4.

In this section, spaces analysed are the ones that change from the previous stage. If a space is not mentioned in this section, it is because it has the exact same purpose as in the Client Requirements HoQ.

Space 1 - Additional Requirements

It is almost the same as Client/Customer Requirements, however, these are usually not directly transmitted to the team as essential, or at all. This is also a column that should be filled by the whole team, and it is in this House of Quality that requirements that maybe are not directly mentioned as "Easy to Assembly" or "Respect safety norms" may appear.

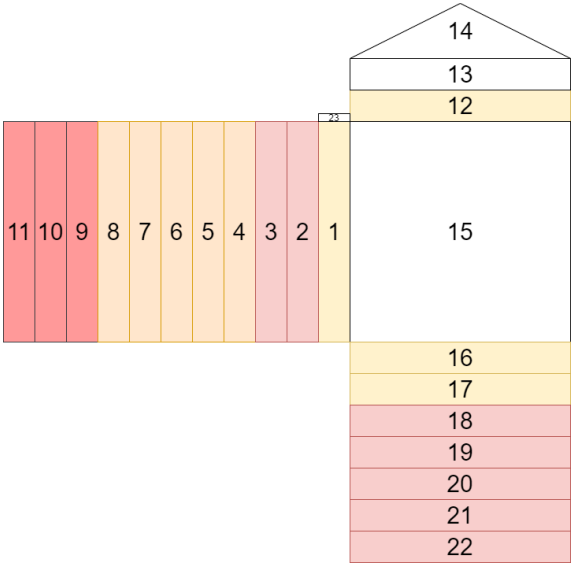


Figure B.4: Concept figure of Additional Requirements HoQ

Space 5 - Type of Requirement

It is exactly the same as in Client/Customer Requirements QFD, however it is mentioned because here a larger range of types of requirements may appear. "Structural" or "Environmental" are some examples of what can be filled here, instead of mainly "Client" or "Customer".

B.2.3 Stage 3 - CRAR (Customer Requirements and Additional Requirements) QFD-LeanDfX

The possible final stage under the user responsibility is filling the House of Quality that helps the direct translation of all requirements into X-Domains that will be used further in LeanDfX framework deployment. It has the conceptual structure represented in figure B.5 and it is the simplest of the three.

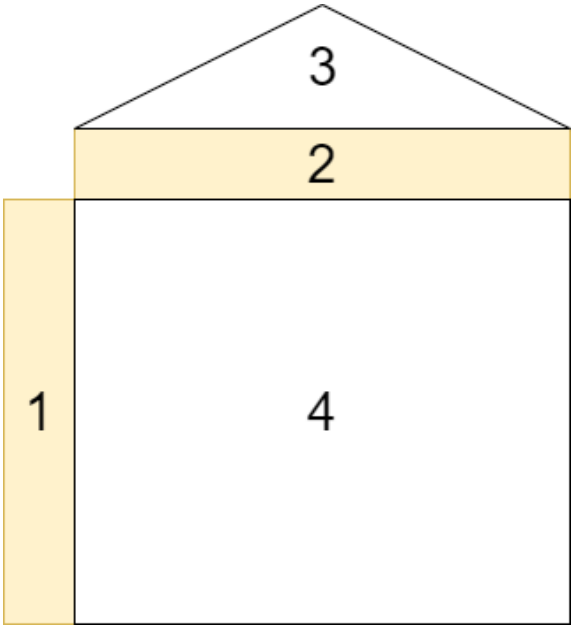


Figure B.5: Concept figure of CRAR QFD-LeanDfX

Space 1 - X-Domains

In this column, all X-Domains that are regarded in LeanDfX framework are displayed in an alphabetical order. If the team wants, it can also add more X-Domains that may not be in.

Space 2 - Total Functional Requirements

Here, all requirements from the previous two stages are displayed, having in this case, a much larger matrix than the previous one. So far, this step must also be done by the team by copying the information from the other two House of Quality's.

Space 3 - Roof Matrix

Like in the previous stages, this has the same motivation behind, where the team must fill in to know how two requirements relate and influence each other. However, in this CRAR QFD-LeanDfX, if the team wants it, a relationship between additional requirements and functional requirements may be also done to help further developments.

Space 4 - Relationship Matrix

This final space relates to the connection between the X-Domain on the row r and the requirement on column c . From two possible options (X or *blank space*), the user must put an X in the X-Domains in which the requirement has to be related with. This matrix helps the decision of which domains shall be selected in the deployment phase of LeanDfX.

B.2.4 (Optional)Stage 4 - LeanDfX Domains Weighting;

In this optional step, the users should give a weight to each domain, where the Job Experience of the user is taken into account also. The conceptual figure of the sheet is in figure B.6.

		2	3	4
	5			
1	6		3	4

Figure B.6: Concept figure of Lean DfX Weighting table

Due to the simple nature of this stage, only a small explanation is given.

Space 1 - X-Domains

As in the previous stage, in this column, the several X-Domains are considered.

Space 2 - Users and Fuzzy Importance

In this space, five columns are dedicated to each user. The first is dedicated to the name of the user and the remaining, dedicated to the fuzzy importance, that is automatically calculated in space 6.

Space 3 - Total

Column number three has the responsibility of showing the final importance for each X-Domain. This is obtained by the sum of the defuzzified importance value of every user for each X-Domain. To understand the mathematical process behind this, a dedicated section is available in the dissertation dedicated.

Space 4 - Relative Weight

Here, total values are converted in relative weights, so it is possible to have an easier analysis to know which X-Domains are more important.

Space 5 - Job Experience

In the same as the first two stages, here, for each user, the correspondent Job Experience should be chosen so a fuzzyfied importance can be calculated.

Space 6 - Importance Matrix

Here, each user should give, also in a 9 value scale, an importance should be given to each X-Domain, where 9 is the value correspondent to the most important. This allows a ranking system also in the X-Domains, allowing the team to know in which ones they should focus first.

B.2.5 Additional sheets and information

Additional information in other sheets of the Excel file is also available. Updating each one is a task team since the software does not do it by itself.

Customer Requirements Order Sheet

In this sheet, functional requirements from Client/Customer Requirements HoQ are sorted by their technical importance, from highest to lowest, helping the decision process and organization.

Additional Requirements Order Sheet

Here, functional requirements from Additional Requirements HoQ are sorted by their technical importance, from highest to lowest, also helping the decision process and organization.

Total Requirements Order Sheet

In this final sheet, functional requirements from both HoQ are sorted by their technical importance, also from highest to lowest. However, since the scale is not the same, a direct analysis should not be made from this table.

B.3 Methodology Steps

In this section, a step by step guide is described as a help to implement the total methodology. If the justification of any space needs to be known, the previous section has a space by space small explanation.

It can be divided in two phases, a team phase, meaning that all people responsible for future filling must work together, and the next phase, done by some individuals or as a team, according to preference.

Phase 1

- Step 1 - Define Customer Requirements
- Step 2 - Define Functional Requirements
- Step 3 - Fill the Target and Unit fields
- Step 4 - Decide direction of improvement
- Step 5 - Define X-Domain, Part and Sub-Part
- Step 6 - Fill Roof matrix
- Step 7 - Repeat the first 6 steps for the Additional Requirements HoQ
- Step 8 - Fill the Requirements field on CRARQFD-LeanDfX
- Step 9 - Fill the relationship Matrix on CRARQFD-LeanDfX
- Step 10(Optional) - Fill Roof Matrix on CRARQFD-LeanDfX
- Step 11(Optional) - Fill the user and Job Experience field in LeanDfX Domains Weighting;

Phase 2

- Step 1 - Choose Job/Experience;
- Step 2 - Fill Importance Columns;
- Step 3 - Fill Relationship Matrices;
- Step 4(Optional) - Fill Importance Matrix;
- Final Step - Send every individual QFD to the responsible for the cross data task;

B.3.1 Phase 1

Step 1 - Define Customer Requirements

The whole team must fill the customer requirements column on the Client/Customer HoQ.

Step 2 - Define Functional Requirements

In this step, the team must translate the customer requirements, the "Whats" into "Hows", this is, functional requirements and fill them in the dedicated space.

Step 3 - Fill the Target and Unit fields

Afterwards, the team must record which are the target value for each functional requirement and its units.

Step 4 - Decide direction of improvement

After all functional requirements are defined, their direction of improvement must be decided by the team. It has 4 possible values in this space:

- $\uparrow$, meaning that the value in the technical or functional requirement shall be maximized;
- X, meaning that the value is the target value;
- $\downarrow$, meaning that the value in the technical or functional requirement shall be minimized;
- *blank space*, meaning that no information is useful for the direction of improvement;

Step 5 - Define X-Domain, Part and Sub-Part

While the team is still together filling the file, at this stage, the columns dedicated to the X-Domain, Part and Sub-Part for each Client/Customer requirement should be filled, in order to help future deployment of LeanDfX methodology.

Step 6 - Fill Roof matrix

The team then must define the relationships between functional requirements, filling the roof matrix to define their dependence. The used 5 value scale is the following:

- ++, meaning that the dependence between functional requirements is strongly positive;
- +, meaning that the dependence between functional requirements is positive;
- NO or *blank space*, meaning that there is not an existing dependence between functional requirements;
- -, meaning that the dependence between functional requirements is negative;
- --, meaning that the dependence between functional requirements is strongly negative;

For a 3 value approach, the values should be: +, NO or *blank space* and -.

Step 7 - Repeat the first 6 steps for the Additional Requirements HoQ

The team must do the same first 6 steps done for the Client/Customer Requirements HoQ for the Additional Requirements HoQ, accounting, of course, the existing differences between the type of requirements on each sheet.

Step 8 - Fill the Requirements field on CRAR QFD-LeanDfX

All requirements, functional requirements and additional requirements must be copied to the dedicated field.

Step 9 - Fill the relationship Matrix on CRAR QFD-LeanDfX

The final main step for the team is to decide on which X-Domains each requirement is regarded. When a X-Domain regards a requirement, a X must be placed. Otherwise, a blank space must be left.

Step 10 (Optional) - Fill Roof Matrix on CRAR QFD-LeanDfX

If it is desired to know relationships between functional and additional requirements, in addition to what was done on the previous HoQ, the team can also fill the available spaces where additional and functional requirements are regarded on the roof Matrix.

Step 11 (Optional) - Fill the user and Job Experience field in LeanDfX Domains Weighting

If the team desires to also weight the several X-Domains, it must first prepare the table. To do it, the name of every user and its respective Job Experience should be filled in the available spaces.

B.3.2 Phase 2**Step 1 - Choose Job/Experience**

On both Client/Customer HoQ and Additional Requirements HoQ, the user must choose their Job/Experience from the 3 available options:

- Poor Experience, if the user has between none to 2 years of experience in the field;
- Medium Experience, if the user has between 2 and 5 years of experience in the field;
- Good Experience, if the user has 5 or more years of experience in the field;

Step 2 - Fill Importance Column

The user then must define the importance weight of each functional requirement and the importance for each additional requirement from a 9 values scale, where 1 is the lowest importance and 9 being the value that represents the most important requirements.

Step 3 - Fill Relationship matrices

For each combination of Client/Customer Requirement and Functional Requirement or Additional Requirement and Functional Requirement, the user must choose from a 9 or 5 or 3 value scale on which magnitude the pair relates. The chosen value should measure the "strength" of relationship between the requirements. In the case that no relationship exists between requirements, a blank space should be left. The values are the following:



Figure B.7: Graphic representation of the 9 value scale and its crisp weights

It is also possible to have a 5 value scale or a 3 value scale and that it is a choice that is made by the team. The advised 5 values scale is: Weakest < Weak < Moderate < Strong < Strongest; and the advised 3 values scale is: Weakest < Weak(It corresponds to Moderate) < Strongest.

Step 4(Optional) - Fill Importance Matrix

Then, if it was previously desired by the team, in its dedicated space, the user must choose from a 9 value scale, an importance to each Domain.

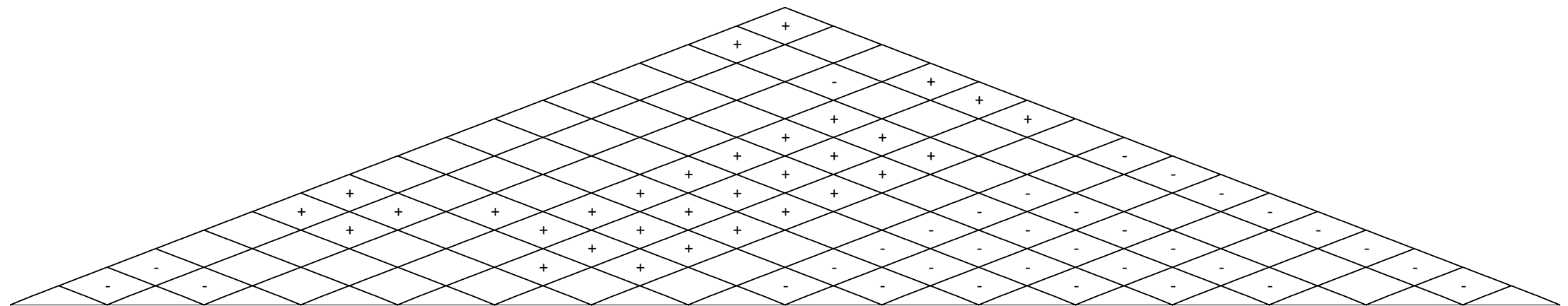
Final Step - Send every individual QFD to the responsible for the cross data task

As the step indicates, after everything is completed, the users must send their QFD to the participants so their data can be crossed and finally, a combined result regarding each user Relationship Matrices, Job and Weights is presented.

Appendix C

LeanDfX Fuzzy QFD examples

Since it is from the connection of foreign pdf files, it is not possible to categorize them as figures. In the first example, a Client/Customer requirements HoQ filled by the writer is available. Then, the next is the Additional Requirements HoQ, also filled by the writer of the dissertation in order to keep the contributions by the supervisors as secret as possible. In third place, the CRAR QFD-LeanDfX is available and in the same way, done by the writer. In the final example, the LeanDfX Weighting matrix is available, this time with the contribution of every contributors since it is everything in one sheet only.



Row	Relative Weight	Weight Chart	Part	Sub-Part	X Domains	Type of Requirement	Fuzzy Importance	Importance	Max Relationship	Experience/Job	Poor Experience	↑	↑	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
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X-Domains		Functional Requirements																																			
		Loading capacity	Lifting capacity	AGV Speed	Chassis Height	Chassis Width	Chassis Length	Elevation Tower	Space for Meanum Wheels	Space for DC Motor	Space for Gearbox	Space for 4 Controller	Space and compaintment for 2 Scanners	Space for 3 electrical Switchboards	Space for Battery	Sustain Battery Weight	Minimum height for Scanner	Tensile Strength	Fracture Toughness	Young's modulus	Simple parts	Symmetry when possible	Modules	Identical components	Number of standard pieces	Stop button	Machine Directory	EN 1525:1997	ISO 34691-5:2014	ISO 12000	Risk analysis (FMEA)	Ergonomics	Easy accessibility to dangerous components	Top transportation made possible	Easy accessibility to upgradable parts	Use recycable material	
DFAssembly					x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x						x	x		x	x		
DFEnvironment								x	x	x	x	x	x	x																	x	x			x		
DFErgonomics							x		x	x	x	x	x	x																		x	x				
DFLogistics	x	x							x	x	x	x	x	x							x	x	x	x	x									x		x	
DFMaintenance	x			x	x	x		x	x	x	x	x	x	x	x	x		x		x	x	x	x	x	x	x	x	x					x		x		
DFManufacturing				x	x	x		x	x	x	x	x	x	x				x		x	x	x	x	x	x								x		x		
DFQuality	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x		x	x	x	x	x	x			x								x	
DFRecycling																																					x
DFReliability	x	x									x	x	x	x	x	x	x	x									x	x					x				
DFSafety	x	x									x	x	x	x													x	x					x				
DFstandardization																																					
DFStructural Integrity	x	x														x		x		x								x	x								

[illegible]

Appendix D

FMEAs

FMEA	COMPONENT				Cross	CURRENT SITUATION				Improved situation									
	FAILURE	FAILURE TYPE	FAILURE CONSEQUENCE	FAILURE CAUSE		Proposed test	O	S	D	RPN	Suggested measures	Applied steps	O	S	D	RPN			
Chassis	Chassis	Weld Failure	Chassis stiffness and safety compromised	Defective Welding					0	Appropriate welding method									0
		Fatigue	Chassis stiffness and safety compromised	Bad Design/Excessive Payload					0	Fatigue strength calculation									0
		Loosiness	Chassis stiffness and safety compromised	Bad Design/Excessive Payload					0	Easy accessibility to loose parts									0
	Wheels	Corrosion	Chassis stiffness and safety compromised	Corrosive ambient					0	Corrosion resistant material									0
		Worn	Loss of car control	Many possible causes					0	Allow easy maintenance and substitution									0
		Worn	Loss of car control	Many possible causes					0	Allow easy maintenance and substitution									0
	Elevation Tower/Install	Fatigue	Damaged Elevation Tower	Bad design/Bad use/Excessive Payload					0	Test maximum load									0
		Loosiness	Damaged Elevation Tower	Bad design/Bad use/Excessive Payload					0	Easy accessibility to loose parts									0
		Worn	Damaged Elevation Tower	Bad design/Bad use/Excessive Payload					0	Design to ease substitution									0
	DC Motor Box	Worn	Loss of Power	Broken Gears					0	Design to ease substitution									0
		Unit fail	Loss of Power	Faulty Unit					0	Design to ease substitution									0
		Overheat	Loss of Power	Faulty Unit					0	Design to ease substitution									0
Chassis	Gearbox Box	Motor controllers Box	No commands/Wrong Commands	Broken Gears					0	Design to ease substitution									0
		Scanners Box	Impossibility to scan the room	Faulty Unit					0	Design to ease substitution									0
		Batteries Box	Fire/Loss of Power and Control	Overheat/Confined Space/					0	Allow easy maintenance and substitution									0
	Batteries Box	Leakage	Loss of Power and Control	Bad use/maintenance					0	Maximize heat dissipation									0
		Performance Degeneration	Loss of Power and Control	Bad use/maintenance					0	Allow easy maintenance and substitution									0
		Overheat	Damaged Switchboard	Dust					0	Allow easy maintenance and cleaning									0
	Electric Switchboard Box	Unit fail	Impaired Control	Faulty Unit					0	Allow easy substitution									0
		Unit fail	Impaired Control	Faulty Unit					0	Allow easy substitution									0
		Unit fail	Impaired Control	Faulty Unit					0	Allow easy substitution									0

Figure D.1: FMEA used and sent

Component Involved	FAILURE	FAILURE TYPE	FAILURE CONSEQUENCE	FAILURE CAUSE	Proposed Int.	O	O	O	S	S	S	D	D	D	RPN	RPN																																																			
Chassis	Weld failure	Chassis stiffness and safety compromised	Defective Welding	0	0	13	28	3	0	6	16	2	0	15	36	4	0	0	1132	16128	24																																														
																						Fatigue	Bad design/Excessive Payload	0	0	12	28	3	0	6	16	2	0	15	36	4	0	0	1132	16128	24																										
																																										Loosiness	Bad design/Excessive Payload	0	0	12	28	3	0	6	16	2	0	15	36	4	0	0	1132	16128	24						
																																																														Corrosion	Corrosive ambient	0	0	6	16
	Worn	Chassis stiffness and safety compromised	Bad Design/Excessive Payload	0	0	12	28	3	0	6	16	2	0	15	36	4	0	0	1132	16128	24																																														
																							Many possible causes	0	0	2	8	1	0	16	36	4	0	6	16	2	0	0	152	468	8																										
																																										Damaged Elevation Tower	Bad design/Bad uses/Excessive Payload	0	0	6	16	2	0	16	36	4	0	6	16	2	0	0	576	9216	16						
																																																														Damaged Elevation Tower	Bad design/Bad uses/Excessive Payload	0	0	6	16
	Unit Fall	Loss of Power	Bad Maintenance / Faulty Unit	0	0	2	8	1	0	12	28	3	0	6	16	2	0	0	24	1024	2																																														
																						Overheat	Broken Gears	0	0	2	8	1	0	16	36	4	0	6	16	2	0	0	48	1792	3																										
																																										Motor controllers Box	No commands/Wrong Commands	0	0	12	28	3	0	16	36	4	0	20	49	5	0	0	3840	40320	60						
																																																														Scanners Box	Impossibility to scan the room	0	0	6	16
Unit Fall	Faulty Unit	0	0	2	8	1	0	16	36	4	0	12	28	3	0	15	36	4	0	0	512																																														
																						Overheat	Fire/Loss of Power and Control	0	0	2	8	1	0	20	40	5	0	2	8	1	0	0	80	2560	5																										
																																										Batteries Box	Loss of Power and Control	Bad use/maintenance	0	0	2	8	1	0	20	40	5	0	2	8	1	0	0	240	5120						
																																																														Performance degradation	Loss of Power and Control	Bad use/maintenance	0	0	12
Overheat	Dust	0	0	6	16	2	0	6	16	2	0	12	28	3	0	0	432	7168	12																																																
																				Electric Switchboard Box	Damaged Switchboard	0	0	6	16	2	0	6	16	2	0	12	28	3	0	0	152	468	8																												
																																								Unit Fall	Faulty Unit	0	0	2	8	1	0	16	36	4	0	6	16	2	0	0	152	468	8								

Figure D.2: FMEA converted to Fuzzy Language

Component Involved	FAILURE	FAILURE TYPE	FAILURE CONSEQUENCE	FAILURE CAUSE	Proposed test	CURRENT SITUATION										RPN	RPNnorm	RPN											
						O	S	D	Diorm	D	S	O	S	D	Diorm				D										
Chassis	Chassis	Weld failure	Chassis stiffness and safety compromised	Defective Welding	0	0	10	22	2.1	8.0	16	27	43	48	33.5	16	27	48	58	30.0	37.3	0	0	20400	63248	193.1	9883.0		
		Corrosion	Chassis stiffness and safety compromised	Bad Design/Excessive Payload	12	0	10	22	2.1	8.0	2	12	15	24	3.6	13.3	2	12	20	34	4.6	17.0	0	0	3600	17992	34.9	1802.0	
		Loosens	Chassis stiffness and safety compromised	Corrosive ambient	0	0	7	16	1.5	5.8	6	18	27	36	5.8	21.8	2	12	18	30	4.2	15.5	0	0	3602	17980	37.5	1938.5	
Wheels	Wheels	Worn	Chassis stiffness and safety compromised	Bad Design/Excessive Payload	6	18	30	42	6.4	24.0	12	21	35	44	7.5	28.0	16	27	48	58	10.0	37.3	1152	10206	50784	484.3	25032.0		
		Loosens	Loss of air control	Many possible causes	0	0	5	12	1.1	4.3	2	12	20	34	4.6	17.0	0	0	7	16	1.5	5.8	0	0	700	6208	8.0	415.4	
		Loosens	Damaged Elevation Tower	Bad design/Bad use/Excessive Payload	0	0	7	16	1.5	5.8	2	12	20	34	4.6	17.0	0	0	7	16	1.5	5.8	0	0	2100	13096	73.1	1295.2	
Elevation Tower/Install	Elevation Tower/Install	Loosens	Damaged Elevation Tower	Bad design/Bad use/Excessive Payload	0	0	7	16	1.5	5.8	2	12	20	34	4.6	17.0	0	0	7	16	1.5	5.8	0	0	2100	13096	73.1	1295.2	
		Unit Fail	Loss of Power	Bad Maintenance/Faulty Unit	6	18	27	36	5.8	21.8	12	21	40	54	8.5	31.8	16	27	43	48	9.0	33.5	1152	10206	66440	93312	447.6	23133.8	
		Overheat	Loss of Power	Overrun/Overheat	0	0	5	12	1.1	4.3	2	12	13	20	8.2	31.8	6	18	27	36	5.8	21.8	0	0	1750	8640	21.0	1086.1	
Gearbox Box	Gearbox Box	Worn	Caused Movement	Broken Gears	0	0	5	12	1.1	4.3	2	12	13	20	8.2	31.8	6	18	27	36	5.8	21.8	0	0	2470	12000	29.2	1510.6	
		Unit Fail	No commands/Wrong Commands	Faulty Unit	0	0	10	22	2.1	8.0	6	18	32	46	6.8	25.5	6	18	34	48	7.1	26.5	0	0	10880	48576	110.6	5406.0	
		Unit Fail	Impossibility to scan the room	Broken Unit	0	0	7	16	1.5	5.8	12	21	38	50	8.1	30.3	6	18	30	42	6.4	24.0	0	0	7980	33600	80.8	4174.5	
Batteries Box	Batteries Box	Unit Fail	Impossibility to scan the room	Faulty Unit	0	0	5	12	1.1	4.3	6	18	32	46	6.8	25.5	6	18	32	46	6.8	25.5	0	0	1320	23892	53.5	2763.6	
		Overheat	Fire/Loss of Power and Control	Overheat/Confined Space/Leakage	0	0	5	12	1.1	4.3	12	21	42	56	8.8	32.8	2	12	13	20	8.2	31.8	0	0	2730	13016	31.6	1635.5	
		Performance Degeneration	Loss of Power and Control	Bad use/maintenance	0	0	5	12	1.1	4.3	6	18	34	48	7.1	26.5	0	0	7	16	1.5	5.8	0	0	1160	9216	12.5	697.6	
Electric Switchboard Box	Electric Switchboard Box	Unit Fail	Loss of Power and Control	Bad use/maintenance	12	21	38	50	8.1	30.3	2	12	15	24	3.6	13.3	2	12	18	30	4.2	15.5	48	3024	10200	36400	120.2	6212.6	
		Unit Fail	Hidden Control	Faulty Unit	0	0	7	16	1.5	5.8	12	21	35	44	7.5	28.0	2	12	15	24	3.6	13.3	0	0	4410	21120	48.3	2495.5	
						0	0	5	12	1.1	4.3	12	21	40	54	8.5	31.8	2	12	15	24	3.6	13.3	0	0	3600	15592	34.6	1797.9

Figure D.3: FMEA with combined values and to normalized language again

Appendix E

Gearbox QFD

In order to understand QFD and HoQ methodologies to their full potential in the start of the project, these were applied to a previous existing project. The project used as scapegoat was developed in a previous curricular unit of the Mechanical Engineering degree, Project Initiation. The basis behind, was the design of a gearbox from a set of requirements, however these were not always clear. Some were given already as technical requirements, such as the output tree rotation (1500 rpm), but not every single one were clearly defined. The need to clarify those requirements and translate them to technical requirements, almost as in engineering language, is essential. This makes it a perfect example to apply QFD methodology.

E.1 QFD

The requirements used to apply QFD methodology are the most vague. They were given at the start of the project and through the designing phases and are presented in the table E.1. Not every requirement was used since some were not relevant to QFD. These are mentioned as Customer Requirements. After the "What's" of the project were defined, the following step is the definition of the "How's". These are the ones that translate the original requirements into engineering characteristics or functional requirements and they are presented in table E.1 as Functional Requirements

Customer Requirements or "What's"	Functional Requirements or "How's"
Little noise	Increase driven ratio
Reliable and Safe performance	Increase Fatigue Strength
High Durability	Low Wear
Comfort at Engaging	Smooth engaging mechanism
6 speeds	Number of Gears
Low Cost	Use standard pieces
Entry and out tree at the same height	Entry and out shaft at the same height
Little Weight	Use lighter materials
Easy Assembly	Allow many accesses to assemble

Table E.1: Gearbox Customer and Functional requirements

Even if it is not demanded, for each customer requirement an attempt was made to get a solution. This makes the relationship matrix sparse and as mentioned in 2.3, this is recommended.

Since it was a classical and direct approach of QFD, an attempt was made to develop more than one HoQ. Even if this was not done in the end, the transformation of the "How's" of table E.1 into the "What's" on a new table, it is an important point to acknowledge. Its translation and transformation is presented in table E.2.

"What's"	"How's"
Increase driven ratio	Increase number of teeth in gears
Increase Fatigue Strength	Avoid stress concentration factors
Low Wear	Teeth correction
Smooth engaging mechanism	Electromagnetic clutches
Number of Gears	3 * 2
Use standard pieces	Shafts/Nuts/Clutches/Screws/Valves from catalogues
Entry and out shaft at the same height	Same number of sum teeth in gears
Use lighter materials	Low density material
Allow many accesses to assemble	Top shell and side holes

Table E.2: Gearbox requirements for further HoQ

It is also important to establish the scales for each matrix, the roof matrix, relationship matrix and direction of improvement. Symbolic scales were used because this eases the process, since visual representation helps the decision making process [165]. For the roof matrix represents the connection between every functional requirements and the used scale is the following:

- +, for positive correlations;
- *blank space*, if no correlation exists;
- -, for negative correlation;

The next scale is the direction of improvement scale. This is:

- $\triangle$, if it is desired to maximize the functional requirement value;
- $\diamond$, if it is desired to meet the functional requirement value;
- ∇ , if it is desired to minimize the functional requirement value;

Finally and most importantly, the relationship matrix scale, representing how each combination of customer requirement/functional requirement relates to each other, if at all. Scaling is also symbolic and it is the following:

- ●, 9 in a numerical scale, if the relationship between requirements is strong;
- ○, 3 in a numerical scale, if the relationship between requirements is moderate;
- ∇ , 1 in a numerical scale, if the relationship between requirements is weak;

For this QFD, additional features were used, but only the most common/classical ones. Since every row and column has its title, through items these are explained item by item:

- Row - Row number;
- Weight Chart and Relative Weight column - Graphical representation and numeric of the relative weight of the Customer Importance for the row in analysis;
- Customer Importance - From a scale from 0 to 10, decide how important it is to meet the customer requirement in analysis;
- Maximum Relationship - For each customer requirement and functional requirement, represent in a numerical scale the maximum relationship. Desirably this value is 9 for each requirement;

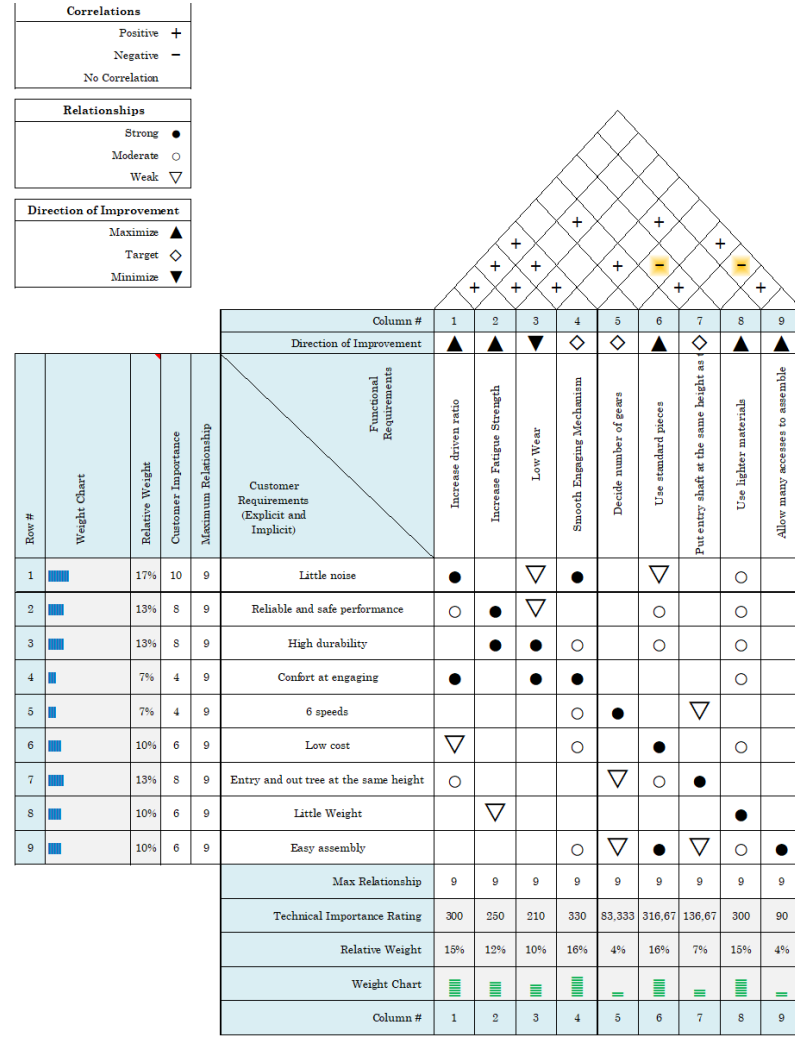


Figure E.1: Gearbox resulting QFD

- Technical Importance Rating - This value has its origin on the product between the customer requirement, and the relationship value for the combination of customer requirement and functional requirement and the sum of that result for every customer requirement for one functional requirement. This helps in determining which functional requirements are most important to meet in order to fulfill the most.
- Relative Weight and Weight Chart rows - The same as in the columns, however, this time, Technical Importance Rating is the value considered;
- Column - Column number;

The resulting QFD is available in figure E.1.

E.2 Results analysis and conclusion

QFD shows that at the start of the project, the main focus of the designer should be the use of standard pieces and the use of a smooth engaging mechanism. With the same importance, driven ratio attention and the use of light material must be taken into consideration. Then, fatigue strength and low wear should be case study. Finally, putting the shafts at the same height, the number of gears and the possibility of multiple accesses must be considered.

Even if a classical approach was used and to an already finished project, many conclusions on the possible utilization of the analysed methodology can be achieved.

In first place, one of the biggest issues of QFD is the assumed time consuming process, however this was not confirmed. The filling process was fast and the only real problem was the development of the Excel file, where getting the roof matrix and the overall HoQ was a time consuming activity. This could be bridged with the existence of a QFD software.

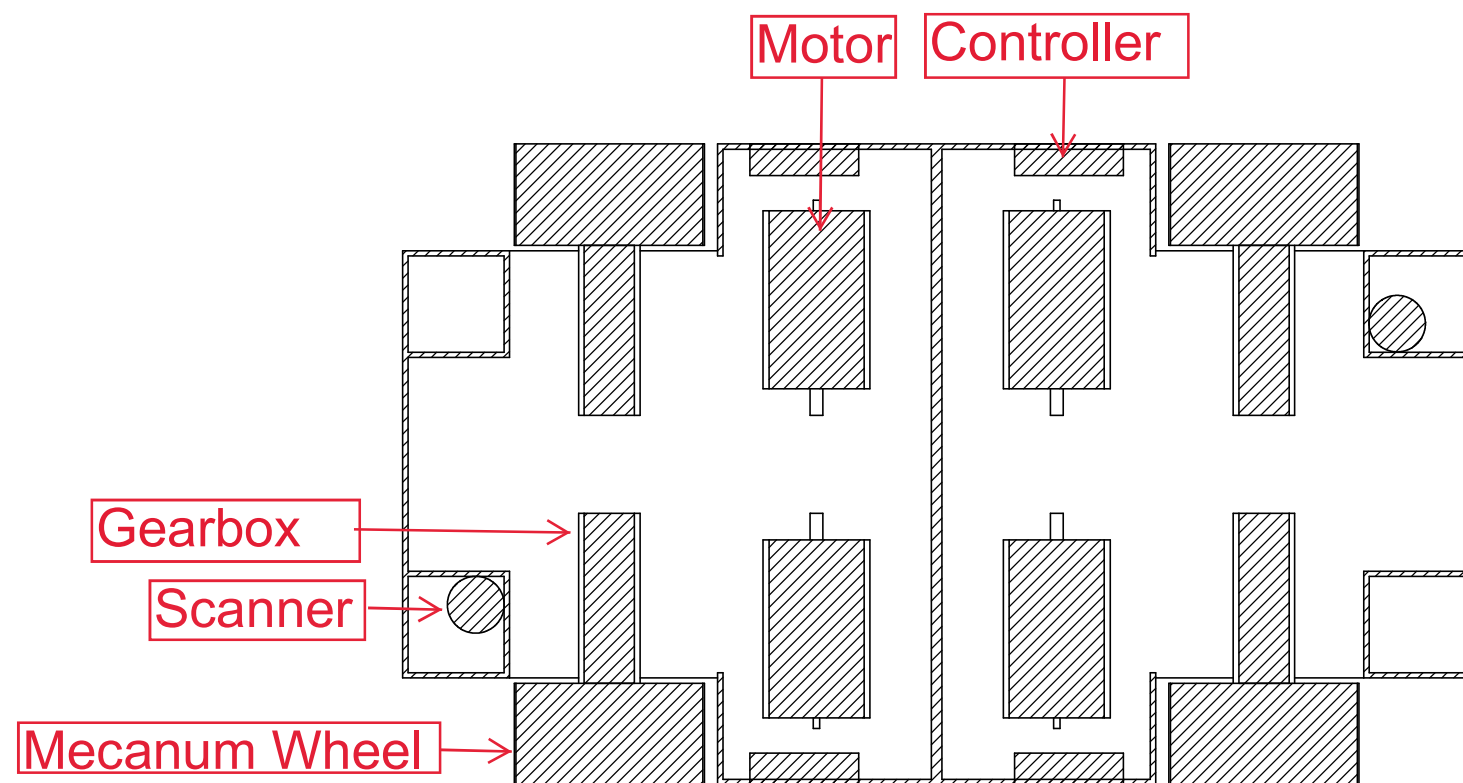
Then, it was also concluded that with a simple explanation, QFD is a rather simple methodology to implement, even for a first time user since it is very visual and intuitive.

However, one issue that can be pointed to it, it is the fact that QFD has a subjective dimension to it, making it propitious to errors. This was concluded to the comments made by both supervisors when QFD was shown, where some values were questioned.

Finally, from the experience of this project in Project Initiation, it can be immediately concluded that, QFD would be a useful method to apply when starting the project. One of the major issues when designing the gearbox in the final stages, was the late driven ratio modifications that influenced all project. In the other requirements, these were timely considered, in the beginning of the project because even then, a systematic approach and planning was done in order to help the designing process. However, this would be other additional tool that would help the overall process. These problems were considered in order to correct them when applying them to the dissertation.

Appendix F

Schematic Design



Appendix G

LeanDfX documents

Especificações Projeto AGV_JPM

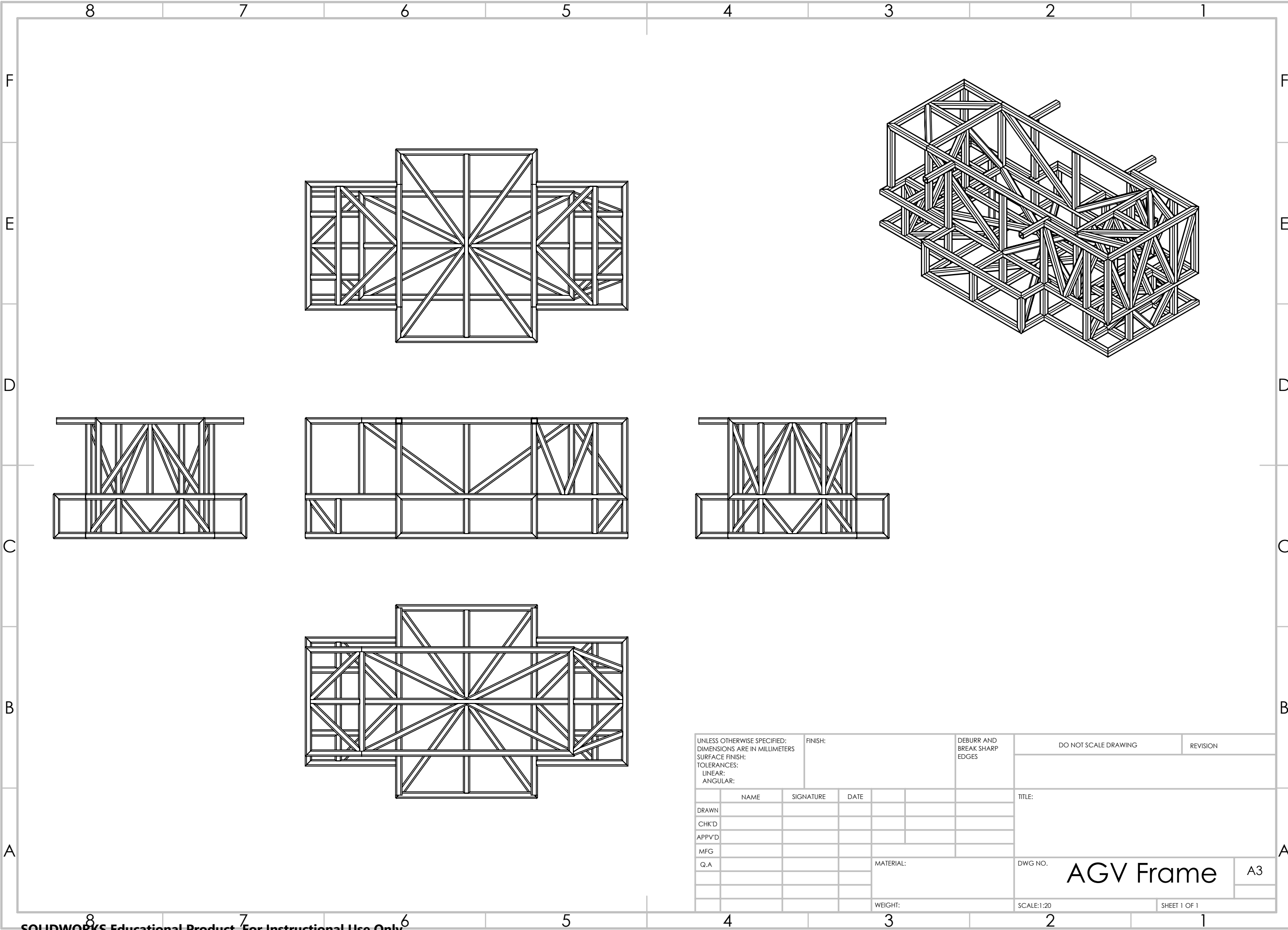


Especificação: 1

Número item	Descrição	Valor	Unidade	Requisito	Estado	Data Criação item
1	Loading Capacity	1500	kg	Capacity to Transport the desired loads	true	2020-04-30T06:35:05.000Z
2	Lifting capacity	1.5	m	Capacity to lift the loads to desired height	true	2020-04-30T06:35:45.000Z
3	AGV speed	3	Km/h	Safe moving speed	true	2020-04-30T06:36:11.000Z
4	Chassis Height	800	mm	Allowed height	true	2020-04-30T06:36:39.000Z
5	Chassis width	[800;1200]	mm	Allowed width	true	2020-04-30T06:37:27.000Z
6	Chassis length	[1500;2000]	mm	Allowed Length	true	2020-04-30T06:38:04.000Z
7	Elevation Tower	Forklifts	-	System to elevate loads	true	2020-04-30T06:38:42.000Z
8	Space for 4 Mecanum Wheels	d=356; w=200	mm	Omnidirectional movement	true	2020-04-30T06:39:41.000Z
9	Space for 4 DC Motor	d=200; l=400	mm	Autonomous Movement	true	2020-04-30T06:40:45.000Z
10	Space for 4 Gearboxes	d=115; l=320	mm	Speed Reduction	true	2020-04-30T06:42:37.000Z
11	Space for 4 Controllers	(l)x(h)x(w)-204x140x60	mm	Capacity to control	true	2020-04-30T06:44:40.000Z
12	Space and compartiment for 2 Scanners	d=130; h=150	mm	Alocate 2 Scanners	true	2020-04-30T06:48:03.000Z
13	Space for Electric Cabinet	(l)x(h)x(w)-555x430x275	mm	Alocate Electrical Switchbox	true	2020-04-30T06:49:16.000Z
14	Space for 2 Electric Cabinets	(l)x(h)x(w)-800x470x250	mm	Alocate Electric Switchbox	true	2020-04-30T06:50:00.000Z
15	Space for Battery	(l)x(h)x(w)-1106x604x400	mm	Autonomy (Battery)	true	2020-04-30T06:51:14.000Z
16	Sustain Battery Weight	600	kg	Autonomy (Battery)	true	2020-04-30T06:51:53.000Z
17	Minimum height for Scanner	150	mm	Alocate 2 Scanners	true	2020-04-30T06:52:55.000Z

Appendix H

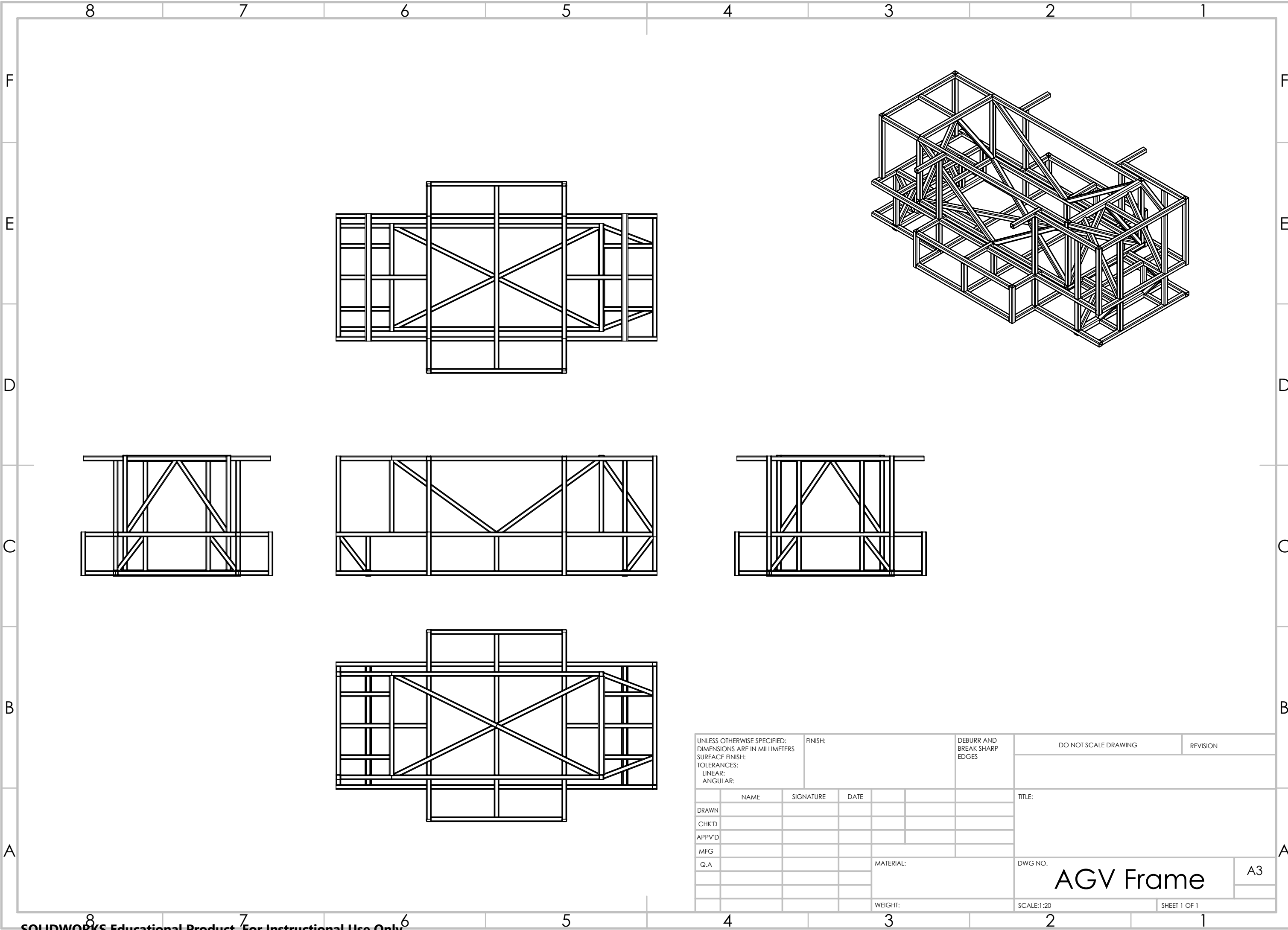
Designs iterations



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:				FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN				NAME		SIGNATURE		DATE		TITLE:	
CHK'D											
APPV'D											
MFG											
Q.A								MATERIAL:		DWG NO.	
								WEIGHT:		SCALE:1:20	
										SHEET 1 OF 1	

AGV Frame

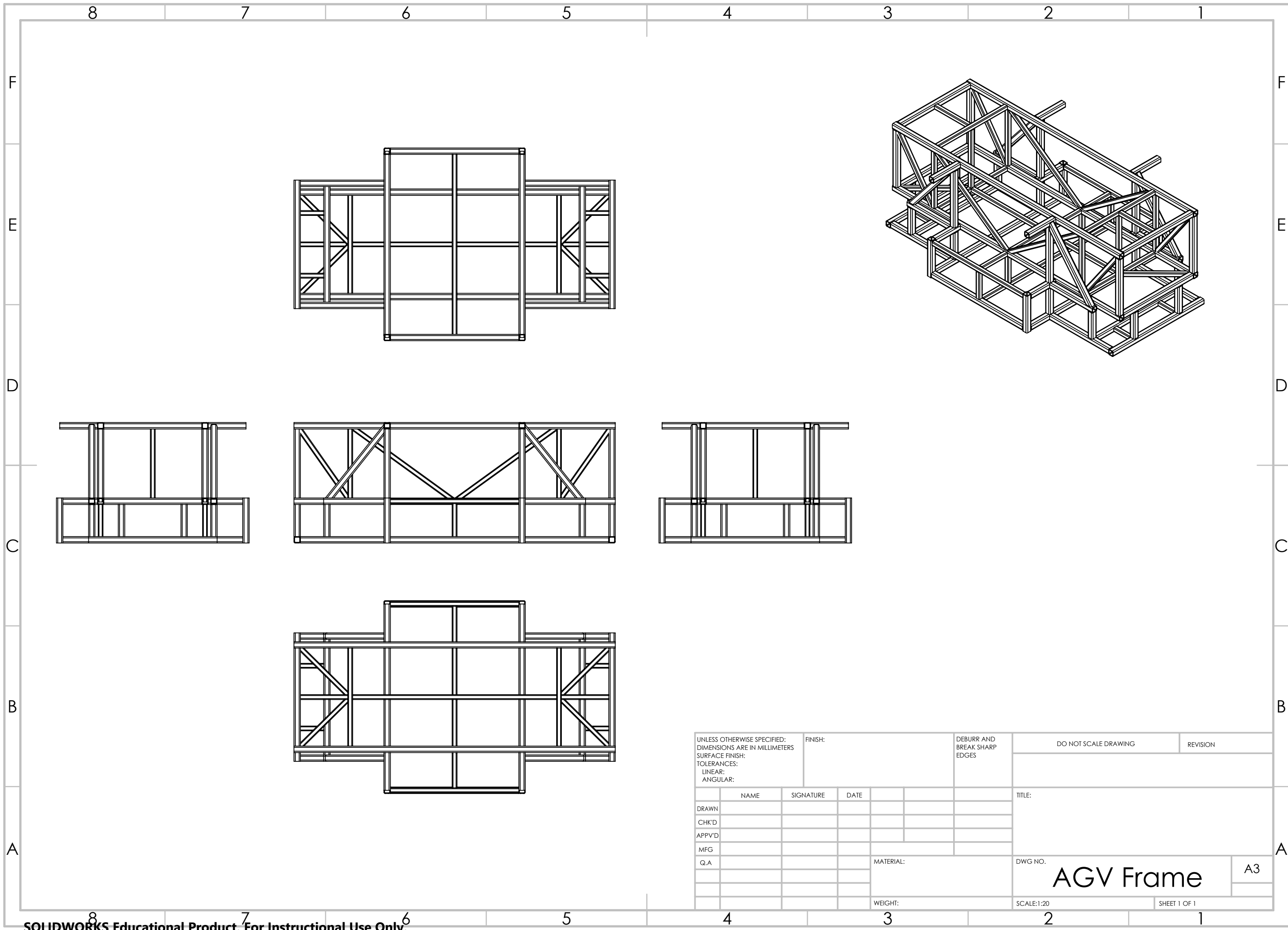
A3



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:				FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN				NAME		SIGNATURE		DATE		TITLE:	
CHK'D											
APPV'D											
MFG											
Q.A								MATERIAL:		DWG NO.	
								WEIGHT:		SCALE:1:20	
										SHEET 1 OF 1	

AGV Frame

A3



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:				FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN CHK'D APPV'D MFG Q.A				NAME		SIGNATURE		DATE		TITLE:	
								DWG NO.		A3	
								SCALE:1:20		SHEET 1 OF 1	

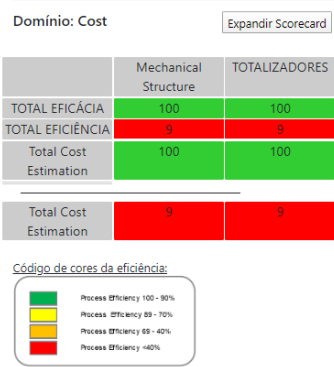
AGV Frame

Appendix I

Scorecards Generated

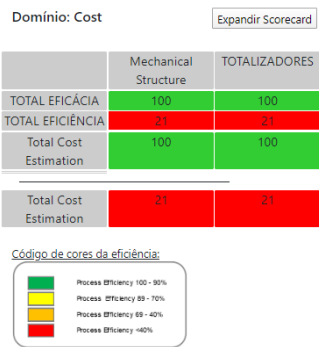
I.1 Cost Domain

Scorecard do Módulo: Mechanical Structure



(a) Cost scorecard for iteration 1.1

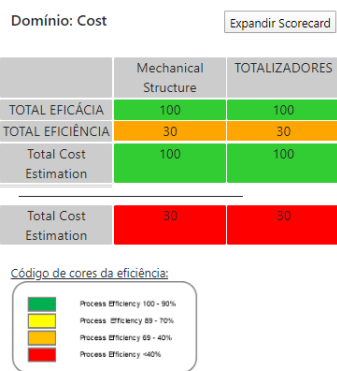
Scorecard do Módulo: Mechanical Structure



(b) Cost scorecard for iteration 1.2

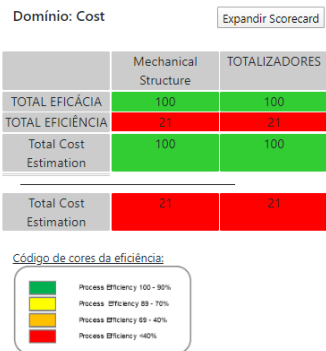
Figure I.1: Cost scorecards in LeanDfX for iterations 1.1 and 1.2

Scorecard do Módulo: Mechanical Structure



(a) Cost scorecard for iteration 1.3

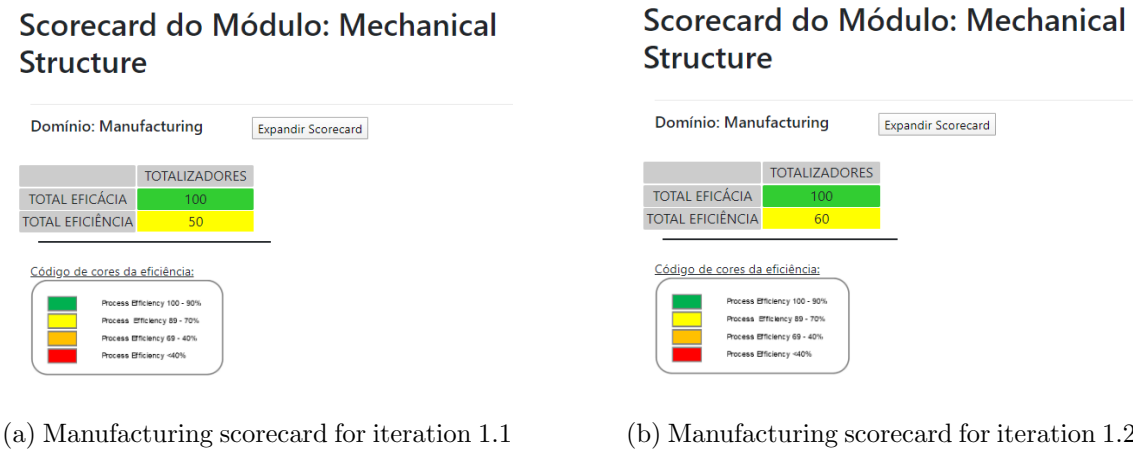
Scorecard do Módulo: Mechanical Structure



(b) Cost scorecard for iteration 1.4

Figure I.2: Cost scorecards in LeanDfX for iterations 1.3 and 1.4

I.2 Manufacturing Domain



Scorecard do Módulo: Mechanical Structure

Domínio: Manufacturing

Expandir Scorecard

	TOTALIZADORES
TOTAL EFICÁCIA	100
TOTAL EFICIÊNCIA	60

Código de cores da eficiência:

Process Efficiency 100 - 90%

Process Efficiency 89 - 70%

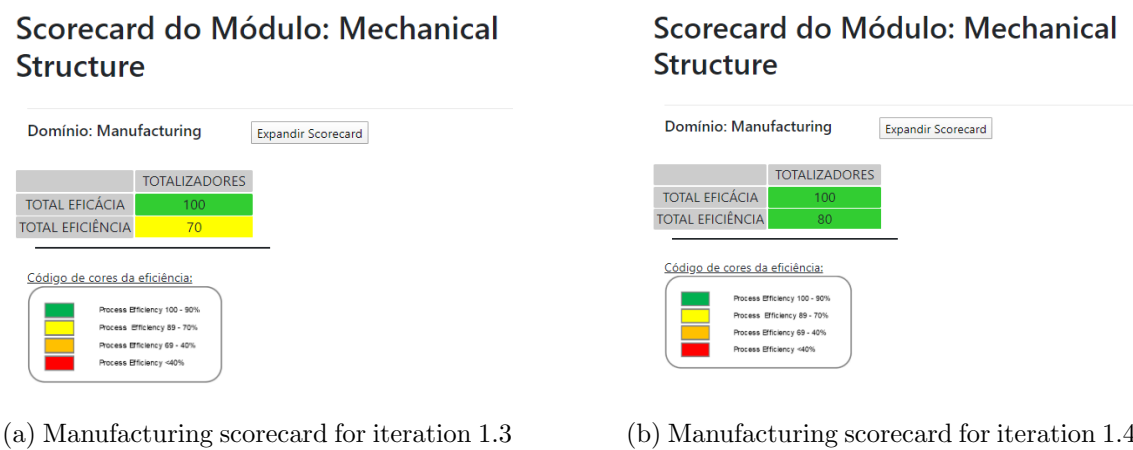
Process Efficiency 69 - 40%

Process Efficiency <40%

(a) Manufacturing scorecard for iteration 1.1

(b) Manufacturing scorecard for iteration 1.2

Figure I.3: Manufacturing scorecards in LeanDfX for iterations 1.1 and 1.2



Scorecard do Módulo: Mechanical Structure

Domínio: Manufacturing

Expandir Scorecard

	TOTALIZADORES
TOTAL EFICÁCIA	100
TOTAL EFICIÊNCIA	80

Código de cores da eficiência:

Process Efficiency 100 - 90%

Process Efficiency 89 - 70%

Process Efficiency 69 - 40%

Process Efficiency <40%

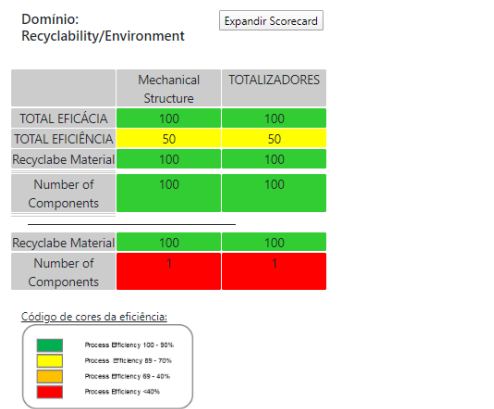
(a) Manufacturing scorecard for iteration 1.3

(b) Manufacturing scorecard for iteration 1.4

Figure I.4: Manufacturing scorecards in LeanDfX for iterations 1.3 and 1.4

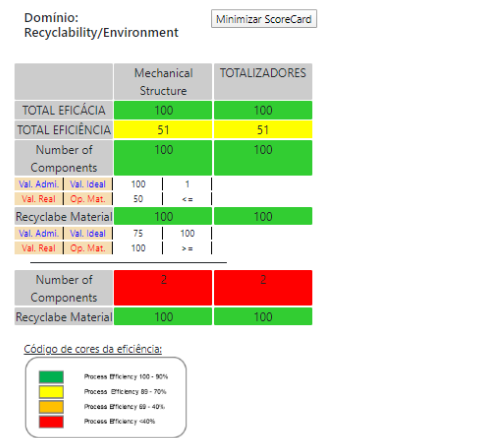
I.3 Recyclability/Environment Domain

Scorecard do Módulo: Mechanical Structure



(a) Recyclability/Environment scorecard for iteration 1.1

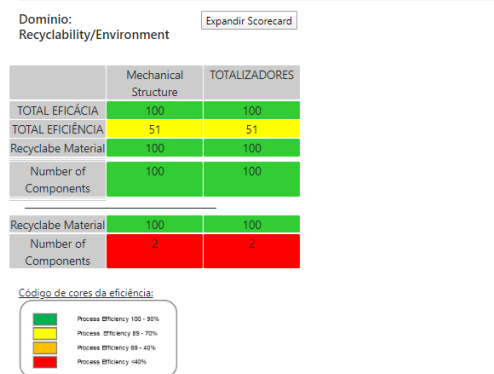
Scorecard do Módulo: Mechanical Structure



(b) Recyclability/Environment scorecard for iteration 1.2

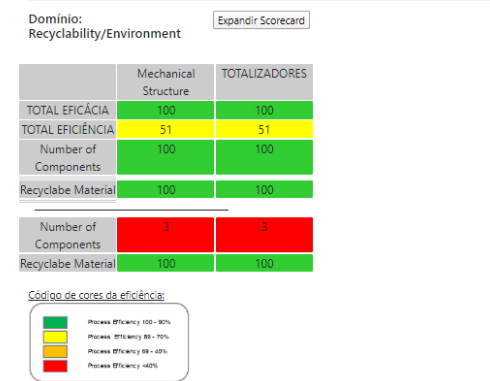
Figure I.5: Recyclability/Environment scorecards in LeanDfX for iterations 1.1 and 1.2

Scorecard do Módulo: Mechanical Structure



(a) Recyclability/Environment scorecard for iteration 1.3

Scorecard do Módulo: Mechanical Structure

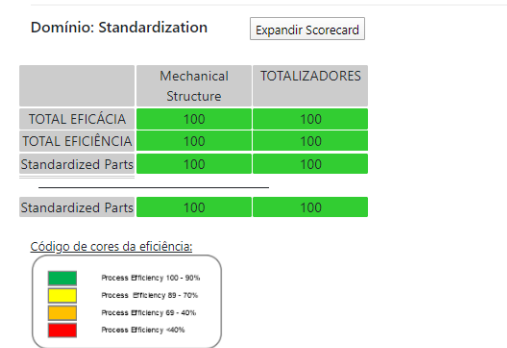


(b) Recyclability/Environment scorecard for iteration 1.4

Figure I.6: Recyclability/Environment scorecards in LeanDfX for iterations 1.3 and 1.4

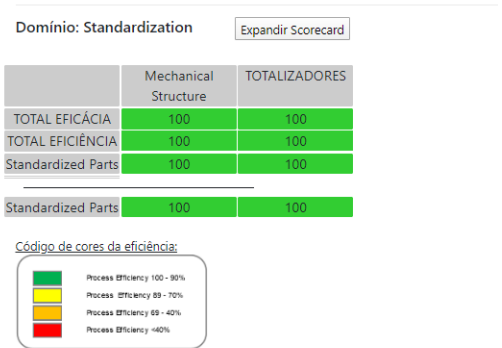
I.4 Standardization Domain

Scorecard do Módulo: Mechanical Structure



(a) Standardization scorecard for iteration 1.1

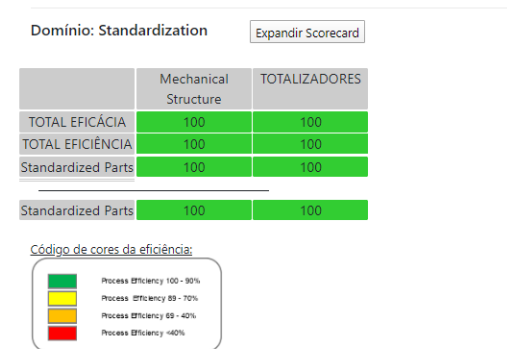
Scorecard do Módulo: Mechanical Structure



(b) Standardization scorecard for iteration 1.2

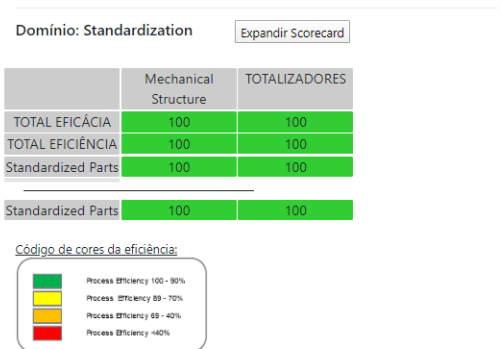
Figure I.7: Standardization scorecards in LeanDfX for iterations 1.1 and 1.2

Scorecard do Módulo: Mechanical Structure



(a) Standardization scorecard for iteration 1.3

Scorecard do Módulo: Mechanical Structure



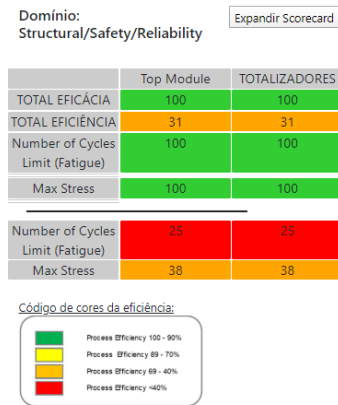
(b) Standardization scorecard for iteration 1.4

Figure I.8: Standardization scorecards in LeanDfX for iterations 1.3 and 1.4

I.5 Structural/Safety/Reliability Domain

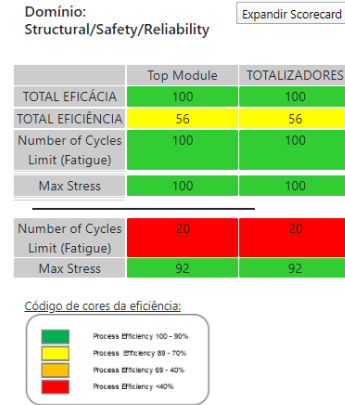
I.5.1 Top Module

Scorecard do Módulo: Top Module



(a) Structural/Safety/Reliability scorecard for iteration 1.1 Top Module

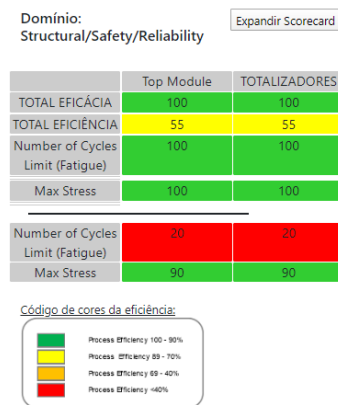
Scorecard do Módulo: Top Module



(b) Structural/Safety/Reliability scorecard for iteration 1.2 Top Module

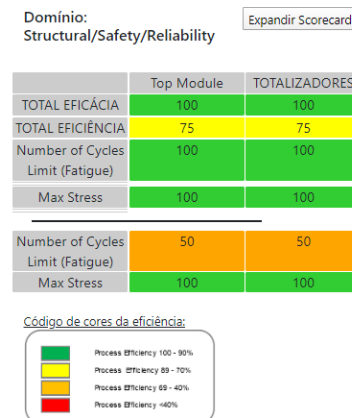
Figure I.9: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.1 and 1.2 Top Modules

Scorecard do Módulo: Top Module



(a) Structural/Safety/Reliability scorecard for iteration 1.3 Top Module

Scorecard do Módulo: Top Module



(b) Structural/Safety/Reliability scorecard for iteration 1.4 Top Module

Figure I.10: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.3 and 1.4 Top Modules

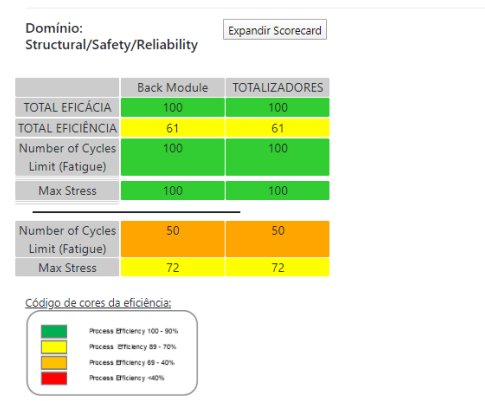
I.5.2 Back Module

Scorecard do Módulo: Back Module



(a) Structural/Safety/Reliability scorecard for iteration 1.1 Back Module

Scorecard do Módulo: Back Module



(b) Structural/Safety/Reliability scorecard for iteration 1.2 Back Module

Figure I.11: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.1 and 1.2 Back Modules

Scorecard do Módulo: Back Module



(a) Structural/Safety/Reliability scorecard for iteration 1.3 Back Module

Scorecard do Módulo: Back Module

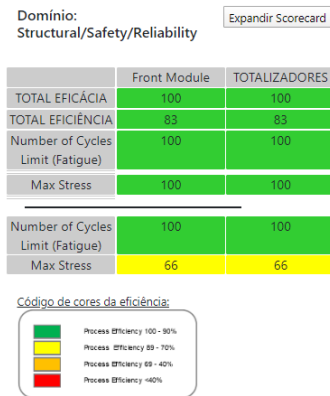


(b) Structural/Safety/Reliability scorecard for iteration 1.4 Back Module

Figure I.12: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.3 and 1.4 Back Modules

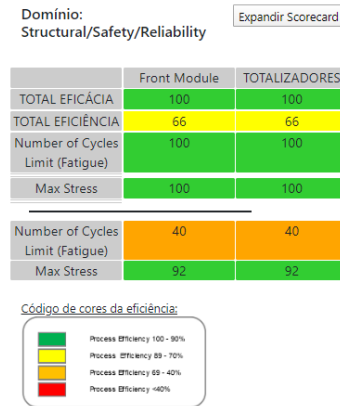
I.5.3 Front Module

Scorecard do Módulo: Front Module



(a) Structural/Safety/Reliability scorecard for iteration 1.1 Front Module

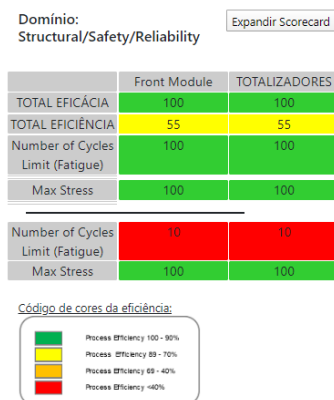
Scorecard do Módulo: Front Module



(b) Structural/Safety/Reliability scorecard for iteration 1.2 Front Module

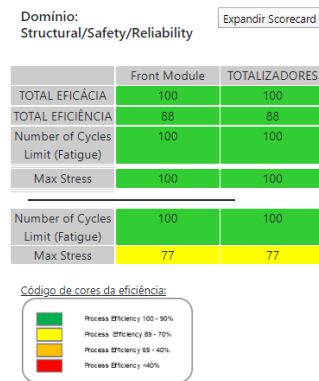
Figure I.13: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.1 and 1.2 Front Modules

Scorecard do Módulo: Front Module



(a) Structural/Safety/Reliability scorecard for iteration 1.3 Front Module

Scorecard do Módulo: Front Module



(b) Structural/Safety/Reliability scorecard for iteration 1.4 Front Module

Figure I.14: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.3 and 1.4 Front Modules

I.5.4 Whole Structure

Scorecard do Módulo: Mechanical Structure



(a) Structural/Safety/Reliability scorecard for iteration 1.1

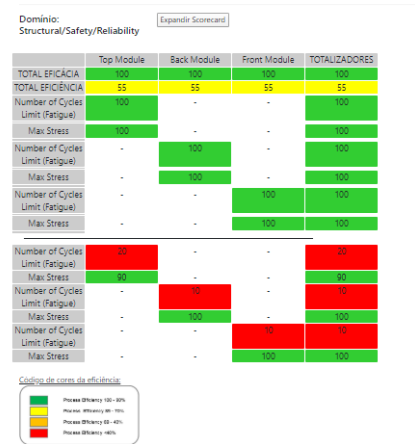
Scorecard do Módulo: Mechanical Structure



(b) Structural/Safety/Reliability scorecard for iteration 1.2

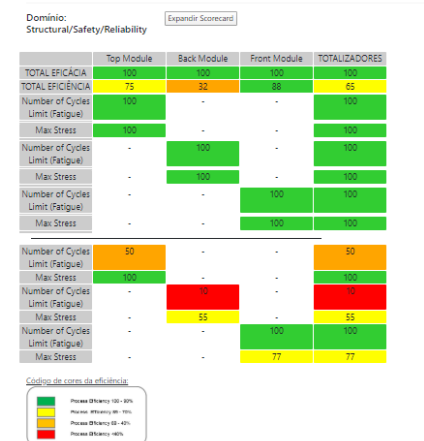
Figure I.15: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.1 and 1.2

Scorecard do Módulo: Mechanical Structure



(a) Structural/Safety/Reliability scorecard for iteration 1.3

Scorecard do Módulo: Mechanical Structure



(b) Structural/Safety/Reliability scorecard for iteration 1.4

Figure I.16: Structural/Safety/Reliability scorecards in LeanDfX for iterations 1.3 and 1.4