Rocket Heuristics for Preliminary Design

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Thesis to obtain the Master of Science Degree in

Aerospace Engineering

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September 2021

Para os pais...demorou mas está feito

Resumo

O desenho de foguetes é um processo iterativo no qual o principal objectivo é diminuir o peso na descolagem e aumentar a capacidade de carga útil que consegue transportar, tornando foguete mais eficiente. Em processos iterativos uma boa primeira aproximação pode reduzir significativamente o esforço na fase de design.

Neste trabalho, uma base de dados de foguetes foi construída, com o objectivo de identificar heurísticas que possam ser utilizadas no desenho preliminar de foguetes. Foram compiladas as principais características de foguetões, analisadas e comparadas com heurísticas conhecidas, de modo a poder confirma-las e obter novas.

Palavras-chave: Heurística, Veículos Espaciais,Base de Dados Foguetes, Pesquisa

Abstract

Rockets design is a iterative process in which the main objective is to reduce the gross lift-off weight (GLOW) and increase the payload ratio making it more efficient. In iterative processes a good first approximation can reduce the efforts in design phase by a significant margin.

In this work, a rocket database was constructed with the objective to identify heuristics that can be used in preliminary design of rockets. The main rocket characteristics were compiled, analysed and compared with known heuristics, in order to confirm them, and acquire new ones.

Keywords: Heuristic, Space Launch Vehicles,Rocket Database, Survey

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Glossary

GEO Geostationary Orbit. xv

GLOW Gross Lift-off Weight. xv

GTO Geostationary Transfer Orbit. xv

HEO High Earth Orbit. xv

HRE Hybrid Rocket Engines. xv

LEO Low Earth Orbit. xv

LRE Liquid Rocket Engine. xv

MDO Multidisciplinary Optimization. xv

MEO Medium Earth Orbit. xv

SLV Space Launch Vehicle. xv

SSTO Single Stage to Orbit. xv

ToF Time of Flight. xv

Chapter 1

Introduction

1.1 Objective

Space Launch Vehicle (SLV) design is a complex endeavour involving multiple subsystems that all influence each other. A survey of both past and present space launchers was made to confirm known or find new heuristics to be used in preliminary design for launchers.

1.2 Rocket Launch Vehicles in the Present

The launch of a spacecraft is fundamental to all space activity, and it is through the development of efficient launch vehicles that the impact of space on many aspects of science, commerce and daily life is possible [1]. Payloads and missions for spacecraft are many and varied. Some have reached the stage of being economically viable, such as satellites for communications, weather and navigation purposes. Other satellites serve the scientific community or are used for military scenarios [2].

Satellites may be categorized in a number of ways such as by orbit altitude, mission or payload [2].

Orbit	Application	Altitude	Mission Example
LEO	Earth Oservation	300 up to 1500 Km	CHAMP
	Weather Monotoring		SAR-Lupe
	Techonology		BIRD
	Astronomy		ROSAT
MEO	Communications	Several Thousand Km	Globalstar
	Navigation		GPS/Galileo
HEO	Communications	a few hundred up to 100 000 Km	Molniya
GEO	Communications	35 786 Km	EUTELSAT
Lagrange Points	$>$1 million Km	SOHO	
	Fundamental Research		JWST

Table 1.1: Examples of orbits for space flight missions [3].

Early satellites were necessarily small. However, the need for ever-larger, more capable and more complex satellites led to a natural growth in the satellite mass [2]. The mass of a satellite plays an important role because of its direct impact on the launch cost, which is a major cost component of space missions [3].

Due to the mass constraint, there weren't many new satellites. The past ten years have seen the nano/microsatellite segment grow by a factor of 10, from as few as 20 satellites in 2011 to nearly 200 in 2019. Key segment players have historically been responsible for a significant number of satellites launched, but new operators continue to gain traction and prove-out new business models, paving the way for future growth. Initially flavoured for technology demonstration missions, the industry has matured rapidly and nano/microsatellites are increasingly being used for commercial applications in earth observation, remote sensing, communications, and more [4].

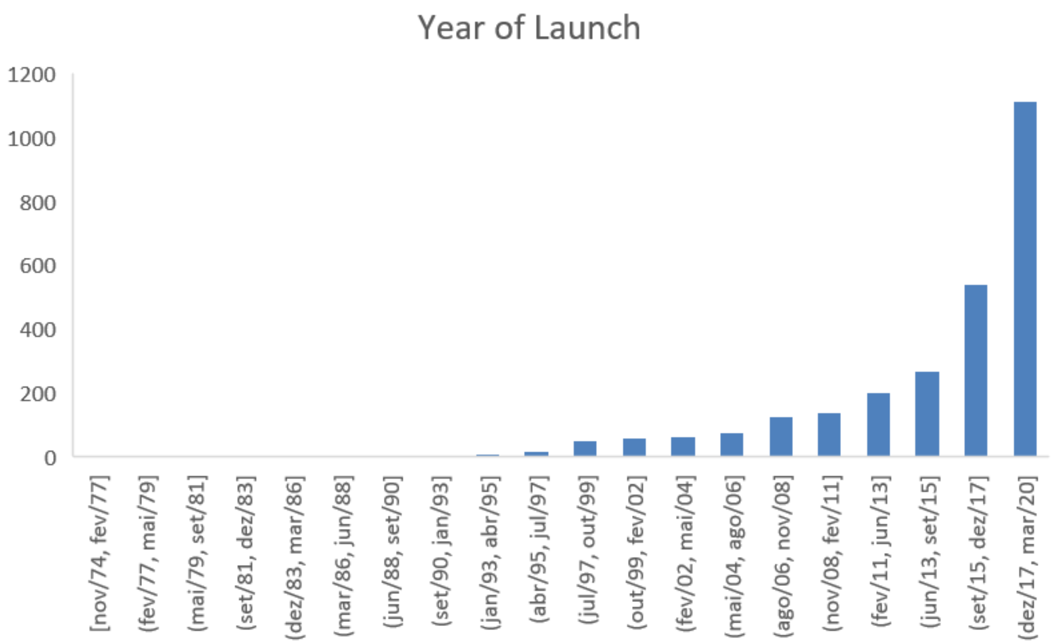

Figure 1.1: Number of new satellites per period of time.
1

The growing interest in launching small satellites into Low Earth Orbit (LEO), including constellations of such satellites, whether for scientific or communications purposes, has prompted a renewed interest in small launchers offering flexible operation and making limited infrastructure demands. A number of such vehicles are already available commercially or in development [2].

1.3 Space Launchers Survey

In this work, a database of space launchers was developed were their main characteristics were collected. In order to do so a collection of launcher user guides [5–17], books on the subject [1–3, 18–20] and, as a last resort, information on the internet [21–25]. Databases have been used in other works to analyse different aspects of rocket launchers from their propulsion systems [26] to costs in manufacturing [27].

Space launchers performance is key for a successful business. When developing a new launcher, a good preliminary design is important to ensure the effectiveness of the design process. There has been some interesting works regarding preliminary rocket design [28–31], even using Multidisciplinary Optimization (MDO) [32, 33]. However, the first concern is always to start with a good initial value in order to make the iterative process quicker and reliable.

The objective of this work is to utilize the database to obtained heuristics that can be used in preliminary design of rockets. A survey of heuristics was also performed in parallel to be crossed with the information on the database [2, 3, 19, 20].

Chapter 2

Rocket Dynamics

In this chapter we briefly review the most important aspects of rockets to determine what parameters should be included in the database. Although the different types of propulsion aren't explored in this work a brief explanation of the different types of chemical propulsion along with their respective advantages and disadvantages is presented.

2.1 Tsiolkovsky's equation

The Tsiolkovsky's equation, also known as the rocket equation, allows to calculate the velocity increase ΔV of a rocket through to propellant consumption and the velocity of the exhaust gases [34]

$$\Delta V = V_e \ln |\frac{m_0}{m}|, \tag{2.1}$$

where V_e is the exhaust velocity, m_0 the initial mass and m the mass at the point considered. It is only valid for a constant exhaust velocity and with no external forces considered. It can be used as a first approximation in many cases since the main exterior forces, drag and gravity, are relatively small.

2.2 delta-v calculation

The ΔV required to fulfil a mission is

$$\Delta V_{\text{Design}} = \Delta V_{\text{orbit}} + \Delta V_{\text{gravity}} + \Delta V_{\text{drag}}, \tag{2.2}$$

where ΔV_{orbit} is the velocity that will be required for the desired orbit, while $\Delta V_{gravity}$ and ΔV_{drag} are losses that will occur and that the rocket will have to overdue. Other losses exist, however the two mentioned are the most significant and the only worth considering in a first approximation. The ΔV provided to the launcher is usually higher than the ΔV_{Design} calculated, in order to provide some safety margin.

For a satellite to maintain a circular orbit, it must have the velocity

$$V_{orbit} = \sqrt{\frac{\mu}{R}}, \tag{2.3}$$

where R is the radius of the orbit and μ is the gravitational parameter of the planet.

Gravity loss is determined by

$$\Delta V_{gravity} = \int g \sin \gamma dt, \tag{2.4}$$

with g being the gravitational acceleration and γ the flight path angle. Analysing the equation 2.4 it is possible to see that one way to reduce the gravity loss is to keep the flight path angle zero. This can't be done for the entire flight but it is possible use a trajectory with small γ to gain velocity early in the launch.

The drag losses are [2]

$$\Delta V_{drag} = \int \frac{D}{m} dt, \tag{2.5}$$

where D is the drag force and m mass of rocket at each time. The drag force present depends on the configuration(size and shape) of the launcher as well as it's speed and angle of attack. The drag force is dependent on the area of the launcher in the direction of the movement, therefore it will increase with the diameter of the launcher. To minimize this losses, the rocket as to rise as slow and vertical as possible. When the rocket reaches a certain height the drag losses became negligible, since the atmospheric density decays exponentially. [2].

2.3 Configuration

The simplest configuration is a single stage rocket (SSTO). However rockets with a single stage can hardly reach the required orbital speed unless the payload is very small [3]. During the powered flight of a single-stage rocket, part of its mass has become 'superfluous', because a significant part of the mass of a rocket is propellant, that requires a lot of structural mass to be carried that becomes empty. So an extra, in fact useless mass has to be accelerated by the rocket engine when it is no longer needed. It is advantageous to discard the useless mass during the flight, using multiple stages. An additional advantage of multiple stages is the possibility of thrust programming, as well as adapting the engines of subsequent stages to the altitude where they are fired, thus reducing losses due to non-ideal expansion [34].

2.3.1 Multistage rockets

Since the performance of a rocket depends significantly on the structural mass of the vehicle, performance can be improved if some way can be found to dispose of useless structural mass whenever possible. The most common method for doing this is to stage the vehicle. Empty tanks and the large engines necessary to lift off from the Earth's surface are shed, and the smaller vehicle proceeds from that point with considerably less parasitic mass [35].

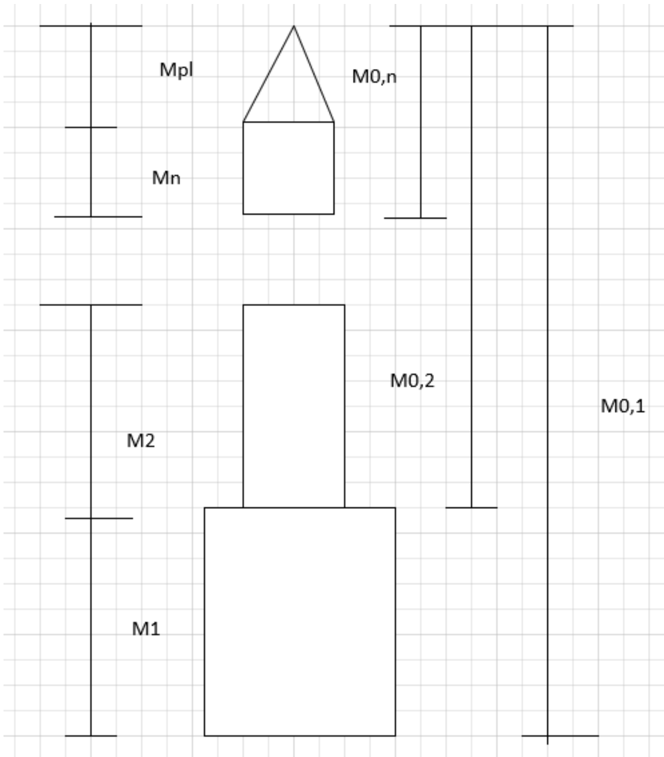

Figure 2.1: Multistage Rocket Configuration.

In a multistage rocket the payload of any given stage is considered all the mass above it. This means that the payload of the first stage is all the other stages plus the actual payload meant to be put in orbit, i.e

$$\lambda_N = \frac{m_{0N+1}}{m_{0N}}, \tag{2.6}$$

where m_{0N} is the total mass and m_{0N+1} is all the mass above that stage. Hence the payload is going to decrease with each stage, typically requiring less thrust for optimum results.

Some parameters about rocket configuration and staging are very important for rocket design

Structural ratio is a measure of the amount of the vehicle that is structure. Usually it is considered for each individually stage

$$\epsilon_N = \frac{m_{sN}}{m_{sN} + m_{pN}}, \tag{2.7}$$

where m_{sN} and m_{pN} are the masses of the structure and of the propellant for a given stage N

Similarly, the propellant mass ratio gives the relative amount of propellant

$$\varphi_N = \frac{m_{pN}}{m_{0N}} = (1 - \epsilon_N)(1 - \lambda_N), \tag{2.8}$$

where m_{pN} and m_{0N} are the propellant mass and the total mass of the stage N, respectively

The final burnout velocity of a multistage vehicle is the sum of the burnout velocities of the individual stages [35].

$$V_* = \prod_{i=1}^{N} V_{eN} \ln\left[\epsilon_N + (1-\epsilon_N)\lambda_N\right] \tag{2.9}$$

2.3.2 Boosters

Boosters can be added to improve the performance of a stage. This is basically a parallel staging making two stages active at the same time. Usually the boosters have a shorter burn time.

In this cases a zeroth stage, that combines both the boosters and the first stage, is considered. The first stage will be the remaining part of it, once the boosters are released.

The main advantage of parallel staging is the reduction of gravitational losses and an increase in thrust necessary to take of the ground. A disadvantage is that the rocket is likely to be bulky, and for flight through the atmosphere the drag penalty may be large. This, however, is of minor importance for large rockets where the drag losses are very small as compared to gravitational losses. A second disadvantage of parallel staging can the reduction in nozzle efficiency of the engines of the first stage. If these engines are used from the start, their expansion ratio is limited by the atmospheric pressure at low altitudes [34]. In this case, the structural and payload ratios are calculated through:

$$\epsilon_0 = \frac{m_{s0} + m_{s1}}{m_{s0} + m_{s1} + m_{p0} + m_{p1}}, \tag{2.10}$$

$$\lambda_0 = \frac{m_{01} + m_{ip1}}{m_{00}}, \tag{2.11}$$

where m_{s0} and m_{p0} are the structural, propellant ratio of the stage respectively and m_{ip1} the remaining propellant of the first stage at the zeroth stage burnout.

After the boosters are released, the first and remaining stages, work as if no parallel staging had happening [35].

2.4 Structure

Generically speaking a launch vehicle can be divided into 3 categories lower stages, upper stages and fairing.

2.4.1 Lower Stages

Two basic functions take place in the lower stages. These are designed to both store the propellant required to fulfil the mission, as well as provide the structural stability required by the entire vehicle, they operate most of the time inside atmosphere. Usually, they are composed of a cylindrical section, which is mainly filled with propellant: in average, 90% of the total mass is propellant. The liquid propellants present in these vehicle stages, consist of fuel and oxidizer, which require the separation of each stage in different tanks. For solid propellant, the rocket stage itself is filled with propellant, which presents a typical grain section, with cylindrical or star form. The grain geometry defines the propellant mass flow

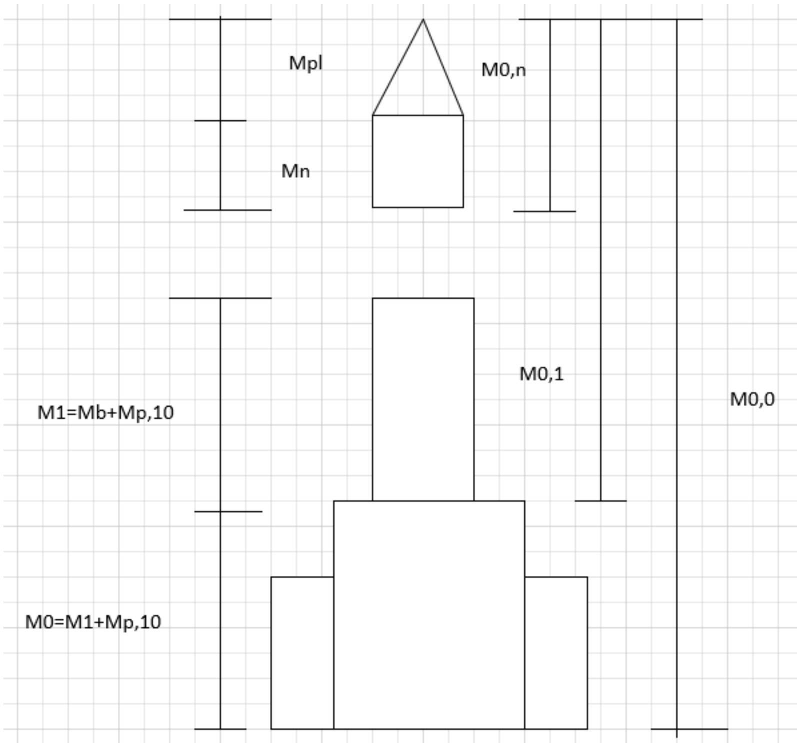

Figure 2.2: Parellel Staging Configuration.

rate, and burning time. For heavy launchers usually the first stage has boosters attached, they increase the payload mass that can be inserted in orbit.

2.4.2 Upper Stages

The upper stage, usually the last stage, is active at higher altitudes, where the atmospheric effects are not so important as in the beginning of the flight and the vehicle's attitude can be improved because the atmosphere forces can be neglected. This offers the advantage of a strict placement of the payload in the target orbit. However, it demands a dedicated and precise avionics system. Allied with the smaller dimension of the stage, this causes a higher structural ratio than the lower stages. Size then can became a problem, as the propellant mass is a function of the tank volume, whereas the structural mass is a function of the tank surface: with smaller tanks the ratio between surface and volume increases. Those stages are designed to operate at high altitudes, that allow to use low pressure in the combustion chamber and obtain a optimum nozzle expansion ratio without having a giant nozzle. In a typical launcher trajectory optimization, the guidance of the vehicle, in particular of the upper stage, is reduced to ensure that the attitude angle rates are lower than the upper limit, achievable by the control system of that stage.

2.4.3 Fairing

Placed at the top of the rocket, a fairing has two main functions: diminish the atmospheric drag force and protect the payload from external loads, that are present while in the presence of atmosphere.

Often it's jettisoned when atmospheric effects become negligible. The shape of the fairing is therefore a compromise between a good aerodynamic effect and a high internal volume, required to accommodate the payload.

2.5 Propulsion

Propulsion in a broad sense is the act of changing the motion of a body. Propulsion mechanisms provide a force that moves bodies that are initially at rest, changes a velocity, or overcomes retarding forces. As a result of space being a vacuum and with no standing places, Space Propulsion System (SPS) need to have unique characteristics in order to give an impulse to a vehicle [19, 36].

The energy source most useful to rocket propulsion is chemical combustion. [19]. A rocket is generally (traditionally) defined as a propulsion system that carries both fuel and oxidizer as storage within the vehicle, burning the propellant as required to produce a high-speed exhaust jet that delivers the needed thrust [37]. Chemical combustion systems are the most common systems for space applications and can be divided into three basic categories: solid, liquid and hybrid. The terminology refers to the physical state of the stored propellants [20].

The standard one-dimensional thrust equation, for thrust generated by a rocket's propulsive exhaust nozzle, is given by

$$T = \dot{m}_e u_e + (p_e - p_a)A_e, \tag{2.12}$$

where the first term is the momentum thrust represented by the product of the propellant mass flow rate and its exhaust velocity relative to the vehicle. The second term represents the pressure thrust consisting of the product of the cross-sectional area at the nozzle exit A_e (where the exhaust jet leaves the vehicle) and the difference between the exhaust gas pressure at the exit and the ambient fluid pressure. If the exhaust pressure is less than the surrounding fluid pressure, the pressure thrust is negative. Because from this condition results a low thrust and is undesirable, the rocket nozzle is usually designed in a way that the exhaust pressure is equal or slightly higher than the ambient fluid pressure [19]. Although the pressure changes with altitude, therefore the best is to optimize the system by selecting the best aperture.

Other key parameter for propulsion is the specific impulse. It's defined the change in linear momentum per unit weight of the propellant consumed

$$I_{sp} = \frac{V_e}{g_0}, \tag{2.13}$$

where g_0 is the acceleration due to gravity at standard sea level of the Earth, and V_e is the velocity of the exhaust gases [38].

2.5.1 Solid Propulsion

Figure 2.3 shows the essential features of a solid-propellant propulsion system. In this case, the fuel and oxidizer are mixed together and cast into a solid mass called the grain. The grain is usually formed with a hole down the middle called the perforation and is firmly cemented to the inside of the combustion chamber. After ignition, the grain burns radially outward, and the hot combustion gases pass down the perforation and are exhausted through the nozzle. The absence of a propellant feed system in the solid-propellant chemical rocket is one of its outstanding advantages.

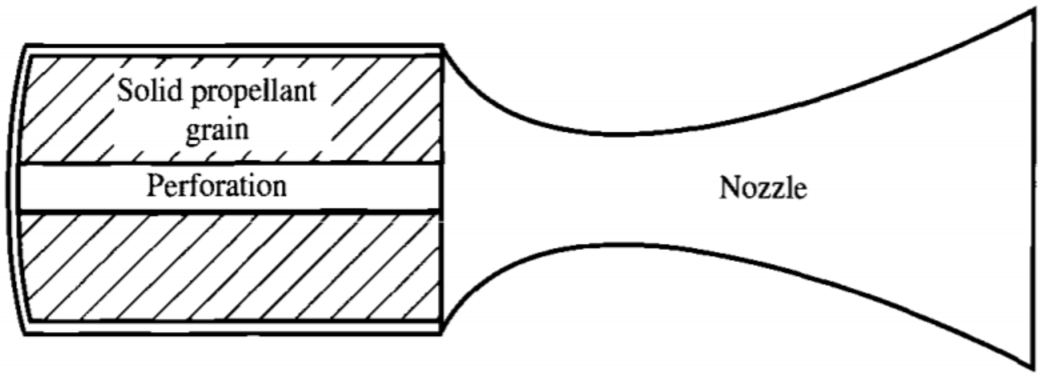

Figure 2.3: Solid Propellant Engine [39].

2.5.2 Liquid Propulsion

Liquid propulsion comes with more complexity of system construction and operation versus the simpler solid propulsion, given the need for tank storage, feed (pumping) systems, cooling systems and an effective spray injection system for delivery of the propellant to the combustion (thrust) chamber. [37] The ready ability to throttle or modulate thrust at different points in the flight mission, or shut down entirely and restart at a later time in the mission, are additional factors that favor LREs for some applications.[37]

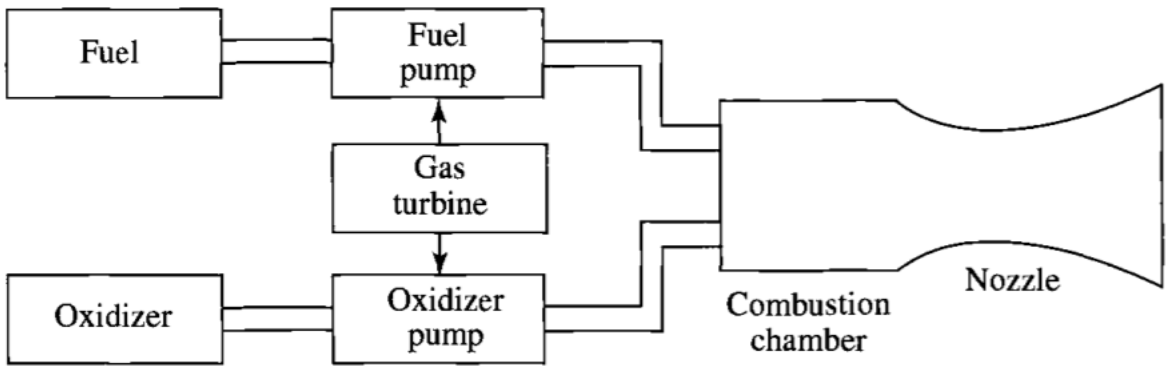

Figure 2.4: Liquid Propellant Engine [39].

2.5.3 Hybrid Propulsion

Hybrid rocket engines (HREs) are an attempt to exploit some advantages of both liquid propellant rocket engine and solid-propellant rocket motor technology. The traditional arrangement of an HRE is a liquid oxidizer being fed to a solid fuel grain, as in fig 2.5 [37]. The main advantages of a hybrid rocket propulsion system are: (1) safety during fabrication, storage, or operation without any possibility of explosion or detonation; (2) start-stop-restart capabilities; (3) relatively low system cost; (4) higher specific impulse than solid rocket motors and higher density-specific impulse than liquid bipropellant engines; and (5) the ability to smoothly change motor thrust over a wide range on demand [19]. The disadvantages of hybrid rocket propulsion systems are: (1) mixture ratio and, hence, specific impulse will vary somewhat during steady-state operation and throttling; (2) lower density-specific impulse than solid propellant systems; (3) some fuel sliver must be retained in the combustion chamber at end-of burn, which slightly reduces motor mass fraction; and (4) unproven propulsion system feasibility at large scale [19].

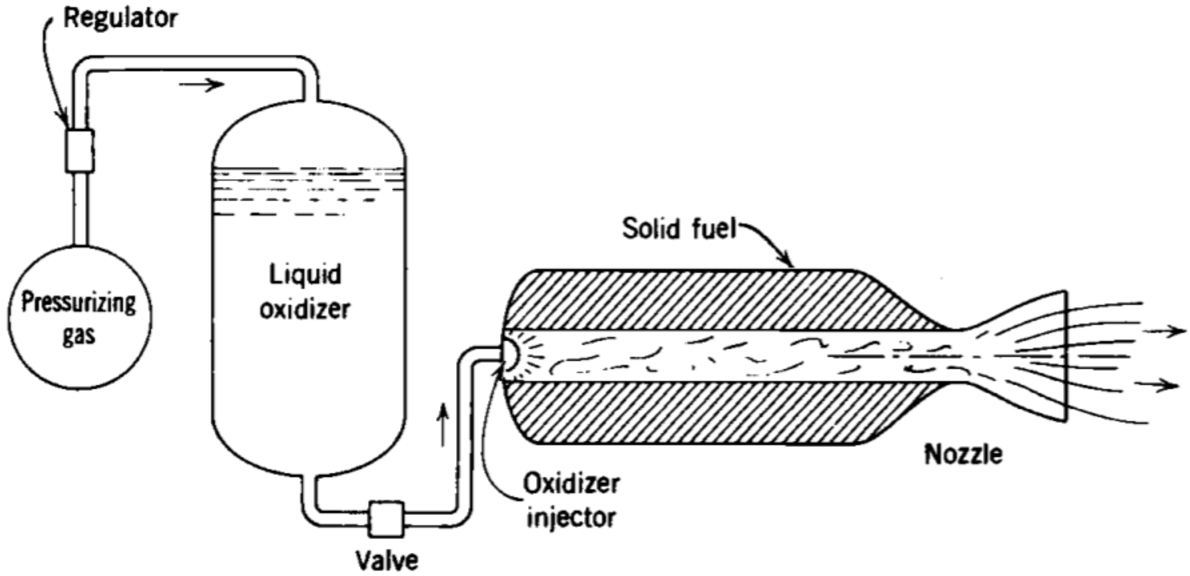

Figure 2.5: Hybrid Propellant Engine [39].

2.6 Trajectory

Trajectory has a great importance and hard because it as to make sure that the rocket is able to take off, gain velocity specially on the horizontal and resist to the aerodynamics stresses. In order to reduce the mass budget, typically the rocket structure can only handle loads in the longitudinal direction, which restricts the movement.

Simplifying, the trajectory can be separated into 3 different parts: the vertical lift off, the gravity turn and exo-atmospheric flight.

During the vertical lift off the SLV ascends with a flight path angle equal to 90° . This is the shortest of the 3 parts of the trajectory and mainly serves to gain velocity and avoid the launch tower. As soon as possible the vehicle enter in the gravity turn phase.

During the gravity turn trajectory, the vehicle slowly rotates its flight orientation, from vertical eventually horizontal. Due to the atmospheric forces, it is required that the SLV maintains a angle of attack nominally at zero or very small, under the risk of structural failure [35]. The gravity turn manoeuvrers allow the rocket to turn to horizontal to minimize gravity losses and gain speed in the required direction, but minimizing possible structural damaging lateral forces at the same time.

Having clear the atmosphere, the gravity turn manoeuvrer id no longer required. It is usually at this point that the fairing can be jettison since there are no longer atmospheric forces being applied.

Chapter 3

Space Launcher Database

In order to compare different SLV and to understand the trends they follow a database was constructed gathering some key characteristics of rockets. We also calculate or estimate some parameters when they were not available at the source using the ones available, if possible. The database was constructed with information gathered from rocket launcher user guides, books on the subject and, as a last resort, information on the internet. Rockets launched horizontally weren't considered since they present some considerable differences in their trajectory and design philosophies. Reusable rockets were also not included, due to small data sample.

We also gathered from literature some heuristics about rockets that can be used as a guide for preliminary design [2, 3, 19, 20]. The database built can be used to confirm or disprove the existing heuristics, as well as to identify new ones.

3.1 Launch Vehicles

To build the database, a survey of both existing and retired rockets was conducted. Some launch vehicles expected to perform their first launch in the near future, for which information was already available, were also included.

Information about a total of 43 launch vehicle was collected. They were separated into 3 different categories according to their payload capability to a certain orbit.

Small rockets are able to deliver up to 2 tons to Low Earth Orbit (LEO) [3]. A total of 11 small rockets are present in the database and are displayed in Table 3.1

Medium launchers serve to place satellites into all Earth orbits: LEO, including polar orbits, Medium Earth Orbits (MEOs), Geostationary Transfer Orbit (GTO), Geostationary Orbit (GEO) and Earth escape missions. They can deliver between 2 and 15 tons at LEO and 3 to 6 tons at GEO [3]. Table 3.2 displays the 20 medium rockets present in the database.

Heavy-lift launch vehicles (HLLVs) mainly launch communications satellites into GTOs and are used specifically for launching very heavy payloads. They can deliver more than 15 tons at LEO and 6 tons at GEO [3]. A total of 11 heavy rockets are present in the database and displayed in Table 3.3

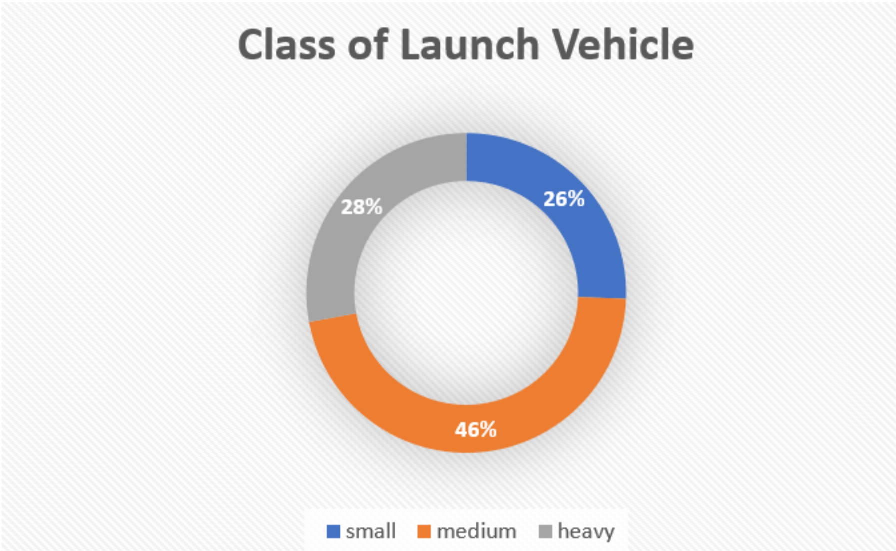

Figure 3.1: Launch Vehicle Class Distribution.

Figure 3.1 allows us to see the distribution of classes within the database with medium launchers being the most represented with 46% of the sample. The number of stages can also be seen in Figure 3.1.

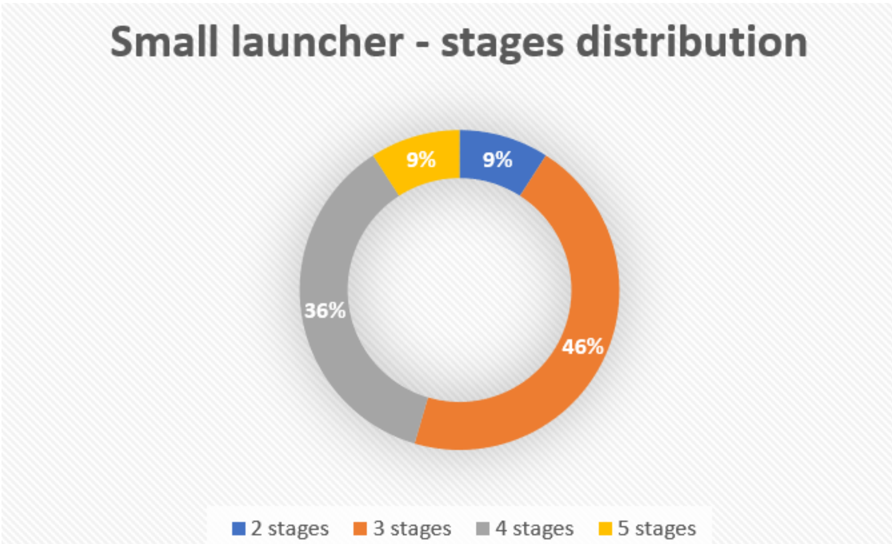

Figure 3.2: Small Launch Vehicle Class Distribution.

The class of small launchers is mainly constituted by three and four stages rockets. It is the only class in the database that as a 5 stage vehicle which corresponds to Minotaur 5. It only has one launcher with two stages that is Alpha 1.

Medium launchers have a more distributed sample divided between two, three and four stage rockets.

More than half of the heavy launchers are three stage rockets. The only one that is a four stage vehicle is the Proton M/Briz-M

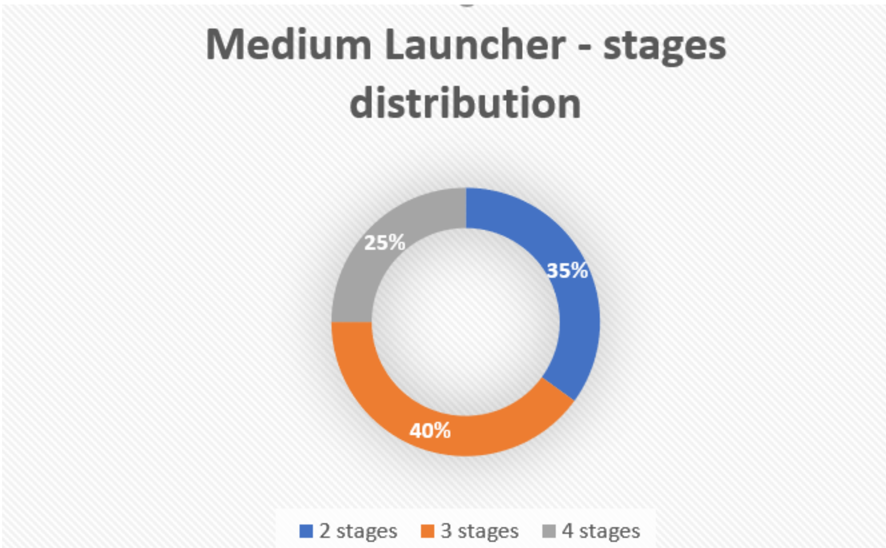

Figure 3.3: Medium Launch Vehicle Class Distribution.

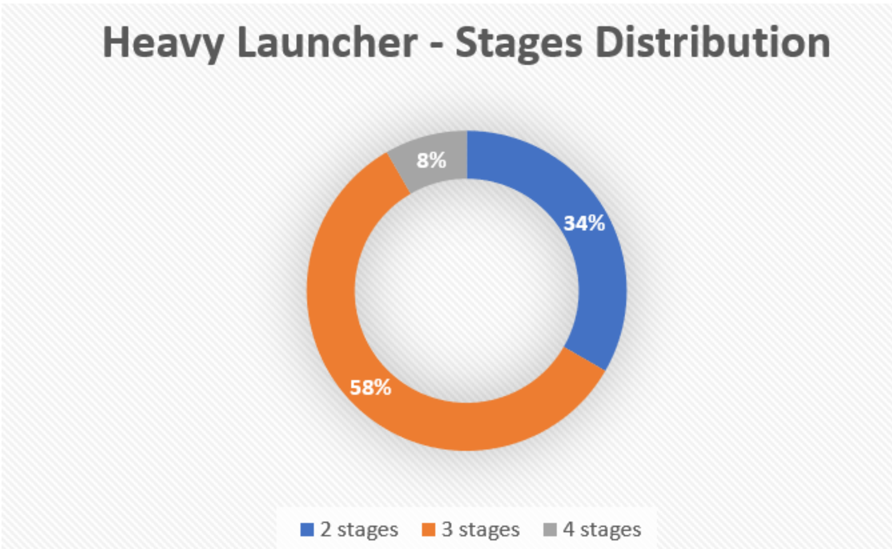

Figure 3.4: Heavy Launch Vehicle Class Distribution.

3.2 Parameters gathered

3.2.1 Launchers Characteristics

The key characteristics gathered for each rocket can be found in Table 3.4. The information was collected for each individual stage. Some characteristics were available for some rockets, such as interstage sections and payload adapters, that were also gathered but for which the sample size isn't enough in order to look for regularities.

With the information gathered some derived relevant characteristics where calculated (see Table 3.5).

When possible this characteristics were derived for each stage and for the launcher as a whole.

Class was attributed to each launcher according to the definitions established in Section 3.1.

Small Launchers	Source
Minotaur 4	[15]
Minotaur 5	[15]
Athena 1	[21]
Athena 2c	[21]
Taurus 2110	[14]
Rockot	[3]
Shavit	[22]
Shavit 1	[22]
Shavit 2	[22]
Alpha 1	[13]
Epsilon	[40]

Table 3.1: Small Launchers

Medium Launchers	Source
falcon 9	[17, 23]
falcon 9v1.1	[17, 23]
Soyuz-LV	[12]
Vega	[11]
Atlas V 400	[10]
Athena III	[41]
Delta 2 - 7420	[9, 24]
Delta 2 - 7925H	[9, 24]
Delta IV-M	[6, 42]
Delta IV-M+5,2	[6, 42]
Titan 23G	[18]
Titan 401B	[25, 43]
Titan 403B	[25, 43]
LM-3A	[8]
Angara 1,2	[44]
Angara A3	[44]
Antares	[44]
Dnepr	[44]
GSVL	[44]
LVM3	[44]

Table 3.2: Medium Launchers

Mass calculations were performed to each stage. The mass for structure and propellant make the total mass. Usually only two of the three are provided, but with them the third can be calculated. This step was performed for each stage individually and for the totality of the launcher. In order to obtain a distribution of the mass through the entire vehicle each stage ratio was also calculated, dividing its mass by the total mass of the launcher. It was also necessary to know how much mass each stage has to lift on its operation. Using the mass it is also possible to calculate the weight. It was considered the acceleration at Earth surface (g=9,81).

In cases where more than on engine operated at the same time, as is the case with boosters, the

Heavy Launchers	Source
falcon 9 block 5	[23]
Falcon Heavy	[17, 45]
Arianne 5	[1, 7]
Atlas V 500	[10]
Delta IV-HU	[6, 42]
Saturn V	[1]
Proton-K	[5]
Proton-M	[5]
Proton M/Briz M	[5]
Angara A5	[44]

Table 3.3: Heavy Launchers

Characteristic	Units
Mass Propellant	kg
Mass Structure	kg
Total Mass	kg
Total mass at lift-off	kg
Length	m
Diameter	m
Engine	-
Engine number	-
Thrust	kN
Isp	s
Propellants	-
Burn time	s
Payload Capability	kg
First Flight date	-

Table 3.4: Characteristics gathered for each stage

total thrust had to be calculated by adding the thrust generated by each source. The total thrust was derived to each stage.

The ratio between the thrust and the weight was also obtained for each individual stage by dividing the total thrust the stage provides by the weight that stage will have to carry.

Both structural and propellant ratios can be calculated using Equations 2.7 and 2.8. The payload ratio follows the same logic using the ratio between the payload and the total mass of the launcher. In this case it was only calculated for the entire launcher and in case of multiple payload values (for different orbits) the largest payload was considered.

To study the size of the launcher the total length was found by adding the length each stage plus the fairing. The length ratio follows the same logic as the mass ratio. Additionally the ratio between the length and the diameter of each stage and for the entire vehicle as derived. For the total launcher, the diameter considered was the highest one from individual stages. For launchers with booster this wasn't considered since information available about the boosters arrangement wasn't enough to have a

Characteristic	Units
Class	-
Mass Propellant	kg
Mass Structure	kg
Total Mass	kg
Mass stage and above	kg
Weight	N
Total thrust	kN
T/W	-
Structural Ratio	-
Mass Stage Ratio	-
Propellant Ratio	-
Payload Ratio	-
Total Length	m
Length/Diameter	-
Length Stage Ratio	-
Exit gasses Velocity	m/s
Ideal Velocity Increment	km/s

Table 3.5: Characteristics derived for each stage

significant sample.

Finally Equation 2.1 was used to discover the ideal velocity increment, which also required to know the exit gases velocity. Both were calculated for each individual stage with the ideal velocity increment of the launcher resulting of the sum of each individual stage.

Trajectory

Additionally some aspects of the trajectory were also included in the database when available, such as the altitude, velocity and time of flight(ToF) of some relevant events of the ascent.

Trajectory Events
Maximum Dynamic Pressure
Fairing Jettison
Stage Engine Cut-off
Stage Engine Ignition
Stage Separation
Spacecraft Separation

Table 3.6: Trajectory relevant units for which ToF, altitude and velocity were gathered

3.2.2 Heuristics Gathered from Literature

The collected information is a historical recoil of the most rockets and can be used to confirm or disprove a a posteriori known heuristics about rockets. For that purpose, some heuristics were compiled from literature [2, 3, 19, 20] and depicted in Table 3.7. For easy reference a code was attributed to each one.

3.3 Database Organization

The database is divided into five sheets: "Guidelines","Heuristics", "Data", "Calculated Data" and "References". "Guidelines" provides explanations to use the database. "Heuristics" is the heuristics gathered from literature. "Data" is the information collected from different sources. For each entry there are three columns for value, reference of the source and comment. Comments are to contextualize some of the values and provide additional information as the orbit for the payload capabilities.

	A	B	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DO
1														
2			Thrust [kN]											
3	Number	Rockets	Thrust 2nd Stage Vac	ref	comment	Thrust 2nd Stage Sea	ref	comment	Thrust 1st Stage Vac	ref	comment	Thrust 1st Stage Sea level		Isp 5th Stage
4	1	falcon 1	33,6				27		320	27		318		
5	2	falcon 9	420,3				27	stage total	4413,4	27	stage total	3864,3		
6	3	falcon 9v1.1	934				6	stage total	5979,5	1	stage total	6804		
7	4	falcon 9 Block 5	949,1				6	stage total	8429,5	6	stage total	7728,6		

Figure 3.5: Excerpt from Database.

"Calculated Data" contains the data from the "Data" sheet without references or comments, but including calculated information is possible, from other entries, to fill the gaps. For example, usually only two of the gross mass, dry mass and propellant mass is provided by the sources but with two, the third can be determined. The expressions used for all calculations are listed in Table 3.5 "References" is a list with all the sources utilized for building the database.

The database also has a colour code for each cell in order to allow a quicker identification of the information. Cells with a green background are values which sources are reliable such as the user guides or books on the subject. If the background is yellow it means that the specific value comes from a internet source which couldn't be verified in the references used but inserted with a array of other values that could. Red cells are for values provided from internet sources. The brown background was reserved for values that were derived from other, meaning they were not collected from any source but calculated.

It is also possible to hide the columns for the ref and the comments and have just the values using the group function.

		Gross Mass [Kg]			
Number	Rockets	gross mass 1st stage	gross mass 2nd stage	gross mass 3rd stage	gross mass 4th stage
5	Soyuz- LV	177652	99765	27755	7540
6	arianne 5	184700	4540		
7	Vega	96243	26300	12000	1265
8	Atlas V 400	305143	23073		
9	Atlas V 500	305440	2247		
10	Atlas V HLV	310443	2316		

(a) Example of data fill

			T/W (N/Kg*g)				
Number	Rockets	[redacted]	T/W stage 0	T/W stage 1	T/W stage 2	T/W stage 3	T/W stage 4
5	Soyuz- LV	[redacted]	1,324479	1,324479	0,738065	0,82084	0,218988
6	arianne 5	[redacted]	3,411081	0,738307	0,946606	0	0
7	Vega	[redacted]	2,254081	2,254081	2,846758	2,340744	0,138363
8	Atlas V 400	[redacted]	1,122538	1,281219	0,401275	0	0
9	Atlas V 500	[redacted]	1,182543	1,359983	1,752232	0	0
10	Atlas V HLV	[redacted]	3,79477	1,334566	1,5104	0	0

(b) Example of new data calculated

Figure 3.6: Excerpts from Calculated Data

Code	Theme	Heuristic	Ref
SR1	Structural Mass Ratio	14% of total mass	[20]
SR2	Structural MassRatio	$5\% - 15\%$ of total mass	[3]
PR1	Propellant Mass Ratio	85% of total mass	[20]
PR2	Propellant Mass Ratio	91% of total mass	[19]
PLR1	Payload Mass Ratio	1% of total mass	[20]
PLR2	Payload Mass Ratio	$1\% - 5\%$ of total mass	[3]
PLR3	Payload Mass Ratio	larger vehicles are able to archive higher payload fractions	[2]
IV	Isp	Usually higher for higher stages	[20]
ST	Structure	Lower stages are longer and often have a larger diameter than upper stages	[3]
TW1	Thrust over Weight	First stage might typically have an T/W ratio less then 1,5	[2]
TW2	Thrust over Weight	T/W has to be higher than 1. $10\% - 20\%$ higher take off thrust helps the launcher	[3]
BT1	Burn Time	Booster engines operate in a duration of 1-3 minutes	[3]
BT2	Burn Time	Main engine operate in a duration of 400-500s	[3]

Table 3.7: Collection of heuristics from literature

Chapter 4

Data Analysis

In this chapter the database is used to analyse the different characteristics of the launchers and try to find regularities. The heuristics gathered from literature are compared with the data from the launchers and new ones are obtained.

4.1 Analysis Criteria

In order to analyse the data acquired, a set of criteria must be placed in order to keep the process consistent.

When describing numerical data, it is common to report a value that is representative of the observations. Such a number describes roughly where the data are located or “centered” along the number line, and it is called a measure of center. The two most popular measures of center are the mean and the median [46]. It was chosen the median value of the population to estimate a launcher characteristic. The median of a population is the middle value of data when rearranged in crescent order, and divides it into two equal parts. This way it is the best single number approximation because it isn’t as sensitive to outliers as the mean [46].

However a point estimation of a population characteristic will depend on the sample. Instead a confidence interval for the median is calculated. It is constructed so that, with a chosen degree of confidence, the value of the characteristic will be captured between the lower and upper endpoints of the interval. A confidence level has to be established before examining the data. A 95% confidence level was chosen since it is the most commonly used.

The sample of launchers obtained is not very large and that is further evidenced when divided into classes. Therefore it is assumed that a t distribution is in place, and the confidence interval can be calculated using

$$x \pm t\frac{s}{\sqrt{n}}, \tag{4.1}$$

where x is the median, t is the confidence coefficient that is dependent on the confidence level and the number of the sample, s is the standard deviation and n is the number of the sample [47].

The mode of the distribution is not presented in this study. It was thought that studying the data mode would be interesting, however the only significant observation resulting was when launchers from the same family where present. SLV from the same family often use the same design for a single stage. For example, the first and second stages from Titan 401B and Titan 403B are the same, with Titan 401B having an extra stage, or Proton-k and Proton M in which the first stage of Proton M is an improvement over Proton-k, while the rest of the stages remain the same. Meaning that the results obtained from mode are not for characteristics that happen to be the same but from the same design.

Outliers are expected in every sample. In order to identify them it was used Tukey's method, because it can be applicable to skewed or non mound-shaped data since it makes no distributional assumptions and it does not depend on a mean or standard deviation because it uses quartiles which are resistant to extreme values. [48]. Also this method fits in the display of results used since it allows the verification with boxplots which is the chosen method to visualize the results.

To find outliers it is necessary to calculate the Inter Quartile Range (IQR), which is the distance between the lower quartile (Q1) and upper quartile (Q3). If a point is at a distance of 1,5 times the IQR below Q1 and above Q3 it is considered a possible outlier and for a distance of 3 times the IQR it is considered a probable outlier. [48].

4.2 Data Overview

4.2.1 General Observations

Saturn V

Most of the launch vehicles present in the database have as mission objective satellite placement in orbit. The energy required to expand the range increases exponentially. Because of that, Saturn V, responsible for take people to the moon, becomes an outlier for most of the characteristics gathered, as exemplified by Figures 4.1, 4.2 and 4.3

Evolution in time

Many characteristic were plotted as a function of the year of first launch to observe their evolution. However no significant evolution was detected. Some evolution was expected but within the same rocket family, the improvements were not significant. This is maybe due to the fact that the basic technology remains the same and improvements, even if important, are relatively small, as exemplified in Figures 4.4, 4.5 and 4.6.

Today's main efforts are focused on reusable rockets which shouldn't bring improvement for the characteristics compared in this work, it should instead greatly reduce costs.

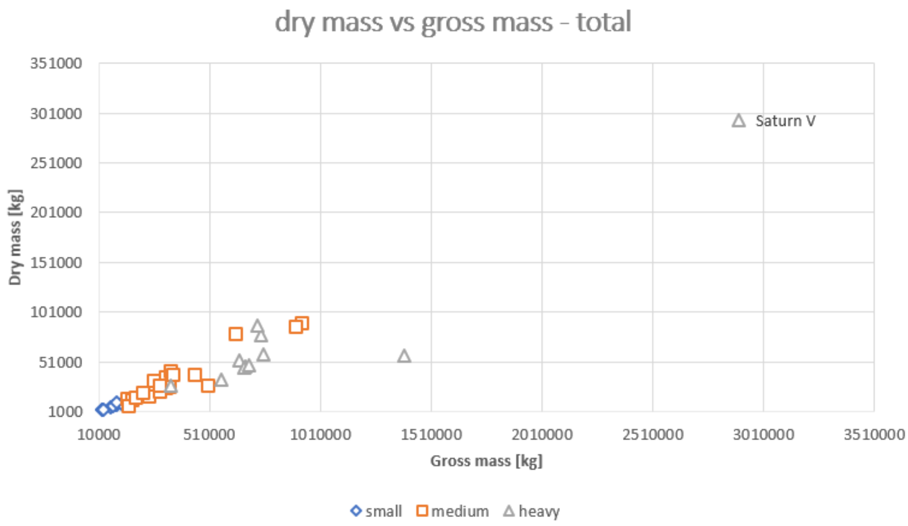

Figure 4.1: Dry mass vs Gross mass Ratio.

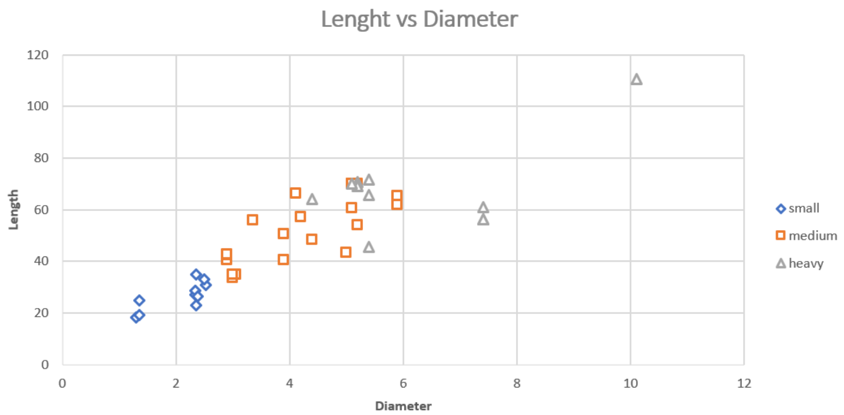

Figure 4.2: Length vs Diameter.

4.2.2 Structural Mass Ratio

The structural mass ratio can be calculated using eq. 2.7 on every stage individually and on the launch vehicle as a whole. Figures 4.7, 4.8, 4.9 and table 4.1 shows how structural ratio fluctuates with different stages and allows the verification of both heuristics gathered on Section 3.2.2. **SR1** and **SR2** stated that the structural ratio was 14% and 5%-15% respectively.

The values are within the expected range of **SR2** except for upper stages which have a wider range, reaching even 0,5 in some cases. This difference for the other stages can be explained by their small size comparatively to original launchers, which makes that the payload and all its support equipment, such as the payload adaptor, have a bigger impact in the percentage of the total mass.

Considering the entire population, **SR2** range is wider than the range between the 5th and 95th percentile, meaning that involves more than 90% of all values gathered. We can use this heuristics as a benchmark of values, however since it includes the majority of values gathered this interval can still

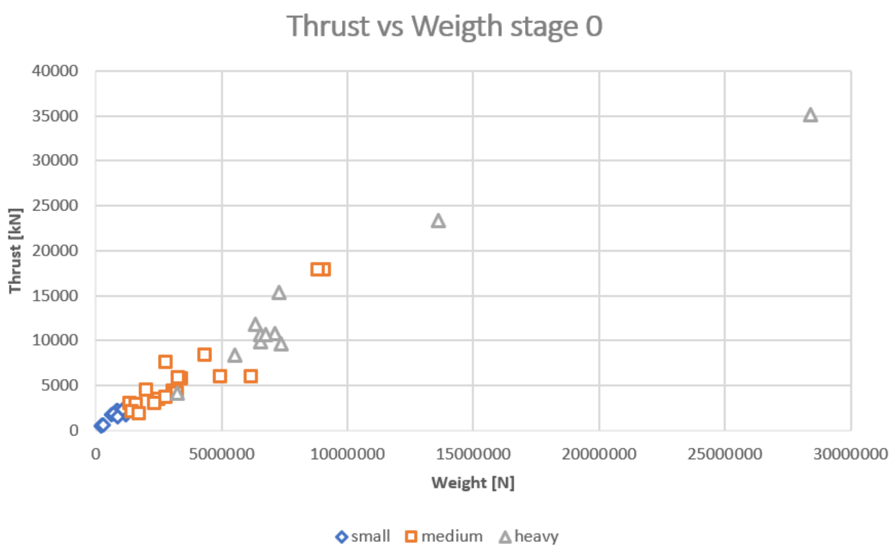

Figure 4.3: Thrust vs Weight.

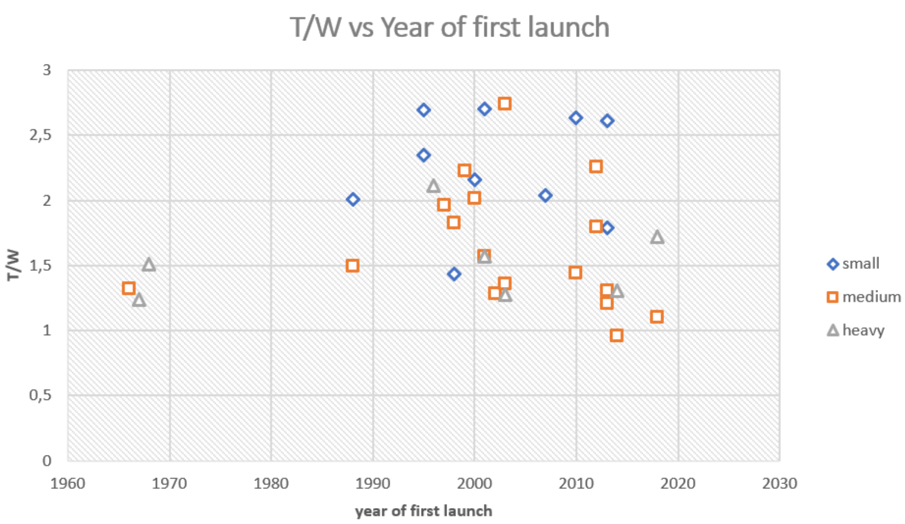

Figure 4.4: T/W vs year of first launch.

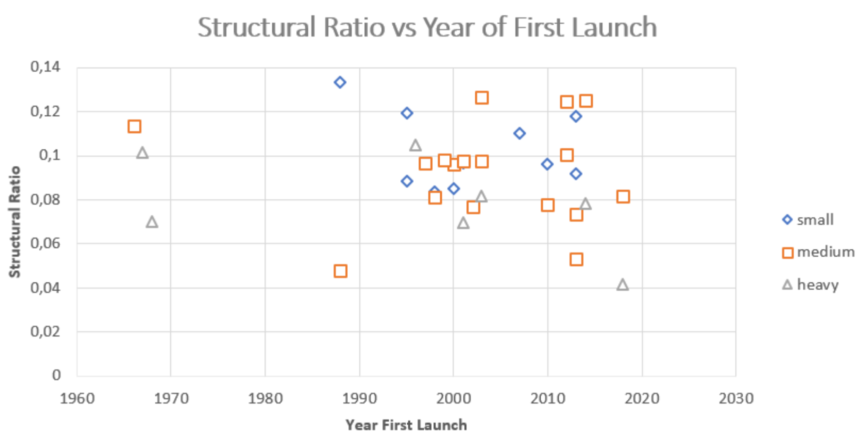

Figure 4.5: Structural Ratio vs year of first launch.

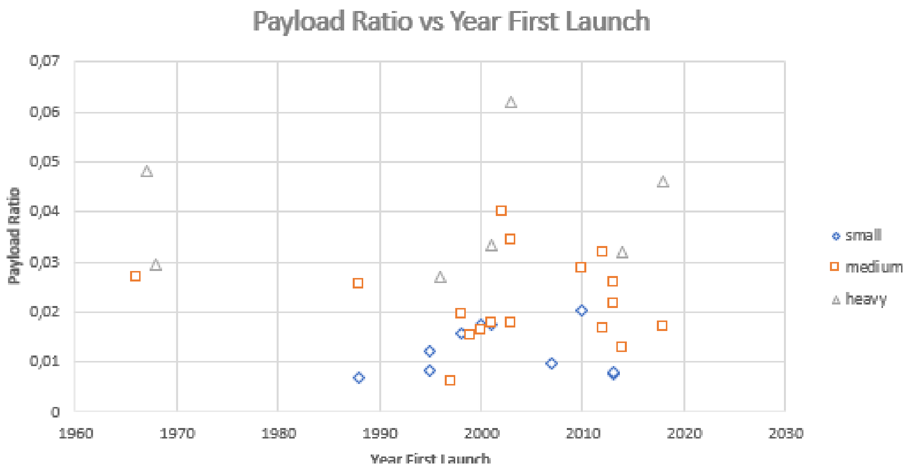

Figure 4.6: Payload Ratio vs year of first launch.

be refined in order to have a narrower set of values for initial design. The estimation interval value for structural mass is 0,086 to 0,101 with a median of 0,094 which can be used as a good first value for preliminary design. According to **SR1** this value should be 0,14. However this value is outside the 95th percentile of the data and therefore it is not verified by it.

Small and medium launchers present a similar structural ratio even having the same median value of 0,096. On heavy launchers this value slightly decrease to 0,081 meaning it could decrease inversely to the gross mass of the SLV.

Upper stages present a wider range of values, which can be explained by their smaller size and lesser requirement of propellant due to operate without drag.

Using the criteria defined we can calculate both the first value for iteration and the range of values expected.

Using the data it is possible to extrapolate New Structural Ratio (NSR) heuristics.

- **NSR1** - Range of Structural Ratio 8,6% - 10,1%
- **NSR2** - Upper stages have a wide range of structural ratio going up to 50% in some cases
- **NSR3** - Structural ratio is slightly lower in heavy launchers with an estimate interval of 6,3% - 9,9%

In order to further explore **NSR4** it was plotted the structural ratio vs the gross mass in Figure 4.11. For small launchers the structural ratio tends to decrease with the total mass but the trend is not clear and is not true for other classes. Even so a trend line for the behaviour of small launchers structural ratio can be obtained resulting in another heuristic

- **NSR4** - Small launcher structural ratio tends to evolve with the gross mass with a logarithmic relation

$$\epsilon = -0,22\ln(m_{\text{Total}}) + 0,347 \tag{4.2}$$

class	number	Q_1	median	Q_3	Average	estimate interval	standard deviation	min	max	
small - 1st stage	10	0,074	0,078	0,094	0,086	0,068-0,088	0,018	0,066	0,124	
small - 2nd stage	10	0,079	0,097	0,117	0,098	0,085-0,109	0,021	0,069	0,124	
small - 3rd stage	10	0,086	0,193	0,266	0,204	0,117-0,269	0,132	0,083	0,504	
small - 4th stage	5	0,140	0,347	0,448	0,305	0,187-0,507	0,168	0,071	0,504	
small - boosters	-	-	-	-	-	-	-	-	-	
small - total	10	0,088	0,096	0,118	0,102	0,086-0,106	0,017	0,084	0,133	
medium - 1st stage	20	0,052	0,075	0,088	0,082	0,059-0,091	0,041	0,041	0,225	
medium - 2nd stage	20	0,084	0,104	0,118	0,106	0,091-0,117	0,033	0,043	0,182	
medium - 3rd stage	9	0,097	0,119	0,161	0,168	0,028-0,211	0,148	0,085	0,553	
medium - 4th stage	3	0,120	0,504	0,544	0,390	0,109-0,899	0,234	0,120	0,544	
medium - boosters	8	0,107	0,115	0,137	0,123	0,099-0,130	0,022	0,106	0,170	
medium - total	20	0,077	0,096	0,112	0,096	0,084-0,109	0,032	0,048	0,192	
heavy - 1st stage	11	0,061	0,069	0,076	0,071	0,059-0,079	0,019	0,040	0,117	
heavy - 2nd stage	11	0,068	0,080	0,102	0,092	0,051-0,108	0,053	0,039	0,234	
heavy - 3rd stage	5	0,074	0,082	0,109	0,090	0,065-0,100	0,018	0,074	0,111	
heavy - 4th stage	1	-	-	-	-	-	-	-	-	-
heavy - boosters	4	0,033	0,091	0,214	0,113		-	-	-	
heavy - total	11	0,068	0,081	0,105	0,087	0,063-0,099	0,033	0,041	0,160	
total - 1st stage	42	0,079	0,075	0,086	0,079	0,067-0,083	0,031	0,040	0,225	
total - 2nd stage	42	0,077	0,097	0,114	0,100	0,088-0,107	0,036	0,039	0,234	
total - 3rd stage	24	0,085	0,113	0,212	0,167	0,068-0,157	0,128	0,074	0,553	
total - 4th stage	9	0,116	0,347	0,504	0,311	0,231-0,464	0,187	0,071	0,544	
total - boosters	12	0,106	0,113	0,137	0,121	0,086-0,139	0,051	0,040	0,248	
total	42	0,076	0,094	0,111	0.095	0.086-0,101	0,029	0,041	0,192	

Table 4.1: Structural Ratio Values through stages

4.2.3 Propellant mass ratio

The propellant mass ratio can be calculated using eq. 2.8 on each stage and the launch vehicle as a whole and Figures 4.12, 4.13 and 4.14 shows the fluctuation in propellant ratio through the number of stages in the vehicle.

From Figures 4.12, 4.13 and 4.14 it is possible to observe that propellants provide the greatest contribution to the launcher total mass. As in Chapter 4.2.2, on Figures 4.12, 4.13 and 4.14 the upper stages have a wider range of values. For the totality of the SLV, propellant ratio does not vary significantly with the class of the launcher as displayed in both Figure 4.15 and Table 4.2. The median value of 0,888 is a good approximation for a first iterative value to be used, with the estimate interval being 0,881 to 0,896.

We can compare our findings with **PR1** and **PR2** which stated the propellant ratio to be 0,85 and

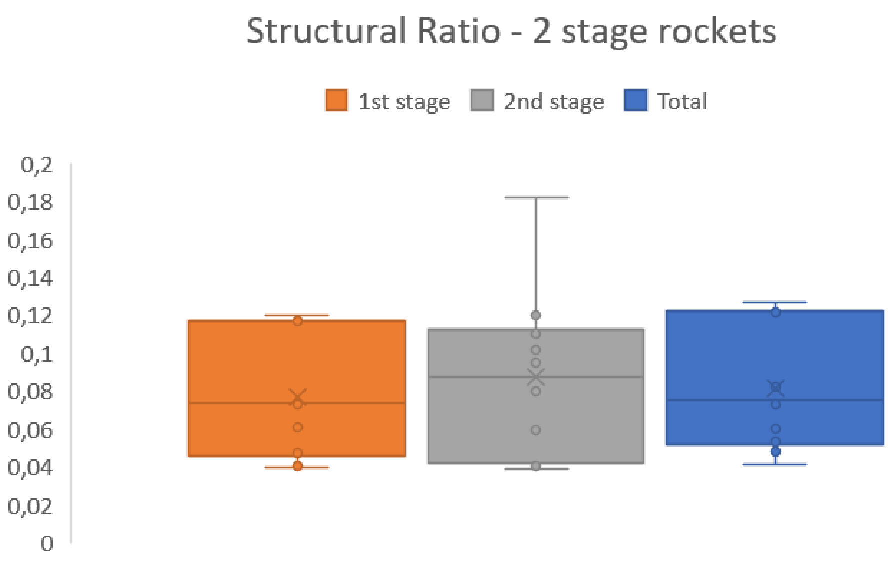

Figure 4.7: Structural Ratio of 2 Stage Launchers.

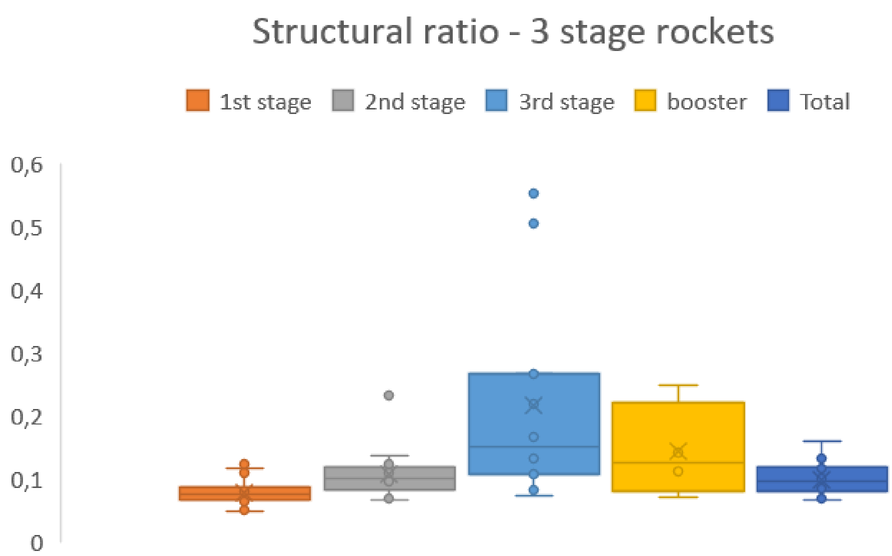

Figure 4.8: Structural Ratio of 3 Stage Launchers.

0,91 respectively. Although at first sigh the values seam close if we take into account the standard deviation we can conclude see that the values are bundle together without much scattering. Analysing the heuristics from literature they are close to the 5th(0,843) and 95th(0,922) percentile of our sample.

Since the propellant ratio depends on the gross mass and propellant mass, if we plot one vs the other it is possible to see how little variation exists, and that a clear trendline appears for the propellant mass.

With this information we can obtain New Propellant Ratio (NPR) heuristics

- **NPR1** - Range of Propellant Ratio - 88% - 89,5%

- **NPR2** - Class of the launcher has no influence on the Propellant Ratio

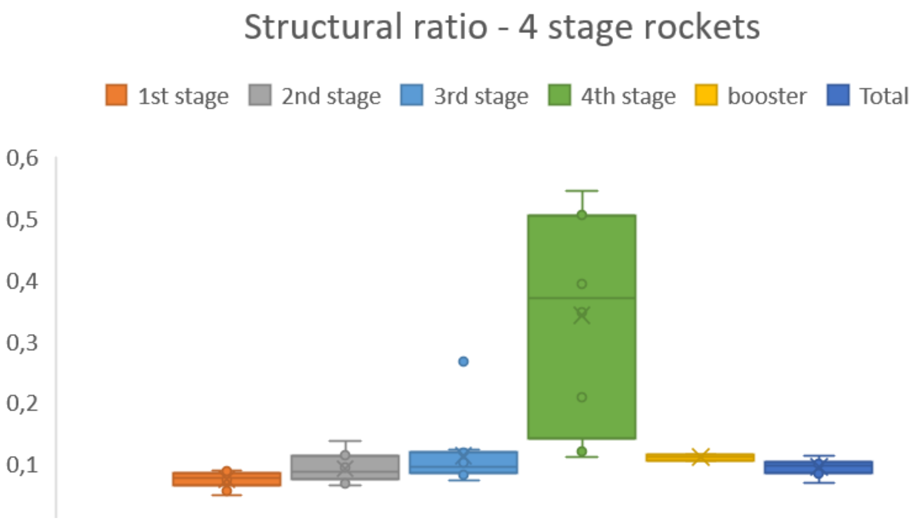

Figure 4.9: Structural Ratio of 4 Stage Launchers.

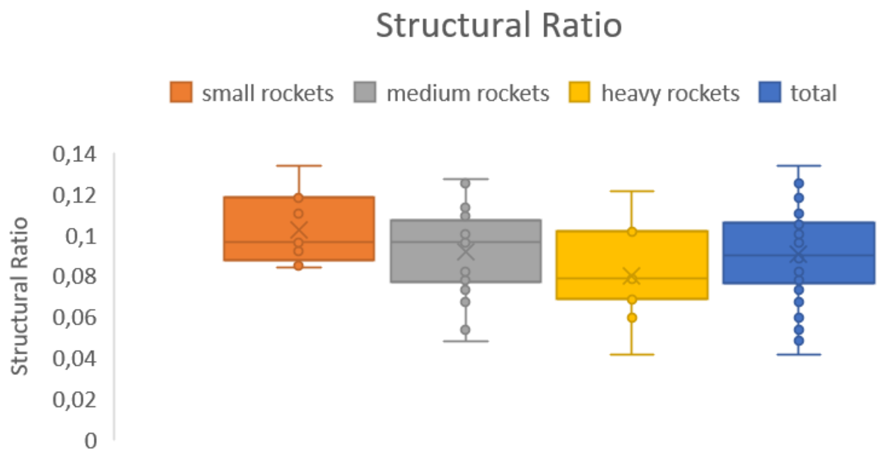

Figure 4.10: Structural Ratio.

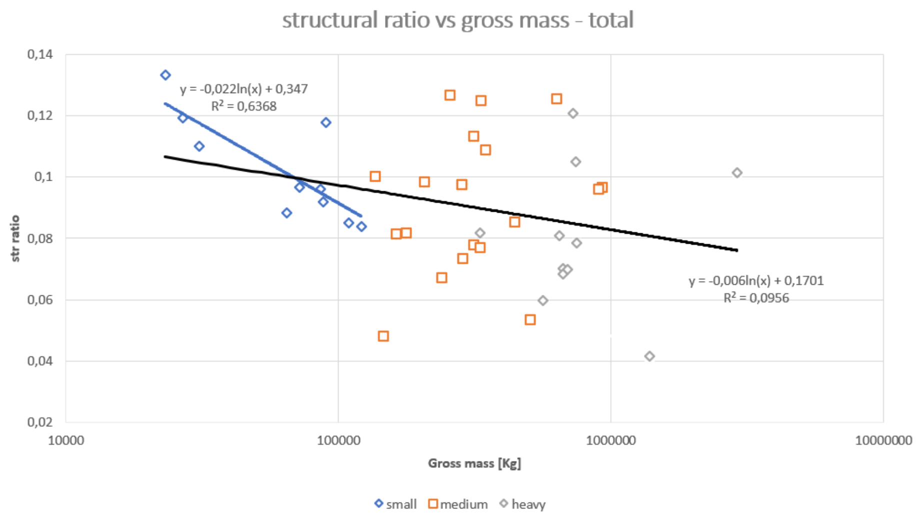

Figure 4.11: Strucutral Ratio vs Total Mass.

class	number	Q_1	median	Q_3	Average	estimate interval	standard deviation	min	max	
small - 1st stage	10	0,906	0,922	0,926	0,914	0,912-0,932	0,018	0,876	0,934	
small - 2nd stage	10	0,876	0,894	0,921	0,897	0,881-0,907	0,023	0,866	0,931	
small - 3rd stage	10	0,734	0,807	0,914	0,796	0,731-0,883	0,132	0,496	0,917	
small - 4th stage	5	0,552	0,653	0,860	0,695	0,493-0,812	0,168	0,496	0,928	
small - total	10	0,875	0,887	0,901	0,887	0,879-0,895	0,014	0,861	0,902	
medium - 1st stage	20	0,890	0,925	0,948	0,917	0,909-0,941	0,042	0,775	0,959	
medium - 2nd stage	20	0,882	0,896	0,916	0,893	0,884-0,908	0,031	0,818	0,940	
medium - 3rd stage	9	0,839	0,881	0,903	0,832	0,789-0,972	0,148	0,447	0,915	
medium - 4th stage	3	-	-	-	-	-	-	-	-	
medium - total	20	0,863	0,888	0,902	0,883	0,877-0,900	0,031	0,789	0,927	
heavy - 1st stage	11	0,924	0,931	0,939	0,929	0,921-0,941	0,019	0,883	0,914	
heavy - 2nd stage	11	0,898	0,920	0,932	0,908	0,892-0,949	0,053	0,766	0,961	
heavy - 3rd stage	4	0,899	0,922	0,926	0,916	0,903-0,940	0,016	0,893	0,926	
heavy - 4th stage	1	-	-	-	-	-	-	-	-	-
heavy - total	11	0,855	0,899	0,902	0,876	0,878-0,920	0,038	0,786	0,914	
total - 1st stage	42	0,911	0,925	0,939	0,920	0,917-0,933	0,032	0,775	0,960	
total - 2nd stage	42	0,885	0,901	0,922	0,898	0,892-0,911	0,036	0,766	0,961	
total - 3rd stage	23	0,781	0,885	0,915	0,831	0,839-0,932	0,130	0,447	0,926	
total - 4th stage	9	0,496	0,653	0,884	0,688	0,536-0,769	0,187	0,456	0,928	
total	42	0,863	0,888	0,902	0,883	0,880-0,895	0,03	0,786	0,927	

Table 4.2: Propellant Ratio Values through stages

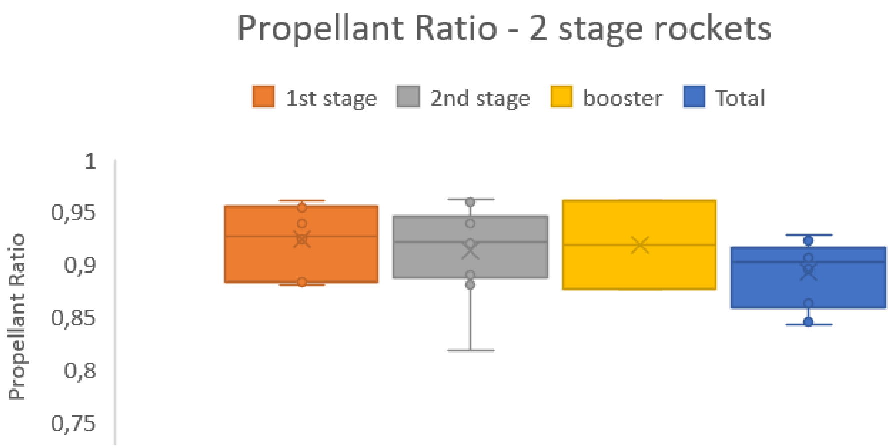

Figure 4.12: Propellant Ratio of 2 Stage Rockets.

- **NPR3** - The propellant mass has a linear clear trend line

$$m_{\text{Propellant}} = 0,901 m_{\text{Total}} - 1914,2 \tag{4.3}$$

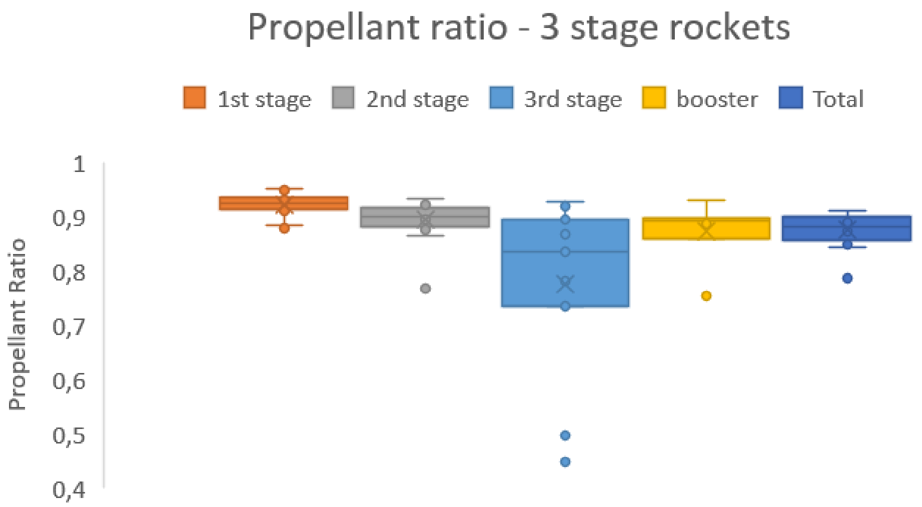

Figure 4.13: Propellant Ratio of 3 Stage Rockets.

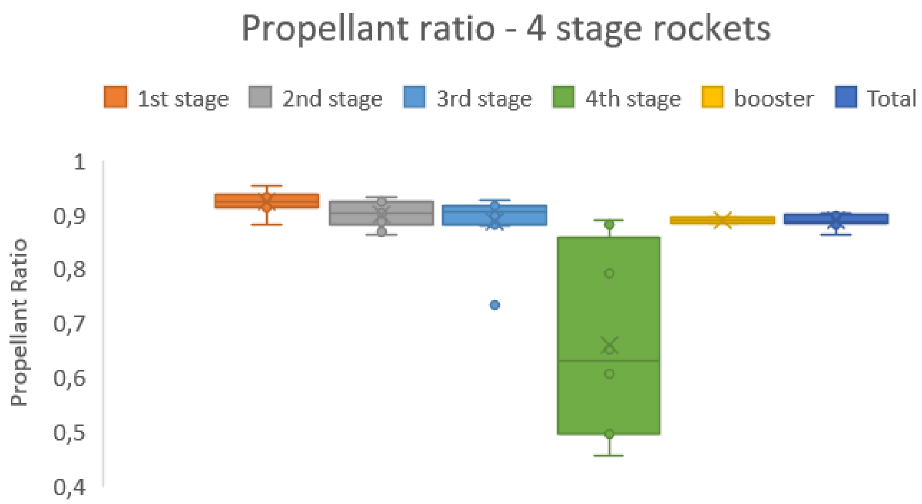

Figure 4.14: Propellant Ratio of 4 Stage Rockets.

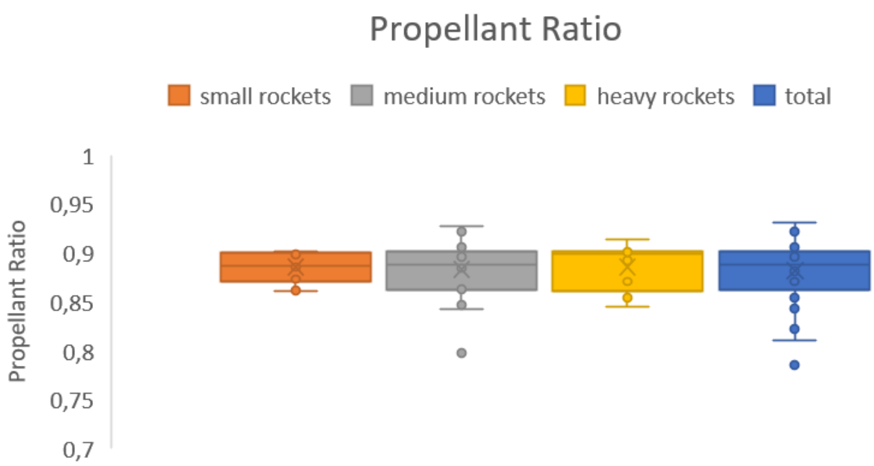

Figure 4.15: Propellant Ratio.

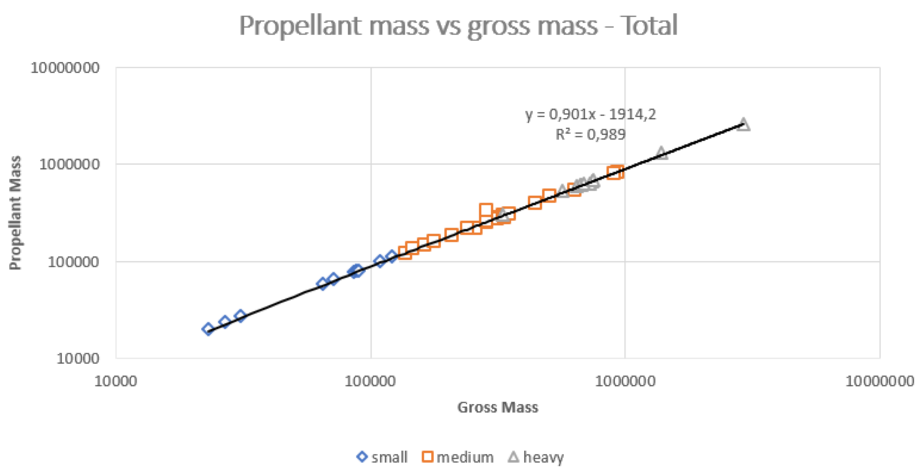

Figure 4.16: Propellant Ratio.

4.2.4 Payload Mass Fraction

The maximum payload of a launch vehicle will depend on the target orbit. In the database some launchers present more than one option for the payload capabilities corresponding to different possible orbits. For this calculations it was considered the data for highest payload value. Payload mass fraction can be calculated using Equation 2.6.

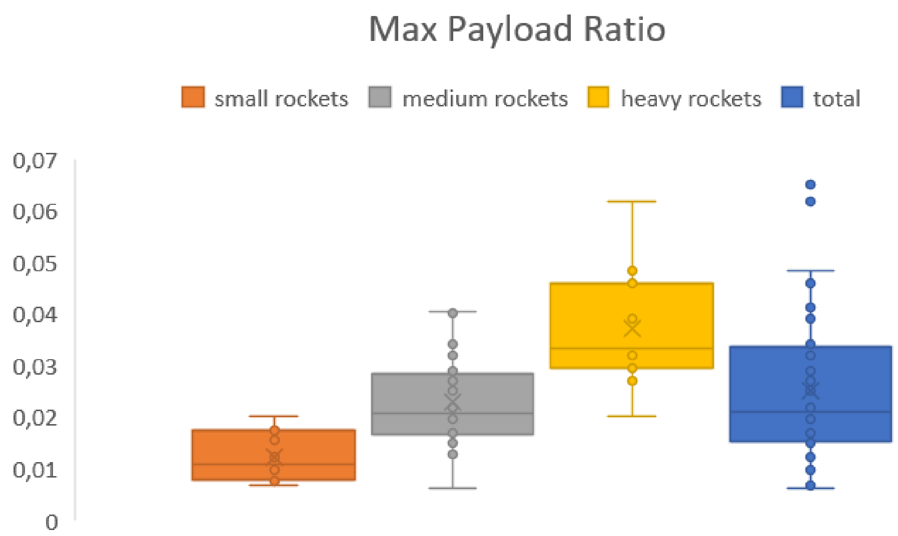

Figure 4.17: Max Payload Ratio.

Comparing Figure 4.17 and Table 4.3 with heuristics gathered in section3.2.2, the payload ratio from all types of rockets fit into **PLR2**(1%-5% of total mass). This range includes 90% of the values gathered making it representative of most possible values.

Looking at **PRL1** (1% of total mass), it doesn't apply to the generality of the launchers, however if we only take the small rockets into account this value is within the estimate interval for that category. The payload ratio actually has different levels for each category, making it possible to estimate heuristics for each one. Small launchers mass ratio interval is 0,8% to 1,4%, which includes **PRL1**. Medium launchers

class	number	Q_1	median	Q_3	Average	estimate interval	standard deviation	min	max
small	10	0,008	0,011	0,017	0,012	0,008-0,014	0,005	0,007	0,020
medium	20	0,016	0,021	0,028	0,023	0,017-0,024	0,009	0,006	0,040
heavy	11	0,030	0,039	0,048	0,040	0,031-0,047	0,014	0,020	0,065
total	41	0,015	0,020	0,033	0,025	0,016-0,024	0,014	0,006	0,065

Table 4.3: Max Payload Ratio Values

1,7% to 2,4% and heavy launchers 3,1% to 4,7%.

This different levels for each category allow to verify **PLR3** which stated that heavy launchers have a higher payload ratio. It also correlates with the findings in chapters 4.2.2 and 4.2.3. The propellant ratio being constant for all classes means that the payload ratio and the structural ratio have an inverse relation.

It is possible to extrapolate New Payload Ratio (NPLR) heuristics

- **NPLR1** - Payload mass ratio for small rockets around - 0,8% - 1,4%
- **NPLR2** - Payload mass ratio for medium rockets - 1,7% - 2,4%
- **NPLR3** - Payload mass ratio for heavy rockets - 3,1% - 4,7%

In an attempt to improve on **PLR3** it was plotted the payload ratio vs gross mass of the launchers in Figure 4.18. The payload ratio tends to slightly increase for launchers with higher gross mass, even with the values scattered around the trend line. The dispersion of values makes it harder to get a good fit. In this case the standard deviation is actually reaching 70% of the median value.

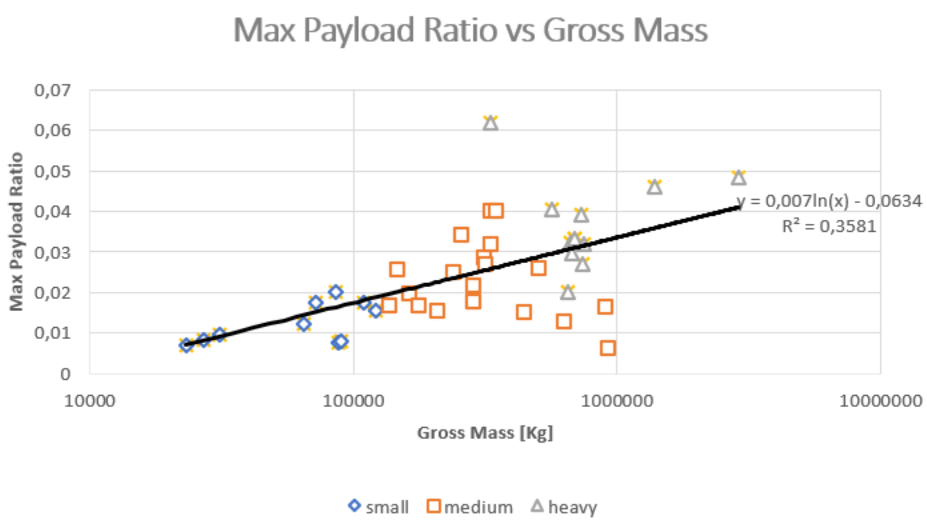

Figure 4.18: Payload ratio vs gross mass.

class	number	Q_1	median	Q_3	Average	estimate interval	standard deviation	min	max
small - 1st stage	10	229	245	282	251	231-259	24,12	229	285
small - 2nd stage	10	277	289	309	292	279-299	17,23	268	320
small - 3rd stage	10	293	298	300	293	283-313	26,57	222	326
small - 4th stage	5	211	287	293	259	245-329	44,4	200	293
small - boosters	-	-	-	-	-	-	-	-	-
medium - 1st stage	20	255	288	310	285	273-302	36,96	226	360
medium - 2nd stage	20	305	319	367	347	296-342	59,51	279	460
medium - 3rd stage	9	295	326	441	347	283-369	68,89	292	454
medium - 4th stage	3	222	315	332	290	215-414	59,13	222	332
medium - boosters	8	241	259	277	263	243-275	24,06	237	310
heavy - 1st stage	11	283	285	311	288	258-312	48,78	162	360
heavy - 2nd stage	11	327	367	451	388	336-398	56,84	327	460
heavy - 3rd stage	5	327	327	374	346	287-367	42,15	326	421
heavy - 4th stage	1	-	-	-	-	-	-	-	- -
heavy - boosters	4	190	292	331	271	201-383	77,28	162	338
total - 1st stage	42	250	283	310	277	272-293	39,8	162	360
total - 2nd stage	42	299	323	367	344	307-338	60,85	268	460
total - 3rd stage	24	296	309	327	328	290-329	56,49	290	329
total - 4th stage	9	222	292	320	277	262-323	49,25	200	332
total - boosters	12	241	266	302	266	243-290	44,88	162	338

Table 4.4: Isp Values through stages

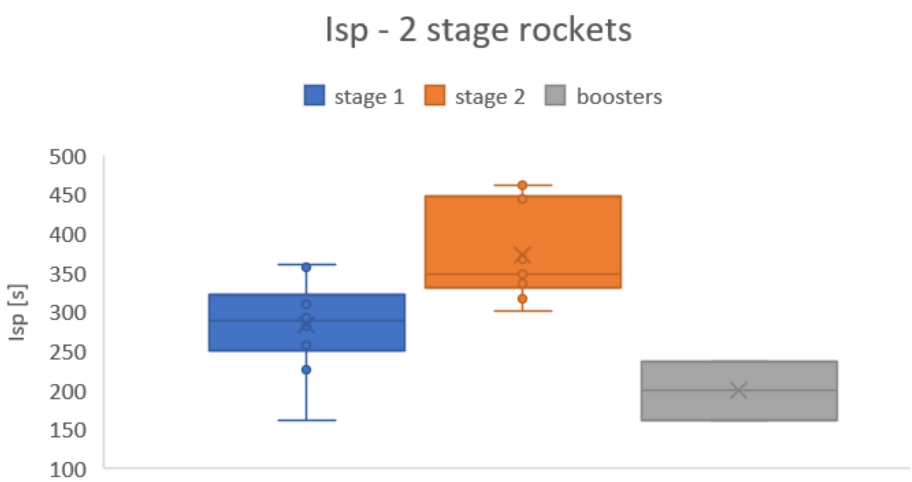

Figure 4.19: Isp of 2 Stage Rockets.

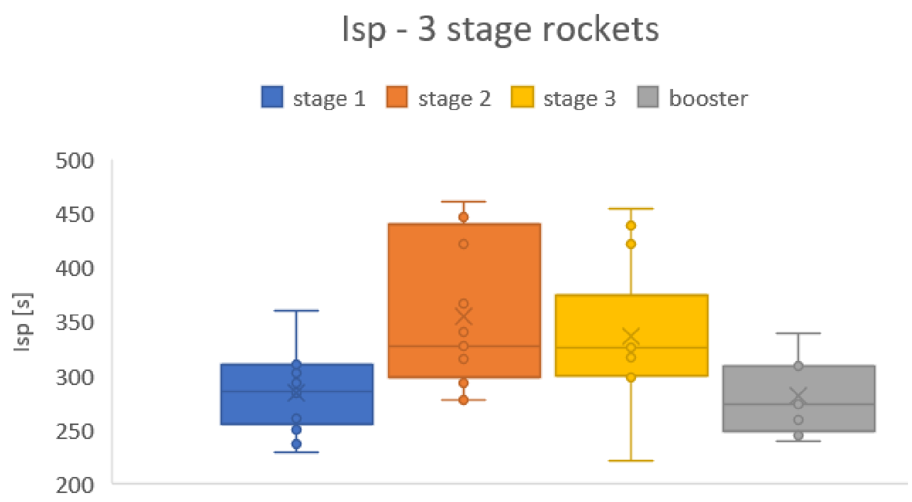

Figure 4.20: Isp of 3 Stage Rockets.

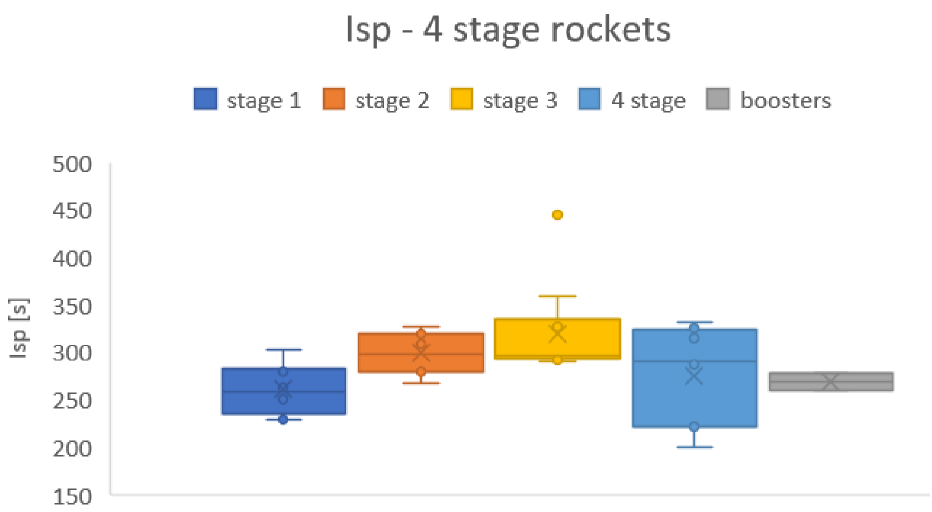

Figure 4.21: Isp of 4 Stage Rockets.

4.2.5 Isp

From Figures 4.19, 4.20 and 4.21 it is possible to observe that the values for I_{sp} are lower for the first stage and boosters verifying **IV** (usually higher values for higher stages). Lower stages main concern is to have enough trust to be able to surpass the weight of the launcher. In higher stages the focus is on fuel efficiency, to which a high I_{sp} value translates. Engine manufactures often present values for its operational value in vacuum and at sea level, with I_{sp} for vacuum always higher. Since upper stage engines operate in rarefied atmosphere its I_{sp} can be higher. For both boosters and first stage the sea level value are taken into account.

The differences in I_{sp} are minimal since the propulsion technology used for every engine in this database is chemical. This means that the main contributing factor is the propellants used.

Looking at the values in Table 4.4 the 1st stage and boosters have a narrower set of values for I_{sp} since the altitude in which they operate is always the same, at sea level. Depending on trajectory other stages can ignited at different points, which allows for optimization according to their operation altitude. Considering the totality of launchers this can be verified with the increase of standard deviation, which translates to values being more scattered, even doubling in some cases.

Due to the possibility of optimization for the altitude the engine will operate, obtaining heuristics values for I_{sp} is not a productive task. However for sea level, where the 1st stage and boosters start, we can use the criteria defined to estimate a interval of 272 to 293 seconds, with a median value of 283 for 1st stages.

New I_{sp} Value (NIV) heuristic

- **NIV** - I_{sp} for the 1st stage is around 272s - 293s

4.2.6 Structure

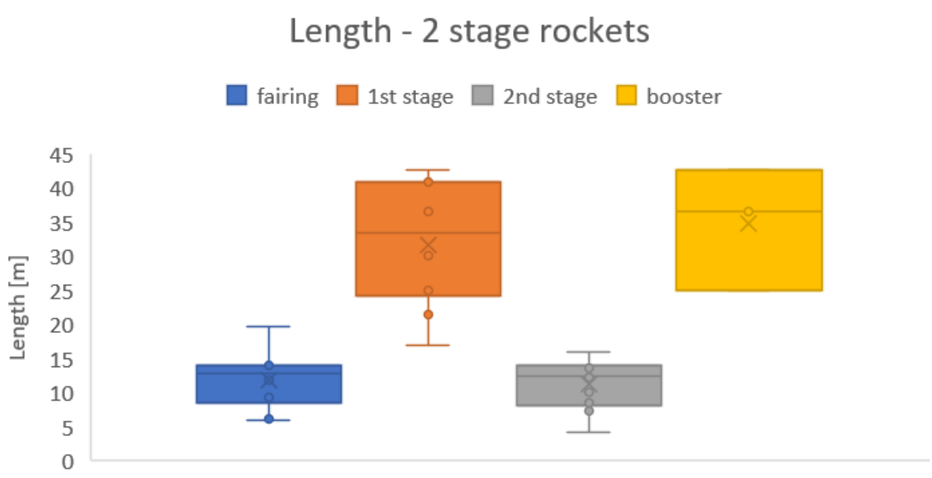

Figure 4.22: Length of 2 Stage Rockets.

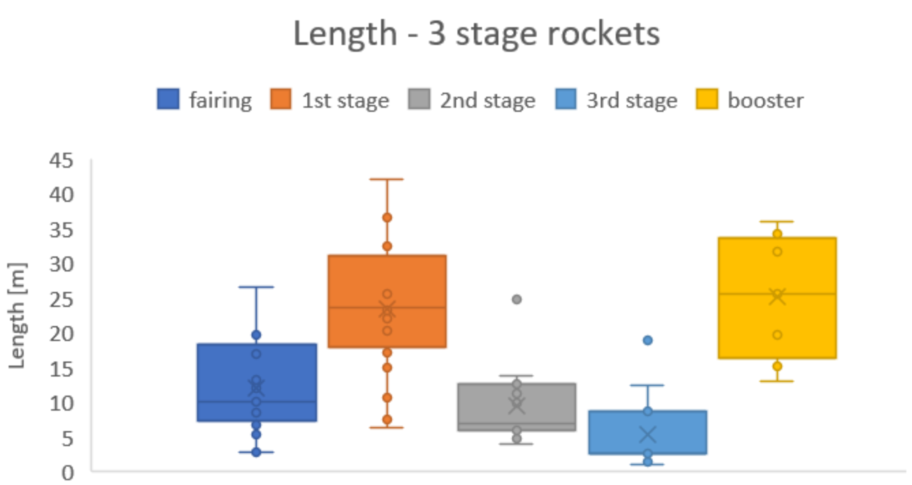

Figure 4.23: Length of 3 Stage Rockets.

The Figures 4.22, 4.23, 4.24 and 4.25, 4.26 and 4.27 display the size (length and diameter) of different stages and how the size of a SLV can change by having a different number of stages. With this

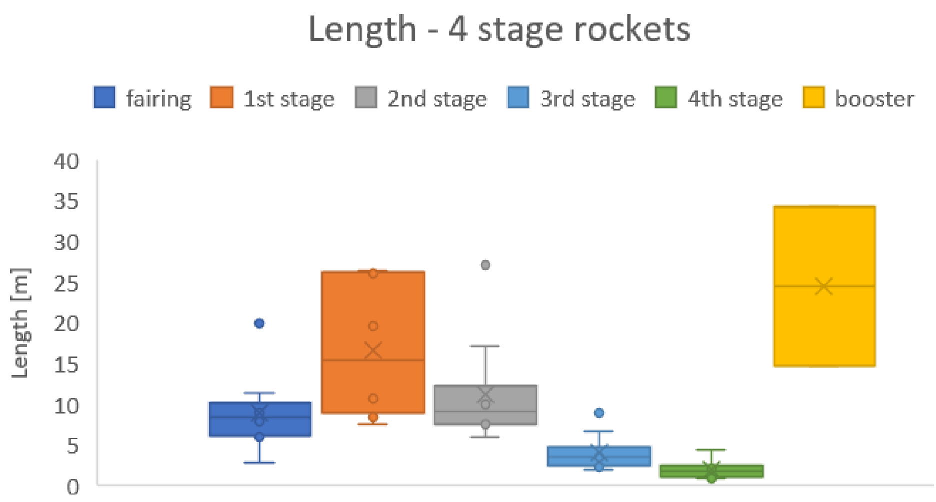

Figure 4.24: Length of 4 Stage Rockets.

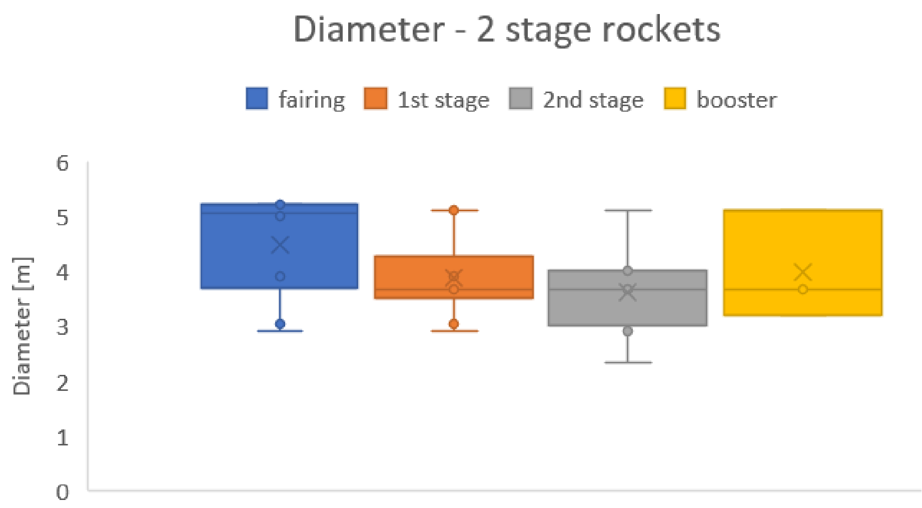

Figure 4.25: Diameter of 2 Stage Rockets.

information is possible to verify the heuristic **ST**, as it stated that lower stages are longer and often have a larger diameter than upper stages, which matches the information gathered. Both first and second stages have the same median value of 3,04m with this value lowering to 2,5m and 2,18m for the third and fourth stages. Regarding the length this is even more noticeable with the median value for the first stage being 23,5m and the second stage median having a value that is less than half at 9,2m. It continues lower with higher stages with values of 2,8m and 2,04m.

As verified in Chapter 4.2.1 it is possible to see a clear outlier on 3 stage launchers corresponding to Saturn V. Other curious outlier the the fairing on 4 stage vehicles. The launcher is Titan 401B which performed the Cassini-Huygens mission delivering a payload of 5712 kg to Saturn's largest moon Titan [49].

The first stages have the responsibility to lift not only the payload but also the other stages above and so it is required higher thrust than on the remaining stages. To do its job it will require more thrust, which results in a increased propellant burning, making it necessary to carry extra propellant and that means it

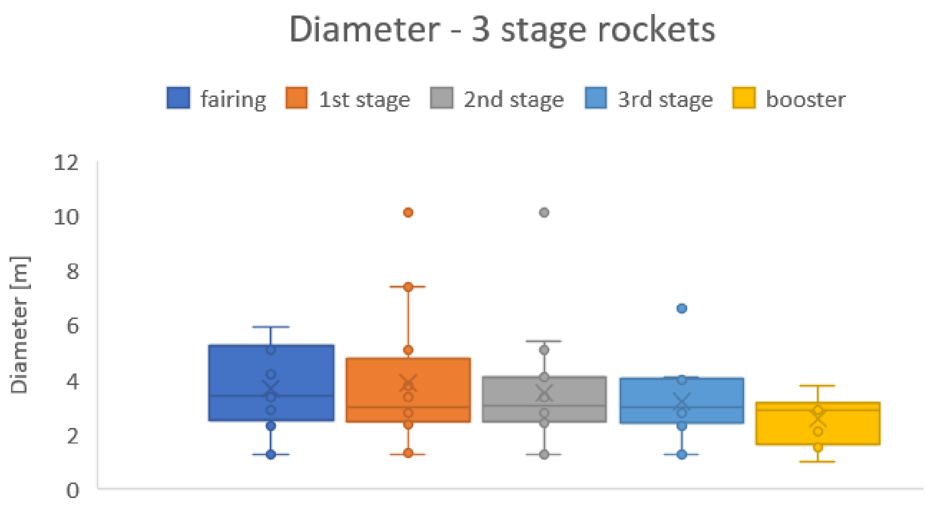

Figure 4.26: Diameter of 3 Stage Rockets.

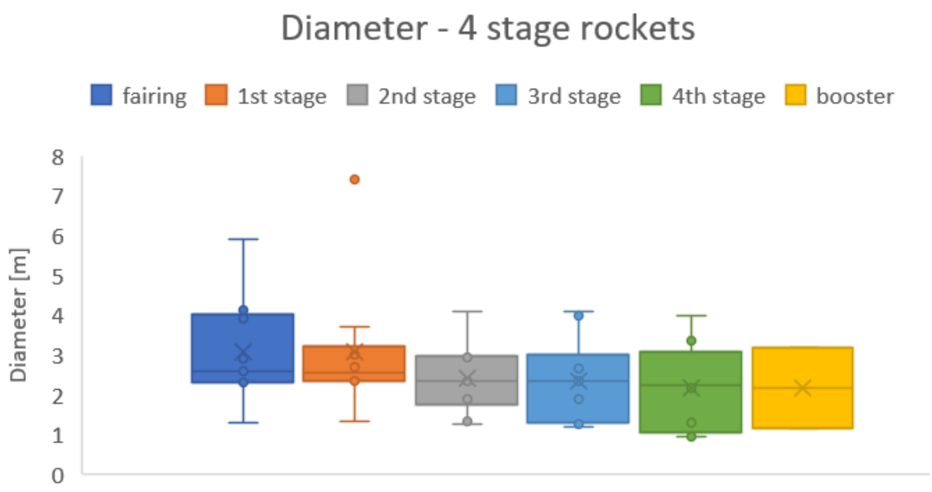

Figure 4.27: Diameter of 4 Stage Rockets.

will have to increase his size. As can be observed in Figures 4.22, 4.23 and 4.24 the first stage is usually responsible for 50% of the total length of the SLV. In two stages launchers only the LVM3 launcher first stage doesn't reach 50% of the total length. This outlier can be explained by the utilization of boosters which reach almost 60% of the total length, compensating the smaller first stage.

Boosters, regardless of the number of stages, are on average around half the total length of the launcher, with a median value of 52%. Their values tend to accompany the ones from the first stage, with some actually having the same design as the case for Falcon Heavy ou Atlas V.

Figures 4.28, 4.29 and 4.30 allows a better understanding of the distribution of mass through the different stages with the first stage and boosters responsible for at least half the mass of the launcher. Which was expected by analysing their relative size to the other stages. Although its deviation is significant, the first stage median value never drops below 0,5. The lower values present are due to the utilization of booster which also tend to have a high value.

In terms of the overall contribution, the fairing mass is almost negligible in the first stages. However,

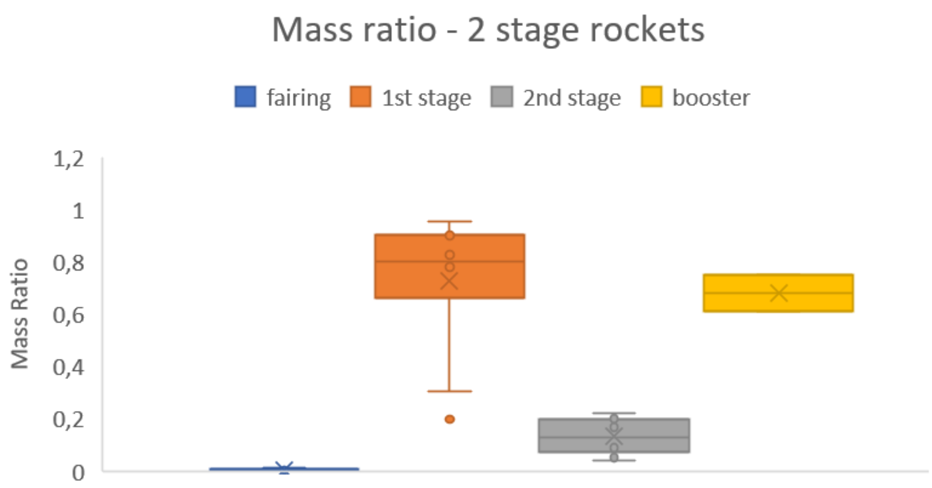

Figure 4.28: Mass Ratio of 2 Stage Rockets.

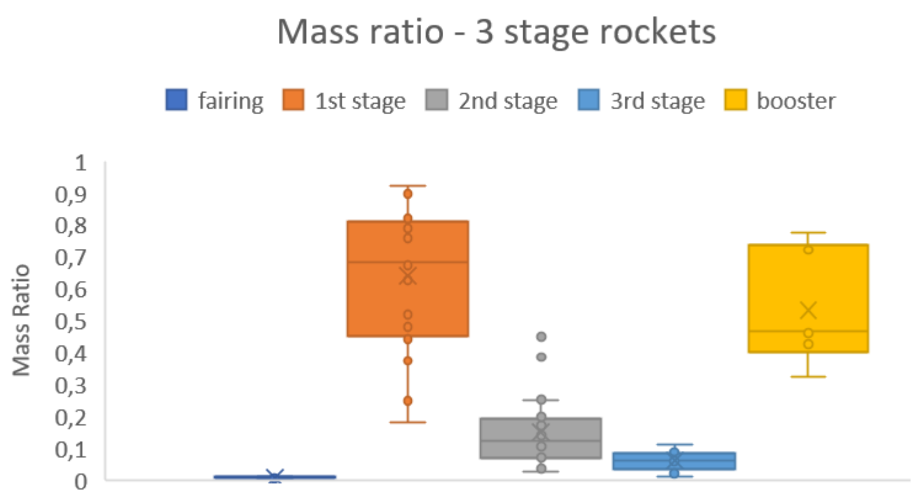

Figure 4.29: Mass Ratio of 3 Stage Rockets.

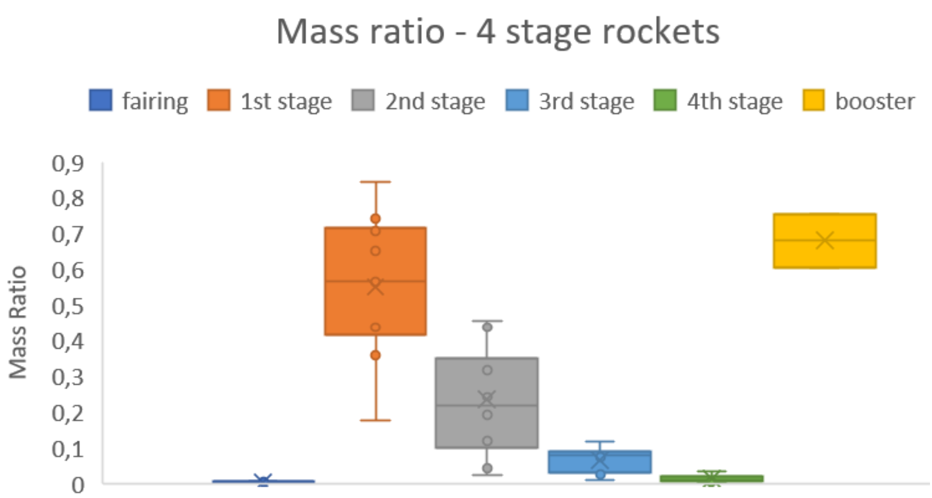

Figure 4.30: Mass Ratio of 4 Stage Rockets.

as the lower stages are discarded, its influence is no longer insignificant as we can see for the 3rd and 4th stages, which is the reason why its jettison occurs as soon as possible. The size of the fairing does not change much with the number of stages. However, in Figures 4.31, 4.32 and Tables4.5 and 4.6 we can see that the class of the SLV has a significant influence. Heavy launchers are capable to deliver heavier payloads, which dimensions should also be bigger. Therefore in order to accommodate heavier payloads, the launchers will have to provide more space to store them.

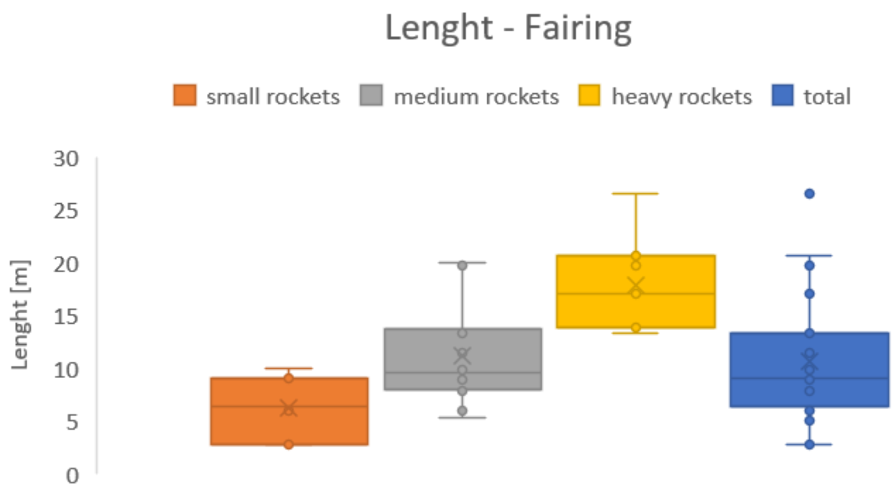

Figure 4.31: Fairing Length.

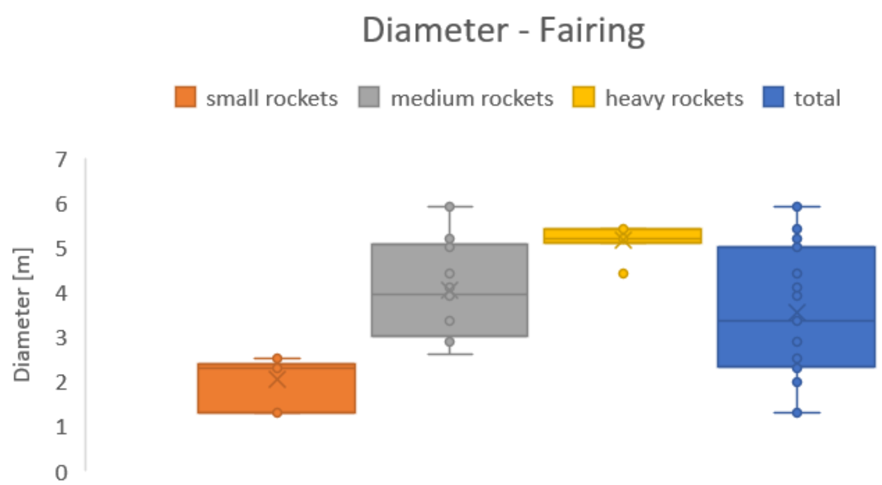

Figure 4.32: Fairing Diameter.

With the values of tables 4.5 and 4.6 it's possible to obtain heuristics for Fairing Length (FL) and Fairing Diameter (FD)

- **FL1** - Fairing length is around 4,8m - 7,9m for small launchers
- **FL2** - Fairing length is around 7,8m - 11,3m for medium launchers
- **FL3** - Fairing length is around 13,5m - 20,5m for heavy launchers

class	number	Q_1	median	Q_3	Average	estimate interval	standard deviation	min	max
small	10	1,3	2,3	2,38	2,05	2-2,6	0,523	1,3	2,52
medium	20	3,01	3,95	5,075	4,05	3,55-4,35	1,05	2,6	5,9
heavy	7	5,1	5,2	5,4	5,2	4,94-5,46	0,36	4,4	5,4
total	38	2,46	3,65	5,125	3,66	3,2-4	1,4	1,3	5,9

Table 4.5: Faring Diameter Values

class	number	Q_1	median	Q_3	Average	estimate interval	standard deviation	min	max
small	10	2,84	6,38	9	6,2	4,8-7,9	2,7	2,84	10
medium	20	8,03	9,55	13,75	11,2	7,8-11,3	4,5	5,3	20
heavy	7	13,9	17	20,7	17,86	13,5-20,5	4,8	13,3	26,5
total	38	6,38	9,1	13,9	10,88	7,5-10,7	5,7	2,84	26,5

Table 4.6: Faring Length Values

- **FD1** - Fairing diameter is around 2m - 2,6m for small launchers
- **FD2** - Fairing diameter is around 3,55m - 4,35m for medium launchers
- **FD3** - Fairing diameter is around 4,94m - 5,46m for heavy launchers

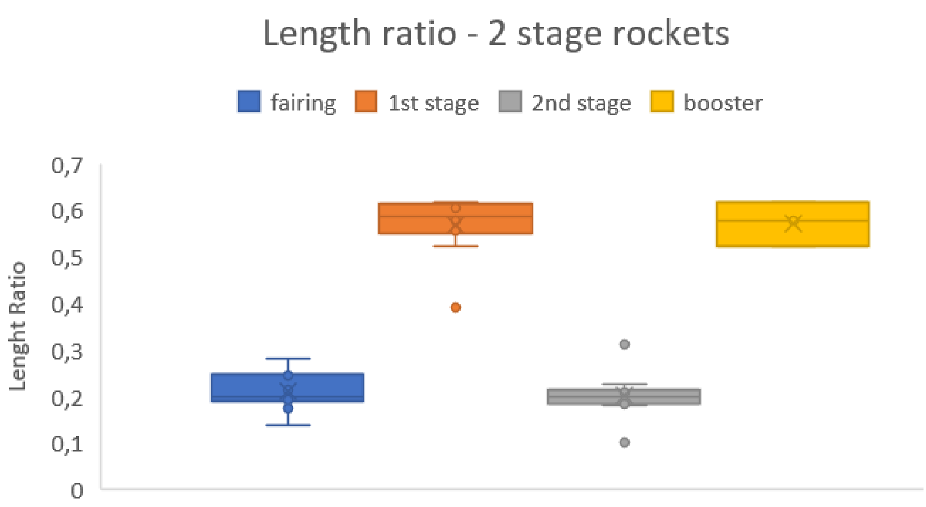

Figure 4.33: Length Ratio of 2 Stage Rockets.

4.2.7 T/W

Figure 4.36 displays the fluctuation in values of T/W with the class of the launcher.

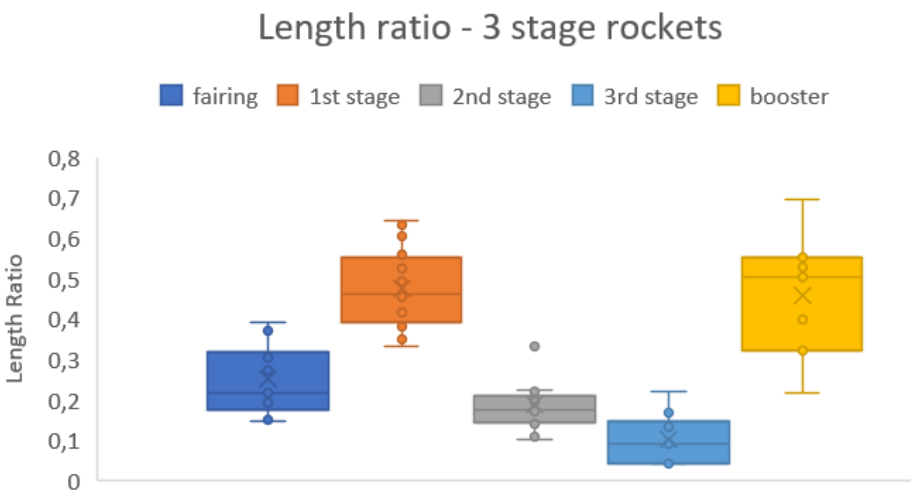

Figure 4.34: Length Ratio of 3 Stage Rockets.

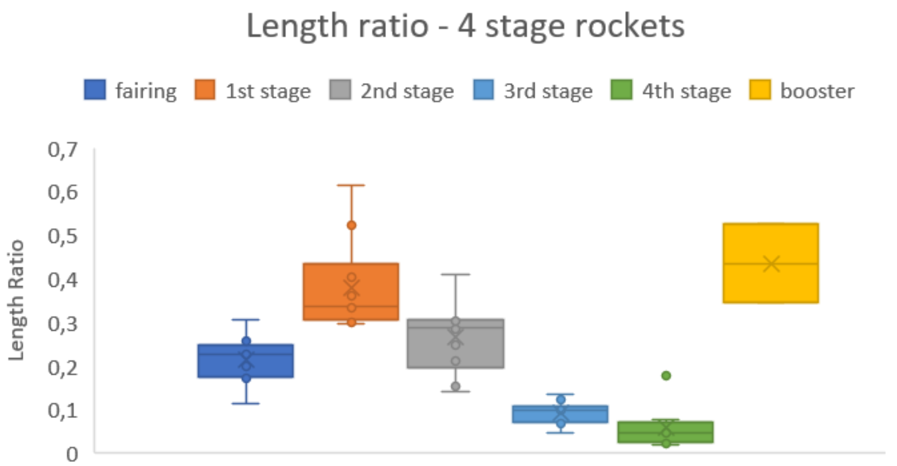

Figure 4.35: Length Ratio of 4 Stage Rockets.

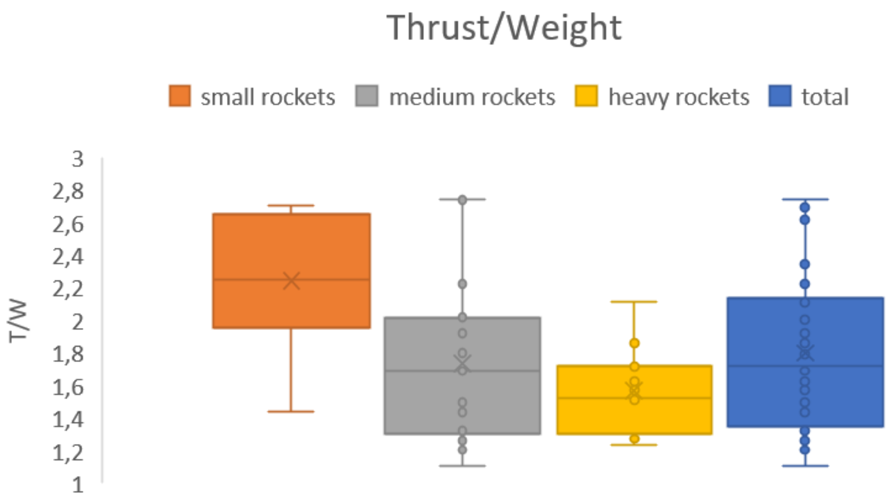

Figure 4.36: T/W.

We can use the values on figure 4.36 and table 4.7 to study the heuristics gathered. **TW2** says that thrust has to be, at least, equal to the mass and that a 10% to 20% higher take off thrust helps to maintain a good trajectory. The first part is verified since the minimum value for T/W is 1,092 from LVM3. In fact this first part can be considered more of a requirement than an heuristic because if the weight is superior to the thrust the SLV wouldn't be able to take off. Even so, after take off and for upper stages it is possible to see that multiple rockets have a T/W inferior to 1.

The 10%-20% margin would correspond to a T/W value of 1,1 to 1,2. Using the entire sample the estimate value for T/W is from 1,6 to 1,8 which is higher than the expected from **TW2**. The 20% margin matches with the 5th percentile, meaning that 95% of the launchers in the database use values superior the it.

class	number	Q_1	median	Q_3	Average	estimate Interval	standard Deviation	min	max
small-0th stage	10	1,952	2,254	2,651	2,243	2,004-2,503	0,431	1,438	2,702
small-1st stage	10	1,952	2,254	2,651	2,243	2,004-2,503	0,431	1,438	2,702
small-2nd stage	10	2,345	3,133	3,728	2,891	2,603-3,662	0,914	1,080	3,840
small-3rd stage	10	1,399	2,430	2,807	2,091	1,839-3,022	1,023	0,279	3,171
small-4th stage	5	0,799	1,880	2,574	1,725	0,932-2,828	1,050	0,079	2,883
small-total	10	1,952	2,254	2,651	2,243	2,004-2,503	0,431	1,438	2,702
medium-0th stage	20	1,287	1,467	1,955	1,631	1,295-1,640	0,449	1,092	2,739
medium-1st stage	20	1,110	1,293	1,481	1,379	1,123-1,463	0,442	0,515	2,254
medium-2nd stage	20	0,510	0,782	1,490	1,068	0,513-1,052	0,700	0,334	2,847
medium-3rd stage	9	0,472	0,811	1,909	1,051	0,323-1,300	0,801	0,090	2,341
medium-4th stage	3	0,138	0,182	0,219	0,180	0,127-0,236	0,040	0,138	0,219
medium-total	20	1,287	1,467	1,955	1,625	1,291-1,643	0,458	0,963	2,739
heavy-0th stage	11	1,512	1,572	1,861	1,692	1,353-1,791	0,404	1,235	2,658
heavy-1st stage	11	1,235	1,512	1,553	1,339	1,354-1,671	0,292	0,685	1,624
heavy-2nd stage	11	0,367	0,820	1,003	0,687	0,650-0,990	0,314	0,309	1,084
heavy-3rd stage	5	0,470	0,868	1,247	0,860	0,441-1,294	0,472	0,090	1,253
heavy-4th stage	1	-	-	-	-	-	-	-	-
heavy-total	11	1,512	1,572	1,861	1,692	1,235-1,791	0,404	1,235	2,658
total-0th stage	42	1,320	1,705	2,125	1,783	1,576-1,834	0,496	1,092	2,739
total-1st stage	42	1,240	1,439	2,014	1,571	1,298-1,580	0,545	0,685	2,702
total-2nd stage	42	0,553	0,973	1,914	1,398	0,692-1,253	1,083	0,309	3,840
total-3rd stage	24	0,534	1,247	2,408	1,445	0,900-1,594	0,994	0,090	3.171
total-4th stage	9	0,115	0,219	2,072	1,028	-0,459-0,897	1,111	0,079	2,883
total	42	1,320	1,705	2,125	1,780	1,575-1,835	0,501	1,092	2,739

Table 4.7: T/W Values through stages

Looking at the numbers for each individual stage we can find some of the minimum values unexpectedly low, even being lower than 0,1 in some upper stages. This cases, which correspond to Athena 2c, Proton M/Briz-M, and both Angara A3 and A5, can be explained by the fact that their are the last stage with high burn times. These stages will operate at altitudes in which the atmospheric drag is no longer a concern so the required thrust to change the trajectory is greatly reduced, choosing to perform a longer burn with reduced thrust.

For small launcher the numbers for the 0th and 1st stage are the same because, in the database, no launcher in that class uses boosters. There is a clear difference in the values depending on the class of the launcher. It is possible to see that T/W tends to reduce for heavy launchers. Smaller launcher are lighter and with the same engine power it is possible to obtain a higher T/W.

Figure 4.37 further explores the idea that T/W decreases with the mass. Although the decline isn't pronounced it is possible to see that in fact T/W tends to be slightly lower.

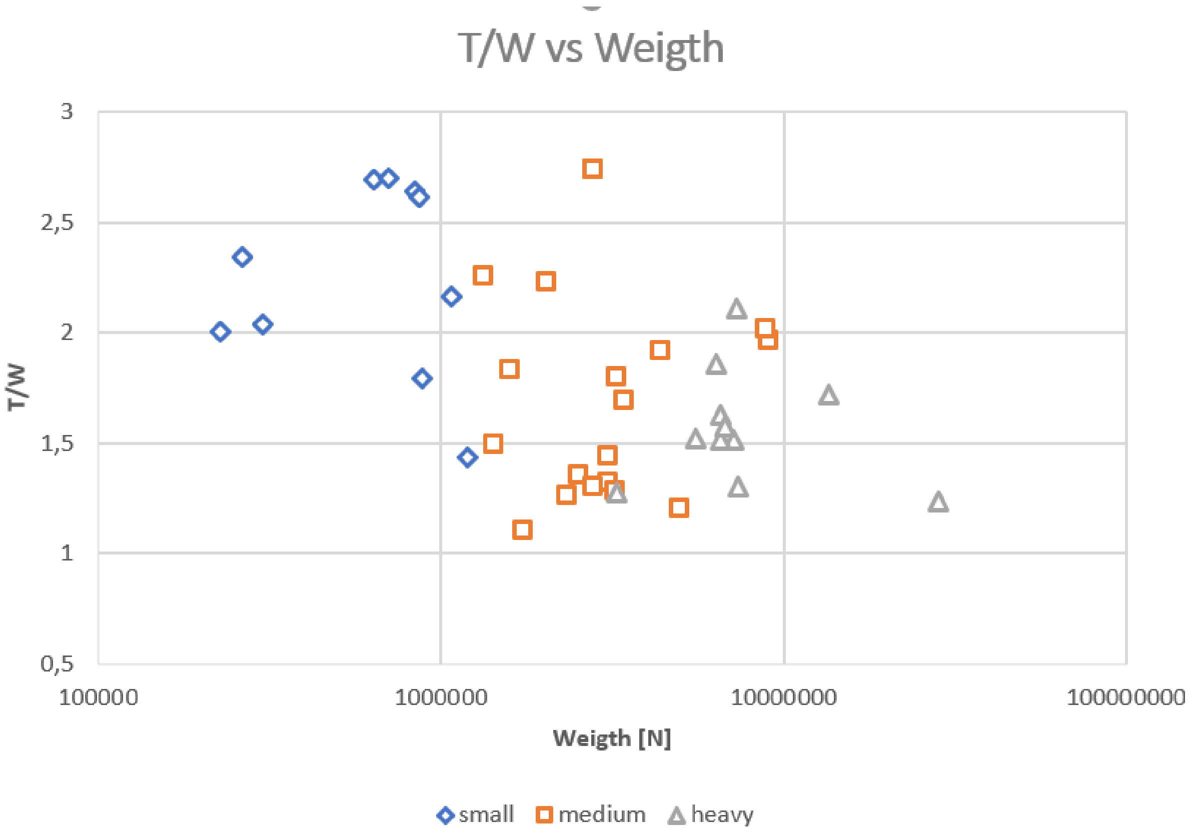

Figure 4.37: T/W vs Weight.

It is possible to extrapolate New Thrust over Weight (NTW) heuristics for each class of SLV

- **NTW1** - T/W for small launchers - 2,004-2,503
- **NTW2** - T/W for medium launchers - 1,291-1,643
- **NTW3** - T/W for heavy launcher - 1,235-1,643

4.2.8 Burn time

Figure 4.38 and Table 4.8 shows the burn time for the first stage and boosters. On launchers without boosters we can observe a burn time for the first stage similar to the one presented by boosters, while

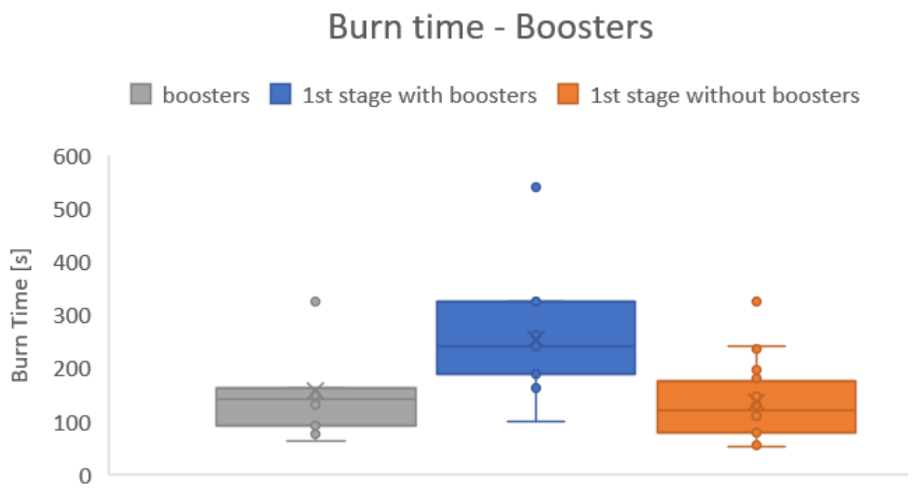

Figure 4.38: Burn Time.

the 1st stage of launchers with boosters continue to burn even after the boosters are released.

The maximum burn time for boosters is 325,2 corresponding to Angara A3 and Angara A5. According to the criteria defined this values are outliers. If we remove them, the maximum value is 162 seconds, which is around half the time of those two. Comparing with **BT1**, which stated that boosters operate in a duration of 1 to 3 minutes, 100% of the values are within the range. As a benchmark of values this heuristic can be useful, however as a design value it provides a range of values that is too wide to be effective. Removing the outliers and using the criteria defined, it is possible to obtain a narrower range that goes from 108 to 151 seconds.

The main engine should operate in a duration of 400 to 500 seconds according to **BT2**. The only launcher that is within the range of values is Arianne 5, which is a outlier from the rest of the sample. If we remove it there are no launchers that verify **BR2**, with the maximum value being 325,2 for the first stage of Angara family launchers.

Figures 4.39, 4.40 and 4.41 displays the burn time for each stage according to the number of stages in the launcher. Burn time increases significantly to the upper stages and has a wide range of values. The increase in the range of values can be explained by the higher accuracy that is required for the final orbit insertion of the payload, which may require a higher burn time, with lower thrust.

Figure 4.42 displays the burn time for first stage by class of launcher. Small launchers present burn time with a significant difference from the rest, with lower values that are estimated to be between 52 and 82 seconds. Medium and heavy launchers minimum burn time for the 1st stage is higher than the interval estimation for small launcher. They also have a standard deviation that is more than doubled when compared with the small launchers which can see its effect on the wider range of values in Figure 4.42.

With the information gathered we can acquire New Burn Time (NBT) heuristics:

- **NBT1** - 1st stage burn time for small launchers is 53 to 82 seconds
- **NBT2** - Burn time for booster is 108 to 151 seconds

class	number	Q_1	median	Q_3	Average	estimate Interval	standard Deviation	min	max
Boosters	11	90,8	140	162	157,2	91,6-188,4	88,6	63,3	325,2
1st stage with boosters	11	189	242	325,2	254,2	178,5-305,5	116,4	100	540
1st stage without boosters	28	79,7	120	175,25	135,3	98,3-141,7	67,5	52	325,2

Table 4.8: Burn Time Values

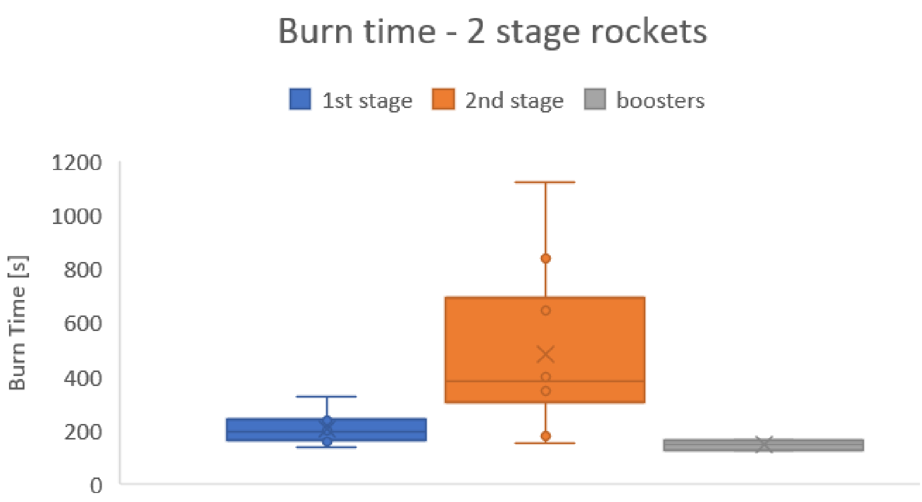

Figure 4.39: Burn Time of 2 Stage Rockets.

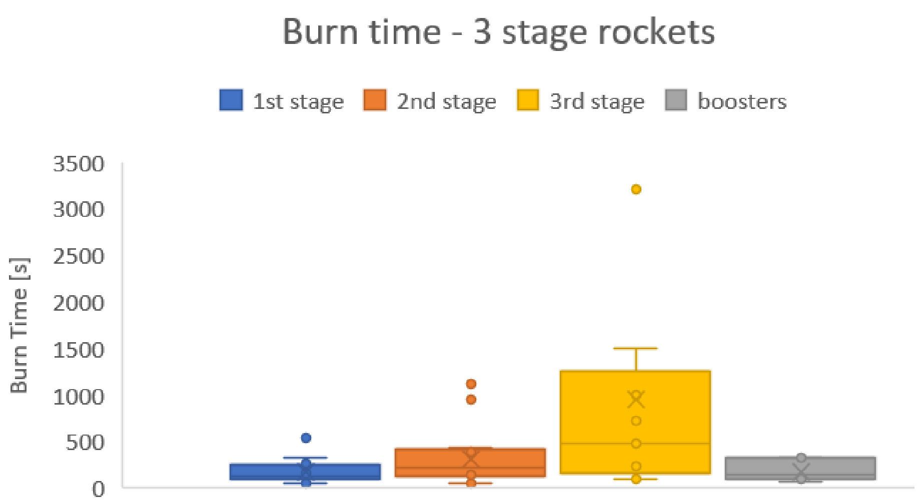

Figure 4.40: Burn Time of 3 Stage Rockets.

- **NBT3** - Upper Stages burn time is significantly superior to the lower stages with a high dispersion values

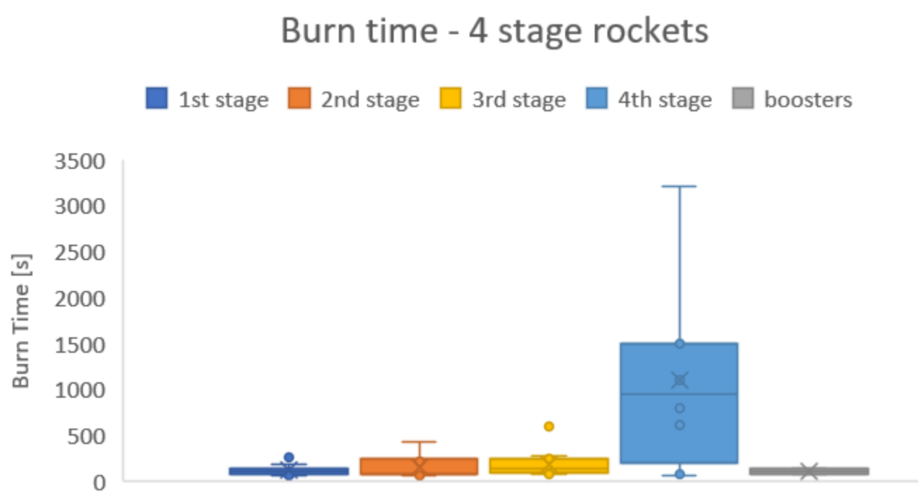

Figure 4.41: Burn Time of 4 Stage Rockets.

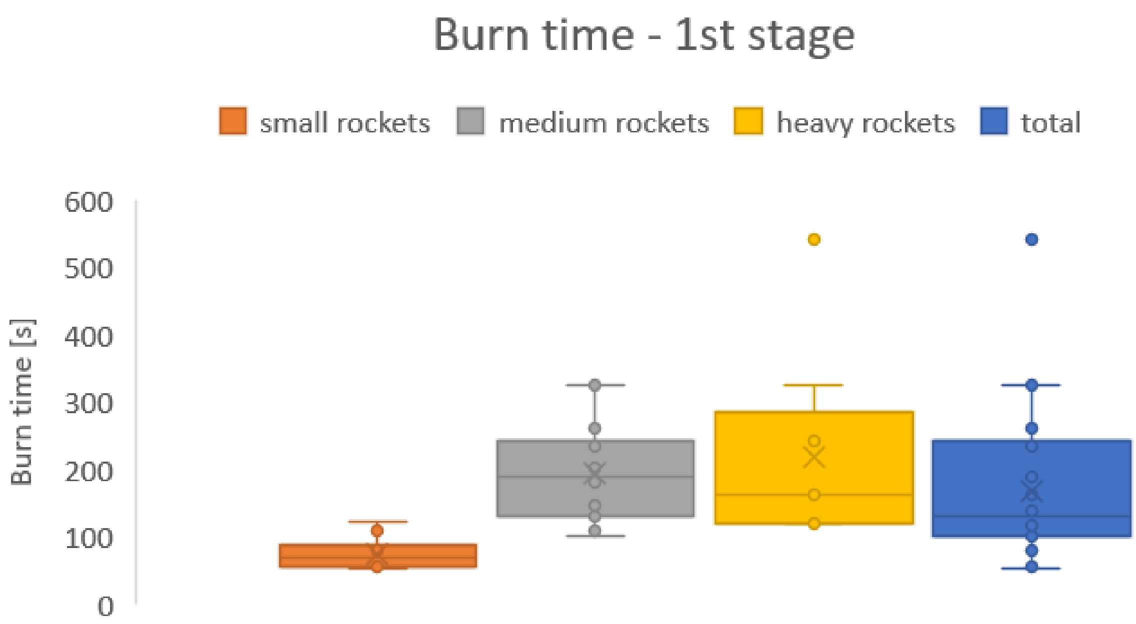

Figure 4.42: Burn time - 1st stage.

4.2.9 Dynamic Pressure

During launch, dynamic pressure, which depends on both the velocity and atmospheric density, plays an important part on both the lift and drag. With velocity increasing, and density decreasing, with time after launch, every launcher passes through the maximum dynamic pressure in different stages of the trajectory. Figures 4.43, 4.44, 4.45 and table 4.9 shows the velocity, time and altitude where dynamic pressure is at its maximum.

- **DPvel** - Maximum dynamic pressure happens when the launchers are around 0,5-0,75 km/s
- **DPtime** - Maximum dynamic pressure happens around 58-79 seconds of flight
- **DPalt** - Maximum dynamic pressure happens around 10-12,5 km altitude

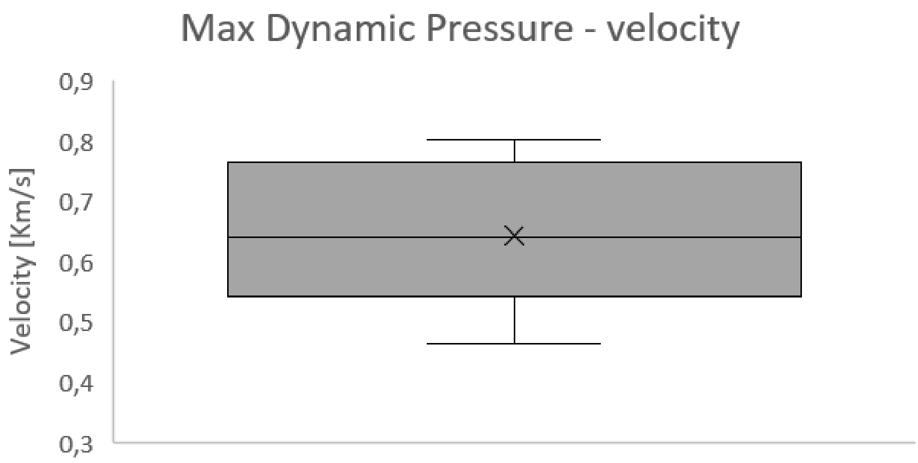

Figure 4.43: Velocity at Maximum Dynamic Pressure.

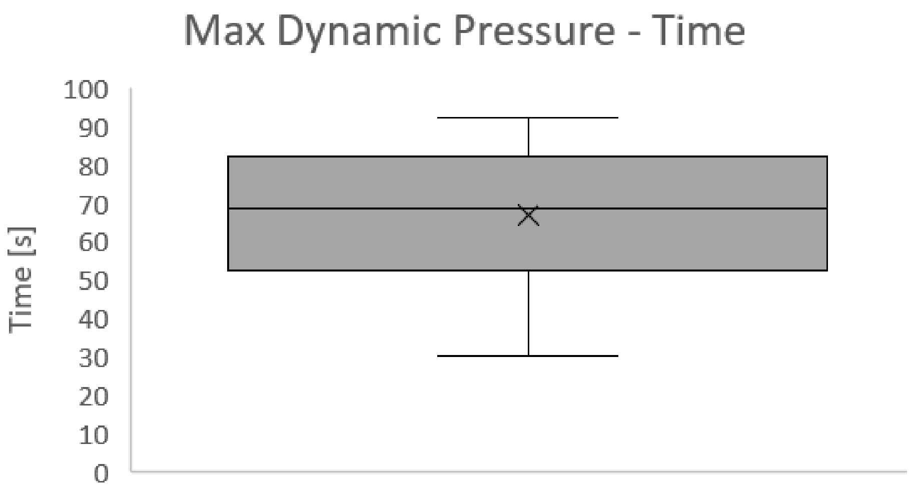

Figure 4.44: Time of Flight at Maximum Dynamic Pressure.

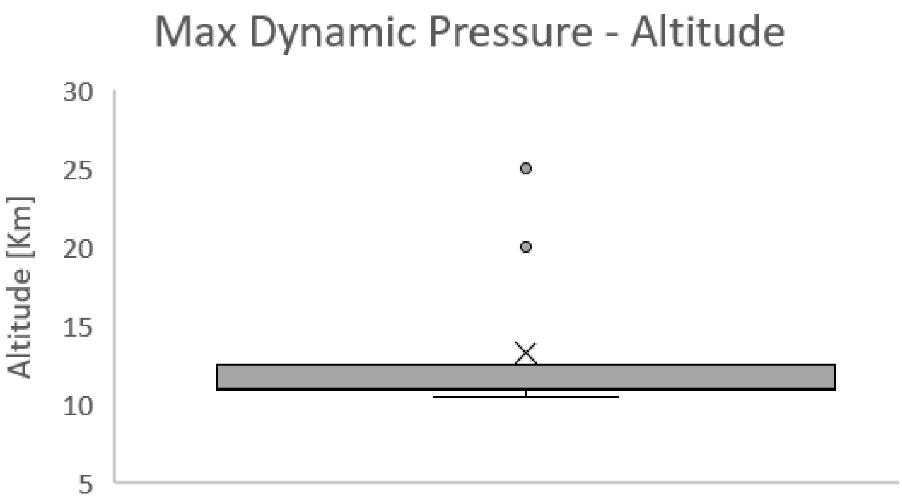

Figure 4.45: Altitude at Maximum Dynamic Pressure.

class	number	Q_1	median	Q_3	Average	estimate Interval	standard Deviation	min	max
velocity	6	0,542	0,64	0,763	0,644	0,536-0,744	0,125	0,465	0,802
time	12	52,25	68,75	82	66,69	58,4-79,1	19,9	30	92
altitude	9	10,8	11	11,8	11,2	10,44-12,5	0,69	10,44	12,5

Table 4.9: Maximum dynamic pressure Values

These values are provided by the launchers user guides for a generic mission, however they will depend heavily on the type of mission and the trajectory associated with it. We can further study them by analysing according to the class of the launcher.

Small launchers achieve maximum dynamic pressure almost twice as fast than the others, with a average of 39 seconds against 75. They reach this point in a slightly lower altitude and with a higher velocity of 10,5 km and 0,7 km/s against 11,5 km and 0,6 km/s respectively.

These findings are not considered as heuristics since the number of entries in data sample is not enough when divided by classes. Even so, it is worthwhile to see if any regularities seem plausible.

4.2.10 Fairing Jettison

As explained in chapter 2, the fairing protects the payload from the external loads during the launch. When these forces become negligible, then fairing can be jettison in order to get rid of the extra mass that is no longer needed.

From figures 4.46, 4.47, 4.46 and Table 4.10 it is possible to obtain

- **FJvel** - Fairing jettison happens when the launchers is around 3,5-4,6 km/s
- **FJtime** - Fairing jettison happens around 213-271 seconds of flight
- **FJalt** - Fairing jettison happens around 112-142 km altitude

class	number	Q_1	median	Q_3	Average	estimate Interval	standard Deviation	min	max
velocity	10	2,7	4	4,55	3,75	3,5-4,6	0,97	2,2	4,86
time	12	187	242	275	241,8	213-271	55,5	173	348,2
altitude	12	120,75	126,9	158,25	140	112,2-141,6	28,29	114	194

Table 4.10: Fairing jettison Values

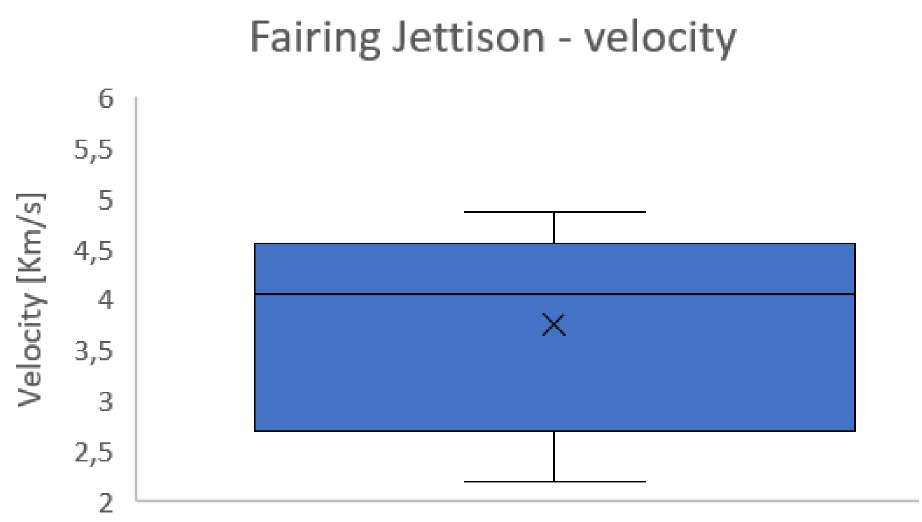

Figure 4.46: Velocity at Fairing Jettison.

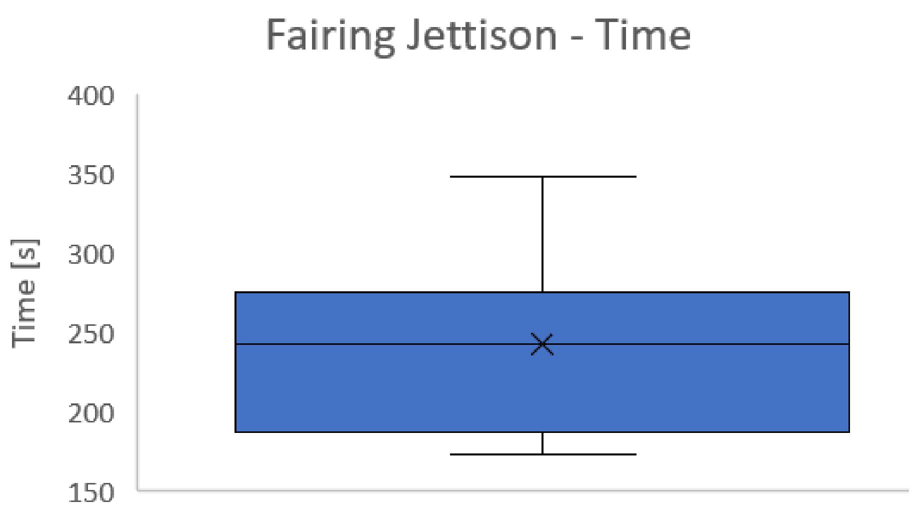

Figure 4.47: Time of Flight at Fairing Jettison.

4.3 Discussion of results

4.3.1 Existing heuristics versus results

Analysing the heuristics that where compiled from literature it is possible to observe those that offer a wide range of values were verified. The ones that gave a pinpoint estimation where proven wrong by the database.

SR1, **PR1** and **PR2** all give us values that are far from the estimate provided by the data, with values that are close to the 95th percentile of our distribution. The only pinpoint estimation that can partially verified is **PRL1** and even that could only be applied to the class of small launchers.

Heuristic that provide broad observation such as **ST** and **IV** were also verified.

Table 4.11 displays how the heuristics collected from literature were validated by the database cre-

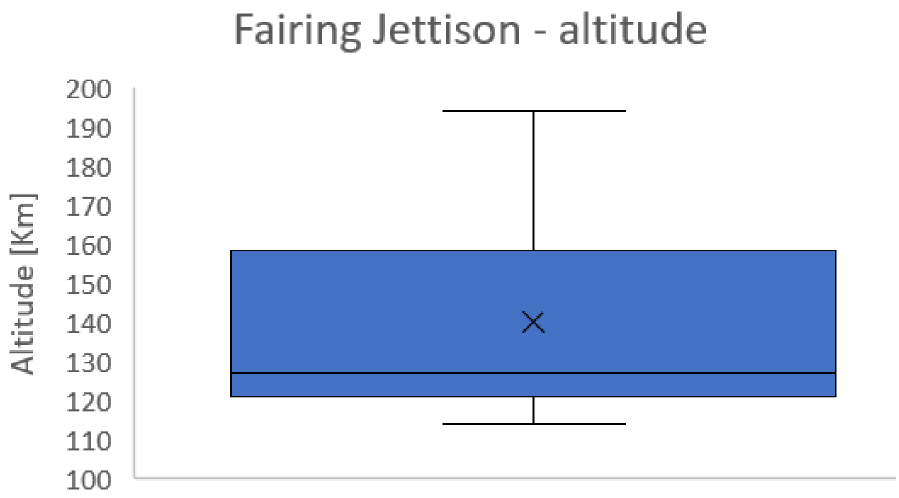

Figure 4.48: Altitude at Fairing Jettison.

ated.

Code	Heuristic from literature	Data	Status	comment
SR1	14% of total mass	8,6%-10,1%	Not verified	
SR2	$5\% - 15\%$ of total mass		Verified	This range represents more than 90% of the sample
PR1	85% of total mass	88%-90%	Not Verified	85% matches the 5th percentile
PR2	91% of total mass	88%-90%	Not Verified	91% matches the 95th percentile
PLR1	1% of total mass		Partially verified	1% value is better applied to small launchers
PLR2	$1\% - 5\%$ of total mass		Verified	This range represents more than 90% of the sample
PLR3	Larger vehicles are able to archive higher payload ratios		Verified	
IV	Usually higher for higher stages		Verified	
ST	Lower stages are longer and often have a larger diameter than upper stages		Verified	
TW1	First stage might typically have an T/W ratio less then 1,5		Partially verified	It doesn't translate for small launchers
TW2	T/W has to be higher than 1. $10\% - 20\%$ higher take off thrust helps the launcher		Partially Verified	
BT1	Booster engines operate in a duration of 1-3 minutes	Max value 325,2s	Verified	
BT2	Main engine operate in a duration of 400-500s		Not Verified	Only one outlier in our data reached this values

Table 4.11: Collection of the new heuristics discovered

4.3.2 New Heuristics

Using the data available a set of new heuristics were found. The criteria set in order to get a confidence interval for the median of the sample. It was chosen the median because from the measurements that describe the center of the distribution, its the one that is less susceptible to outliers. A confidence level of 95% was chosen in order to get the estimate interval.

With this criteria it is possible to formulate heuristics that try to provide a confidence interval estimation for an initial values in preliminary rocket design.

Table 4.12 displays all the heuristics found

Code	Heuristic
NSR1	Range of structural ratio 8,6% - 10,1%
NSR2	Upper stages have a wide range of results going up to 50% in some cases
NSR3	Structural Ratio is slightly lower in heavy launchers with a estimate interval of 6,3%-9,9%
NSR4	Small launcher structural ratio tends to evolve with the gross mass with a logarithmic relation
NPR1	Range of Propellant Ratio 88% - 89,5%
NPR2	Class of the launcher has no influence on the Propellant Ratio
NPR3	The propellant mass has a clear linear trend line
NPRL1	Payload Mass Ratio for small rocket 0,8% - 1,4%
NPLR2	Payload Mass Ratio for medium rockets 1,7% - 2,4%
NPLR3	Payload Mass Ratio for heavy rockets 3,1% - 4,7%
NIV	I_{sp} for the 1st stage goes from 272s - 293s
FL1	Fairing length for small launchers is 4,8m - 7,9m
FL2	Fairing length for medium launchers is 7,8m - 11,3m
FL3	Fairing length for heavy launchers is 13,5m - 20,5m
FD1	Fairing diameter for small launchers is 2m - 2,6m
FD2	Fairing diameter for medium launchers is 3,55m - 4,35m
FD3	Fairing diameter for heavy launchers is 4,94m - 5,46m
NTW1	T/W for small launchers 2,004 - 2,503
NTW2	T/W for medium launchers 1,291 - 1,643
NTW3	T/W for heavy launchers 1,235 - 1,643
NBT1	1st stage burn time for small launchers is 53 to 82 seconds
NBT2	Burn time for boosters is 108 to 151 seconds
NBT3	Upper stages burn time is significantly superior to the lower stages
DPvel	Maximum dynamic pressure at 0,5Km/s - 0,75Km/s
DPtime	Maximum dynamic pressure at 58 - 79 seconds of flight
DPalt	Maximum dynamic pressure at 10Km - 12,5Km altitude
FJvel	Fairing jettison at velocities of 3,5Km/s - 4,6Km/s
FJtime	Fairing jettison at 213 - 271 seconds of flight
FJalt	Fairing jettison at 112Km - 142Km altitude

Table 4.12: Collection of the new heuristics discovered

Chapter 5

Conclusions

Each launcher vehicle is designed for a different set of objectives, according to payload and orbit capabilities. They are complex machines that require an iterative process to be designed. In this work, we gather rocket historical information and used it to establish heuristics, and confirm or disprove existing ones, to be used as guidelines for preliminary rocket design. Results of their validity are summarized in table 4.11

With the values form the database it was possible to refine some of the existing heuristics and even acquire new ones. A list of all the new heuristics can be found in table 4.12.

New heuristics were established and existing ones were confirmed or disproved and thus some empirical relations were established.

5.1 Future Work

Any database is only good as its information is up to date. In order to improve on this work one must continue to fed information into it so that it continues to expand and improve results. Some steps that can be done:

- As it was said in chapter 3.2 some information wasn't available for all the rockets. This was most noticeable on the fairing and on the interstage sections. Whenever possible this gaps of information need to be completed.
- This database is a good starting point, however there still exist launch vehicles that weren't included on it. As information on the database grown so does its usefulness will do the same.
- As new launchers continue to be developed, information about them can be added.
- Launch vehicles manufacturers use previous vehicles as building blocks to improve the future ones. This results in similarities between them, and even some stages that are exactly the same or are multiple rockets of one stage. A recent example of this is the Falcon Heavy first stage that consist in three Falcon 9 rockets. It would be interesting to separate the launchers in the database into a

"family of launchers" to to look for trends inside families and check if any family as an advantage over another one.

- The database presents information for every single stage of the launchers which makes for a lot of information to be processed. It should be interesting to try to use a neural network to be able to acquire correlations between values that one wouldn't necessary think it existed.

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