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# SYSTEM ENGINEERING APPLIED TO HIGH POWER ROCKET DEVELOPMENT

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*Abstract. The project and development of a hybrid rocket engine requires an extensive system engineering analysis throughout its life cycle, even in rocketry projects. Using it correctly is of utmost importance to ensure the mission success and nationally, it is hard to find dedicated bibliography on this topic. Therefore, this paper main goal is to present a guide about the application of decision matrix involved into a rocketry project, so teams can run their projects and take the decisions accordingly to multiple processes which appear along the project. The developed work presented in this work is a result of what was done in Photon project developed by Tau Rocket Team, an undergraduate team made up by students from Federal University of Santa Maria. The project development was conducted initially by defining the main mission requirements, also, decision matrices were built for each sector and their subsystem in order to define the components of the launch vehicle and its possible configurations. Once these decision were taken, weekly meetings were conducted in order to keep the team aware of actual project situation since communication is extremely important on engineering projects. The decision matrices approach has been positive so far and has helped on the choices the team had made and will make on further project phases.*

***Keywords:*** *decision matrix, rocketry, hybrid engine, system engineering*

## 1. INTRODUCTION

Launch vehicles have been widely used nowadays in space missions with various objectives and this may be driven by many factors. Among these, military missions in order to deliver a payload to a desired point; placing satellites into Earth's orbit for telecommunications purpose, that are nowadays are one of the most mission target, for example Global Navigation Satellite System and much more (Taylor, 2017). Lately, commercial mission has been employed more continuously in the last twenty years since it can reduce dramatically the mission costs (ESPI, 2019). Furthermore, a launch vehicle mission is composed by several subsystems like structures, propulsion, avionics, ground support, payload and landing system (Taylor, 2017) and possibly more, as can be seen in Fig. (1). Given the level of space activities and technology developed around the world nowadays, the access to space is mandatory to ensure the country independence and so far the only way forward to achieve space is by using launching vehicles based on rocket with chemical propulsion such as solid, hybrid or liquid propulsion (Sutton and Biblarz, 2017).

However, in an academic level the objective and development of launch vehicles shows different approach due its mission behavior and complexity. This type of mission and the accompanying launcher vehicle receives the name of High Power Rocket (HPR). Nowadays, most of the universities develop its own projects in which the launch vehicle does not reach space, nevertheless, the quest to reach this kind of technology level has increased in the past few years by many students and their respective universities. Unfortunately, the current Brazilian scenario does not present such a technology level in academia when compared to other countries.

The development of a launch vehicle presents a lot of hard requirements that needs to works properly together, in order to ensure all requirements together it is necessary to use system engineering techniques in the whole mission and their subsystems. Thus, system engineering according to NASA (2016) is defined as a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system.

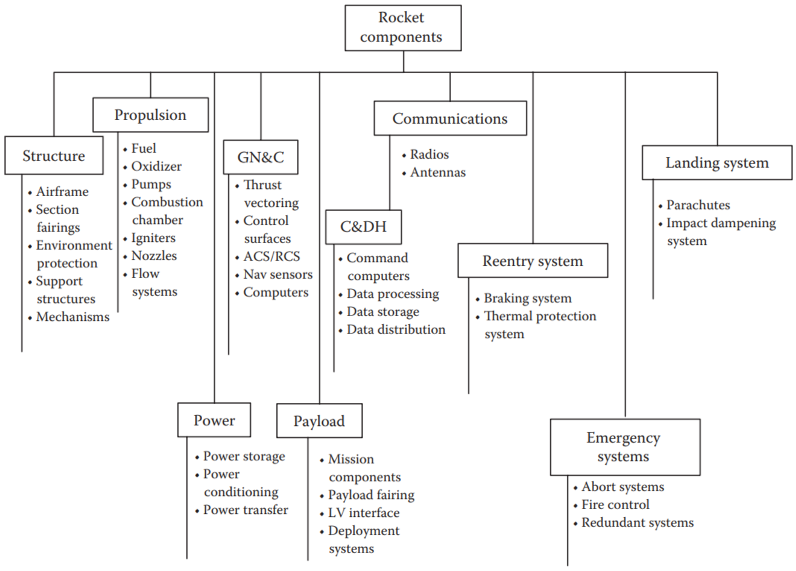


Figure 1. Launch vehicle system components. From (Taylor, 2017).

In this work, we evaluate the application of system engineering in the development of a launch system, known as High-Power Rocket, propelled by an hybrid rocket engine from Tau Rocket Team of Federal University of Santa Maria.

## 2. SYSTEM ENGINEERING

System engineering can be defined as an interdisciplinary field in engineering scope which focus on how to create, design, integrate and manage complex system over the entire life cycle of a project or mission (Haskins, 2006). The system can be defined as a combination of elements where together produce the capability required to achieve the mission objective. In this way, system engineering search for a safe and balanced design and mission considering the opposing interest and multiple constrains (NASA, 2016).

### 2.1 Methodology

All methodology used in this project was based on (NASA, 2016) with adaptations. As can be seen a common division of launch vehicle mission in Fig. (1) the team was also divided in similar manner. Since the mission is to develop a High-Power Rocket the division can become simpler. Also, the team division was based on common division presented in other undergraduate rocketry team in which participate in competitions as LASC and SpacePort America Cup. The team division was made in Aerodynamics, Avionics, Ground Support, Propulsion, Recovery and Structures.

The project was also divided into six different time phases, as well as the schedule (NASA, 2016). Firstly, at the Pre Phase A, an preliminary study of feasibility was made: costs and schedule estimate, technology needs and requirements was evaluated. For the next phase, Phase A, the general mission concept was designed, i. e., the objectives and requirements was defined.

At the Phase B the preliminary design was made: an initial launch vehicle configuration, communication method, motor and recovery. The general manufacture procedure have to be already taking into account. The next phase was dedicated to the detailing the Phase B design. The Phase C is dedicated to take to project more detailed for manufacturing, the software code was developed and other final designs were finished. The Phase D is the longest one, dedicated to assembly and prototypes tests, both assembled and subsystems separated tests. It is also the preparation, integration and launching phase.

At last, the Phase E is the after analysis phase. It is dedicated to review the mission, take and examine the data obtained, check if all the objectives were accomplished and produce lessons learned documentation for future projects.

It is important to notice that between each phase, furthermore some important decisions moments (Key Decision Points - KDPs), a special review was made in order to guarantee the defined requirements.

### 2.2 Decision Matrix

The decision matrix is a management tool to assist in the decision-making process. It enables decision making between some alternatives, weighing different evaluation criteria. Each sector of the Tau Rocket Team made a decision matrix listing all the components, which were chosen according to their qualities compared to each other and later used in the construction of the photon.

This method is highly employed on big enterprises companies and can be extrapolated to severe other branches. According to (Team, 2016), it consists basically listing the plausible options on the first column and list the factors to be considered on the first line, and qualify them via marks. According to the relevance of the evaluated point, its possible to make a weighted average to make the best possible choice among the options.

Also, these do not necessarily need to be made the way quoted above, variations are actually very useful and more than just marks, sometimes it's advantageous to put pros and cons side by side to check what really is more decisive and should receive priority when the decision is being taken. And even this concept is possible to extrapolate and change in a way that the decision becomes more and more clear and visible. Another important thing about them is that, on an interconnect world, these matrix can be made on online sheets tools so that more than a person can work simultaneously on it and they shall and must talk about the evaluations they have been doing, in order to find a proper criterion.

By doing so, we can evaluate the cost benefit of each possible decision on the project. The ideal would be to settle one of these for every and each decision, but this would require a considerable amount of people working on each sector and, sometimes, it is simply not possible to approach things on this way. So, as it's commonly made on engineering, the idea is to optimize the process and use the decision matrix method on the most important decisions of the project, and mainly on those that multiple and directly affect at least more than one subsystem of the rocket.

Decision matrix - Process/Decision to be take

| Criterion | Choices | | | | | |
|---|---|---|---|---|---|---|
| | Choice 1 | Choice 2 | Choice 3 | Choice 4 | Choice 5 | Choice 6 |
| Criterion 1 | xx | xx | xx | xx | xx | xx |
| Criterion 2 | xx | xx | xx | xx | xx | xx |
| Criterion 3 | xx | xx | xx | xx | xx | xx |
| Criterion 4 | xx | xx | xx | xx | xx | xx |
| Weight | 2 | 4 | 3 | 1 | 6 | 5 |

Figure 2. Decision matrix basic structure.

### 2.3 Decision Making Process

In a general way, there are two types of requirements present in launch vehicles, those are: technical requirements and logistic requirements. Both should be taken into consideration together since they are strongly correlated.

Logistics requirements consist of all project requirements that do not involve the practical or theoretical aspects of each subsystem and component. This involves the team's financial situation, access to the manufacturing site, and availability of access to suitable machinery for that manufacturing. Technical requirements consist of the requirements that each subsystem has due to the project's objectives. Both are taken into account together with the decisions made in the decision matrices, and this in teamwork with the administrative subsystem.

All the logistics requirements depend on the team's financial condition, which is the key point in all the project's phases, that is, the access to machinery, for example, can be circumvented depending on the team's cash flow. Plus, one can mention the materials chosen, although they may be the best for the project, from a monetary point of view it can be a challenge to use them. Therefore, along with the decision making present in the matrices (Technical Requirements), the team must take into account all these logistical factors to achieve the success of the mission.

## 3. HIGH POWER ROCKET

High-power rocketry is one of the many names the practice of developing launch vehicles on a reduced scale. In order to develop a rocket requires the development of skills from its participants that enable them to become qualified professionals. It is more than a simple hobby and, nowadays, is the front door to the professional rocket world for those who desire to work on aerospace organizations and companies.

Among these, there are three possible choices for the teams, to develop a solid propulsion rocket motor, a hybrid propulsion rocket engine or a liquid propulsion rocket engine. The difference between those are mostly in their complexity, once hybrid and liquid designs require fluid systems to operate. Among hybrid and liquid it is obvious that liquids are more complex because both a fluid system for oxidizer and for fuel are necessary (Sutton and Biblarz, 2017). In that way, hybrids sit in a middle ground between complexity and feasibility.

On this section of the paper, the intention is to discourse what every subsystem on a rocketry team must do in order to ensure a safe and successful mission. The responsibilities are considerable and, as said before, in order for the project to happen appropriately, lots of system engineering shows necessary and, thus, lots of team effort and committed people.

### 3.1 Aerodynamics

Aerodynamics section is responsible for analysing fluids behavior, which includes the motion study of air and other gases through the launch vehicle and analyse the resultant forces of this interaction, known as aerodynamic forces. During the entire phase of vehicle launch till landing phase, the motion is greatly influenced by aerodynamics forces (Anderson, 2010). In this sector, the team must develop devices to ensure the correct trajectory, maintain the stability during the entire mission and minimize drag force. The most common devices developed by this sector are the nose cone, boat tail, fins and canards.

Into aerodynamic forces there are two types, drag and lift forces. Drag refers to the force acting opposite to the relative motion of any object witnessing fluid flow thought it and this force is greater during launch phase and landing/reentry (Taylor, 2017). The drag forces are commonly divided into parasitic, induced and wave drag. Also, parasitic drag is divided into form, skin friction and interference drag (R Newlands, 2016). Whereas, lift force is the component that is perpendicular to the oncoming flow direction, then, it contrasts with the drag force. In a launch vehicle lift occurs in the fuselage and boat tail. Also, if there is an angle of the velocity vector and the longitudinal axis, fins also will produce lift (Anderson, 2010).

Regarding to the devices, according to Anderson (2010) and LearningHub (2011) nose cone has the objective of reducing drag in the entire vehicle and since it is the first contact of the vehicle with fluid flow, the material and integrity has to be ensured due to mechanical and thermal loading. Boat tail also is used to reduce drag, primarily, wave drag (R Newlands, 2016), however, it is not always used and it will depend on mission constrains. Finally, on HPR, fins or canards are developed aiming the stability and control direction of the vehicle ensuring the proper trajectory. In Figure (3) can be seen the schematic of commonly HPR control surfaces, emphasizing the omission of boat tail since in *Photon* project it was not implemented.


Figure 3. Common control surface in HPR.

On *Photon* project the aerodynamics team start the project with the entire inputs provided by each sector, such as fuselage dimensions, mass distribution and propulsion force. Having that, with preliminary simulations was defined the flow regime in order to select common geometries to aerodynamic devices with decision matrices. Once this was finished and decisions were taken, trajectory, stability and Computation Fluid Dynamics (CFD) simulations must be done aiming optimal devices and increase the project safety.

### 3.2 Avionics

Avionics is the subsystem responsible for collecting the rocket information during flight, as well as to project the electronic system in order to ensure the communication between the ground station and the rocket. Avionics is also responsible for starting the launch (besides the rocket fueling), for the parachute ejection and rocket location for after recovery. The embedded system has three most important interfaces: the structure-avionics interface, the recovery-avionics interface and the propulsion-avionics interface.

The recovery interface was based in the recovery subsystem requirements and in order to have a double redundancy for a safety rocket landing. The safety requirements were based on (Challenge, 2020). The propulsion interface was also based in propulsion subsystem necessities, considering the engine ignition and fueling. For the ignition it was defined a mechanic valve actuated by an servo motor. The servo was chosen in order to guarantee the valve opening with a minimum security factor defined in the beginning of the project. For fueling, it was defined a system that could be disconnected from the rocket automatically and with a second valve to control the quantity of fuel in the tank. This second valve is also a safety valve, once that can be used as a emergency way to drain out the tank. Some security definitions and requirements were determined before the mission design specifications.

Lastly, the structure interface was defined to comply the basic avionics requirements: free sign transmission (restriction for the fuselage material), avionics' bay position at the rocket (in such a way to have the easiest connection possible to the other interfaces) and the bay fixation. The last one was design to provide a straightforward way to assembly and built the hole module, and the integration with the rest of the rocket.

It was chosen a micro-controller according to the availability in the market that could satisfy all the mission and other subsystem requirements, i. e., the interface requirements. The sensors were chosen according to the data the need to be measured: an accelerometer, a gyroscope and a barometer. For communication was defined a radio transmitter and receiver modules that is also available at the market, easy to assembly and with the lower frequency - once the energy transfer will be higher at lower frequencies.

The last component to define is the battery. It has to be capable to power all the system, taking into account the maximum power consumption, and a minimum operational time. It also has to be capable to provide the discharge rate corresponding to the maximum system current.

### 3.3 Ground Support

The ground support sector is responsible for designing and developing the vehicle launch pad, ensuring that it is properly coupled to the rail and the tower in a stable manner. Also, must be capable of, before the launching, define a minimum safe area of operation. Furthermore, in the pre flight phase, the ground support must define and secure that all the safety protocols are complied with during testing and handling of the rocket. The sector also must be capable of analyse the weather conditions and verify if the launch must or not start. Lastly, the sector must be able to receive the telemetry data in real time since the beginning of the rocket engine ignition.

Regarding the launch pad, due to the stability provided, it was decided to choose a model consisting of a lattice launch tower and a pedestal which has three support bars and a metal plate, all the sketches were made by using a three-dimensional computer aided design software. The total height of the tower must be six meters to accommodate the rail used in the Latin America Space Challenge (LASC), and regarding the material, aluminum or steel should be used. The design of the launch tower is shown Fig. (4).

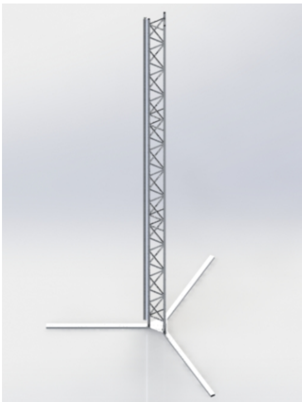

Figure 4. Launch Tower

Regarding protocols and procedures, the following sources were consulted to ensure maximum security at all stages of the launch: Esrange Safety Manual SSC (2020), LASC Guia de Projeto , Spaceport Range Standard Operating Procedures Cup (2021b) e Spaceport Intercollegiate Rocket Engineering Competition Design, Test, and Evaluation Guide Cup (2021a). Some of the tests that must be implemented on the pre flight phase are: the first, that usually happen at least 2 times, months or weeks before the launching date, is the test of burning which is executed on a properly stand with the engine alone, without the others systems. On the launch day, the test of the avionic systems must be executed, which consist of certify if each sensor is reading and sending the data correctly and if each servo motor is working nominally, the test of safety for all the cables and electrical connections, which consists of a verification on each one of the cables are rightly connected and if they support a load - this is made simply pulling the cables. And the test of charging and discharging of the propellant with the launch vehicle already assembled on the tower and ready for launch.

### 3.4 Propulsion

The propulsion subsystem has as its main objective the development of the hybrid rocket engine responsible for delivering the necessary impulse to the rocket, so that it can achieve the desired apogee. In order to do that, it is necessary to address, at first, the requirements of the engine performance that are the total impulse and the thrust. The impulse can be estimated by comparison with other projects and their apogees or by simulations on a simplified software. The necessary thrust can be easily determined by having the mass estimation and the acceleration necessary to the rocket, so that it would have the required velocity to be stable (F. Heeg, 2020).

Once the performance is known, it is time to determine the rocket ballistic parameters as oxidizer to fuel ratio, oxidizer mass flow, fuel mass flow, combustion chamber pressure and burn time. After those parameters are obtained, one could already determine the rocket engine dimensions, based on the grain necessary space. The nozzle dimensions can be calculated using the CEA software (McBride and Gordon, 1994) and the relation between the chamber pressure as well as throat area (for more details see Sutton and Biblarz (2017)).

As a hybrid engine has a fluid system (the feed system) on its top, it is necessary to determine every component of it. Firstly, the oxidizer tank needs to be able to store at least the required amount of oxidizer needed to achieve the apogee, on hybrid engines that use nitrous oxide ($N_2O$) as oxidizer it is also necessary to leave between 15% to 20% of ullage volume in the tank, so that the nitrous oxide can expand (V. Zakirov, 2001). As well, for nitrous oxide hybrids, it is necessary to maintain as less change as possible in the line connecting the tank to the combustion chamber because an expansion in the line can cause the nitrous oxide to change phases and it would result in cavitation and flash vaporization (B. S. Waxman, 2013). It is necessary to have an entrance for the oxidizer in the feed line, so that the tank can be filled when the rocket is in the launch tower, this is done usually by a quick connect coupling. A really important item in the feed system is a component that has the capability to release the oxidizer when necessary, this would enable the rocket team to control the pressure in the oxidizer tank and to empty it if an abort of the mission is called. The oxidizer flow in the line connecting the combustion chamber and the tank is controlled by the main valve, this valve is a ball valve either pneumatic or electric actuated.

After the dimensions of the hybrid rocket engine are defined, it is required for the propulsion system to develop a numerical algorithm that is able to compute the engine parameters for the entirety of the burn time. In this code, it is of prime importance to create a model of the tank emptying, for a self-pressurizing feed system, as is used for nitrous oxide, it changes the results of the engine performance dramatically (Fernandez, 2009). The injector model can take into consideration that the nitrous oxide is incompressible, as only liquid flow through the injector, or can account for the consideration of phase change and compressibility effects during the injection (B. S. Waxman, 2013). The ballistics calculations necessary to determine the engine parameters can be obtained by a chemical equilibrium software. As outputs, there is the need to have the thrust through time curve, the mass flow of fuel and oxidizer through time and the total impulse for example. Those outputs are inputs for other subsystems, so they can develop their work.

For the *Photon* project, a lateral view of the propulsive system can be seen in Fig. (5) where is presented all components mentioned before.

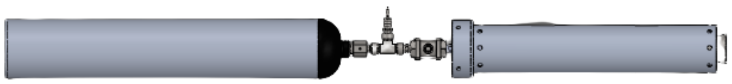

Figure 5. Hybrid propulsion system used in this project.

### 3.5 Recovery

The recovery subsystem is responsible for ensuring the safe return of the vehicle in order enabling an overall analysis of all components after the mission. Recovery will take place in three stages: on the first, the **co2** system contained within rocket is activated causing the rocket cone to be ejected; the second stage consists of opening the auxiliary parachute which will and that will take place when the nose cone is ejected, pulling the auxiliary parachute out of the launch vehicle; by the final and third stage of recovery, the main parachute will be opened.

For the opening of the main parachute, what can be called a "ripple effect" will be used, this parachute is contained inside a bay and this is connected to the auxiliary parachute. When the auxiliary is opened, it will pull the main parachute contained within the bay out of the rocket, opening the bay and separating it from the rest of the launch vehicle, recovering only the cone and leaving the responsibility for recovering the rocket body to the main parachute. This type of recovery with the auxiliary parachute separating from the rest of the rocket and recovering only the cone was seen on (Team, 2018b), a project of the North American spaceport competition and thus designed and adapted for *Photon's* recovery.

It is noteworthy that recovery is directly linked to the avionics of the launch vehicle, where the information to trigger the ejection system comes from the sensors contained in the avionics. The ejection system consists of two $CO_2$ cylinders containing 12g and 60 bar of pressure each, enough to eject the rocket cone. This system will be activated by two redundant squibs, each one coming from a different source of information, thus avoiding failures and risks of the system not being activated. The information for the squibs will be both in relation to the altitude of the rocket and its speed. In a nutshell, as there are two cylinders, there will be two squibs for each $CO_2$ cylinder and even if only one $CO_2$ cylinder is opened in the process, it already has enough pressure to open the cone, thus minimizing the risk of any failure.

Activation and release of $CO_2$ to the recovery chamber will be through a two-piston system, with each piston below to a cylinder. These two pistons will have a load body underneath them where the squibs will go along with the gunpowder, which after being activated will generate enough pressure to push the piston up, and this pushes the cylinder against a metal tip, perforating the cylinder and releasing the gas that fills the recovery chamber and pushes the cone out of the vehicle.

The Fig. (6) shows the two $CO_2$ cylinders, one at rest state with its piston ready to be actuated and the other activated with its upper part being pierced by the piercing tip, it is worth remembering that the spring will serve as a relief for the cylinder since it has to rise with the help of the piston and descend back to its rest state.

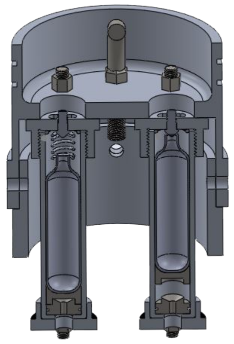

Figure 6. Section view of the $CO_2$ ejection system.

### 3.6 Structures

Firstly, the structures is the sector responsible for ensuring the safety of the launch vehicle as a whole during the flight. However, that is only their main goal and, in order to achieve it, there is a complex process that starts on the conception of the launch vehicle and ends up on the after the operation, considering recovery and data studies that shall be made, according to (NASA, 2016). And, as said before, there are high demands on system engineering during the development.

The first moves that shall be taken by this sector during the development is defining the main characteristics of the vehicle, and this must be done with every and each sector to make sure that their requirements can be achieved considering these decisions. One of them, of utmost importance, is to define the external diameter of the vehicle.

As the conception of the rocket is on course, the ensuing procedures that must be taken by this sector includes the definition of the internal order and again, every subsystem must agree on this decision due to the fact that this completely affects the way they will be developing their work during the entire procedure. Of course that, by the nature of rockets, some systems like propulsion do not have an actual choice to made about their position, once that for high-power rocketry, and mainly on *Photon's* case, the project consist on a rocket of one-stage and, therefore, there is no position to place the engine if not on the bottom of the launch vehicle. A similar analysis can be made with aerodynamics subsystem, that, as said before, are directly responsible for the development of components that will induce stability and affect the fluid flow during flight.

However, the other systems are quite free to intersperse among them, although it is commonly found on reports such as (Branson, 2018) and (Team, 2018a) that the payload system and avionics system are often placed together as an electronic module of the launch vehicle, fetching practicality for the moment that tests are taken and to the assembly in general terms.

With the internal structure defined, it is possible to start thinking where the couplers will be positioned at on the rocket, This represents also a crucial decision for the project due to the fact that it is very likely that inner access will be useful during the pre-launch procedures. More than that, from this point, the projection itself can begin, and for this, it is highly recommended the use of *Computer Aided Design* (CAD) software in order to visualize on the best possible way how parts will fit together on the rocket and if the proposed model is actually compatible with its location, i.e, if the coupler is to thick it may affect the components around him, carrying problems to the valve system of the propulsion sector, and structures is the sector that must worry about this compatibility, mainly on the inner of the rocket.

It is important to highlight that every and each part produced must be compatible with the desired material for it. As said by (Klopp, 1968), the material decision can be the difference between success and failures for these missions. For the couplers of high-power rocketry teams, it is easy to find via reports that the most advantageous material are some aluminum alloys of aeronautical use, such as 7075-T6, 6061-T6 and 6351-T6, depending on other factors such as budget for the project and availability of the material on the country the project is being developed. The logic for the body tube, also known as fuselage, is similar, however the material that presents the better cost benefit is the fiber glass, due to its properties and, even more importantly, its specific mass when combined with resin.

Regarding other structures, their need will be shown during the development and requirements shown by other sectors, such as avionics and payload with its module, and propulsion with adjacent structures requirement, such as a tank support or even alignment rings in order to maintain the vibrations low around the engine. It is also important to consider really particular situations such as the one with the proper bolts for the problem the team is facing. As said in (Canepa, 2005), this is one of the factors that separates model rocketry from high-power rocketry.

Another consideration for the fuselage, is that their geometries may trick. This is said in a sense that, though they seem pretty simple by the outside, every positioning is crucial and, in some places, there are some factors and exits that are defined on a later part of the development, such as the injection valve supply of propulsion subsystem and the rail guide that is developed jointly with the ground support, also responsible for the launch tower.

After all this is set, the next step is to make, initially, analytical calculations and, from this point, start to cope with numerical simulations such as finite element analysis. As the name says, these analysis shall be made with computational software assistance and must not just only match with the analytical calculations, but validate both the geometry and the material chosen to each part.

## 4. CONCLUSION

Considering all approaches taken, it is possible to say that during the project and design moments, the system engineering methods used has been working as it is expected. There are many hard requirements involved in the development of in high-power rocketry projects and these requirement often are contradictory so the decision matrix are very helpful. Also, due to its own nature rocketry is a dangerous activity that must follow all procedures and must be done carefully. We must assume that mistakes can and may happen, so everything must be considered to avoid a chain of reaction problems, therefore the mission must be postponed until we can ensure its safety. For *Photon* project the decision matrix shown a powerful tool in order to take important decision in initial phases which was strongly helpful in posterior phases. Also, the phase division is ensuring to all subsystem a development with a high level of engineering increasing project safety.

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## 6. RESPONSIBILITY NOTICE