DIPLOMA THESIS

Mission Performance and Cost Calculation for variable Rotor Speed Drivetrain

carried out for the purpose of obtaining the degree of

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from

Andreas Auer BSc
Matr.Nr.: 01425931
Liechtensteinstraße 96/18,
1090 Vienna, Austria

Christopher Gross BSc
Matr.Nr.: 01325307
Sonnenweg 115,
1140 Vienna, Austria

under the supervision of

Dr. techn. **Hanns Amri**
Institute of Engineering Design and Logistics Engineering
TU Wien
Karlsplatz 13, 1040 Vienna, Austria

and

Univ.-Prof. Dipl.-Ing. Dr.-Ing. **Michael Weigand**
Institute of Engineering Design and Logistics Engineering
TU Wien
Karlsplatz 13, 1040 Vienna, Austria

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I confirm, that going to press of this thesis needs the confirmation of the examination committee.

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume. If text passages from sources are used literally, they are marked as such. I confirm that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.

Vienna, February 2020

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Andreas Auer Christopher Gross

Aknowledgment

We thank Dipl.-Ing. Dr. techn. Hanns Amri for the excellent support and supervision during our diploma thesis.

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Abstract

The thesis is part of the project VARI-SPEED which aims to develop a variable rotor speed drivetrain for rotorcraft.

In this thesis the performance behavior of rotor speed variation in the context of missions was investigated. Three different transmission systems, a single speed transmission, a two speed transmission and a continuous variable transmission were assumed as technology for the rotor speed variation. The single speed transmission was used as reference. The two speed transmission and the continuous variable transmission were assumed with a weight penalty of 65 kg. The considered missions were categorized in 3 different industry sectors: Oil and Gas producing Industry, construction industry and Search and Rescue. A simulation model was set up which first determines the power-optimized single rotor speed for a branch as well as the power-optimized two rotor speeds. In a next step the missions of a branch are simulated with all three transmission system types and the required power and the fuel consumption was evaluated. Knowing the rotorcraft performance the cost of each mission was calculated. In the cost calculation the following costs were considered: depreciation and overhaul costs, fuel and oil costs, crew costs, maintenance costs and indirect costs. In the end the fuel consumption, costs and the variation range of the rotor speed were determined for the whole branch.

The investigation was performed to evaluate the different possible transmission technologies for speed variation from the point of view of an operator.

It has been shown that using a continuous variable transmission leads to an increase of the flight envelope of up to 17%. The greatest performance advantages of the continuous variable transmission are obtained at high altitudes, airspeeds and payloads. Costs are mainly dependent on flight time. There is a discrepancy between optimum rotor speed for minimum fuel consumption and minimum cost. The economic and ecological interests are therefore in conflict with each other. For standard gearboxes, it was found that the calculated, performance-optimal rotor speed was about 10% lower than the reference speed of the helicopter under consideration. However, no safety aspects such as autorotation capability were taken into account in the calculation. A Two speed transmission does only lead to improvements in the fuel usage and cost during a mission, if the two possible rotor speeds reflect the variation in rotor speed well. This was only the case for a few missions. It was also shown, that a spread between minimum and maximum rotor speed of the continuous variable transmission of 1.5 is sufficient. The findings support the assumption, that the use of variable speed gearboxes in helicopters lead to cost and fuel savings while increasing performance.

The cost and performance investigation indicates important design parameters, like spread or target weight, for transmission variable drivetrains. Rotor speed variation can improve the performance of rotorcraft, decrease the fuel consumption and CO_2-emissions and can overcome the different requirement between low and fast forward flight for new rotorcraft concepts.

Zusammenfassung

Diese Diplomarbeit ist Teil des Projekts VARI-SPEED, welches die Entwicklung eines drehzahlvariablen Antriebsstranges für Drehflügler zum Ziel hat.

In dieser Arbeit wurde das Leistungsverhalten bei Drehzahlvariation im Rahmen von Missionen untersucht. Es wurden drei verschiedene Getriebesysteme, ein Standardgetriebe, ein Zweiganggetriebe und ein stufenloses Getriebe betrachtet, wobei das Standardgetriebe als Referenz diente. Für das Zweiganggetriebe und das stufenlose Getriebe wurde eine Massenerhöhung von 65kg angenommen. Die betrachteten Missionen wurden in 3 verschiedene Branchen eingeteilt: Öl- und Gas Industrie, Bauindustrie und Such- und Rettungsdienst. Es wurde ein Simulationsmodell entwickelt, welches die leistungsoptimierte Standarddrehzahl, sowie die beiden leistungsoptimierten Drehzahlen des Zweiganggetriebes für jede Branche berechnet. Im nächsten Schritt werden die Missionen einer Branche mit allen drei Getriebevarianten simuliert und die benötigte Leistung sowie der Kraftstoffverbrauch ermittelt. Anschließend wurden die Kosten jeder Mission berechnet. Bei der Kostenberechnung wurden folgende Kosten berücksichtigt: Abschreibungs- und Überholungskosten, Treibstoff- und Ölkosten, Besatzungskosten, Wartungskosten und indirekte Kosten. Am Ende wurden der Treibstoffverbrauch, die Kosten und der Drehzahlbereich für die gesamte Branche ermittelt.

Die Untersuchung wurde durchgeführt um die verschiedenen möglichen Getriebetechnologien für die Drehzahlvariation aus der Sicht eines Hubschrauberbetreibers zu bewerten.

Es wurde gezeigt, dass durch den Einsatz eines stufenlosen Getriebes die Flugenveloppe um bis zu 17% vergrößert werden kann. Die größten Leistungsvorteile des stufenlosen Getriebes ergeben sich bei großen Höhen, Fluggeschwindigkeiten und Beladungen. Die Kosten sind Hauptsächlich von der Flugzeit abhänging, daher gibt es eine Diskrepanz zwischen der Fluggeschwindigkeit für minimalen Treibstoffverbrauch und minimalen Kosten. Die ökonomischen und ökologischen Interessen stehen daher im Widerspruch zueinander. Für Standardgetriebe zeigte sich, dass die berechnete, leistungsoptimale Drehzahl 10% geringer als die Referenzdrehzahl des betrachteten Hubschraubers ist. Jedoch wurden keine Sicherheitsaspekte wie die Autorotationsfähigkeit bei der Berechnung berücksichtigt. Ein Zweiganggetriebe führt nur dann zur Verringerung des Treibstoffverbrauchs und der Kosten, wenn die beiden Rotordrehzahlen den Drehzahlverlauf gut abbilden. Dies war nur bei einigen wenigen Missionen der Fall. Es wurde außerdem gezeigt, dass eine Spreizung zwischen minimaler und maximaler Drehzahl des stufenlosen Getriebes von 1,5 ausreichend ist. Die erlangten Erkenntnisse stützen die Annahme, dass der Einsatz von drehzahlvariablen Getrieben bei Hubschraubern zu Kosten- und Treibstoffeinsparungen bei gleichzeitiger Leistungssteigerung führt.

Die Kosten- und Leistungsuntersuchung liefert wichtige Konstruktionsparameter wie Spreizung oder Zielgewicht für stufenlose Getriebeantriebe. Die Variation der Rotordrehzahl kann die Leistung von Drehflüglern verbessern, sowie den Treibstoffverbrauch und die CO_2-Emissionen senken. Auch die unterschiedlichen Anforderungen für niedrigen und schnellen Vorwärtsflug bei neuen Drehflügler-Konzepten können erfüllt werden.

Contents

Nomenclature

SYMBOL	DESCRIPTION
CVT	Continously variable transmission
NDARC	NASA Design and Analysis of Rotorcraft
RPM	Revolutions per Minute
SAR	Search and Rescue
WF	Weighting factor
SFC	Specific fuel consumption $[kg/kW \cdot h]$
P	Power $[kw]$
v	speed $[m/s]$
v_{tip}	Rotor tip speed $[m/s]$
m	mass $[kg]$
Alt	Altitude $[m]$
ts	timestep $[s]$

Chapter 1

Introduction

In today's world, calls for energy-efficient technologies are becoming ever louder, and this trend is now also gaining ground in aviation. The project VARI-SPEED focuses on the possibility of reducing the required propulsion power of helicopters by varying the main rotor speed. VARI-SPEED is a joint project of the TU Vienna, the TU Munich and the company Zörkler.

For helicopter operators, operating costs and helicopter performance are the most decisive factor in the purchase decision. When developing a new helicopter or its drivetrain, it should therefore be possible to estimate the impact of new technologies on these parameters, as early as possible. To evaluate the effects of the variable rotor speed technology in real world applications, an investigation in context of missions needs to be performed.

In the course of the VARI-SPEED project H. Amri et al. [1] investigated the possible savings from variable main rotor speed on helicopters. For this purpose the Bo105 was modeled in CAMRAD II (Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics). Subsequently, the required power for different flight speeds was calculated for the reference tip speed as well as for the optimal tip speed. It was found that at the point of maximum flight duration, the power reduction can be up to 23 percent. However, the increased weight of the new drive train was not considered.

Which technologies are suitable for the implementation of the variable rotor speed was investigated by H. Amri et al. [3]. Four approaches were examined in more detail. The speed variation through the main rotor, through the electric drive systems, through the turbine and through the gearbox. It turned out that only two technologies are worth considering, variable-speed turbines or transmissions. The increase in mass of such a turbine is very low at 5 percent, but the possible speed range is also not as wide as with the transmission variant.

The most promising technology to vary the transmission ratio is the use of a compound split gearbox. The impact on transmission mass an the kinematics were investigated by H. Amri et al. [2]. A compound split consists of two planetary gear stages, which are interconnected by variators. These variators are used to control the main rotor speed. Since at least one additional planetary gear stage is needed in comparison to a conventional fixed speed gearbox, the mass increases. Also the two variators, which act as a hydraulic motor or pump, depending on the working point, increase the empty weight of the aircraft.

W. Garre [8] dealt with the influence of variable rotor speed on the flight envelope and power savings. For this purpose, five helicopter types with different rotor arrangements were investigated. The calculations were performed with the NDARC (NASA Design and Analysis of Rotorcraft) program. The performance data were calculated depending on the flight speed, altitude, weight and rotational speed. For the flight speed, the height, and the weight 30 points each were chosen, for the tip speed 50 points. This results in a 4 dimensional 30x30x30x50 matrix with the performance data for each helicopter. These matrices were thankfully provided by W. Garre for this thesis. In his work [7] ,presented at the Deutscher Luft- und Raumfahrtkongress 2016, Garre et al. did a performance calculation of three different missions. These were used for the Validation of the simulation tool.

The missions analyzed in this thesis are defined on basis of the report on Rotorcraft Missions during Operation in Various Fields of the Russian Economy [18]. In their report Zhuravlev, V. and Zhuravlev, P. surveyed the rotorcraft missions to identify the requirements to apply the variable speed transmission systems in actual helicopter operation. The list of the missions is based on the *'Guidelines on Aerial Works'* that were issued by the International Civil Aviation Organization (ICAO) in 1984. Also the *'GOST (State Standard) R 54265-2010, Air transport, Aviation works, Classification'* developed by the Russian Federation in 2012 was used to develop the different mission profiles. There are 126 missions divided into 13 industry sectors included in the report. For each mission the flight profile, containing the weights of the transported payload, the flight stages and the speeds, altitudes and ranges, are given.

The report 'Cost Model for Helicopter Missions' [17] gives an insight into how the different costs that arise during the execution of a mission are composed. It goes into detail about the calculation of the cost shares like depreciation costs, fuel costs and overhaul costs. The cost model described in section 2.5 is built on basis of this report.

1.1 Effects of rotor speed variation

Why can a variable main rotor speed lead to a reduction of the required propulsion power and in consequence to a higher performance and lower fuel consumption?

To understand this, a short introduction to the relation between lift and drag is needed. The formulas for lift and drag look very similar and are given as follows

$$dF_{L,D} = \rho \cdot \frac{v^2}{2} \cdot C_{L,D} \cdot L \cdot dy \tag{1.1}$$

$dF_{L,D}$	Lift or Drag force
ρ	air density
v	airspeed
$C_{L,D}$	Lift or Drag coefficient
L	wing area
α	angle of attack

Because of this similarity, the ratio between the lift coefficient and the drag coefficient is equal to the lift to drag ratio. The lift coefficient is, as well as the drag coefficient a function of the angle of attack.

$$C_{L,D} = f(\alpha) \tag{1.2}$$

The lift to drag ratio is a determining parameter of an airfoil, which can be measured in a wind tunnel. By plotting the ratio over the angle of attack, the most efficient angle of attack can be metered where the curve reaches its maximum (See figure 1.1).

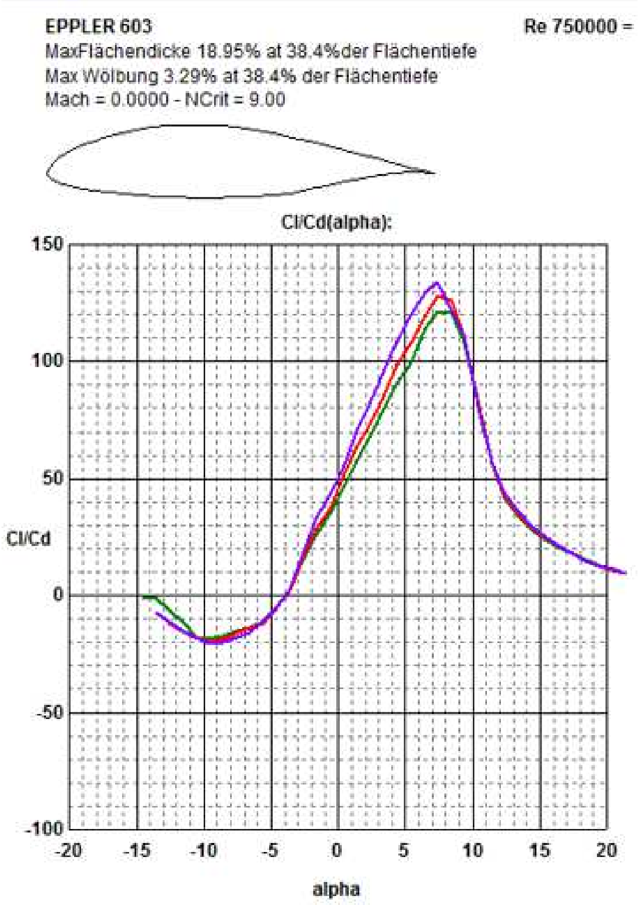


Figure 1.1. *C_L/C_D over angle of attack*

While maintaining this optimum angle of attack with its corresponding lift and drag coefficient, the needed lift can be adjusted by varying the rotor speed. In conventional helicopters, the lift is controlled by a variaton of the angle of attack of the rotor blade. This does not allow the rotor to operate with its highest efficiency. Without a gearbox which allows a variation of the rotor speed, adjustments are only possible via the propulsion system. But the common propulsion Systems like reciprocal engines and jet engines only have a small speed range where they reach good efficiency. So a deviation from their designed working point leads to a reduction of the powerplant efficiency.

The efficiency can be increased using variable rotor speed, but also the transmission mass will grow. Garre showed that there are areas of the flight envelope, where a CVT does not have a benefit over a standard transmission, because of the additional weight[8]. In order to assess whether speed variation brings benefits not only in theory, it must be evaluated in the context of missions and industry sectors.

1.2 Aims

Therefore the aims of this thesis are:

- to build a simulation tool to evaluate new technologies for rotorcraft in the context of missions and branches
- to evaluate the performance of rotor speed variation in the context of mission
- to evaluate the costs of the new technologies.

The purpose of this thesis is to estimate and evaluate the effects of rotor speed variation on performance and costs in real life operation. This serves as a basis for further research on rotor speed variation and an experimental gearbox investigation.

1.3 Allocation of work

This work is divided into two main areas. The performance calculation and the cost calculation. These two areas are closely intertwined, but Mr. Auer was leading the performance calculation and Mr. Gross the cost calculation.

- **Materials and Methods:** The mission definition was done by Mr. Auer and the definition of the helicopter data and the cost factors was done by Mr. Gross. The speed and RPM optimiziation was split into two parts. The calculation for optimum endurance was done by Mr. Auer, the calculation for optimum range by Mr. Gross. Mr.Auer evaluated the optimum speeds of the Two-speed tranmission, while Mr. Gross was in charge of the Standard tranmission and the CVT. The performance calculation was lead by Mr. Auer. The Cost calculation was lead by Mr. Gross.
- **Validation:** This chapter was shared between the authors in order to ensure correct functionality of the simulation tool.
- **Results:** The results of the performance calculation were evaluated by Mr. Auer. The impact on the costs by Mr. Gross.
- **Discussion:** The comparison of the different transmission technologies were examined by the two authors together. The results of the performance calculation were discussed by Mr. Auer and Mr. Gross was in charge of the Mission Cost discussion.

Chapter 2

Materials and Methods

Based on the investigations of Amri [2] and Garre [8] specified in chapter 1, the effects of rotor speed variation on helicopter performance and mission costs are simulated. For this purpose a mission simulation tool was created in Python. It simulates flights and outputs all relevant performance data and cost shares for typical rotorcraft missions in various industry branches. The missions, which serve as a basis for the calculations, were elaborated by Zhuravlev [18]. Garre [8] investigated 5 different helicopter configurations: a UH-60A "Black Hawk", with conventional single main rotor and tail rotor configuration, the CH47, which is the most succesful tandem rotor helicopter, a coaxial rotorcraft, a compound helicopter and a tilt rotor rotorcraft. It was decided to use the data from the UH60A for the development of the calculation model, because there is a lot of real world data available and many calculations of the VARI-SPEED project refer to this helicopter. Nevertheless, the simulation program also works for each of the other 5 helicopter types.

The procedure of the Python program is divided into 5 steps. First the input data of the helicopter and the mission data are read in. The next step is to calculate the optimal speeds and rotor rpm. Then the different speeds or speed ranges of the three transmission configurations, standard, two-speed transmission and CVT are calculated. After obtaining the speeds, the performance of the helicopter in the flown missions are evaluated. The last step is to calculate the costs incurred for the flight of a mission. These costs are composed of different shares.

A detailed description of the performed steps is given in the this chapter. Each section is based on one part of the procedure seen in figure 2.1 on the next page.

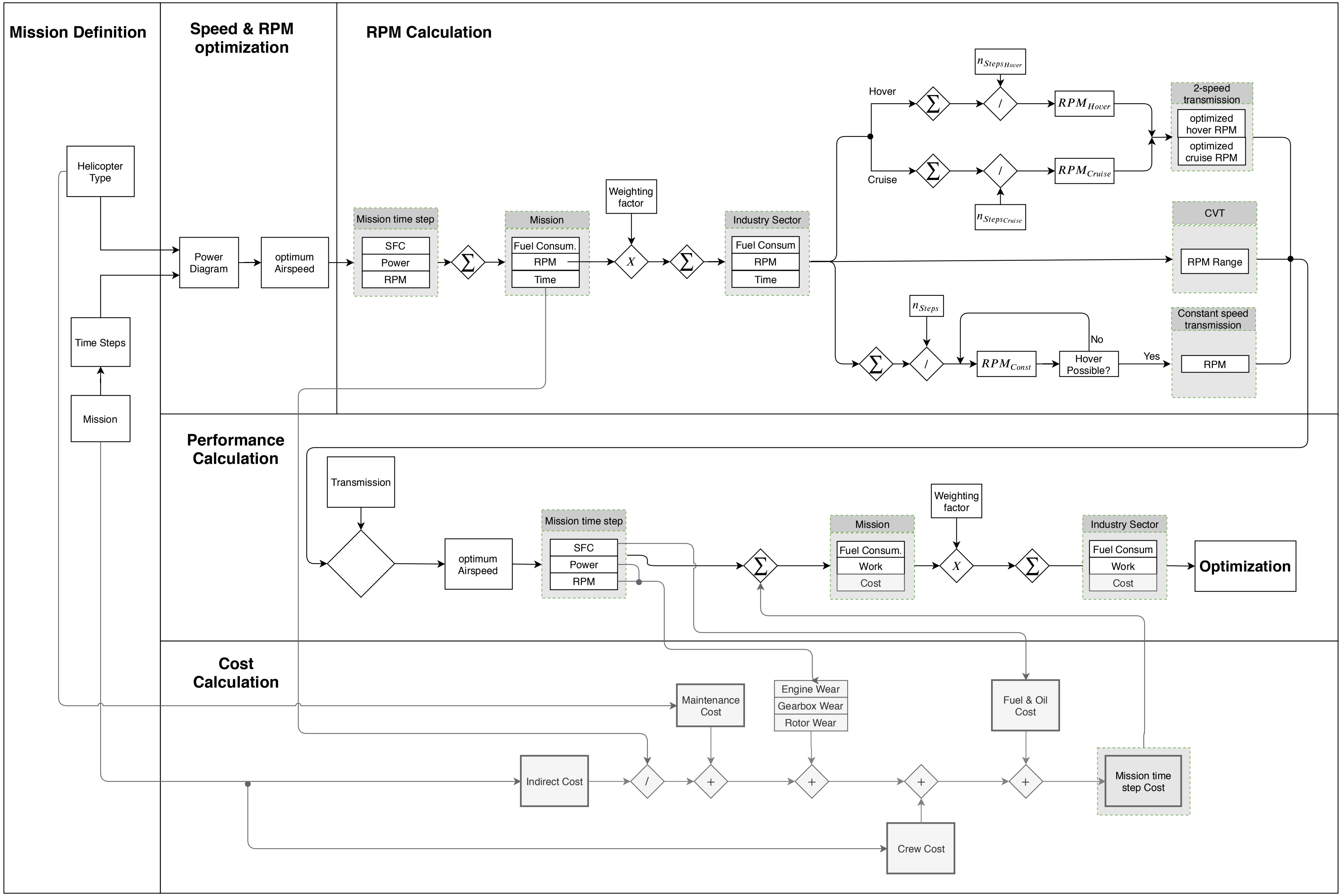


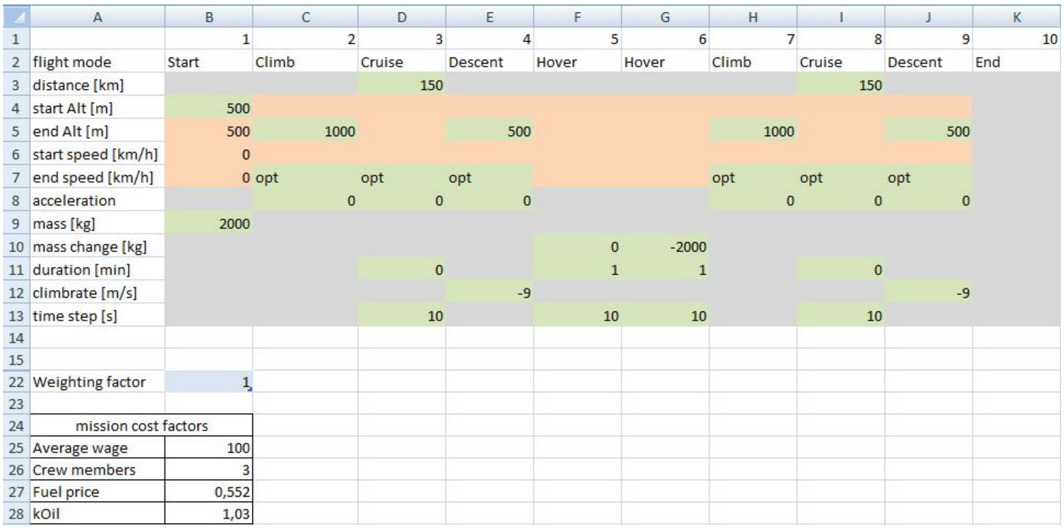
Figure 2.1. *Procedure of Simulation program*

2.1 Mission Definition

To import the missions from the different industry sectors defined in [18], a mission template was defined. This template includes information about

- the mission profile,
- the payload,
- the crew,
- the helicopter,
- and the factors needed for the cost calculation.

Every possible mission of the considered industry sectors can be described in the template. In the mission definition there is also a description of the used helicopter and the used transmission system. The next chapters describe and explain the mission template shown in figure 2.2 in detail. The wording has been chosen, so that the chapter can also serve as an users guide for complementary investigations.



	A	B	C	D	E	F	G	H	I	J	K
1		1	2	3	4	5	6	7	8	9	10
2	flight mode	Start	Climb	Cruise	Descent	Hover	Hover	Climb	Cruise	Descent	End
3	distance [km]			150					150		
4	start Alt [m]	500									
5	end Alt [m]	500	1000		500			1000		500	
6	start speed [km/h]	0									
7	end speed [km/h]	0	opt	opt	opt			opt	opt	opt	
8	acceleration		0	0	0			0	0	0	
9	mass [kg]	2000									
10	mass change [kg]					0	-2000				
11	duration [min]			0		1	1		0		
12	climbrate [m/s]				-9					-9	
13	time step [s]			10		10	10		10		
14											
15											
22	Weighting factor	1									
23											
24	mission cost factors										
25	Average wage	100									
26	Crew members	3									
27	Fuel price	0,552									
28	kOil	1,03									

Figure 2.2. *Mission 1.1.1 defined in the mission template*

2.1.1 Mission

This first sheet enables the user to define any helicopter mission. Therefore the mission has to be disassembled into small elements, which represent the different flight modes. At the moment it is possible to define twenty elements per mission. There are six different flight modes, while the first one is always **Start** and the last one has to be **end**. When selecting a flight mode for an element, different colors are shown for different parameters. Green means, that an input value is needed. Red means, there is an input value, but the python script calculates it. For example, for reasons of consistency, the end height in the previous section must be equal to the initial height in the new section. Grey means, that no input value is needed.

Start

By default, this flightmode is always the first one, and cannot be chosen in any other position. The "start altitude", which is the takeoff altitude and the "payload" are the required input parameters. The payload includes the mass of the crew members, additional equipment for the mission and cargo.

Climb

"Climb" can be set on any position. The required inputs are "end Alt" which is the altitude climbed to and the "end speed" which is the speed while climbing. There are two possibilities to define the "end speed". It is possible to choose "opt", which means the speed is always optimized to low fuel consumption and low power required, or to choose a fixed speed.

Cruise

This flightmode can also be set on any position. There are two possible types of cruising. On the one hand distance based and on the other hand duration based. It is only allowed to give an input to one of those two cells, the other one has to be set to zero. There are also two possibilities to define the "end speed", either "opt" or a fixed speed. For "Cruise" also the size of the time steps has to be set. Ten seconds are recommended.

Descent

"Descent" can be set on any position. The required inputs are "end Alt", which is the altitude descended to and the "end speed" which is the speed while descending. There are again two possibilities to define the "end speed", either "opt" or a fixed speed. Choosing "opt" means the speed is always optimized to low fuel consumption and low power required. For the "Descent" also the rate of descent "climbrate" has to be defined. Please make sure, that the input value is negative.

Hover

"Hover" can be set on any position. The required inputs are "duration" and "time step".A time step size of ten seconds is recommended. While hovering it is also possible to change the payload, this is done via "mass change". A negative value means unloading, a positive loading. If no change of the payload is desired, the value has to be set to zero. The mass change always takes place on the begin of the element. So if cargo should be dropped after five minutes in a six minute hover, two hover elements are needed. One with five minutes and "mass change" equal zero and the other one with one minute and the desired mass change.

End

"End" ends the mission. All elements defined after "End" are not considered.

Cost Parameters and Weighting Factor

In a block of cells located underneath of the flightmodes, the mission cost parameters can be set. These are the number and the average wage of the crewmembers on board, as well as the fuel price and an oil consumption factor. All cost factors which correspond to the helicopter type, are defined in the helicopter sheet.

Because not every mission is equally important within an industry sector, a weighting factor was implemented. It is recommended that the weighting factor of the mission which is flown least, gets $WF = 1$, all the other missions accordingly more. The WF can only be a natural positive number.

2.1.2 Helicopter

The Helicopter Sheet provides the data of the helicopter and transmission for the calculation. The only parameter that has to be chosen by the user is the helicopter type. All the masses needed for the calculation are then automatically written to the output cells marked red. Also all helicopter specific data for the cost calculation defined in this sheet is written to the output cells. In this first version, the data for the individual variants is not hidden. So if the estimation of the mass of a transmission type changes, the values can be changed by the user. To begin with, the additional mass of the two-speed transmission and CVT has been chosen as 65kg. This was done to ensure comparability with the results from Garre [8].

2.2 Speed and RPM Optimization

In this stage the aim is to calculate and provide the matrices necessary for the later steps. These matrices contain the optimum flight speed and tip speed for any combination of mass and altitiude. The physical basis for the optimization is the ”power-velocity-diagram (P-v)” shown in figure 2.3. This diagram shows the required power in relation to the flight speed. However, the required power is not only dependent on the flight speed, but on many more parameters which change within a mission. These parameters are the altitude, the mass and of course the rotor speed. So for each combination of the parameters mentioned above a P-v diagram must be drawn. Starting from these diagrams the optimum rotor speed and speed for each possible combination of altitude and mass can be calculated. But there is not only one optimum, also the current flight mode has an impact on which point in the P-v-diagram is chosen. This is discribed in the following subsections. Finally, the results are stored in matrices.

2.2.1 Endurance

To find the parameters for the greatest endurance the lowest point of the bathtub like curve needs to be found. This is quite intuitive because low power also means low fuel consumption. Therefore the lowest horizontal tangent is laid on the curve, shown in figure 2.4. The optimum flight speed can be read at the contact point of the two lines. At first for every combination of altitude, mass and tip speed the lowest power required is searched. With this value given, the speed can be calculated with the P-v-diagram. The result is a 3 dimensional matrix named ’VoptEndurance’, which returns the optimum flightspeed for given mass, altitude and tip speed. If only fixed tip speeds are to be considered, the

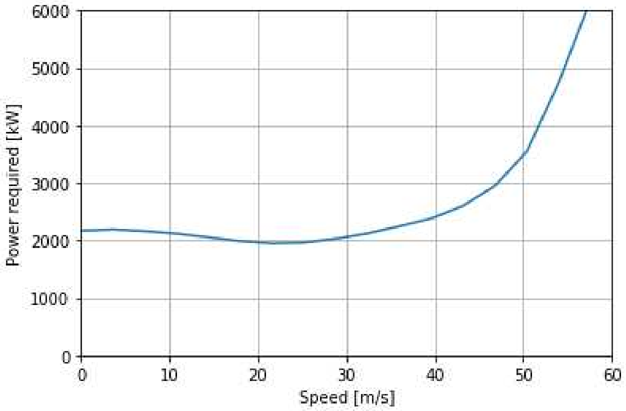


Figure 2.3. *P-v-diagram*

information obtained so far was already sufficient. However, since the rotor speed of a variable-speed transmission can be freely selected at any time, the optimum rotor speed is now determined. For this purpose the tip speed with the lowest required power at optimum flight speed is searched, which results in a 2 dimensional matrix named 'VtipoptEndurcance'. This Matrix returns the optimum tip speed for the CVT for given mass and altitude. The corresponding optimum flightspeed can then be taken from 'VoptEndurance'.

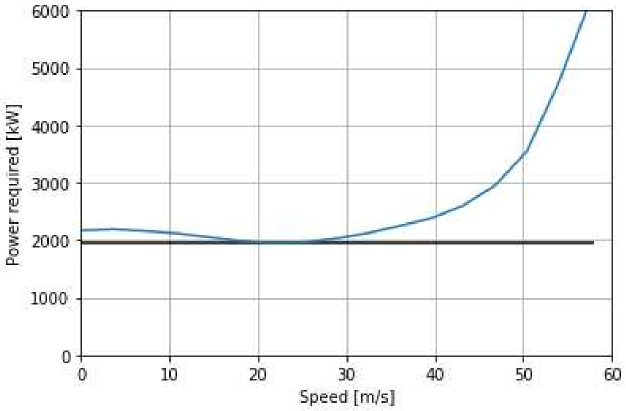


Figure 2.4. *Speed of opt. endurance in the P-v-diagram*

2.2.2 Range

To find the airspeed that allows the maximum range another point is needed. In contrast to the maximum endurance, the point in the P-v-diagram shifts to higher speeds when flying in maximum range condition. Since the power requirement and thus fuel consumption is also higher at higher speeds, it is necessary to find an optimal relationship between these two values. This optimum ratio exists when the groundspeed per power assumes a maximum. This point can be graphically described as where the tangent to the P-v-diagram through the zero point shown in figure 2.5 touches the curve.

For the sake of completeness, it should be mentioned that this only applies if the wind is calm. This is assumed in all missions, so the flightspeed is equal to the groundspeed. In case of tailwind the intersection of the tangent with the abscissa shifts to the left by its amount, in case of headwind to the right.

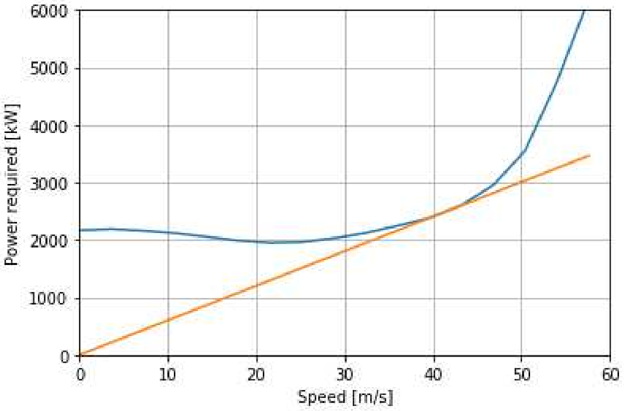


Figure 2.5. *Speed of opt. range in the P-v-diagram*

2.3 RPM Calculation

Using NDARC (NASA Design and Analysis of Rotorcraft) W. Garre [8] carried out a performance calculation of different helicopter models. This was done to simulate and investigate the effects of a rotor speed variation on different flight characteristics and power savings. NDARC is based on advanced momentum theory, where the required power for a given flight state is calculated as the sum of a component power P_{comp}, transmission losses P_{xmsx} and accessory losses P_{acc}. These power components are modeled in a way that incorporates rotor performance characteristics, which are not present in classical momentum theory. [10]

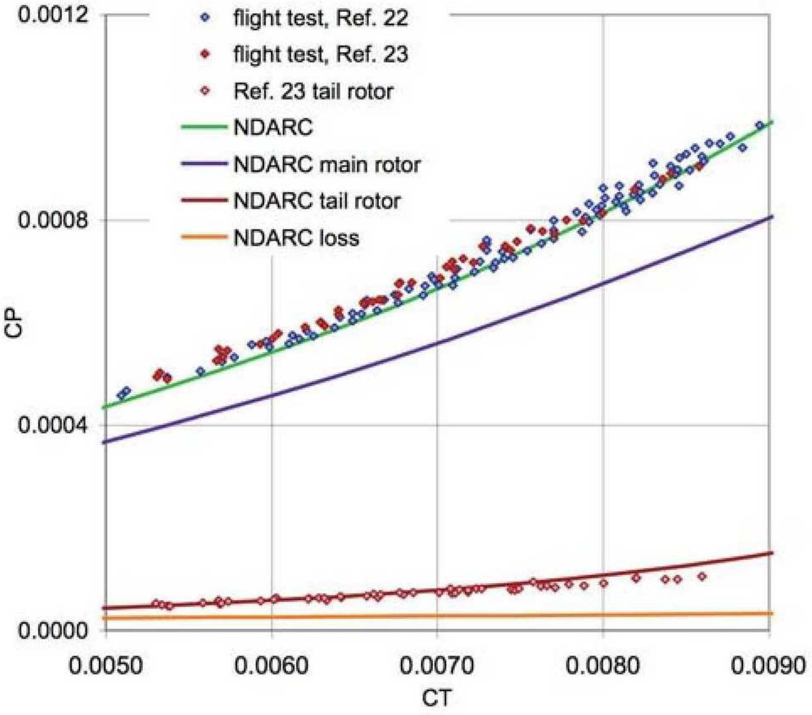


Figure 2.6. *UH-60A Hover Performance, comparing NDARC calculations with flight test [9]*

A four-dimensional field was established, defined by flight speed, altitude, mass and rotor tip speed. The field was bounded by the NDARC Convergence limit. A validation of the performance data against real world data showed a high confidence (see figure 2.6). About 30x30x30x50 (v x m x Alt x v_{tip}) performance calculations where done. The performance calculation resulted in different matrices, which for example, contain the required power P_{req}, the available power P_{av} and the specific fuel consumption SFC. In each of these four dimensional matrices one flight state is defined by a flight speed, an altitude, a helicopter mass and a rotor tip speed. Throughout this master thesis the rotor tip speed v_{tip} is used instead of the rotor speed of rotation, because the aerodynamic forces directly correlate with it. If the rotor speed were to be used, it would need to be converted to the tip speed.

In order to be able to calculate the missions to be flown, they were broken down into small time steps ts . Thus, for each time step a momentary flight state, defined by the variables flight speed, altitude, mass an tip speed, mentioned above, could be specified. From these initial data the optimal speeds and tip speeds were then selected for each time step, as described in section 2.2. In climb and descent the time step is variable between one and ten seconds, depending on the climb or descent rate. In hover and cruise flight the time step was set to ten seconds. This has shown to be a good compromise between calculation accuracy and performance. Since only discrete values appear in the matrices, calculated by the NDARC model, an interpolation had to be performend. It was decided to interpolate only between the discrete helicopter masses, as this caused the highest errors in the output. A further interpolation between speed, altitude and tip speed points was not carried out due to the excessive computing effort and the not too great benefit in the final results.

For each individual time step, the optimum flight speed and rotor tip speed where selected from the previously calculated optimum values. This was done, through the different flight modes which where specified in the individual mission definition files. If a flight speed was defined by the mission, it was used instead of the optimum value, but nevertheless the rotor tip speed was still the optimum for this specified flight speed. Then the complete mission was simulated, to gain the optimum rotor speed for every time step. This had to be done once for every transmission type, since the different transmission masses had to be taken into consideration. The result of this mission simulation was a matrix, which contained the values: time, speed, mass, altitude, rotor tip speed, distance flown, fuel used, power needed and available, and the specific fuel consumption for every second of the flight. It may seem premature to already calculate the fuel consumption at this stage, but this was done because the optimum speed and rotor speed is dependent on the helicopter mass which changes with the consumed fuel.

By appending the individual mission result matrices, weighted by their frequency of occurence, to a big result matrix, it was possible to gain an insight into the behaviour of the optimum rotor speed for a complete industry sector. Based on this matrix it is possible to calculate the optimum fixed RPM for the standard transmission and the optimum low and high rotor speeds for the two-speed transmission.

2.3.1 Continously variable Transmission ratio

First the speeds for the CVT transmission were calculated. For this purpose complete industries with several missions were evaluated. The result matrix now contained all flown missions weighted by their respective weighting factor. Then the minimum and maximum occurring speeds were identified in the result matrix. The spread φ, i.e. the ratio of maximum speed Ω_{max} to minimum speed Ω_{min} could be calculated with this:

$$\varphi = \frac{\Omega_{max}}{\Omega_{min}} \tag{2.1}$$

This is an important value for the design of the CVT transmission, since it determines the design of the gearbox. The transmission topology that yields the smallest mass differs based on the scale of φ. [6]

2.3.2 Two speed Transmission

A special procedure was used to find the two speeds that best represent the optimum speeds. This procedure is based on the method of the smallest absolute deviations according to Rugjer Josip Boskovic [5].

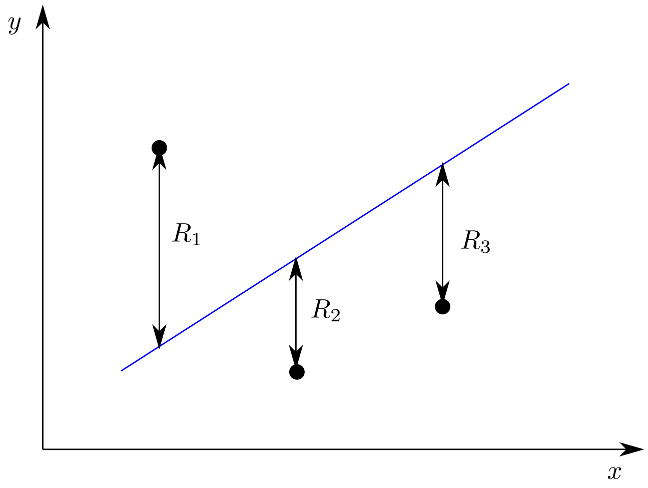


Figure 2.7. *Method of the smallest absolute deviations*

Figure 2.7 shows a simple case of the method of the smallest absolute deviations, in which a straight line, in other words a 1st order polynomial, is placed through a point cloud. The position of the straight line is best when the following applies:

$$R = \sum_{i=1}^{n} \mid R_i \mid \mapsto min \tag{2.2}$$

Our problem can be described on this basis. On the one hand, the point cloud generated by the optimum speeds has to be described by two straight lines. On the other hand, it should be horizontal straight lines, i.e. polynomials of 0th order. Thus, for each of the two lines L (Low) and H (High) the sum of the absolute deviations must be added up separately. First the absolute deviation between the considered point P_i and both straight lines is determined (figure 2.8).

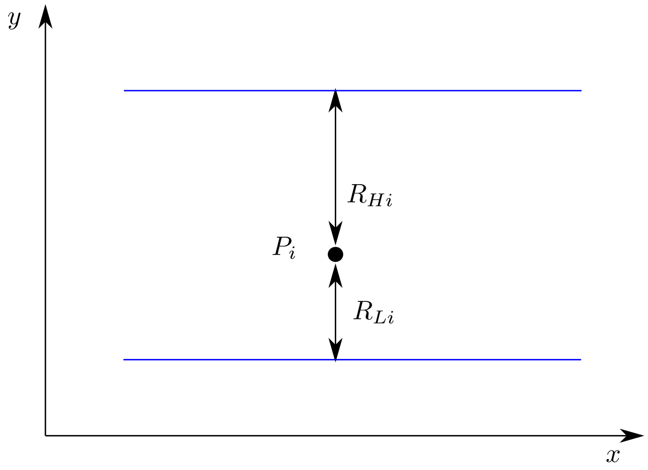


Figure 2.8. *Procedure of Two-Speed determination*

The smaller of the two deviations is then determined. If it applies that

$$|R_{Hi}| < |R_{Li}| \tag{2.3}$$

R_{Hi} is added to R_H, otherwise R_{Li} is added to R_L.

This is done for each point.

In order to find the optimum position of the two straight lines, i.e. the minimum of R_H and R_L, the highest speed is selected as the starting value for the line H, and the lowest speed for the line L. Then, for each possible combination of L and H, the sum of the absolute deviations is calculated. The combination for which

$$R_H + R_L \mapsto min \tag{2.4}$$

determines the optimum speeds for the two-speed gearbox.

2.3.3 Standard Transmission

For this type of gearbox, which has only one fixed gear ratio, the optimum speeds for each time step were multiplied by the correlating time step and then divided by the total time to obtain the average speed $v_{tip_{av}}$. This average speed is the optimum speed for the missions considered if the helicopter is equipped with a fixed ratio gearbox.

$$v_{tip_{av}} = \frac{1}{\sum_{n=0}^{N} ts_n} \cdot \sum_{n=0}^{N} v_{tip_n} \cdot ts_n \tag{2.5}$$

After obtaining this speed, however, it had to be checked if hovering is possible. If the weight of the helicopter or the flying altitude is too high, it may happen that the calculated optimum rotor tip speed is too low to enable safe hovering. In this instance the simulation tool issues an error message wich includes the maximum possible hovering altitude. Either the weight or the hovering altitude in the mission file then has to be changed to accommodate this error.

2.4 Performance Calculation

Knowing the optimum speeds for the various transmission variants, the calculation of fuel consumption and the required power can be carried out. In the process, all missions of the industry under consideration are simulated again. The results of the mission calculation can be summed up to the industry sector. Because the missions vary in frequency a weighting factor was introduced. Only the examination on industry sector level, allows statements about possible fuel, CO_2 and cost savings.

In order to determine the take-off mass, the fuel mass carried must first be determined. This is done separately for each mission. In addition to the determined fuel mass, a safety reserve of 100kg is always included. For this purpose, the entire performance calculation described in the following is iterated until the actual fuel consumed, differs from the carried fuel (without the reserve), by less than 1kg. The starting value for the iteration is half the tank size of the respective helicopter.

As already mentioned, each mission is broken down into small time steps. The choice of speed naturally depends on the gearbox variant, but it follows the same scheme in every flight mode. In the case of the CVT, the speed at which the power requirement is the lowest is selected in each timestep. Also for the two-speed gearbox the optimal speed for the current time step is searched for first. Based on this, however, the speed for the time step that is closer to the optimum is then selected. There is no interpolation between the discrete speed values, because this would mean a big increase in calculation time. For the fixed speed variant, the previously determined speed is used directly. Depending on the current flight mode, however, the processes differ in the calculation.

In the following these processes and assumptions are described for each flight mode.

2.4.1 Cruise

For the cruise there are two possible cases, endurance based or range based. That is, whether the distance of the flight is predetermined or the flight duration. If you want to fly from A to B, the distance is always given as the relevant parameter. For observation flights, where no defined distance is specified, the flight time is relevant and used to describe the flight.

The difference in the calculation can be seen in the airspeed as well as in the abort criterion. If "opt" is entered as airspeed, the speed for maximum endurance is selected when the flight duration is given, the speed for maximum range is selected when the flight distance is given. If the power is not sufficient to reach the maximum -range speed, it will be throttled down until the power is sufficient. If the power is also insufficient at the maximum-endurance speed, the flight state is not possible and the calculation is aborted. The abort criterion of the loop is of course also different and either the reaching of the required distance or the reaching of the required flight time.

2.4.2 Climb

If no special speed is specified but "opt", the maximum-endurance speed is always selected. At this point the helicopter has its greatest reserve of power, which can be used for the climb. With the available data, the climb can only be represented as a discrete sequence of straight flights at increasing altitude. With this simplified assumption, the overall power P_{req} can be calculated by superposition of climb power P_{climb} and cruise power P_{reqCr}:

$$P_{req} = P_{reqCr} + P_{climb} \tag{2.6}$$

The power reserve P_{res} is the difference of power available P_{av} and cruise power P_{reqCr}:

$$P_{res} = P_{av} - P_{reqCr} \tag{2.7}$$

Assuming, that the entire power reserve is used for climbing, applies for the climb power:

$$P_{climb} = P_{av} - P_{reqCr} \tag{2.8}$$

So the possible rate of climb can be finally calculated as:

$$climbrate = \frac{P_{climb}}{m \cdot g} \tag{2.9}$$

m	helicopter mass
g	gravitational acceleration

To make the time resolution dependent on the change of the system, the time step ts in climb was defined as follows:

$$ts = \frac{10}{climbrate} \tag{2.10}$$

Within the limits:

$$1 \leq ts \leq 10 \tag{2.11}$$

2.4.3 Hover

By definition, the airspeed in a hover is zero, but this also means that the power required is higher than in stationary cruise flight. So while cruising is still possible at a certain altitude with a given weight, hovering can already be impossible. Therfore in this flight mode it is always checked if the flight condition is still possible. If it is not possible, the maximum altitude for hovering is given. Another special feature of this state is that the program provides the possibility to load and unload the helicopter. These mass changes are always performed at the beginning of the hover flight. The abort criterion of the hover loop is reaching the selected hover time.

2.4.4 Descent

In the Russian mission report [18], two possibilities are mentioned for the optimal airspeed in descending flight. One is the speed with the lowest power requirement, which corresponds to the max-endurance speed, and the other is 50-60km/h above the max-endurance speed to maximize the distance covered during descent. Since this calculation model does not take into account the distance covered during climb or descent, the choice of ”opt” corresponds to the max-endurance speed.

The sink rate is specified in the mission definition, because the calculation like in the climb mode is not possible. (Theoretically, the free fall would be the most ideal for fuel consumption.) Like the climb, the descent is also represented as a discrete sequence of straight flights, but this time with decreasing altitude. However, the required power in descending flight is reduced by the descent power compared to cruising flight as follows:

$$P_{req} = P_{reqCr} - descentrate \cdot m \cdot g \tag{2.12}$$

The termination criterion for this loop is the reaching of the specified height.

2.5 Cost Calculation

The cost calculation model used in this master thesis, is based on the report done by Vladimir Zhuravlev and Pavel Zhuravlev for the Vari-Speed project [17].

The costs of carrying out a mission can be divided into two parts. One part of the costs depends only on the duration of the flight, which will be called time-dependent costs, and one part depends on the duration as well as on the requested power and rotor speed, which will be called RPM-dependent costs.

The following equations can be found in [17]. The factors that are used in the equation are read into the program from the sheet "helicopter data" in the mission file.

2.5.1 RPM-dependent costs

Depreciation and Overhaul costs

The cost of depreciation is calculated by dividing the production costs of the different subsystems by their respective service life. To determine the share of depreciation and overhaul costs on the total costs it was first necessary to estimate the production costs of the different helicopter subsystems. These include the fuselage, engine, gearbox as well as the rotor blades and the rotor hub. The manufacturing costs always refer to the entire system, for example all the rotor blades of a helicopter, instead of just one.

We will now be taking a look at each subsystem:

Complete Helicopter C_{Hel}

The estimated cost of the mass production of the complete helicopter in dollars is:

$$C_{Hel} = 269 \cdot \left(\frac{WE}{0.453}\right)^{0.4638} \cdot (P \cdot 1.36)^{0.5945} \cdot N_{Bl}^{0.1643} \cdot k_{eng} \cdot k_{N,eng} \cdot k_{Rotor} \cdot k_{LG} \cdot k_{country} \cdot k_{YIF}^{26} \tag{2.13}$$

WE	helicopter empty weight [kg]
P	total engine power [kW]
Nbl	number of blades per main rotor
k_{eng}	engine type coefficient
$k_{N,eng}$	engine number coefficient
k_{Rotor}	coefficient of the number of main rotors
k_{LG}	coefficient of the landing gear type
$k_{Country}$	coefficient of the manufacturing country
k_{YIF}	average yearly inflation factor

Main gearbox C_{MGB}

The production costs of the main gearboxes amount to:

$$C_{MGB} = NGB \cdot \frac{k_{GBType} \cdot \tau \cdot RR^{0.66} \cdot \left(\frac{DTORQ}{9.8}\right)^{0.33}}{NMGB^{0.06}} \cdot 1.3208 \tag{2.14}$$

NGB	number of main gearboxes
k_{GBType}	Gearbox type coefficient
τ	man hour cost [$\$/hour$]
RR	maximum reduction ratio of main gearbox
$DTORQ$	maximum drive torque
$NMGB$	quantity of mass produced main gearboxes

It is estimated that the CVT Transmission is about 50% more expensive than the standard transmission. This is reflected in the factor k_{GBType}.

Rotor blades $C_{MRblades}$

$$C_{MRblades} = NMR \cdot \frac{26192 \cdot \tau \cdot DMR^{0.88} \cdot \sigma_{MR}^{0.97}}{(NMRB \cdot N_{bl})^{0.055}} \cdot 1.27 \tag{2.15}$$

NMR	number of main rotors
DMR	main rotor diameter [m]
τ	man hour cost [$\$/hour$]
$sigma_{MR}$	main rotor solidity
$NMRB$	quantity of mass produced main rotor blades
N_{bl}	number of blades per main rotor

Rotor hub C_{MRhub}

$$C_{MRhubs} = NMR \cdot \frac{60 \cdot \tau \cdot WMRH^{0.59} \cdot N_{bl}^{2.4}}{NMRH^{0.125}} \cdot 1.3208 \tag{2.16}$$

NMR	number of main rotors
τ	man hour cost [$\$/hour$]
$WMRH$	weight of one main rotor hub [kg]
$NMRH$	quantity of mass produced main rotor hubs
N_{bl}	number of blades per main rotor

Engines C_eng

$$C_{MRhubs} = N_{eng} \cdot \frac{15.134 \cdot (P_{1eng} \cdot 1.36)^{0.8152} \cdot (SP \cdot 0.6803)^{0.83044} \cdot PR^{0.75576} \cdot TBO_{eng}^{0.36565}}{N_{eng,prod}} \cdot 1.3208 \tag{2.17}$$

N_{eng}	number of engines
P_{1eng}	power of one engine [kw]
SP	specific power of engine [kW/kg]
PR	pressure ratio of turboshaft compressor
TBO_{eng}	time between overhaul of engine
$N_{eng,prod}$	quantity of mass produced engines

Fuselage with equipment $C_{fus,eq}$

The cost of the fuselage and installed equipment is calculated by subtracting the costs of the individual subsystems from the complete helicopter cost.

$$C_{fus,eq} = C_{Hel} - C_{MGB} - C_{MRblades} - C_{MRhubs} - C_{eng} \tag{2.18}$$

The next step is to calculate the service lifes of the subsystems. These differ between the three gearbox types because they are dependent on the rotor speed, used engine power and the torque. This means that the life spending rates have to be calculated for each timestep individually.

Engine life

The normal service life of an engine is determined bases on the average missions flown in its entire life. The engines operate in cruise mode most of their life. In cruise the engine life spending rate is set to 100%. When idling the spending rate is 5 times lower and during take-off an high power applications the spending rate is about two to 2.5 times higher than in cruise. [11], [15]. With this data points it is possible to create the following approximation function. [17]

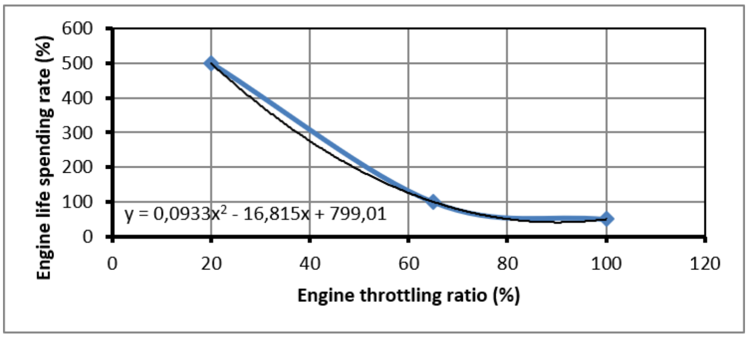


Figure 2.9. *Engine life spending rate vs. engine throttling ratio [17]*

$$L^{Eng}_{var} = \frac{L^{Eng}_{Standard}}{100} \cdot \left(0.0933 \cdot ETR^2_{var} - 16.815 \cdot ETR_{var} + 799.01\right) \tag{2.19}$$

L^{Eng}_{var}	Engine service life of present timestep
$L^{Eng}_{Standard}$	service life in cruise operation
ETR_{var}	Engine throttling ratio at timestep

Main gearbox life

According to [16] the gear and bearing life of a gearbox are a function of the surface loads and the number of loading cycles. The magnitude of surface loading is related to the to torque transmitted by the gearbox. As there is a correlation between torque, power and rotational speed, it is possible to calculate the lifetime as follows:

$$L^{MGB}_{var,ts} = L^{MGB}_{const} \cdot \left(\frac{\frac{ETR_{const}}{ETR_{var}}}{\frac{\Omega_{const}}{\Omega_{var}}}\right)^m \cdot \frac{\Omega_{const}}{\Omega_{var}} \tag{2.20}$$

$L^{MGB}_{var,ts}$	Service life of main gearbox with variable speed of rotation at current timestep
L^{MGB}_{const}	Service life of main gearbox with constant speed of rotation
ETR_{const}	Engine throttling ratio with constant speed of rotation
ETR_{var}	Engine throttling ratio with variable speed of rotation
$\Omega_c onst$	Constant speed of rotation
$\Omega_v ar$	Variable speed of rotation
m	exponent of Wöhler curve, in this application $m = 3$.

Rotor life

There are two loads that influence the depreciation period of a helicopter Rotor. One is the magnitude of the static load, i.e. the average bending moment in the blade flap plane, and the magnitude of the dynamic load. Both of these loads can be seen in figure 2.10. The same equation can be used to calculate either the rotor blade or the rotor hub life. The only difference will be the standard service life of the components.

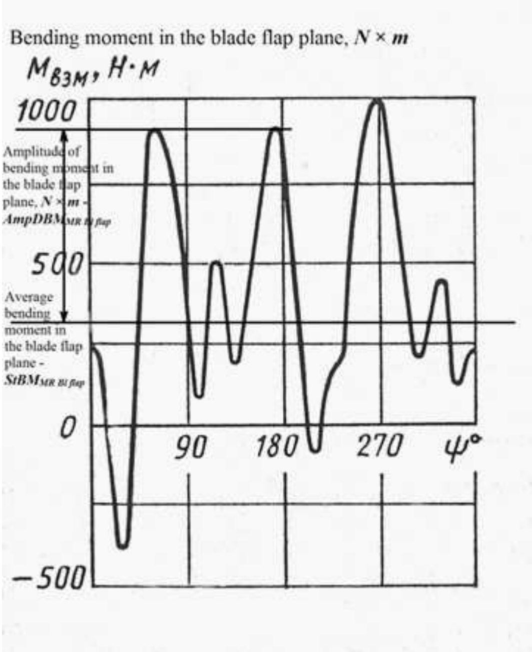


Figure 2.10. *Bending Moment in the blade flap plane, for Mil-8 Helicopter [4]*

$$L^{Rotor}_{var,ts} = L^{Rotor}_{const} \cdot \left(\frac{\sqrt{1 + \frac{\sigma_{const}}{\Delta\sigma}}}{\sqrt{1 + \frac{\sigma_{const}}{\Delta\sigma} \cdot \left(\frac{\Omega_{var}}{\Omega_{const}}\right)^2}} \right)^m \cdot \left(\frac{\Omega_{const}}{\Omega_{var}}\right) \tag{2.21}$$

L_{var}^{Rotor}	Service life of Rotor with variable speed of rotation at current timestep
L_{const}^{MGB}	Service life of Rotor with constant speed of rotation
σ_{const}^{0}	Ampltitude of the static stress which acts on the rotor blade or hub with constant speed of rotation
$\Delta\sigma$	Amplitude of the real dynamic stress
Ω_{const}	Constant speed of rotation
Ω_{var}	Variable speed of rotation
m	exponent of Wöhler curve, in this application $m = 6$.

After the calculation of the production costs and the service lifes of the subsystems it was now possible to compute the depreciation and the overhaul costs. The depreciation and overhaul cost of each timestep is derived as:

$$C_{D,OH_{ts}}^{GB,Eng,Rotorhub,fuselage} = C^{GB,Eng,Rotorhub,fuselage} \cdot \frac{1 + k_{OH} \cdot \left(\frac{L_{ts}^{GB,Eng,Rotorhub,fuselage}}{L_{const}^{GB,Eng,Rotorhub,fuselage}} - 1 \right)}{L_{ts}^{GB,Eng,Rotorhub,fuselage}} \tag{2.22}$$

$C_{D,OH_{ts}}^{GB,Eng,Rotorhub,fuselage}$	Cost of Depreciation and Overhaul per timestep
$C^{GB,Eng,Rotorhub,fuselage}$	Cost of mass production
k_{OH}	ratio of overhaul costs to purchase cost
$L_{ts}^{GB,Eng,Rotorhub,fuselage}$	Service life for each timestep with variable speed of rotation
$L_{const}^{GB,Eng,Rotorhub,fuselage}$	Service life with constant speed of rotation

Since the rotor blades are not overhauled after reaching their service life, there are only depreciation costs.

$$C_{D_{ts}}^{Rotorblades} = \frac{C^{Rotorblade}}{L_{ts}^{Rotorblade}} \tag{2.23}$$

The complete cost of depreciation and overhaul for each timestep amounts to:

$$C_{D,OH_{ts}} = C_{D,OH_{ts}}^{GB} + C_{D,OH_{ts}}^{Eng} + C_{D,OH_{ts}}^{Rotorhub} + C_{D,OH_{ts}}^{fuselage} + C_{D_{ts}}^{Rotorblades} \tag{2.24}$$

Fuel and oil costs

Since the fuel that is needed to fly a mission is already determined in the performance calculation, the fuel costs are rather easy to identify. The oil that is used is also taken into account.

$$C_{fuel,Oil} = m_{Fuel} \cdot P_{Fuel} \cdot k_{Oil} \tag{2.25}$$

$C_{fuel,Oil}$	Fuel and Oil Cost for a complete mission
m_{Fuel}	used fuel for a mission
P_{Fuel}	fuel price $[\$/kg]$
k_{Oil}	coefficient that takes oil usage into account

2.5.2 Time-dependent cost

Crew costs

The number of crew members and the average wage of the crew members is read into the program from the mission file.

$$C_{FlightCrew_{ts}} = AverageWage \cdot CrewMember \;/\; 3600\frac{s}{h} \tag{2.26}$$

Maintenance Costs

It is important to understand the difference between maintenance and overhaul. Overhaul is a major repair, remake or revision and maintenance operations are done to keep a machine functioning or in service. A multitude of maintenance operations has to be done during a lifecycle of a helicopter. These include engine changes, 300-, 150- and 75 hour maintenance as well as pre- and post-flight maintenance.

The costs of engine changes are:

$$N_{engChanges} = \frac{TBO_{fuselage}}{TBO_{Eng}} - 1 \tag{2.27}$$

$$C_{engChange_{ts}} = \frac{C_{MHo} \cdot h_{work} \cdot N_{engChanges} \cdot N_{eng}}{TBO_{fuselage}} \;/\; 3600\frac{s}{h} \tag{2.28}$$

The costs of hour based maintenances are calculated as follows:

$$N_{maint} = \frac{TBO_{fuselage}}{hour_{maint}} - N_{engChanges} \tag{2.29}$$

$$C_{maint_{ts}} = \frac{C_{MHo} \cdot h_{work} \cdot N_{maint}}{TBO_{fuselage}} \;/\; 3600\frac{s}{h} \tag{2.30}$$

$N_{engChanges}$	Number of engine changes during a helicopter life cycle
$TBO_{fuselage}$	Time between overhaul of fuselage
TBO_{Eng}	Time between overhaul of engines
N_{Eng}	Number of engines
N_{maint}	Number of maintenance operations during a helicopter life cycle
$hour_{maint}$	time between maintenance [hours]
$N_{engchange}$	number of engine changes
C_{maint}	Cost of maintenance
C_{MHo}	Cost of maintenance hour
h_{work}	work hours for one maintenance operation

Indirect Costs

The indirect costs are calculated by an equation, which is based on statistical data.

$$C_{ind_{ts}} = 5.85 \cdot \frac{MTOW}{1000} \cdot C_{MH,AL} \;/\; 3600\frac{s}{h} \tag{2.31}$$

C_{ind}	Indirect costs of a time step
$MTOW$	Maximum take-off weight
$C_{MH,AL}$	Average man hour cost in the airline company [$\$/hr$]

2.5.3 complete Mission Cost

Once the individual cost shares had been calculated, it was now possible to calculate the total expenses that the flight of one mission costs.

$$\sum_{i=0}^{T}\left(C_{D,OH_{ts,i}} + C_{FlightCrew_{ts,i}} + C_{engChange_{ts,i}} + \sum\left(C_{maint_{ts,i}}\right) + C_{ind_{ts,i}}\right)\cdot ts_i + C_{fuel,oil} \tag{2.32}$$

The individual missions are then multiplied by a weighting factor, which indicates the frequency of occurrence of a mission. The sum of the mission costs multiplied by the weighting factors result in the costs of one industry sector.

Chapter 3

Validation

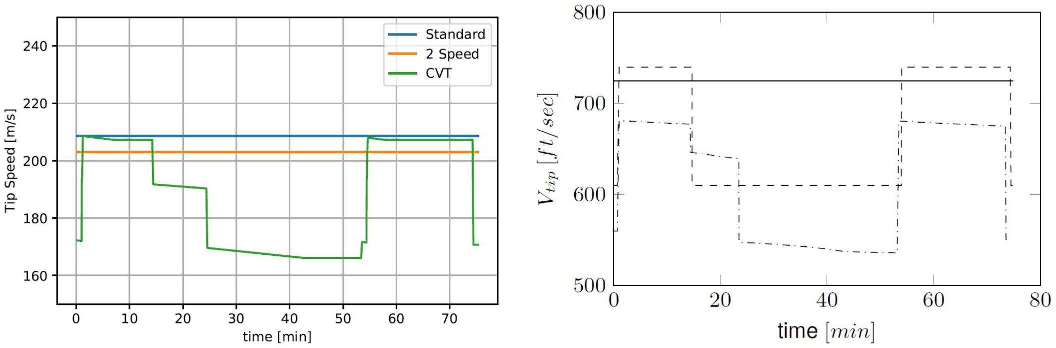
To ensure the correct function of the developed model, it is compared to the performance calculation of Garre [7]. In this validation the order of magnitude of the calculated values should be checked.

The three missions of the UH-60A described and calculated in [7] were taken as comparison values. These are very different missions which cover a wide range of the helicopter performance spectrum. Beside an troop transport mission, it is also a search and rescue mission with high airspeed and a high altitude mountain flight with heavy load. The missions are described in detail in table 3.1.

In contrast to the missions flown in [7], the climb and descent were taken into account. A consideration without climb and descent is not possible, because the change of the flight altitude in the python program can only be given by them. Also the defined take-off mass cannot be given in our program, because the fuel load depends on the mission. In order to get close to the specifications, the payload was iterated manually. There are also differences in the choice of the single speed, in [7] the speed of the existing helicopter is chosen, in this thesis the optimum speed for the three flown missions is used. How the choice of the tip speeds for the two-speed gearbox was made was not described in detail in [7], only that it was selected taking into account all three missions. Therefore a quantitive Validation of the tip speed is only possible for the CVT.

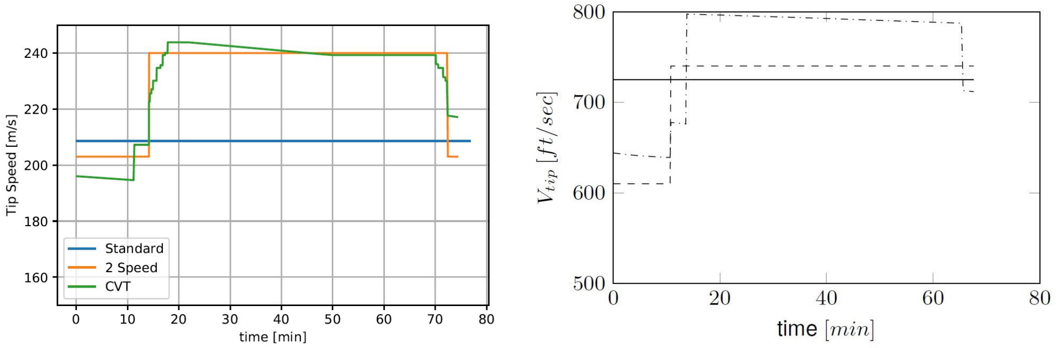
segment	flightmode	speed [km/h]	GW [kg]	altitude [m]	time/ range
UH-60A - maritime SAR					
1	hover	0	7200	15	60 s
2	climb	opt	+0	to 90	-
3	cruise	275	+0	90	60 km
4	cruise	opt	+0	90	30 km
5	descent	opt	+0	to 15	-
6	hover	0	-100	15	1740 s
7	hover	0	+500	15	60 s
8	climb	opt	+0	to 90	-
9	cruise	275	+0	90	90 km
10	descent	275	+0	to 15	-
11	hover	0	+0	15	60 s
UH-60A - high altitude external transport					
1	cruise	165	6900	850	30 km
2	descent	165	+0	to 760	-
3	hover	0	+2500	760	180 s
4	climb	140	+0	to 3350	-
5	cruise	140	+0	3350	120 km
6	descent	140	+0	1980	-
7	hover	0	+0	1980	120 s
UH-60A - troop transport					
1	hover	0	7100	1220	120 s
2	climb	opt	+0	to 1520	-
3	cruise	200	+0	1520	30 km
4	descent	200	+0	to 1400	-
5	hover	0	+1300	1400	180 s
6	climb	opt	+0	to 1520	-
7	cruise	220	+0	1520	80 km
8	descent	220	+0	to 1400	-
9	hover	0	-1300	1400	180 s
10	climb	opt	+0	to 1520	-
11	cruise	165	+0	1520	90 km
12	descent	165	+0	to 1220	-
13	hover	0	+0	1220	120 s

Table 3.1. *Mission definition of validation missions according to [7]*



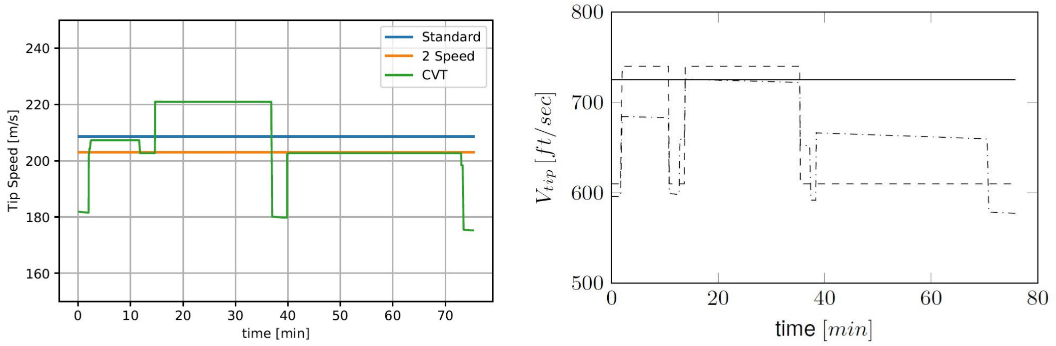
(a) *Tip Speed calculated* **(b)** *Tip Speed by [7]*

Figure 3.1. *Tip Speed comparison maritime SAR*



(a) *Tip Speed calculated* **(b)** *Tip Speed by [7]*

Figure 3.2. *Tip Speed comparison high altitude external transport*



(a) *Tip Speed calculated* **(b)** *Tip Speed by [7]*

Figure 3.3. *Tip Speed comparison troop transport*

The comparison of the results in figures 3.1, 3.2, 3.3 show that the CVT curves are in very good agreement, both qualitatively and quantitatively. For the quantitative review the conversion factor between $[ft/s]$ and $[m/s]$ has to be considered.

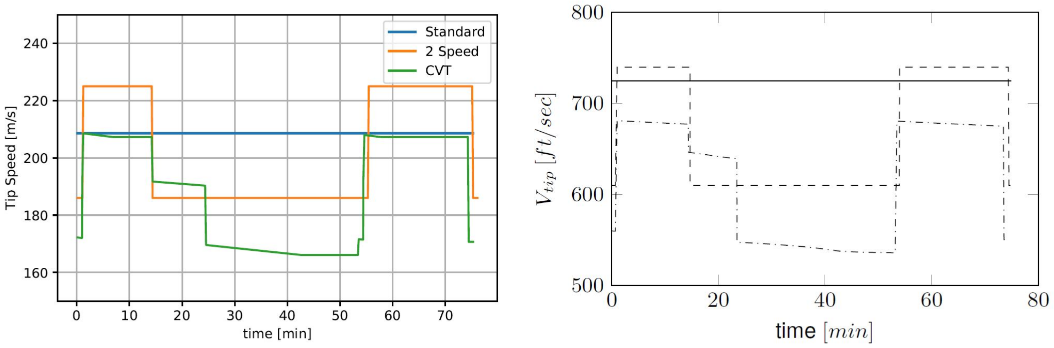
	tip speeds CVT	
	model	Garre [7]
min	166 m/s	540 ft/s = 165 m/s
max	208 m/s	680 ft/s = 207 m/s

Table 3.2. *Comparison of the CVT speeds in the SAR mission*

$$1[m/s] \triangleq 3,28[ft/s] \tag{3.1}$$

The only difference, the jumps while hovering in the SAR and the troop transport mission, are due to different definitions of the time of loading and unloading. This is not defined more precisely in [7].In table 3.2 the tip speeds of the CVT of the different models are compared. It can be seen, that also quantitatively the results match up very well.

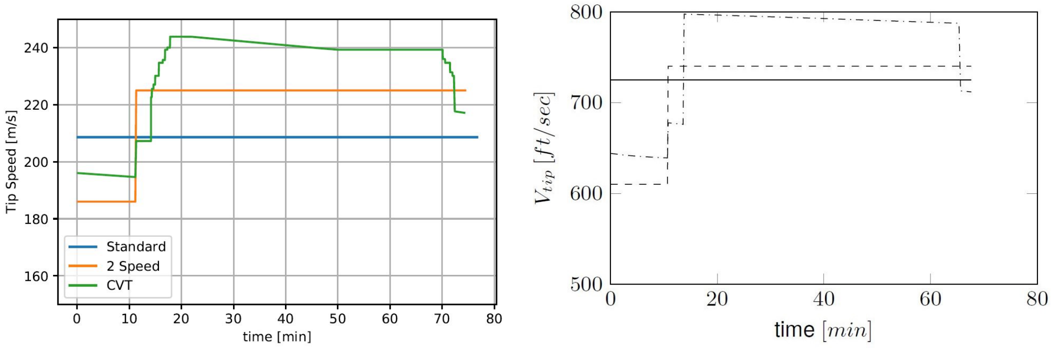
The courses of the two speed transmission differ clearly, only in the high alt mission a shifting process takes place. This is due to the fact that the choice of the optimum speeds differs. Therefore two further investigations were made. On the one hand, a calculation run was carried out with the speeds specified in [7] to be able to analyze the correspondence of the shifting times. On the other hand, the quality of the calculation algorithm for the two-speed tip speeds was examined.



(a) *Tip Speed calculated* **(b)** *Tip Speed by [7]*

Figure 3.4. *Tip Speed comparision maritime SAR*

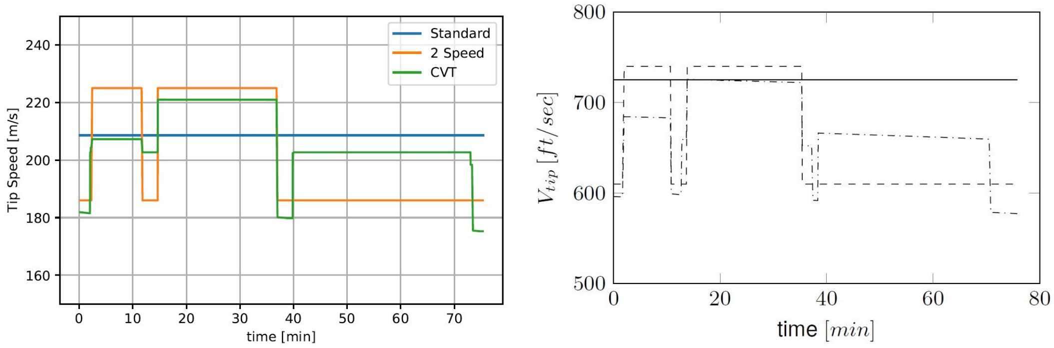
The figures 3.4, 3.5, 3.6 show that the switching times at equal speeds correspond very well. Finally, it remains to be seen which of the two variants is the better choice. For this purpose, Figure 3.7 and 3.8 compare the costs as well as the fuel consumption.



(a) *Tip Speed calculated*

(b) *Tip Speed by [7]*

Figure 3.5. *Tip Speed comparision high altitude external transport*



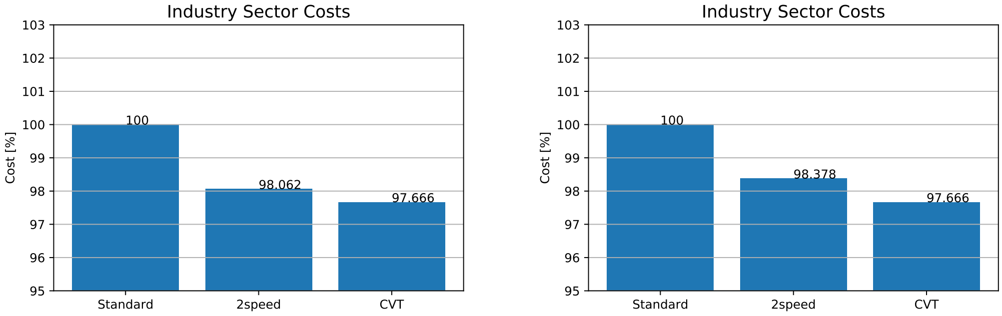
(a) *Tip Speed calculated*

(b) *Tip Speed by [7]*

Figure 3.6. *Tip Speed comparision troop transport*

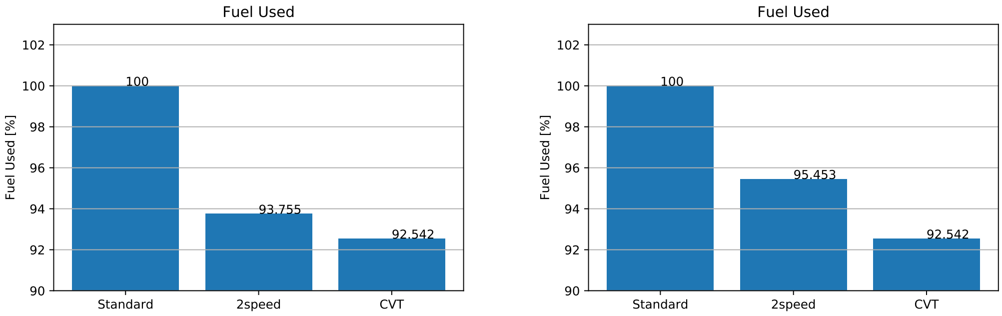
It can be clearly seen that the algorithm described in chapter 2.3.2 offers a much better coverage of the required speed band. Although the optimisation takes place at the power level, it can be seen that the calculated two-speed tip speeds also bring a small cost saving. Therefore, the deviation of the speed curve from the comparison values in the figures 3.1, 3.2, 3.3 is explained.

To conclude this chapter, it can be said that the results of the simulation show a high degree of agreement with the results in [7].



(a) *Costs* **(b)** *Costs with tip speeds form [7]*

Figure 3.7. *Cost comparison of the different two-speed tip speeds*



(a) *Used fuel* **(b)** *Used fuel with tip speeds from [7]*

Figure 3.8. *Fuel comparison of the different two-speed tip speeds*

Chapter 4

Results

This chapter focuses on the results of the mission performance and cost investigation performed for different industry sectors. Each industry is considered both, as a whole and the individual missions of which it is composed. The numbering of the missions refers to [18]. The first digit describes the industry sector the second digit indicates the main task area. In each of these main task areas there are several missions, which can be distinguished by the third digit.

4.1 Industry Sector

Each Industry sector has its own sheet. It contains a description and a list of the missions included in this sector, with their corresponding weighting factors WF. Furthermore the rotor speeds and helicopter performance data of the different transmission types is given.

The rotor tip speed histogram shows the distribution of the frequency that various rotor speeds are used. The diagram also contains the fixed rotor speed $avTip$ of the standard transmission and the two rotor tip speeds ($vTipLow$ and $vTipHigh$) of the two speed gearbox.

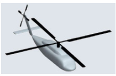
The total industry cost of the helicopters equipped with the different transmissions is given as a percentage of the standard tranmission. The fuel, which is needed to carry out the missions is presented for each tranmission type at the bottom of the industry sector sheet.

4.2 Mission

A sheet was created, for each analyzed mission. These include a short description of the mission with their altitude profile. The tip speed and the used power is plotted over the duration of the flight for every transmission type that was examined. The power is given as a percentage of the available power, in the **used power diagram** e.g. if the value is 100% all the available power is used. The fuel savings over the standard transmission can be seen in the **fuel used diagram**.

The usage diagrams provide information about the wear and tear of gearbox, rotor and engine incurred during a the flight of a mission. On the y-axis of the usage diagram, the fraction of the used life over the component service life in per mil [‰] is indicated.

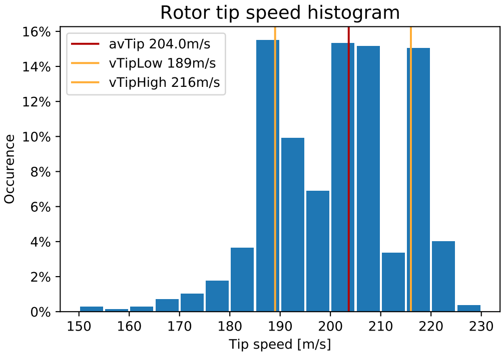
4.3 Oil- and gas- producing industry

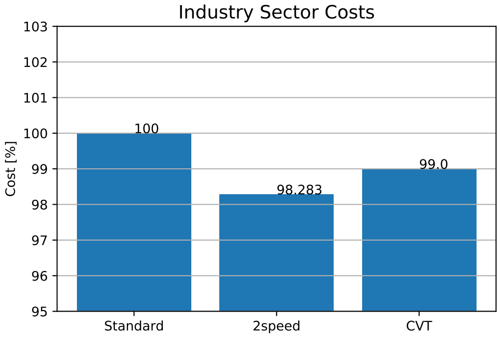


In the Oil and Gas producing industry three main task areas were taken into account.
1.1 Construction of drilling rigs, derricks and adjacent infrastructure on the land
1.2 Construction of drilling rigs and platforms on the sea
1.3 Pipeline construction

Flown Missions

Name	Type	WF
Mission 1.1.1	Cargo in Fuselage	1
Mission 1.1.2	Cargo on ext. sling	2
Mission 1.1.3	Passenger transport	10
Mission 1.1.4	Construction works	1
Mission 1.2.1	Cargo in Fuselage	5
Mission 1.2.2	Cargo on ext. sling	1
Mission 1.2.3	Passenger transport	10
Mission 1.2.4	Construction works	1
Mission 1.3.1	Cargo in Fuselage	5
Mission 1.3.2	Cargo on ext. sling	1
Mission 1.3.3	Passenger transport	10
Mission 1.3.4	Construction works	1



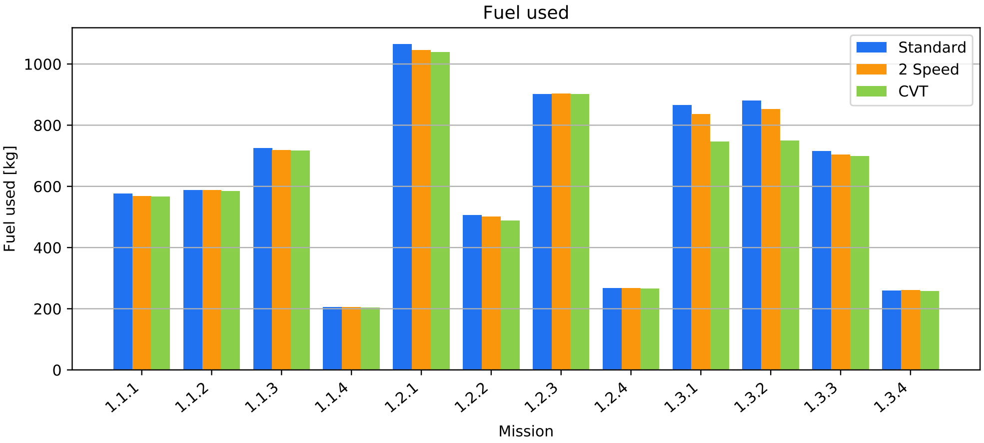


Helicopter Data

Helicopter Type: UH-60A

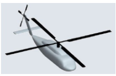
	standard	2 speed	CVT
max. tip speed [m/s]	204	216	239
min. tip speed [m/s]	-	189	152
Spread	-	1.38	1.57
*Climb-rate [m/s]	9.67	10.95	11.48
**Service Ceiling [m]	2094	3413	4672
Gearbox Weight [kg]	-	+65	+65

*at 1000m with MTOW
**with MTOW

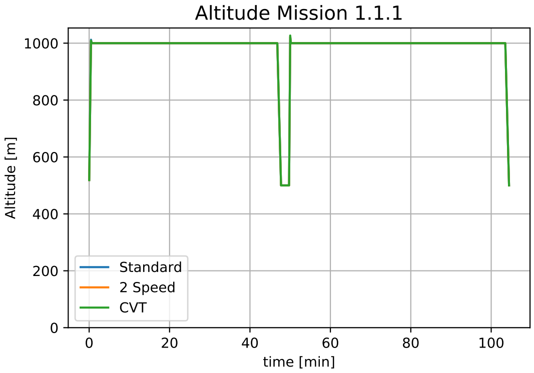


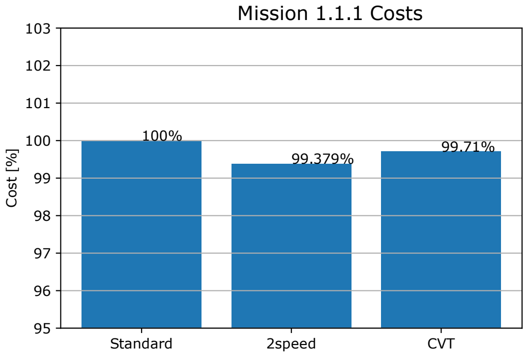
Oil industry

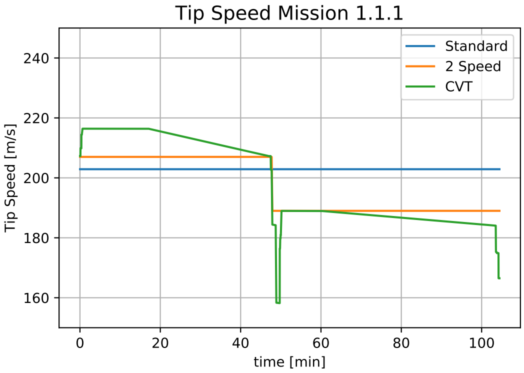
Mission 1.1.1

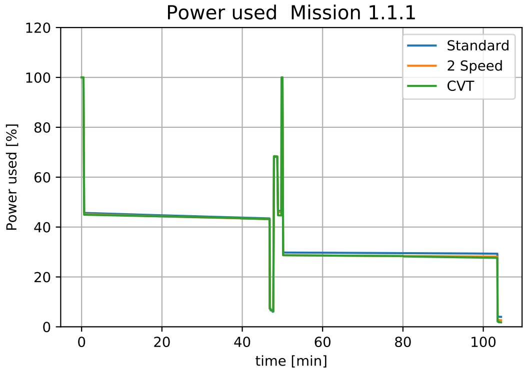


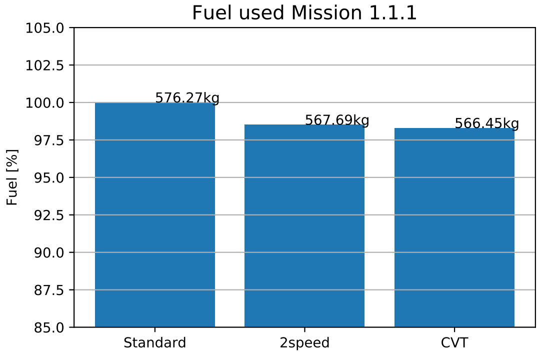
Transportation of the cargo inside the fuselage
Take off at 500m with 2000kg cargo. Then climbing to 1000m and cruising 150km with optimum speed. Descending to 500m and unloading with short hover, then climbing again at 1000m and cruising back with optimum speed.

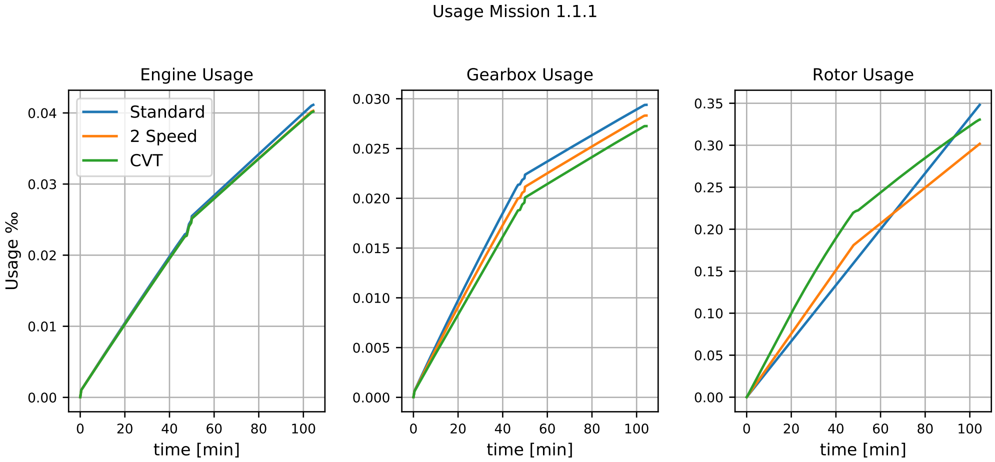




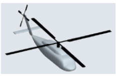


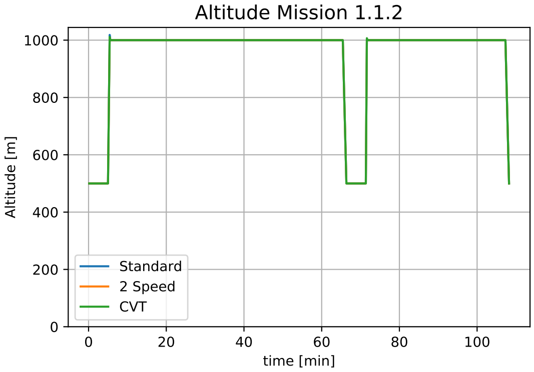




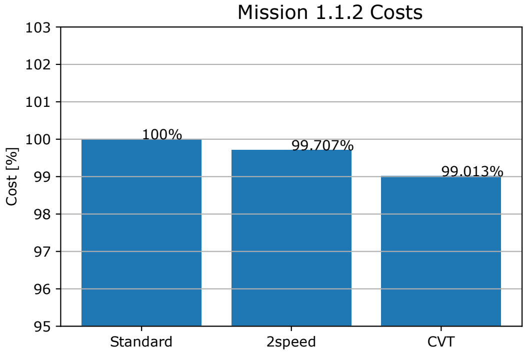


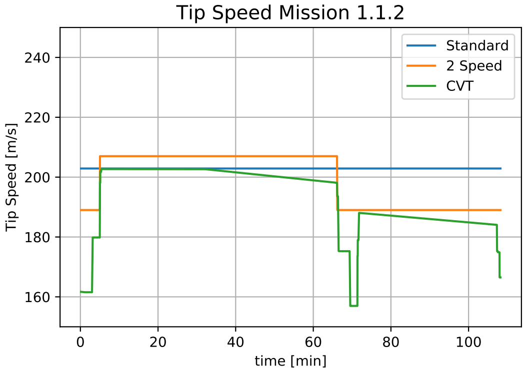
Oil industry Mission 1.1.2

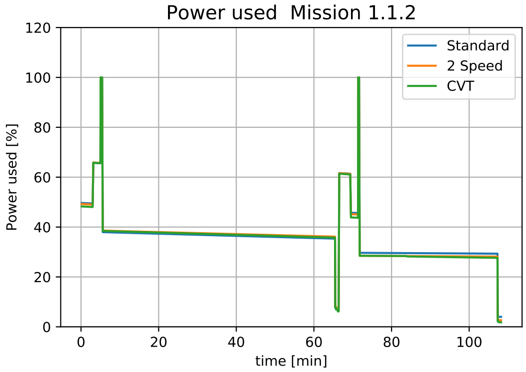


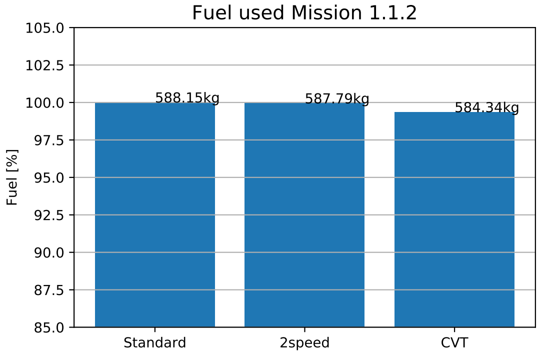


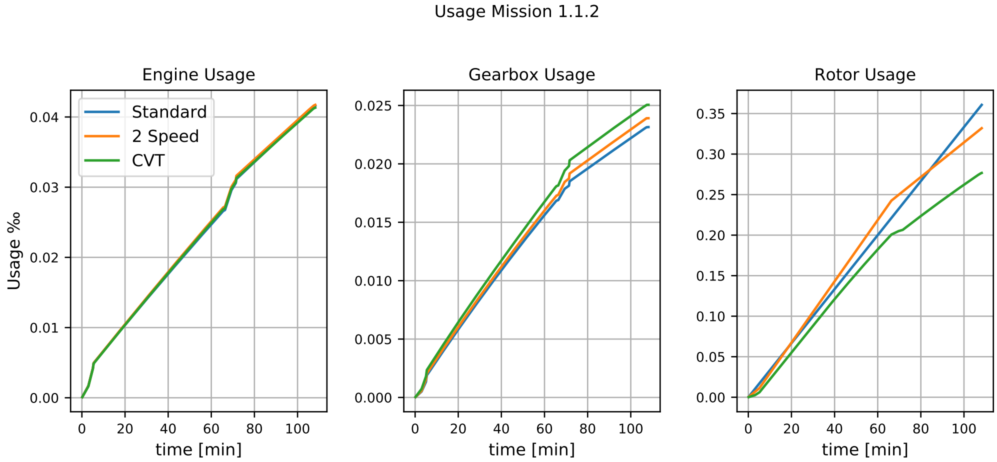
Transportation of the cargo on external sling
Take off at 500m and hovering near to ground to attach the 1500kg cargo. Then climbing to 1000m and cruising 100km with 100km/h. Descending to 500m and deattach cargo while hovering, then climbing again at 1000m and cruising back with optimum speed.





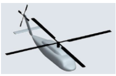






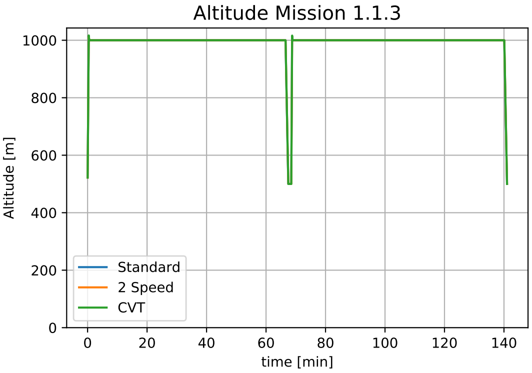
Oil industry

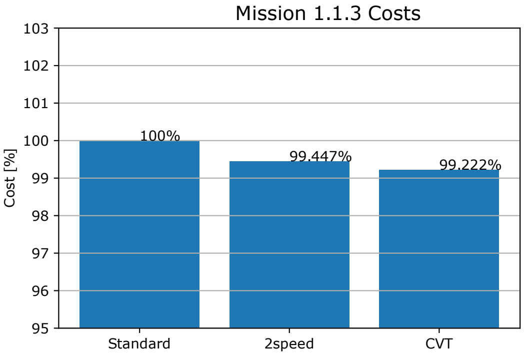
Mission 1.1.3

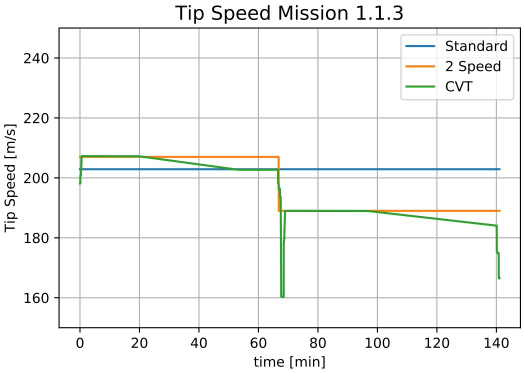


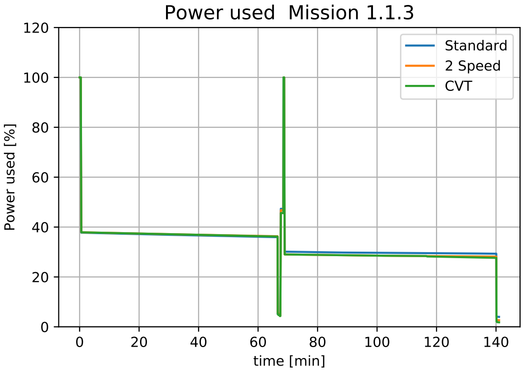
Passenger transportation

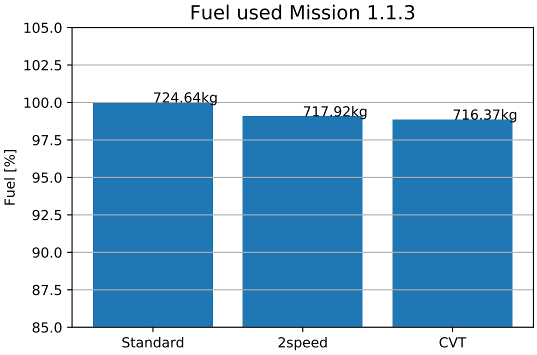
Take off at 500m with 11Pax, 100kg each. Then climbing to 1000m and cruising 200km with optimum speed. Descending to 500m and unloading with short hover, then climbing again at 1000m and cruising back with optimum speed.

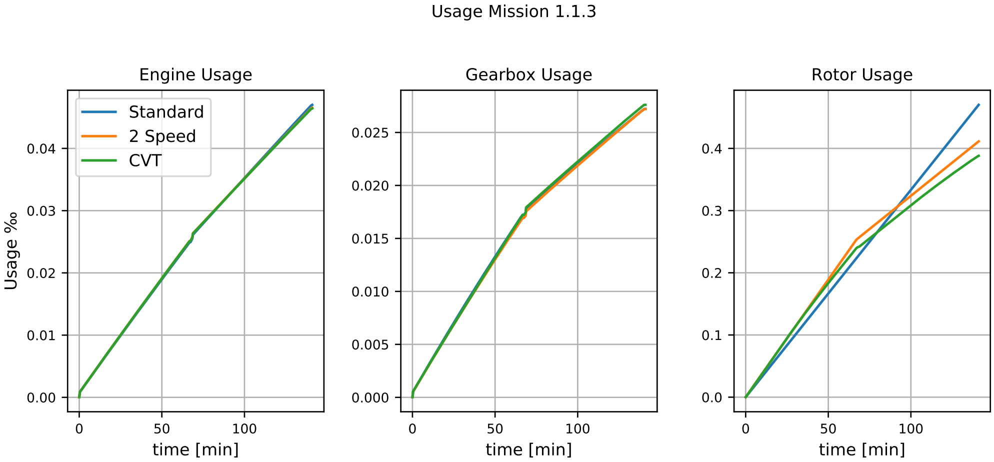






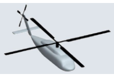




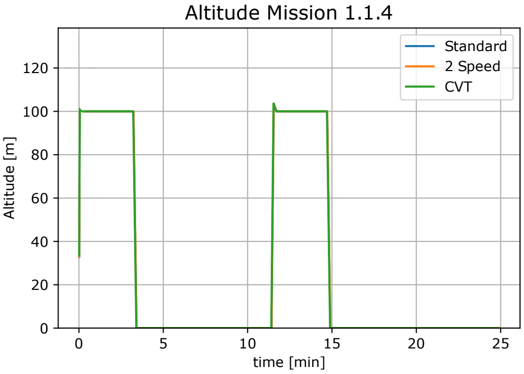


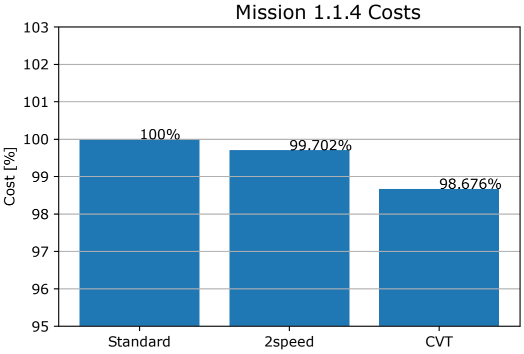
Oil industry

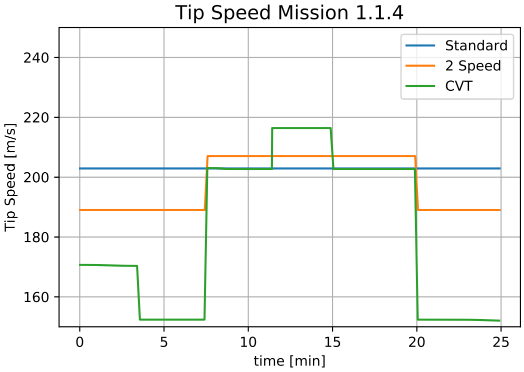
Mission 1.1.4

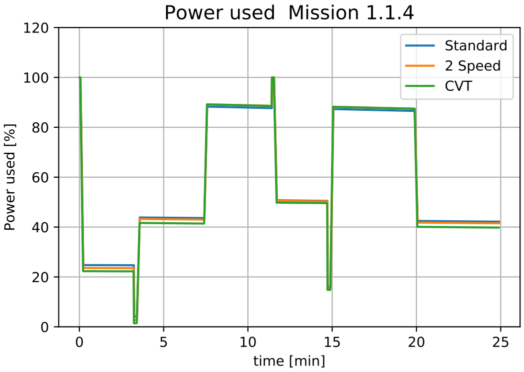


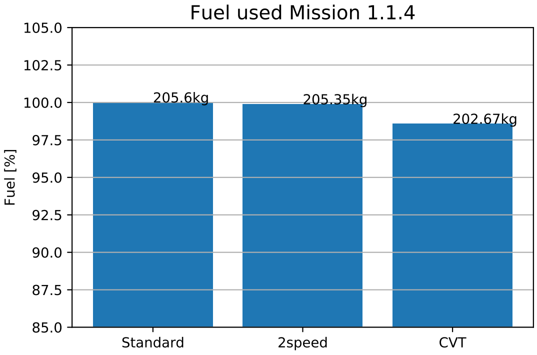
Construction and installation works Take off at 0m without cargo. Then climbing to 100m and cruising 5km with 100km/h. Descending to 0m and hovering while the 4000kg cargo is attached on external sling, then climbing to 100m and cruising 5km with 100km/h to construction site. Descending to 0m and hovering while cargo is installed.

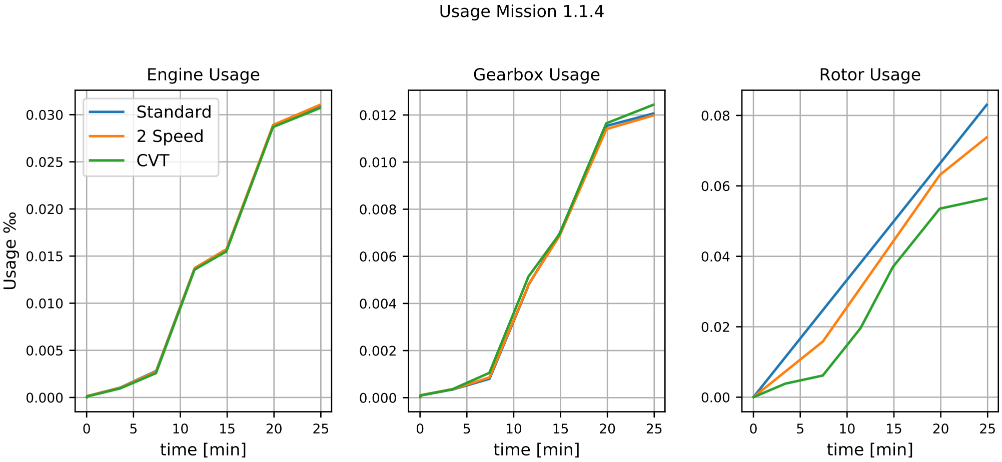




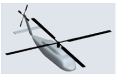






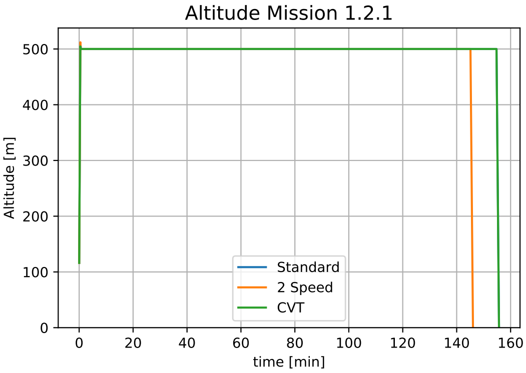


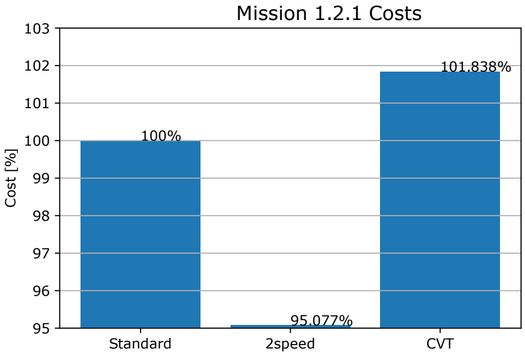
Oil industry Mission 1.2.1

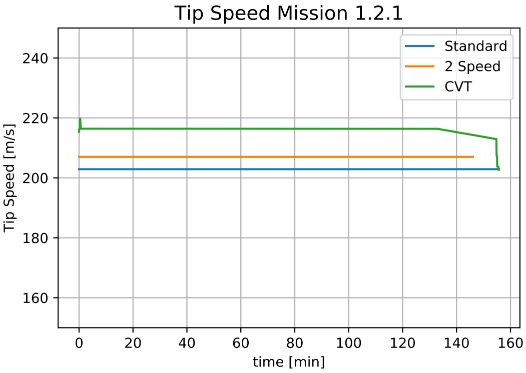


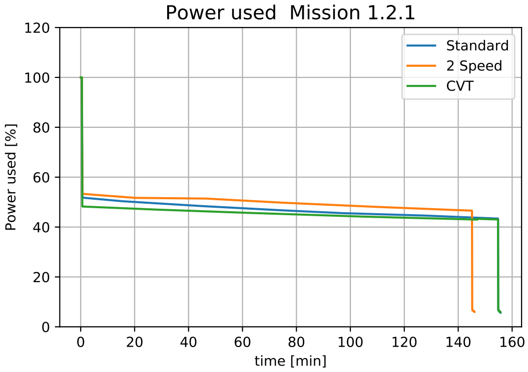
Transportation of the cargo inside the fuselage

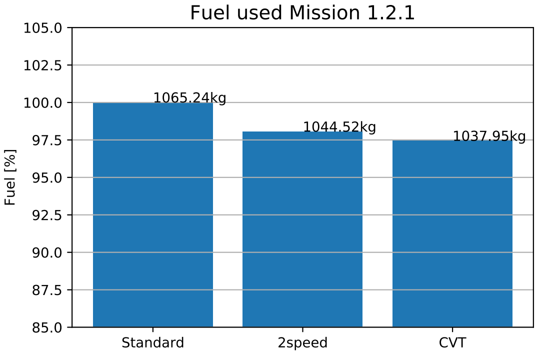
Take off at 100m with 2500kg cargo. Then climbing to 500m and cruising 500km with optimal speed. Then descending to 0m and landing.

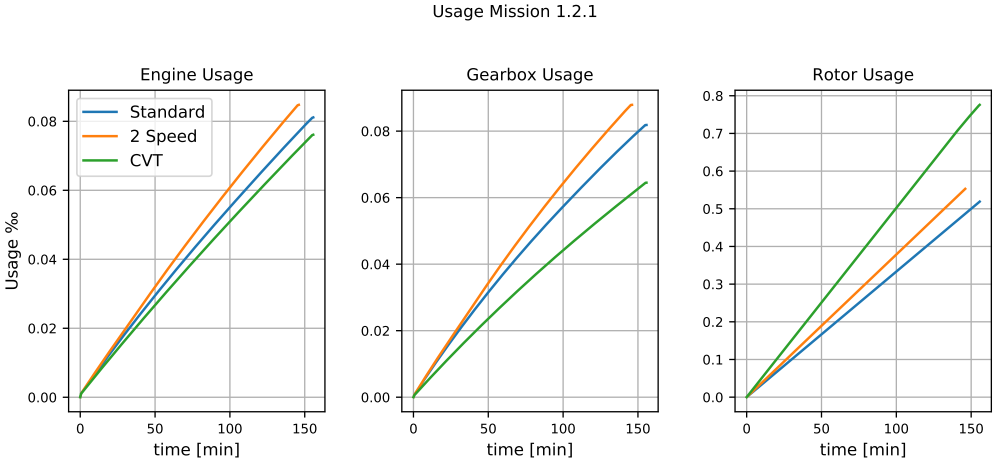




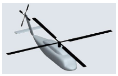


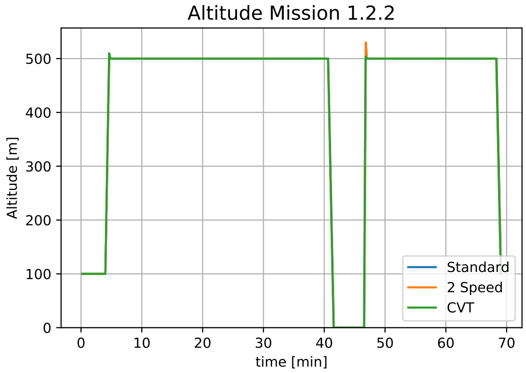




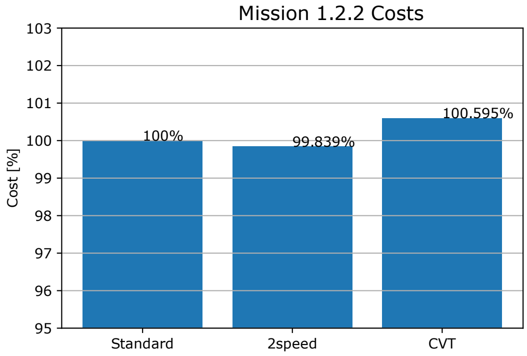


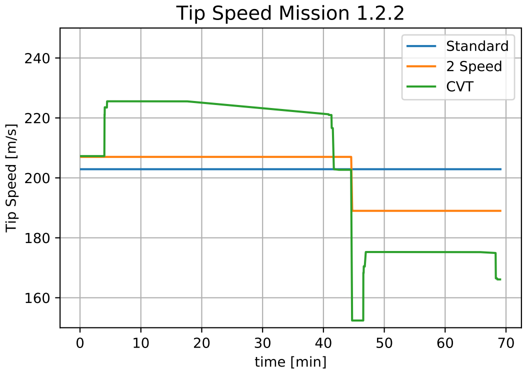
Oil industry Mission 1.2.2

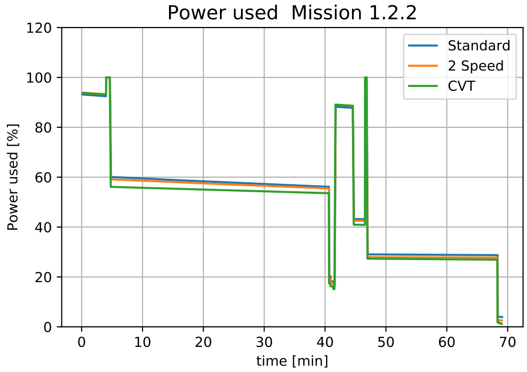


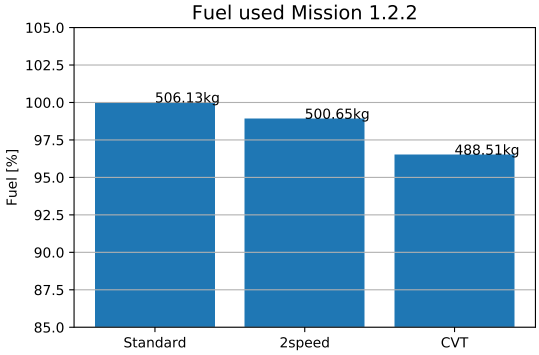


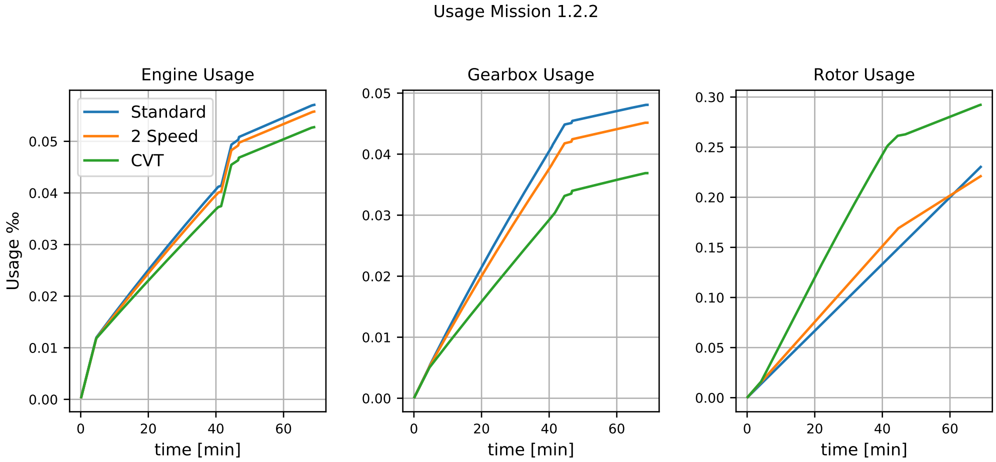
Transportation of the cargo on external sling
Take off at 100m and hovering near to ground to attach the 4000kg cargo. Then climbing to 500m and cruising 60km with 100km/h. Descending to 0m and deattach cargo while hovering, then climbing again at 500m and cruising back with optimum speed.





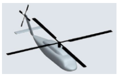


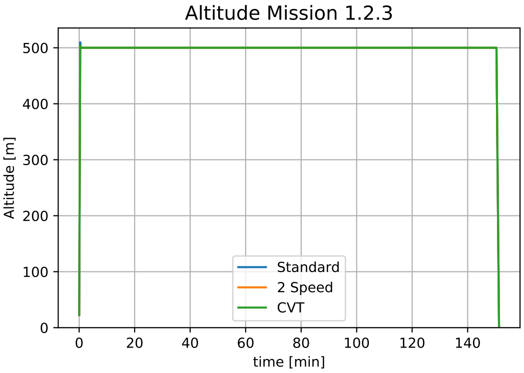




Oil industry

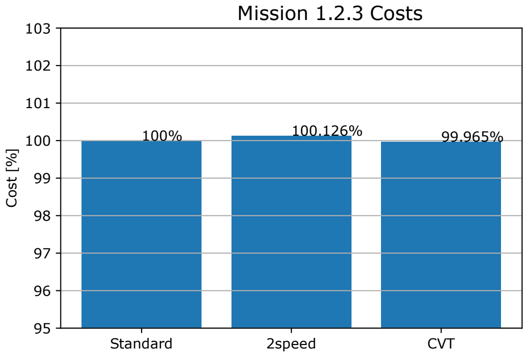
Mission 1.2.3

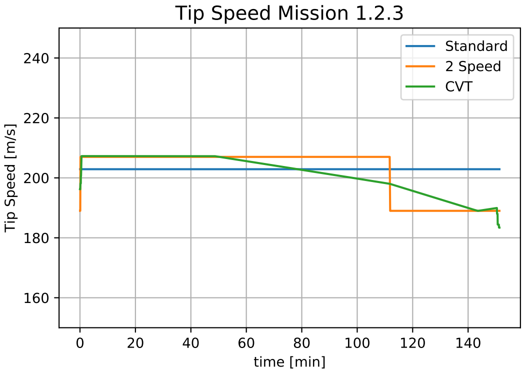


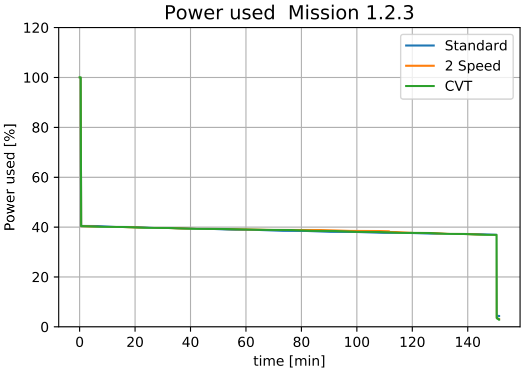


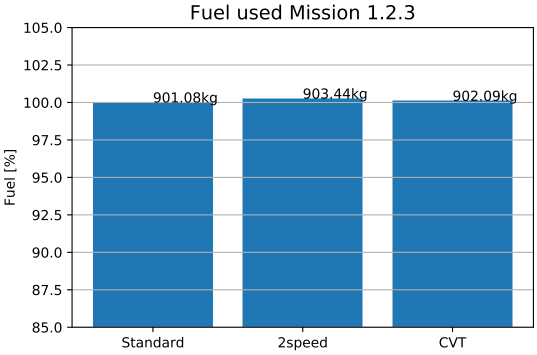
Passenger transportation

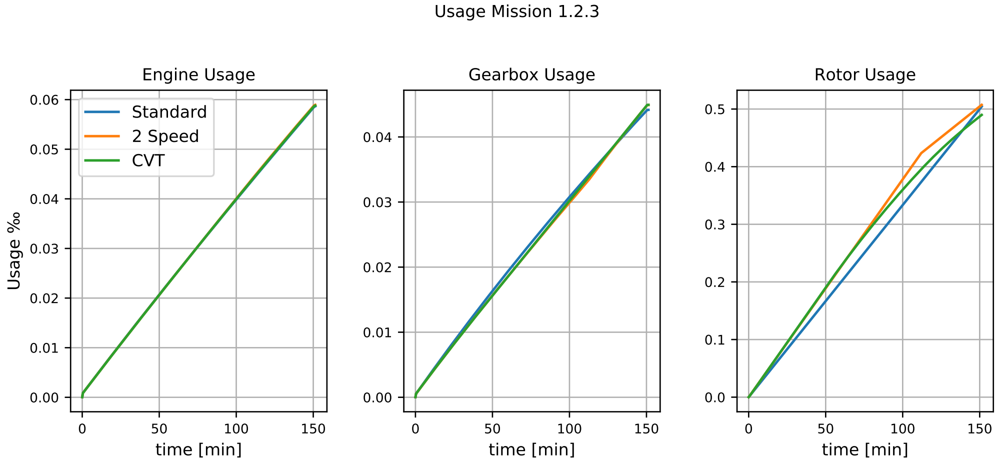
Take off at 0m with 11Pax, 100kg each. Then climbing to 500m and cruising 500km with 200km/h. Then descending to 0m and landing.



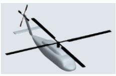


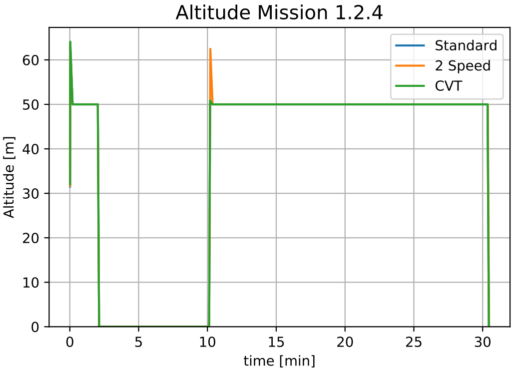




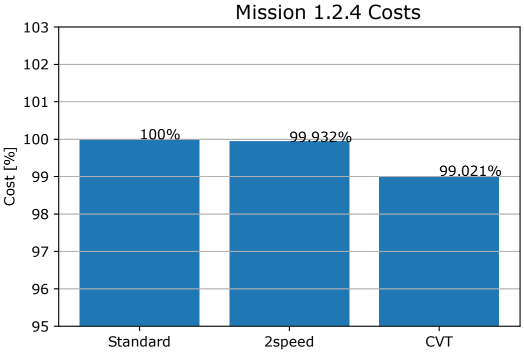


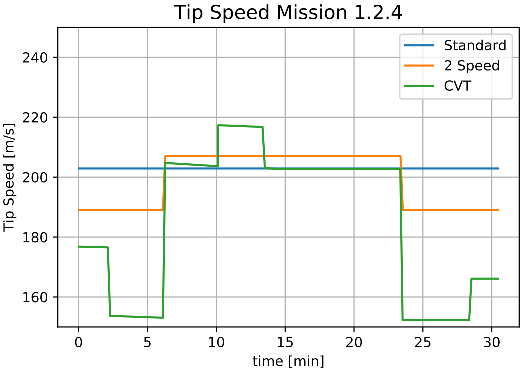
Oil industry Mission 1.2.4

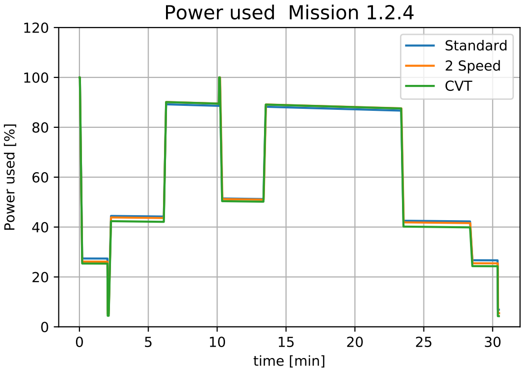


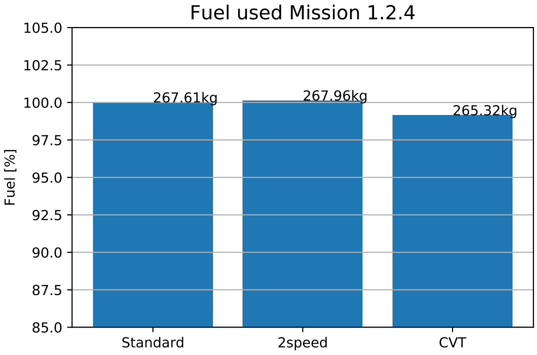


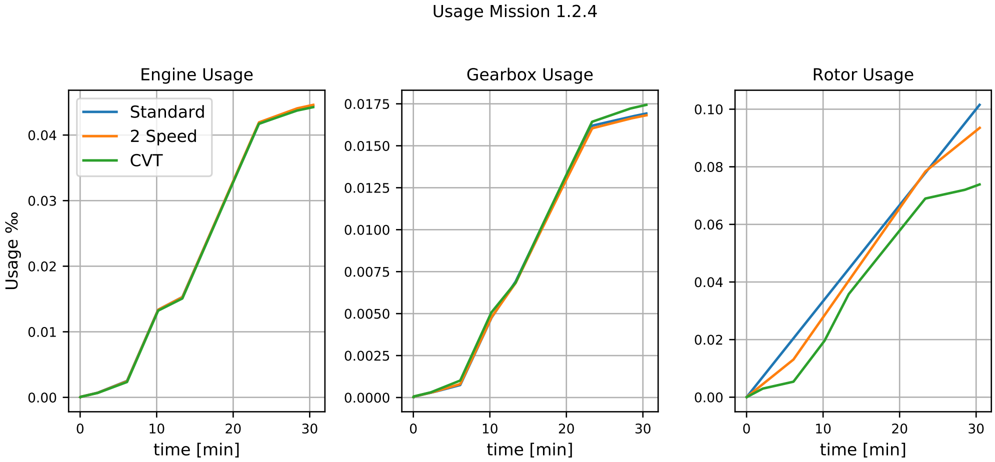
Construction and installation works
Take off at 0m without cargo. Then climbing to 50m and cruising 5km with 150km/h. Descending to 0m and hovering while the 4000kg cargo is attached on external sling, then climbing to 50m and cruising 5km with 100km/h to construction site. Hovering in 50m while cargo is installed, then cruising back with 150km/h.



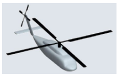


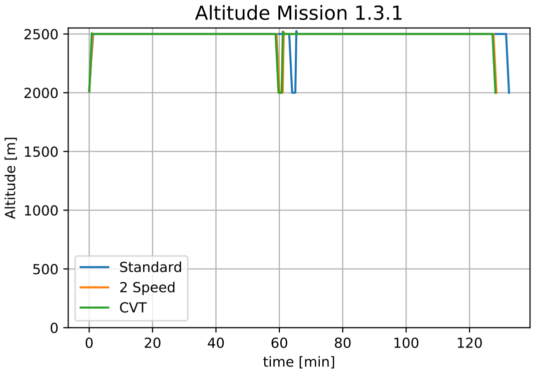






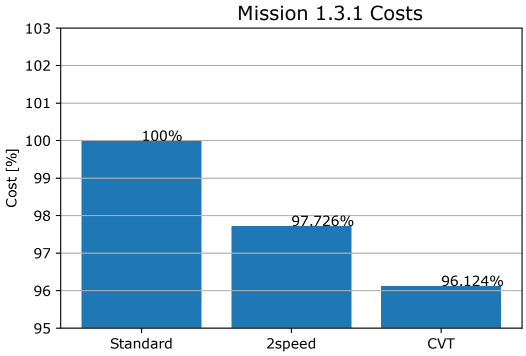
Oil industry Mission 1.3.1

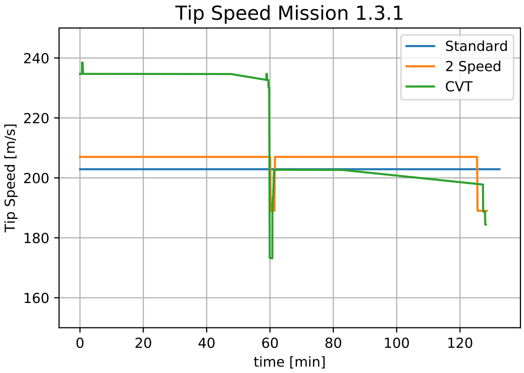


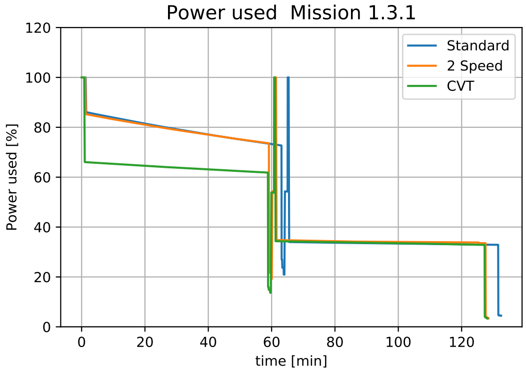


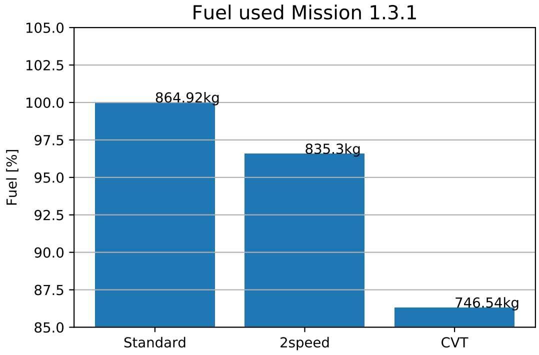
Transportation of the cargo inside the fuselage

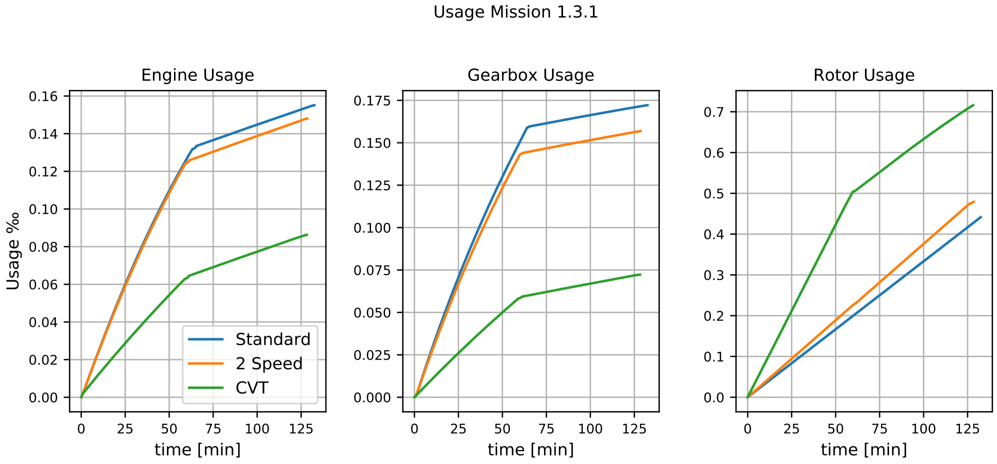
Take off at 2000m with 3000kg cargo. Then climbing to 2500m and cruising 200km with optimum speed. Descending to 2000m and unloading with short hover, then climbing again at 2500m and cruising back with optimum speed.



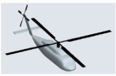




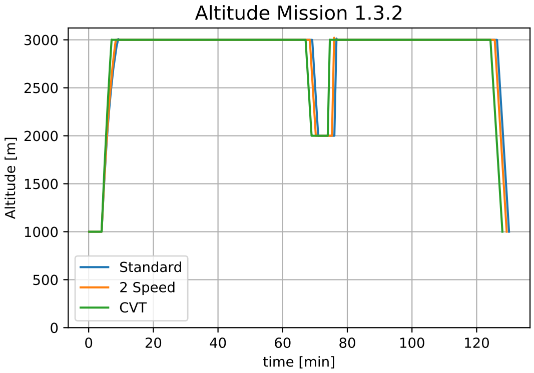


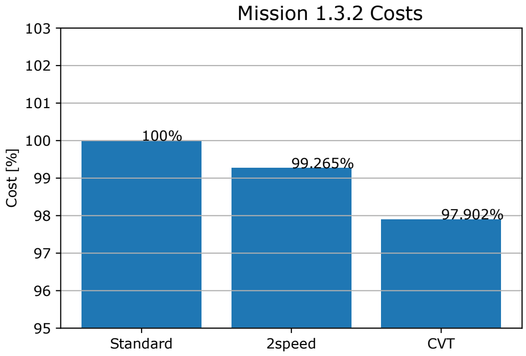


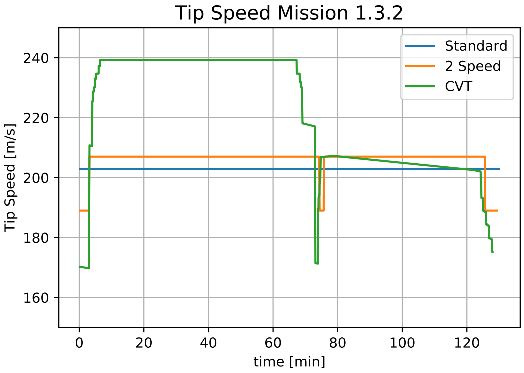
Oil industry Mission 1.3.2

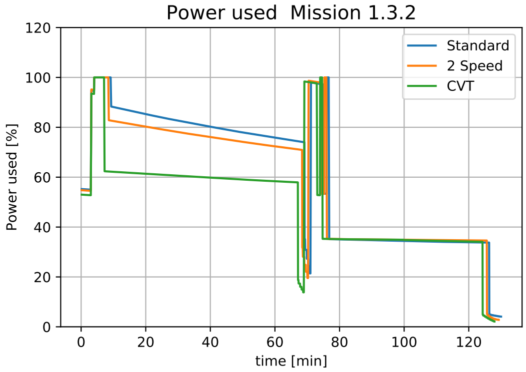


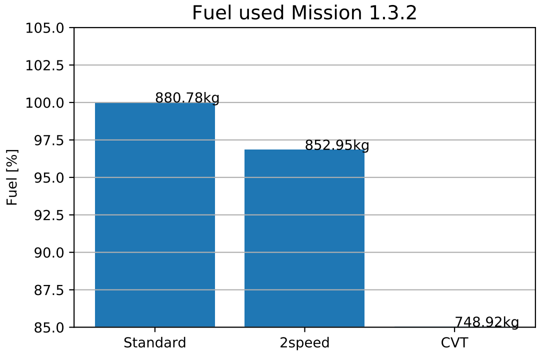
Transportation of the cargo on external sling
Take off at 1000m and hovering near to ground to attach the 2500kg cargo. Then climbing to 3000m and cruising 150km with 150km/h. Descending to 2500m and deattach cargo while hovering, then climbing again at 3000m and cruising back with optimum speed.

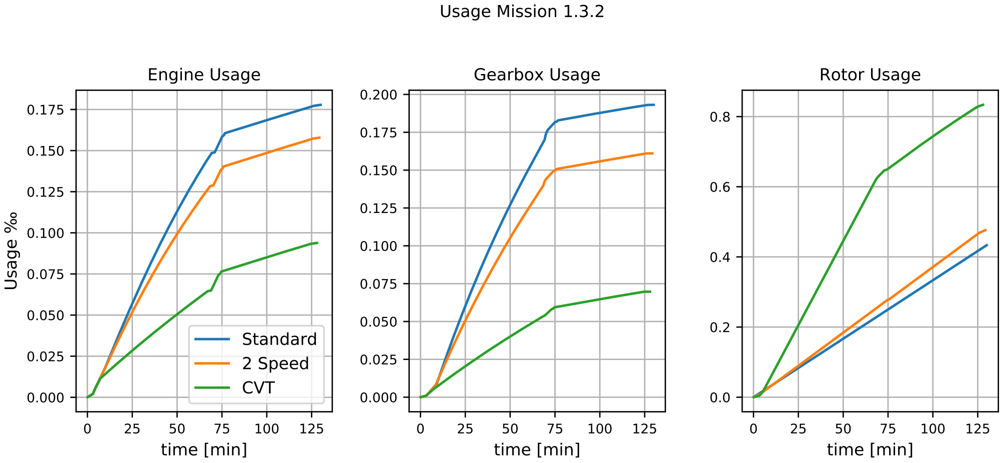




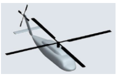


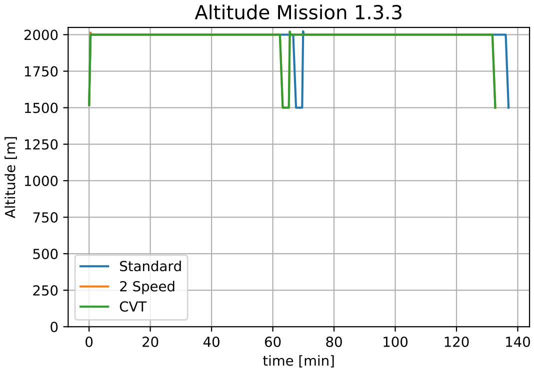




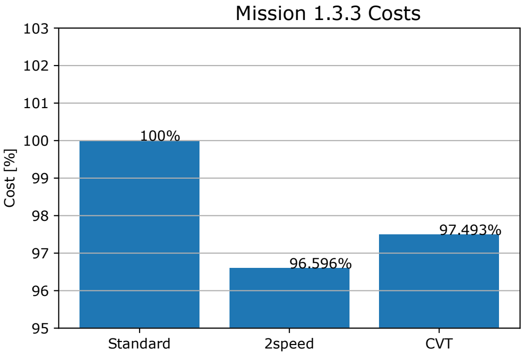


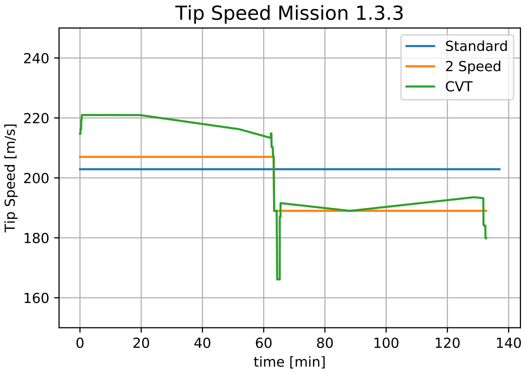
Oil industry Mission 1.3.3

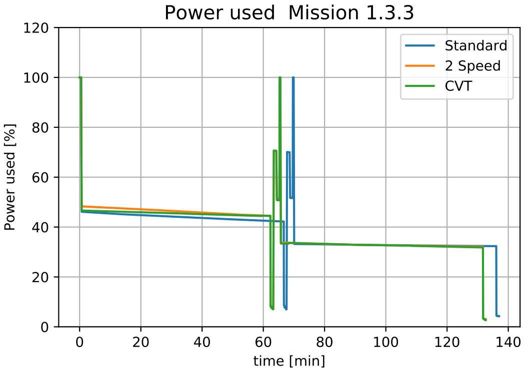


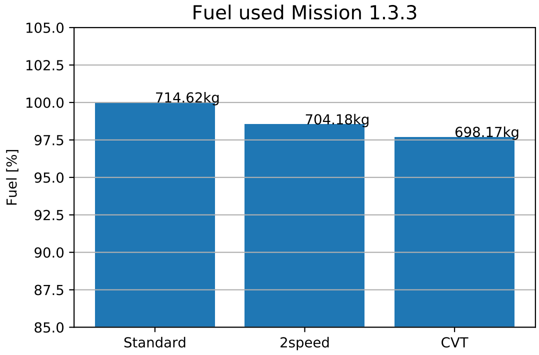


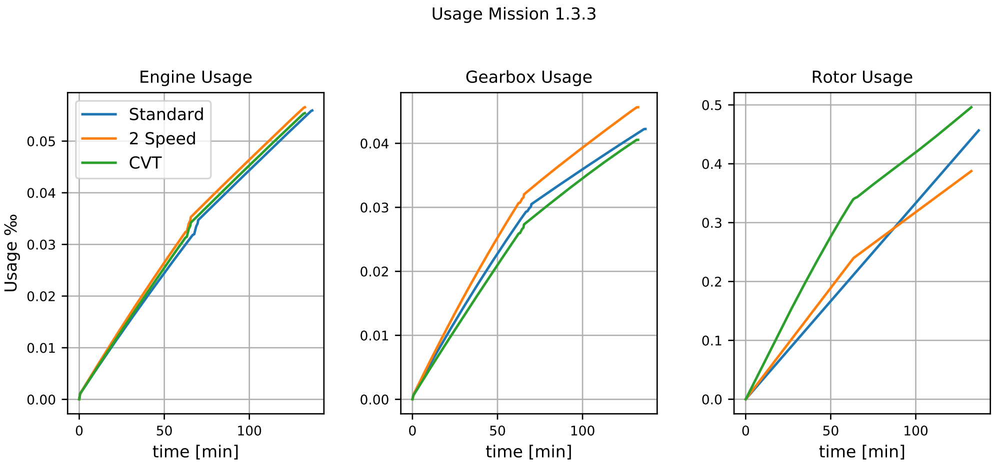
Passenger transportation
Take off at 1500m with 11Pax, 135kg each. Then climbing to 2000m and cruising 200km with optimum speed. Descending to 1500m and unloading with short hover, then climbing again at 2000m and cruising back with optimum speed.



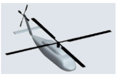






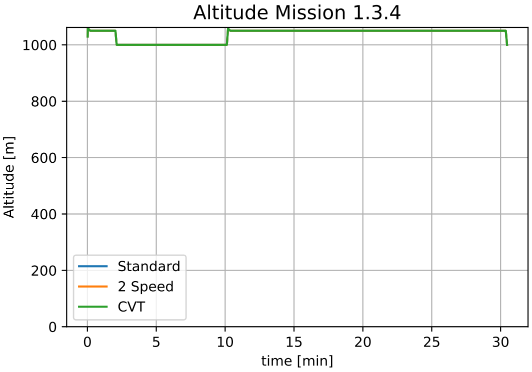


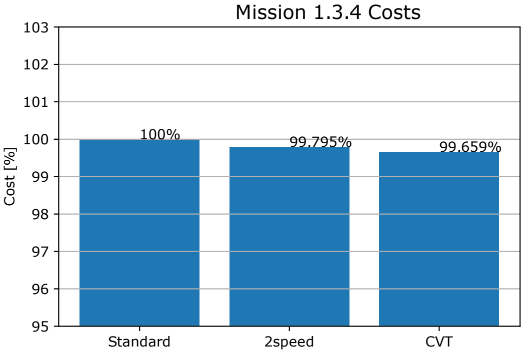
Oil industry Mission 1.3.4

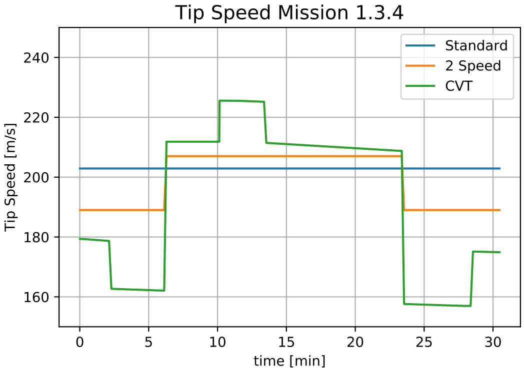


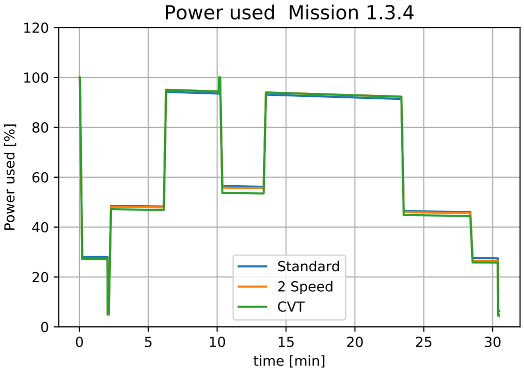
Construction and installation works

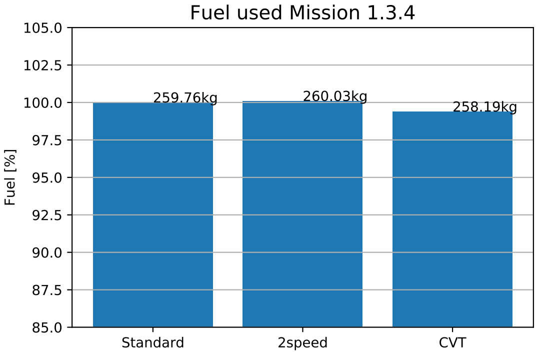
Take off at 1000m without cargo. Then climbing to 1050m and cruising 5km with 150km/h. Descending to 1000m and hovering while the 3500kg cargo is attached on external sling, then climbing to 1050m and cruising 5km with 100km/h to construction site. Hovering in 1050m while cargo is installed, then cruising back with 150km/h.

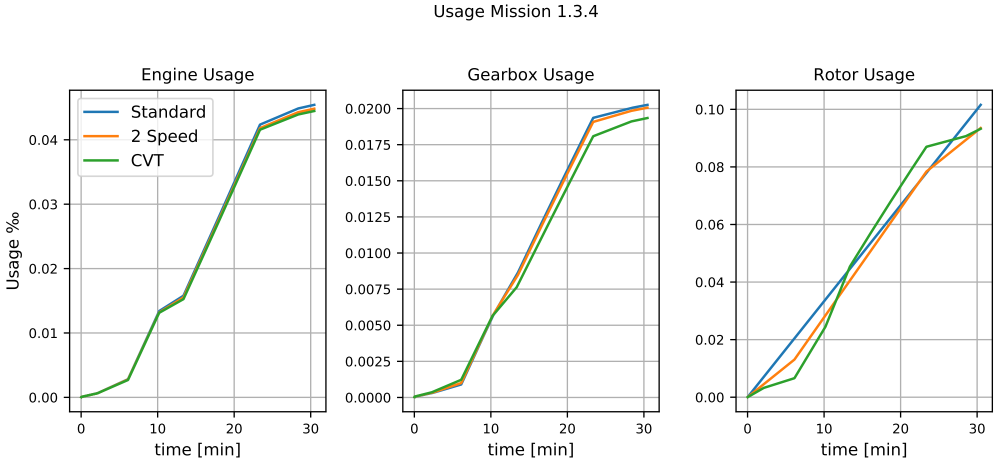




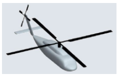






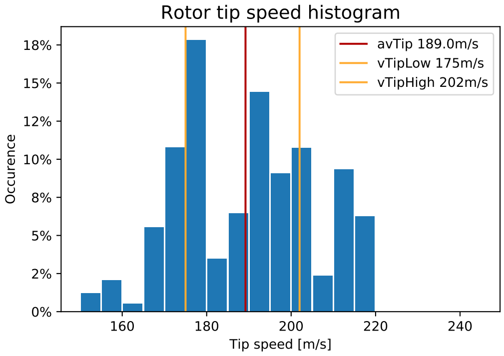


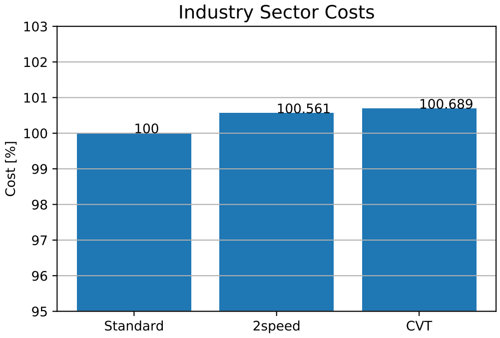
4.4 Construction



The construction industry is separated into two catagories.
5.1 Construction-and-installation works on installation and deinstallation of construction elements
5.2 Railway electrification

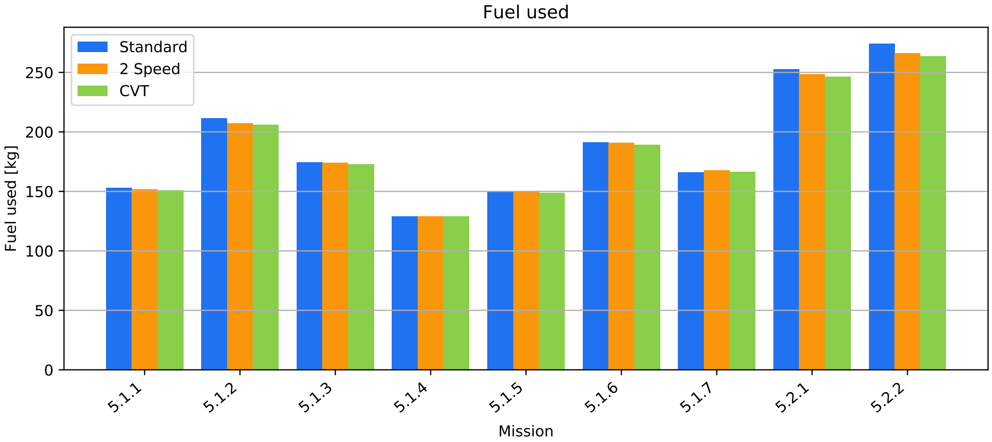
Flown Missions		
Name	Type	WF
Mission 5.1.1	Antenna tower inst.	1
Mission 5.1.2	Construction works	1
Mission 5.1.3	Bridge construction	1
Mission 5.1.4	Cableway constr.	1
Mission 5.1.5	Powerplant constr.	1
Mission 5.1.6	Installation works	1
Mission 5.1.7	Installation works	1
Mission 5.2.1	Transmission Tower	1
Mission 5.2.2	Transmission Tower	1



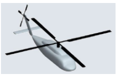


Helicopter Data			
Helicopter Type: UH-60A			
	standard	2 speed	CVT
max. tip speed [m/s]	189	202	216
min. tip speed [m/s]	-	175	152
Spread	-	1.15	1.42
*Climb-rate [m/s]	6.59	9.38	11.48
**Service Ceiling [m]	1904	2909	4672
Gearbox Weight [kg]	-	+65	+65

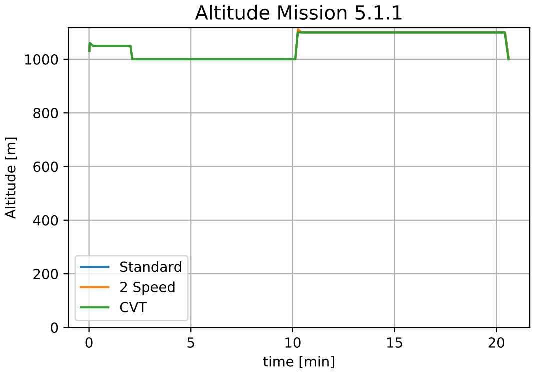
*at 1000m with MTOW
**with MTOW

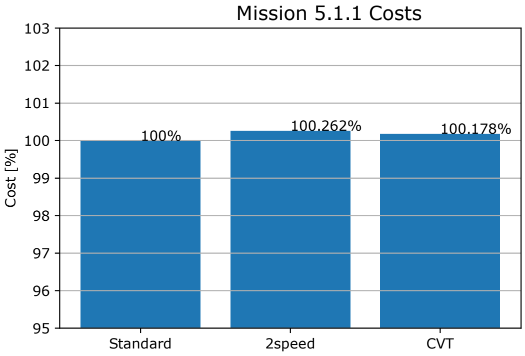


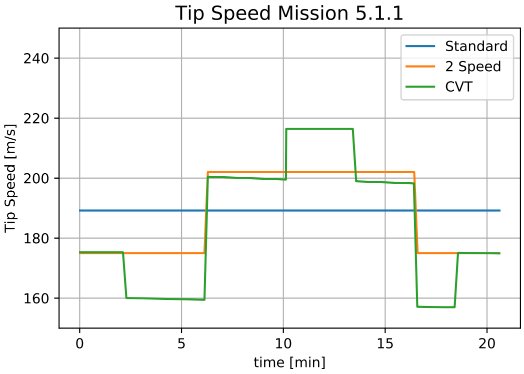
Construction Mission 5.1.1

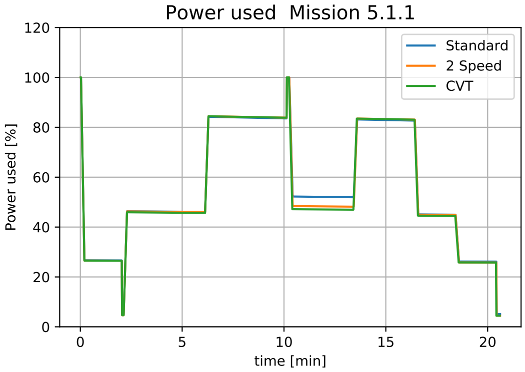


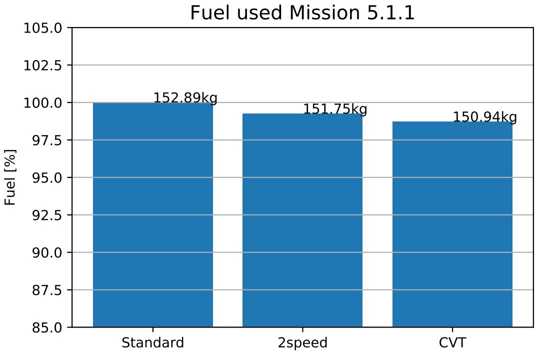
Installation-and-deinstallation of antenna tower structures
Take off at 1000m without cargo. Then climbing to 1050m and cruising 5km with 150km/h. Descending to 1000m and hovering while the 3000kg cargo is attached on external sling, then climbing to 1100m and cruising 5km with 100km/h to construction site. Hovering in 1100m while cargo is installed, then cruising back with 150km/h.

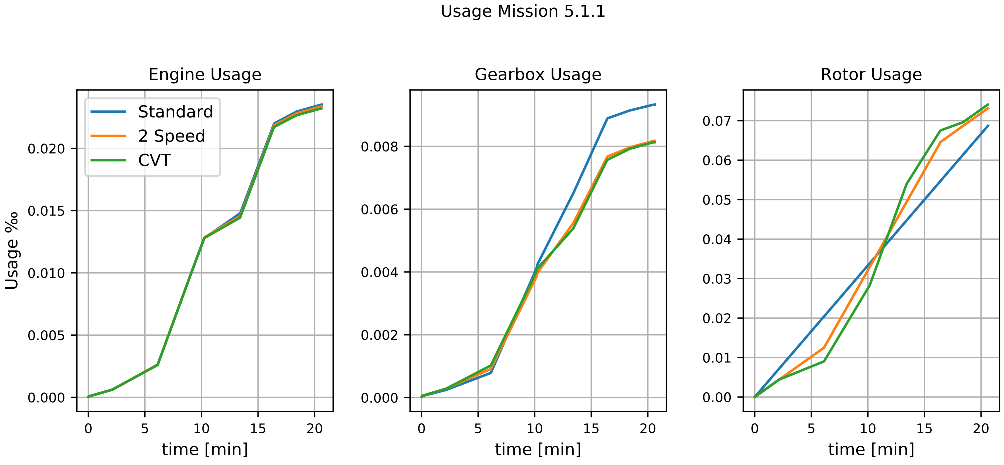




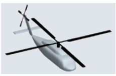




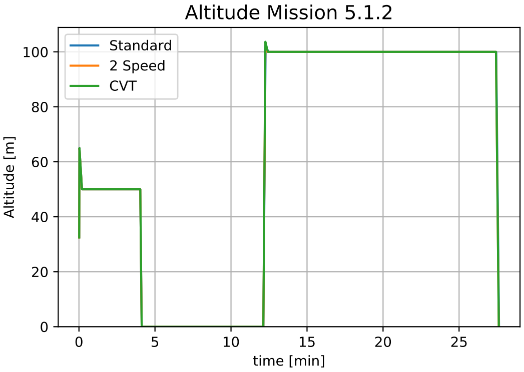


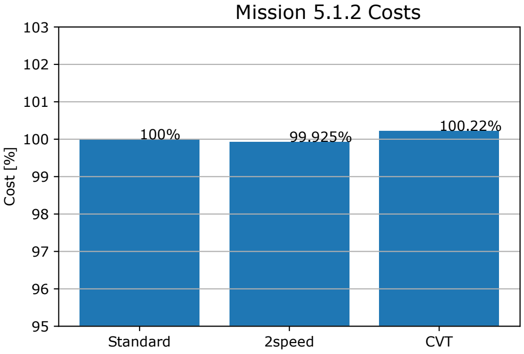


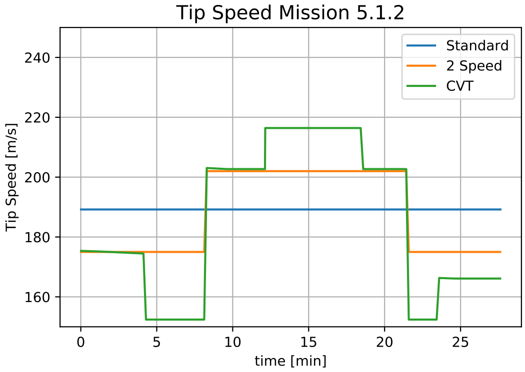
Construction Mission 5.1.2

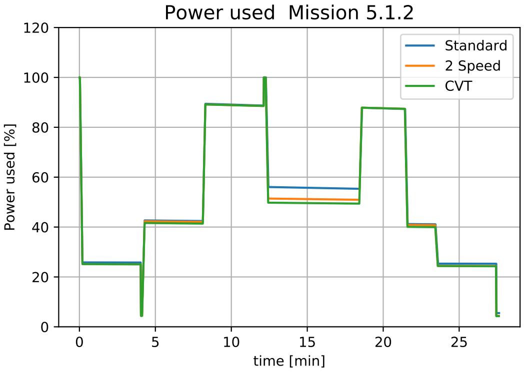


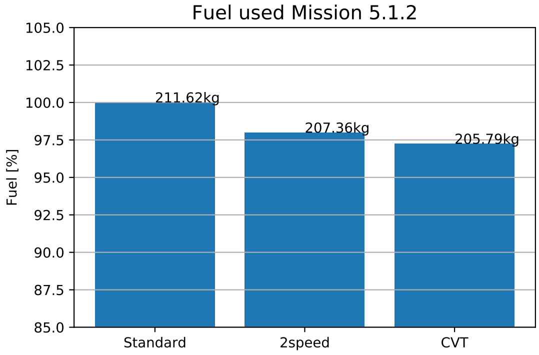
Construction of industrial facilities and installation of equipment
Take off at 0m without cargo. Then climbing to 50m and cruising 10km with 150km/h. Descending to 0m and hovering while the 4000kg cargo is attached on external sling, then climbing to 100m and cruising 10km with 100km/h to construction site. Hovering in 100m while cargo is installed, then cruising back with 150km/h.

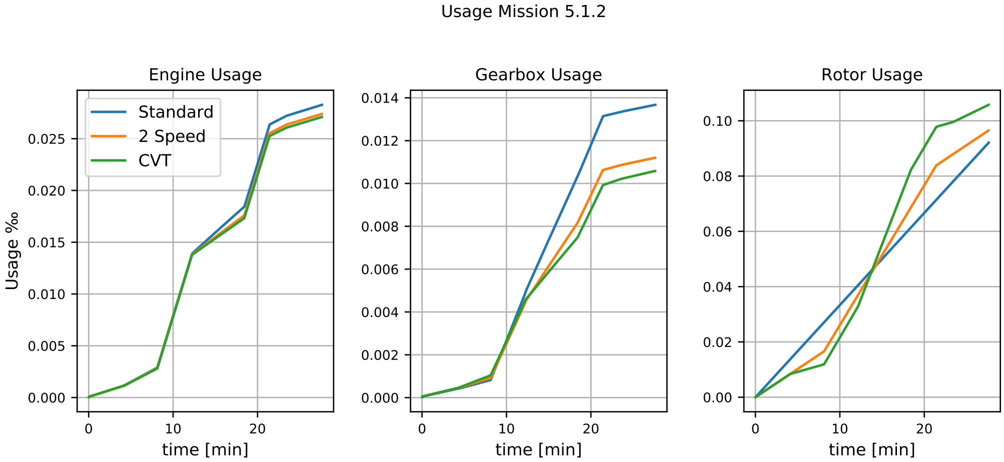




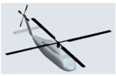




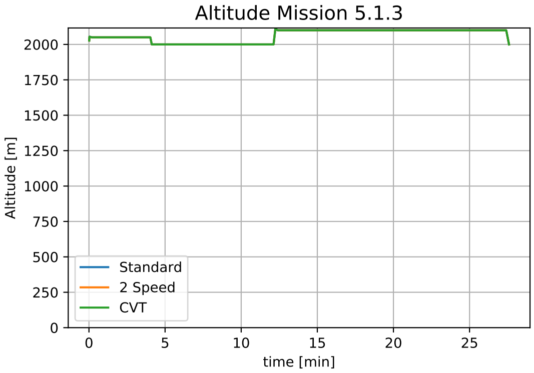


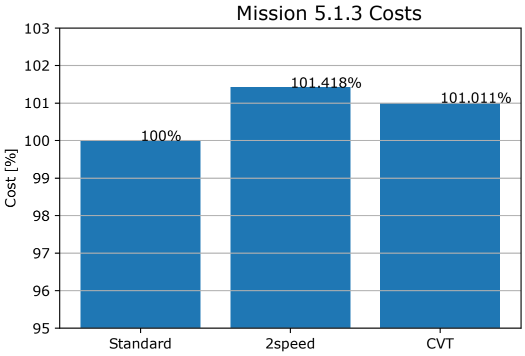


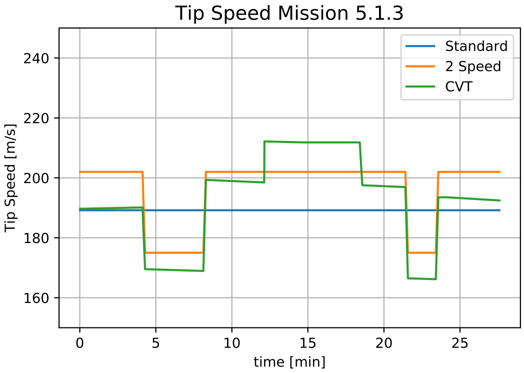
Construction Mission 5.1.3

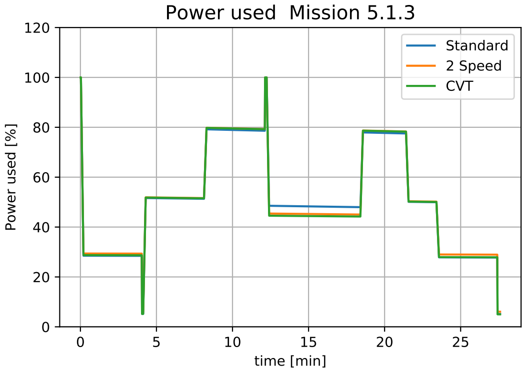


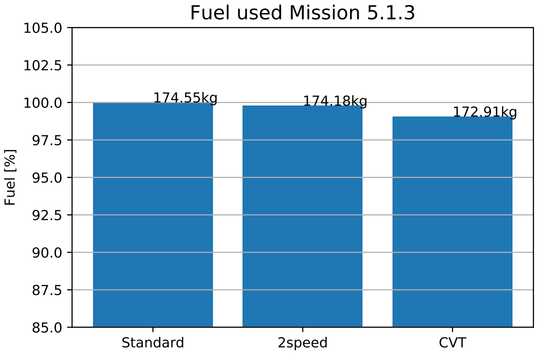
Bridge construction
Take off at 2000m without cargo. Then climbing to 2050m and cruising 10km with 150km/h. Descending to 2000m and hovering while the 2000kg cargo is attached on external sling, then climbing to 2100m and cruising 10km with 100km/h to construction site. Hovering in 1100m while cargo is installed, then cruising back with 150km/h.

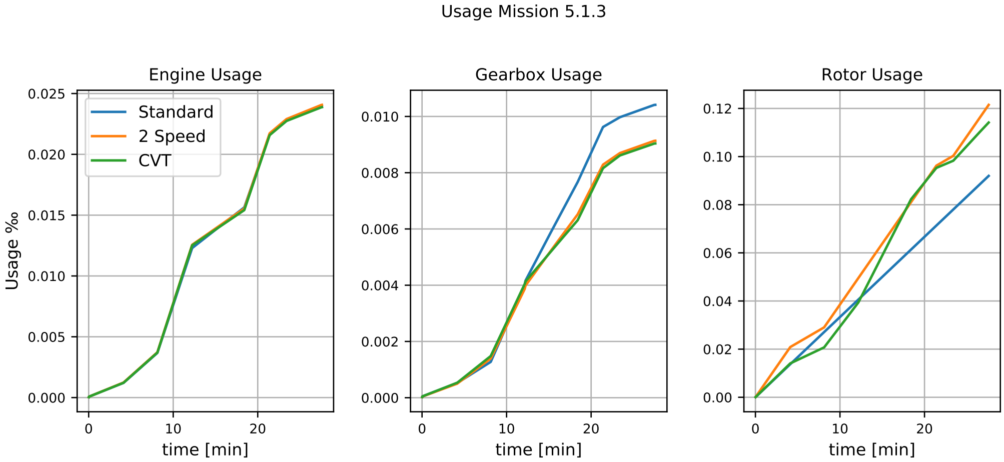




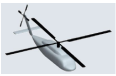






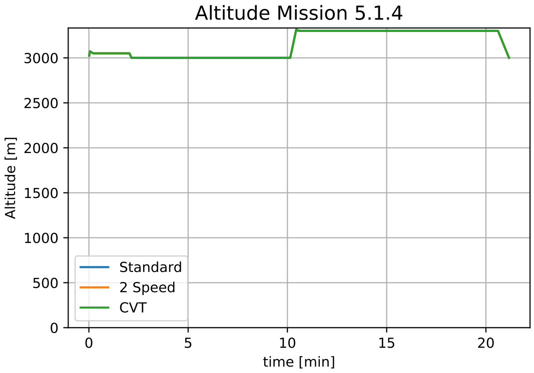


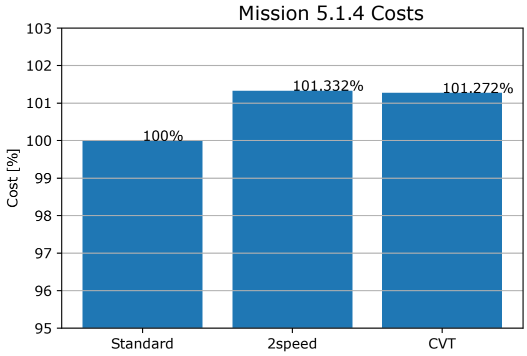
Construction Mission 5.1.4

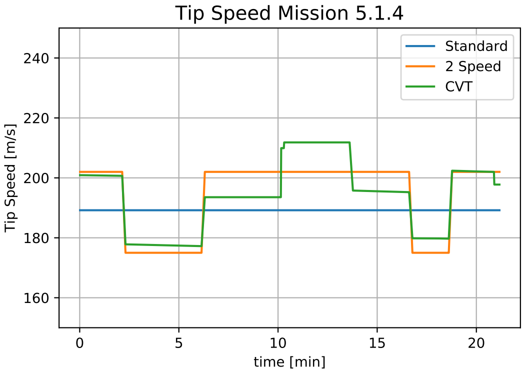


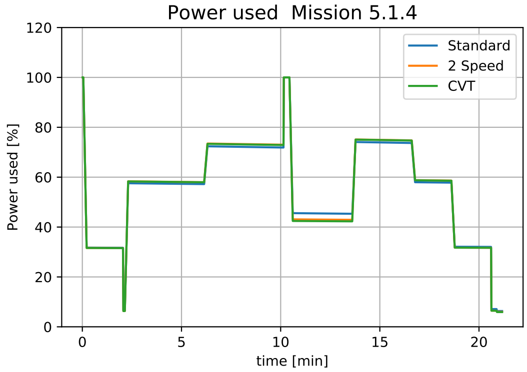
Construction of aerial cableways

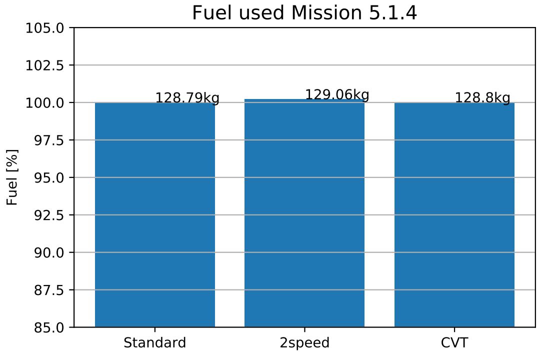
Take off at 3000m without cargo. Then climbing to 3050m and cruising 5km with 150km/h. Descending to 3000m and hovering while the 1000kg cargo is attached on external sling, then climbing to 3300m and cruising 5km with 100km/h to construction site. Hovering in 3300m while cargo is installed, then cruising back with 150km/h.

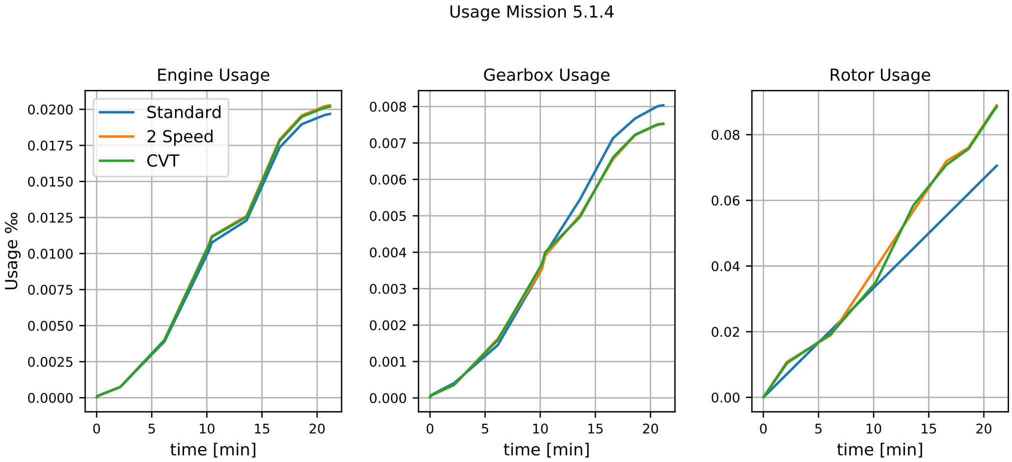




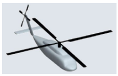




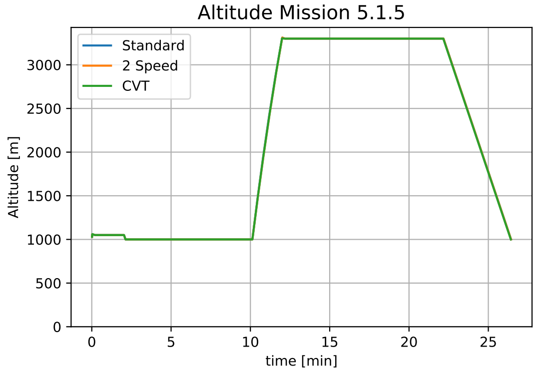


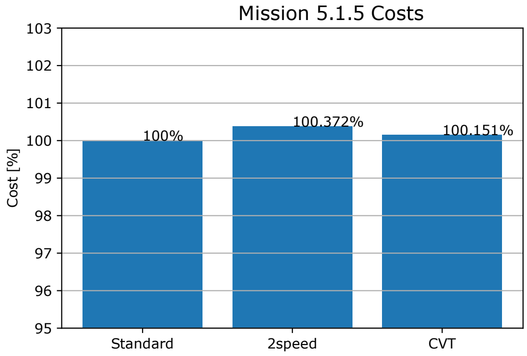


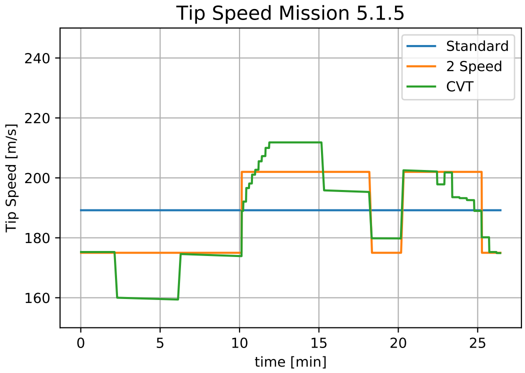
Construction Mission 5.1.5

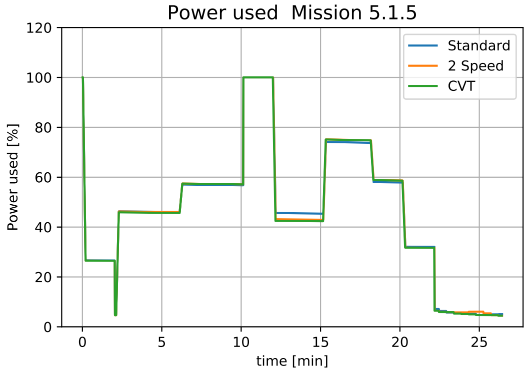


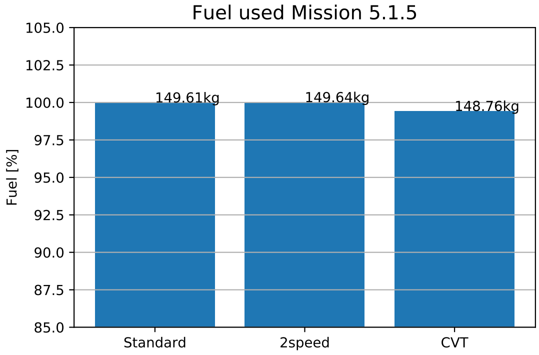
Construction of hydroelectric powerplants in the mountains
Take off at 1000m without cargo. Then climbing to 1050m and cruising 5km with 150km/h. Descending to 1000m and hovering while the 1000kg cargo is attached on external sling, then climbing to 3300m and cruising 5km with 100km/h to construction site. Hovering in 1100m while cargo is installed, then cruising back with 150km/h.

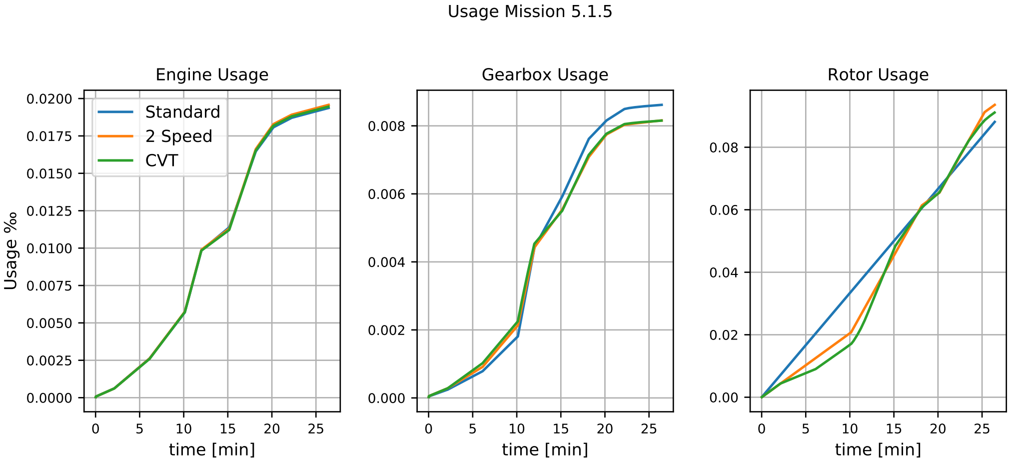






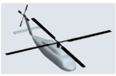






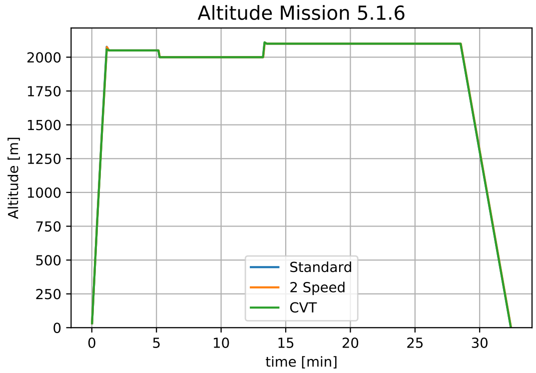
Construction

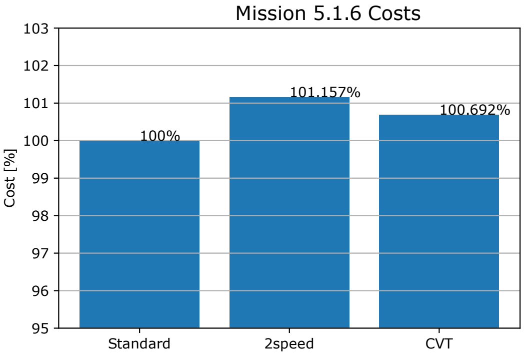
Mission 5.1.6

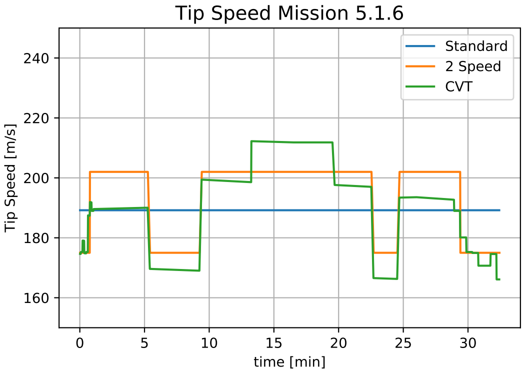


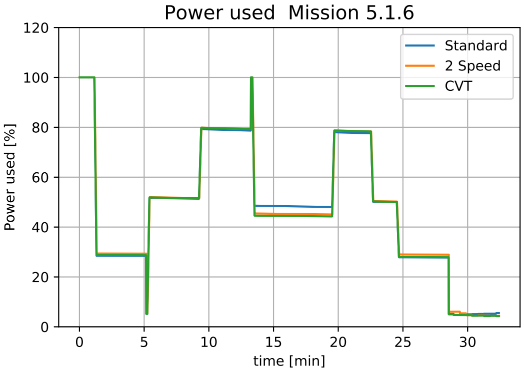
Installation of unique (non-standard) structures and equipment

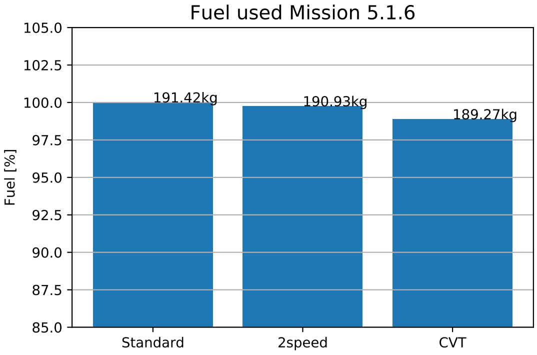
Take off at 0m without cargo. Then climbing to 2050m and cruising 10km with 150km/h. Descending to 2000m and hovering while the 2000kg cargo is attached on external sling, then climbing to 2100m and cruising 10km with 100km/h to construction site. Hovering in 2100m while cargo is installed, then cruising back with 150km/h.

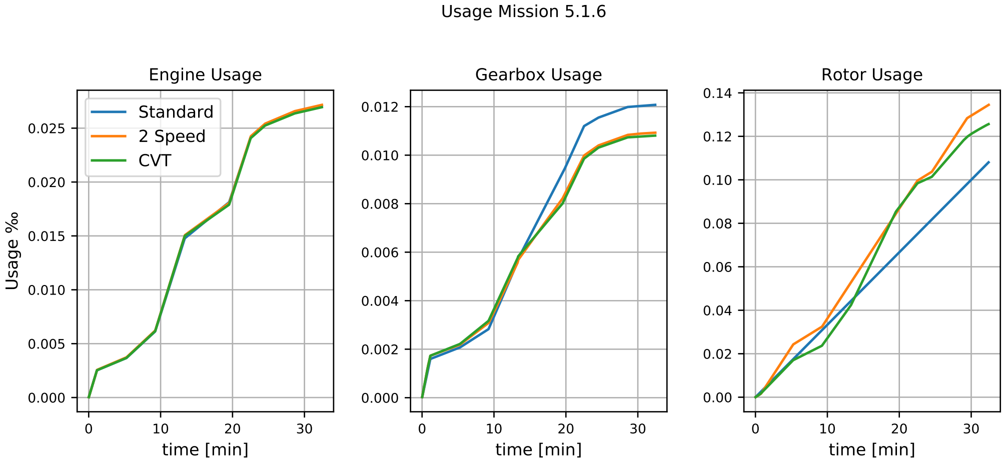




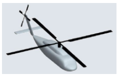




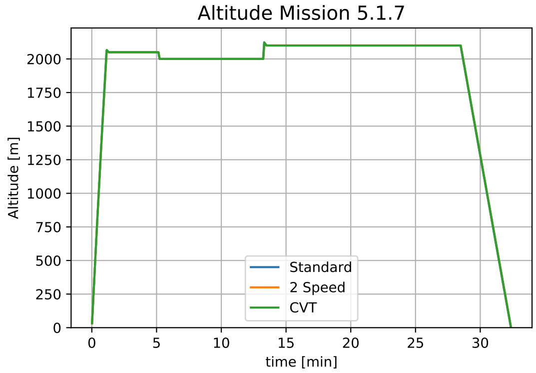


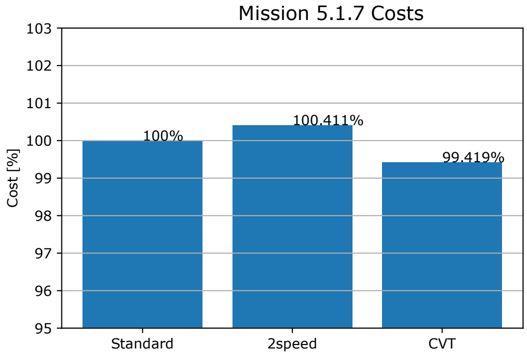


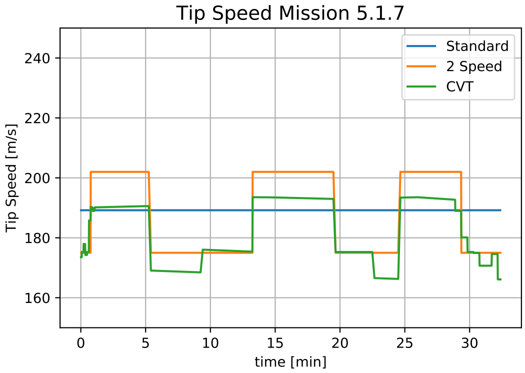
Construction Mission 5.1.7

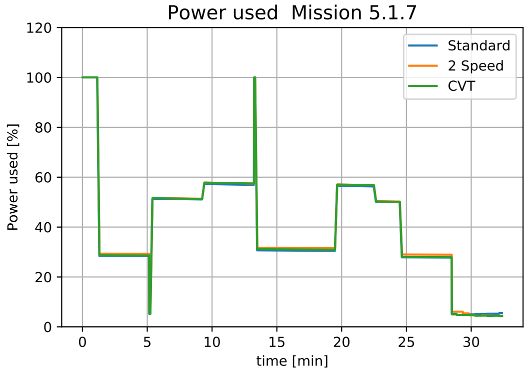


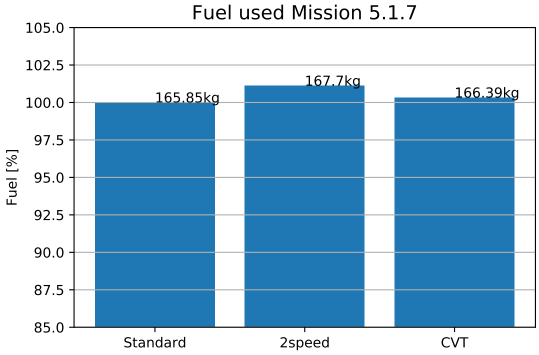
Installation of the hangar roof elements
Take off at 0m without cargo. Then climbing to 2050m and cruising 10km with 150km/h. Descending to 2000m and hovering while the 500kg cargo is attached on external sling, then climbing to 2100m and cruising 10km with 100km/h to construction site. Hovering in 2100m while cargo is installed, then cruising back with 150km/h.

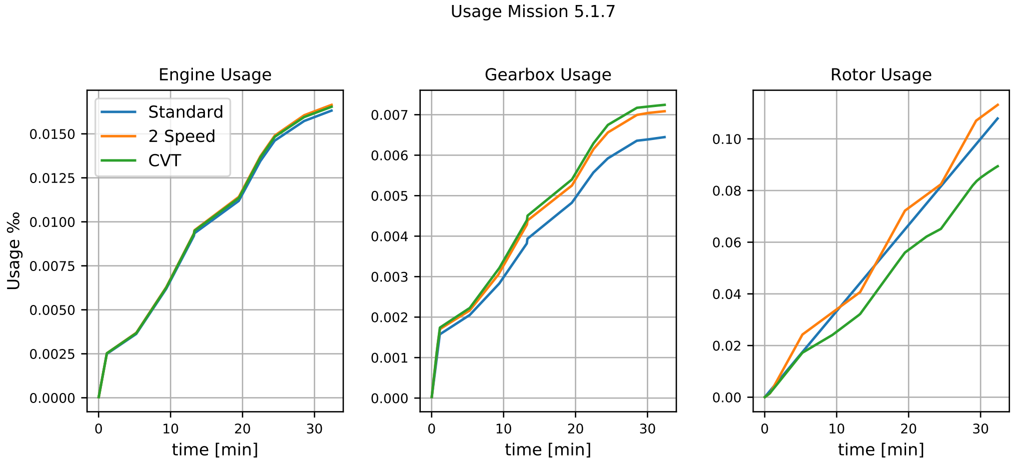






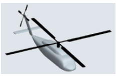






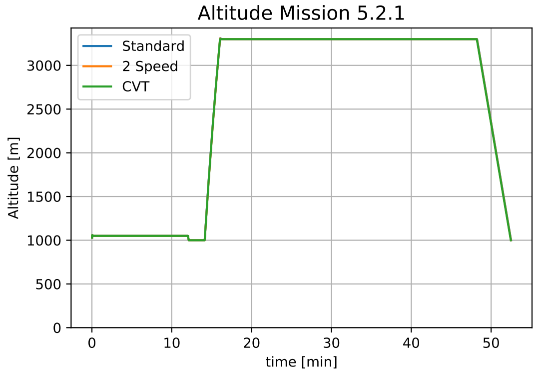
Construction

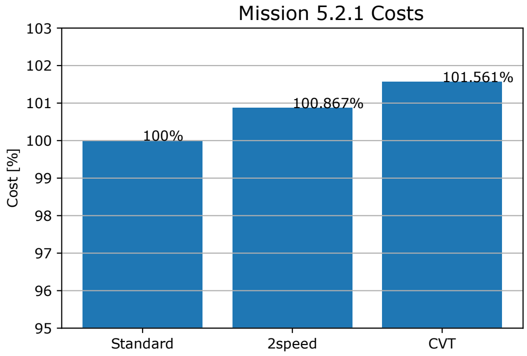
Mission 5.2.1

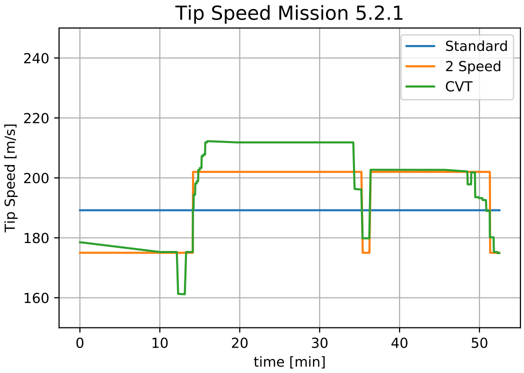


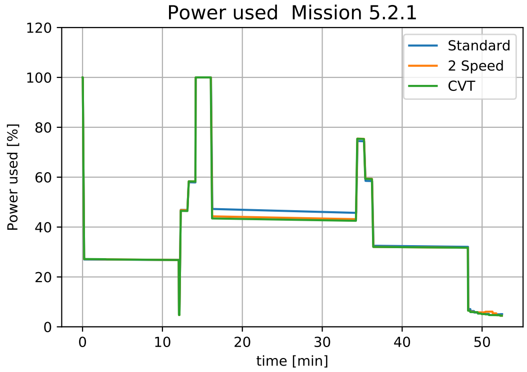
Transportation of transmission tower footings on external sling and their installation

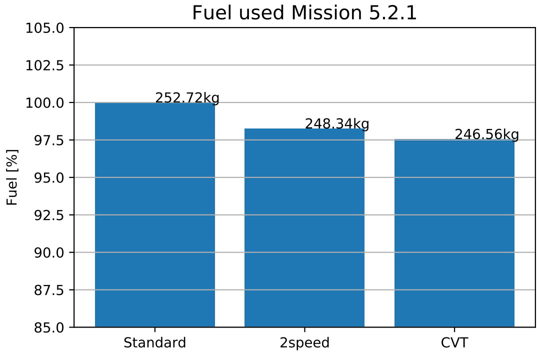
Take off at 1000m without cargo. Then climbing to 1050m and cruising 30km with 150km/h. Descending to 1000m and hovering while the 1000kg cargo is attached on external sling, then climbing to 3300m and cruising 30km with 100km/h to construction site. Hovering in 3300m while cargo is installed, then cruising back with 150km/h.

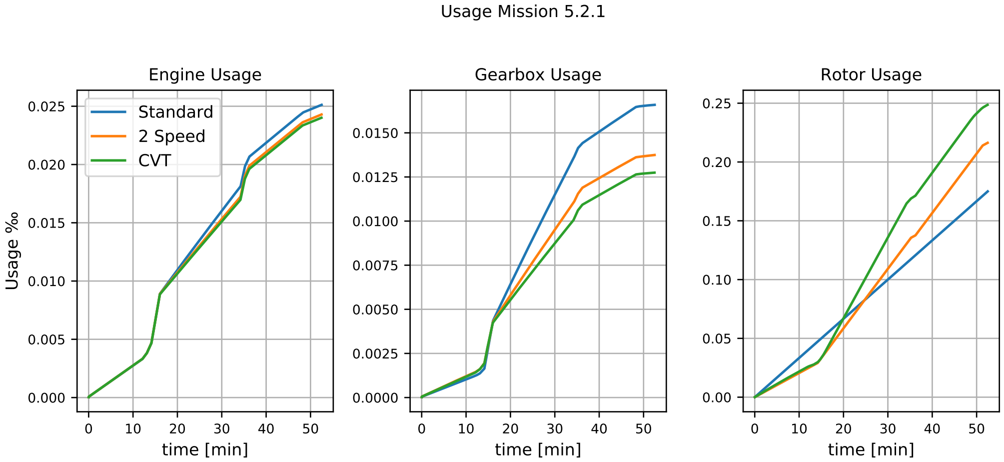






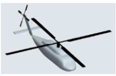




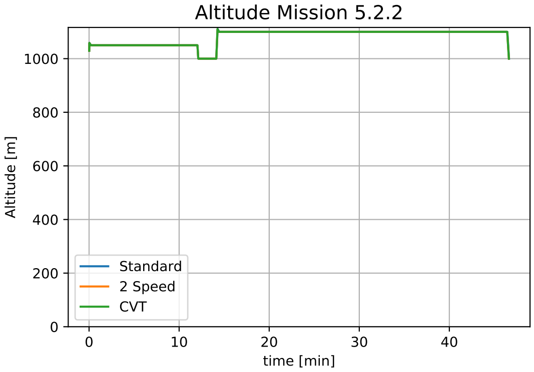


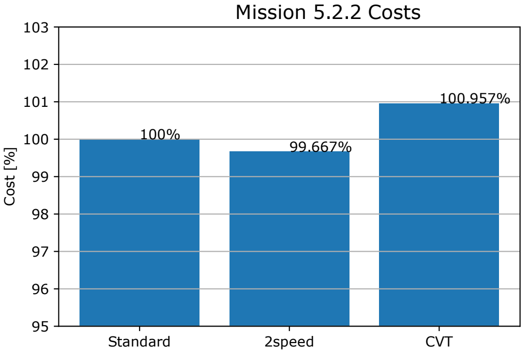
Construction

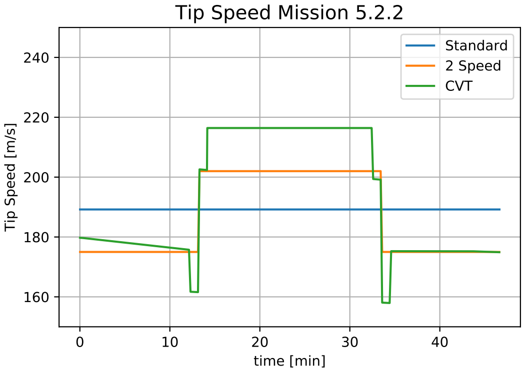
Mission 5.2.2

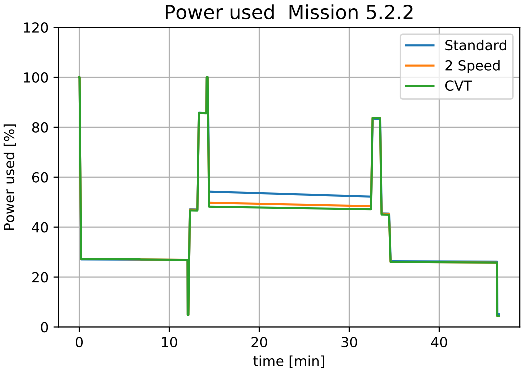


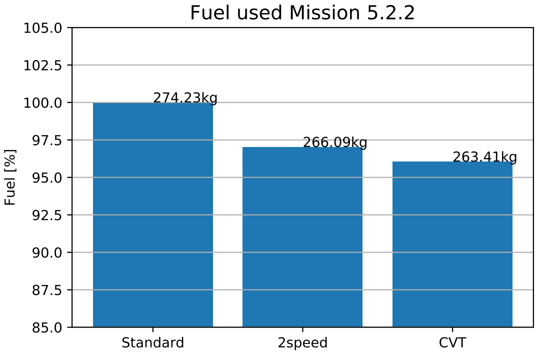
Transportation of transmission towers on external sling and their installation Take off at 1000m without cargo. Then climbing to 1050m and cruising 30km with 150km/h. Descending to 1000m and hovering while the 3000kg cargo is attached on external sling, then climbing to 1100m and cruising 30km with 100km/h to construction site. Hovering in 1100m while cargo is installed, then cruising back with 150km/h.

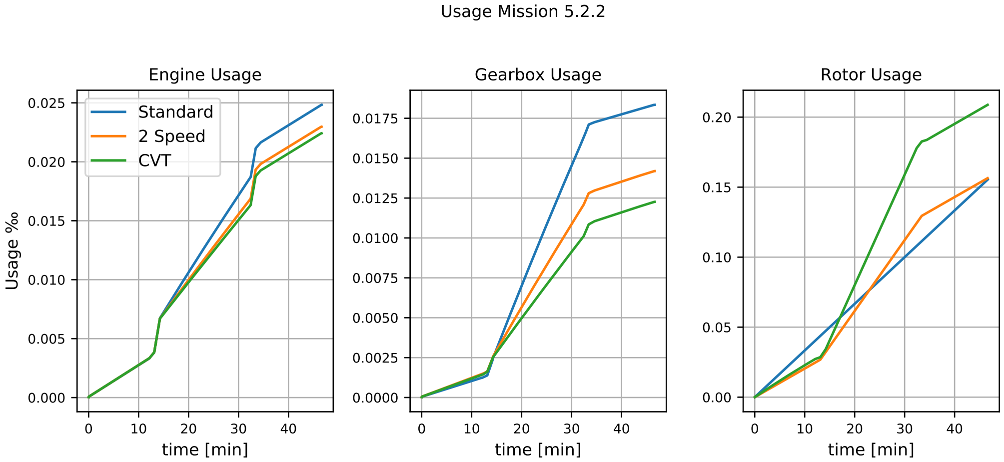




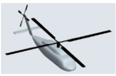








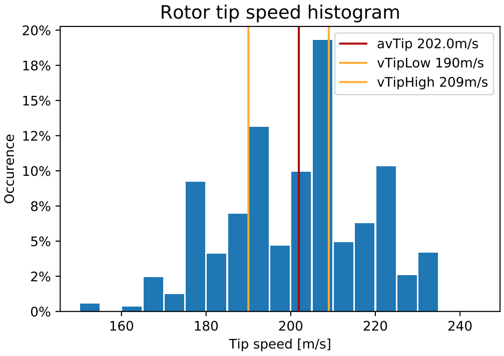
4.5 Search and Rescue

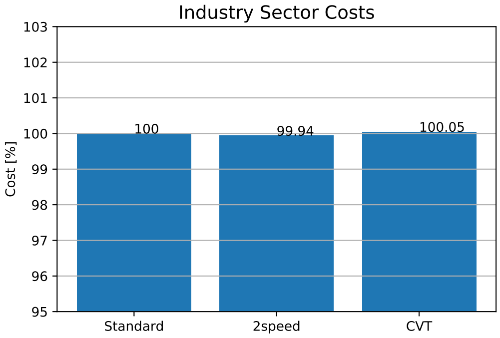


The SAR industry is separated into four catagories.
7.1 Search and evacuation of victims in natural disasters, incidents and accidents of the aerial vehicles and sea vessels
7.2 Transportation of emergency rescue team
7.3 Cargo transportation
7.4 Monitoring of the areas of natural disasters and catastrophes

Flown Missions

Name	Type	WF
Mission 7.1.1	Evacuation w. landing	1
Mission 7.1.2	Evacuation w. winch	1
Mission 7.2.1	Transp. of rescue team	1
Mission 7.2.2	Transp. of rescue team	1
Mission 7.2.3	Transp. of rescue team	1
Mission 7.3.1	Cargo in fuselage	1
Mission 7.3.2	Cargo in fuselage	1
Mission 7.3.3	Cargo in fuselage	1
Mission 7.3.4	Cargo in fuselage	1
Mission 7.3.5	Cargo on ext. sling	1
Mission 7.4.1	Patrolling flight	1
Mission 7.4.2.	Search for objects	1



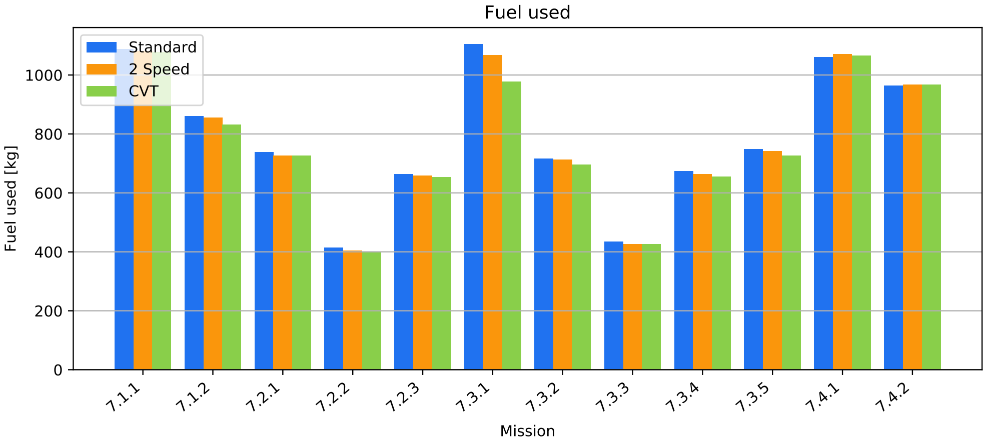


Helicopter Data

Helicopter Type: UH-60A

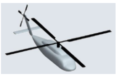
	standard	2 speed	CVT
max. tip speed [m/s]	202	209	235
min. tip speed [m/s]	-	190	152
Spread	-	1.1	1.54
*Climb-rate [m/s]	9.67	10.04	11.48
**Service Ceiling [m]	2904	3160	4672
Gearbox Weight [kg]	-	+65	+65

*at 1000m with MTOW
**with MTOW

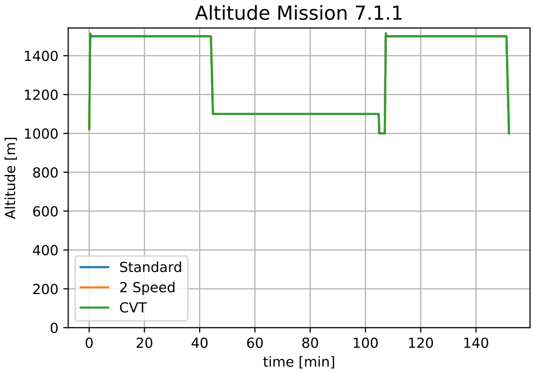


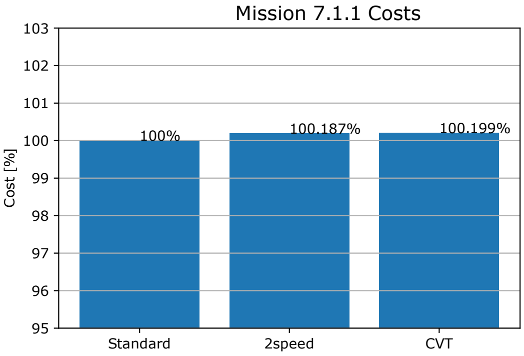
SAR

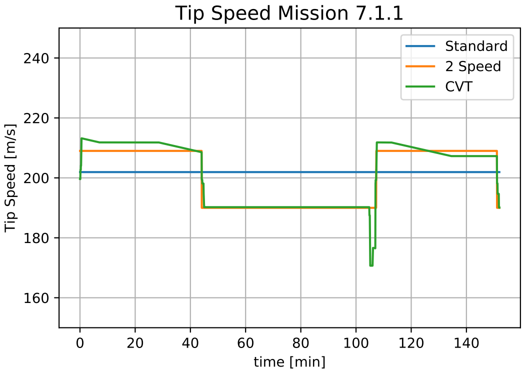
Mission 7.1.1

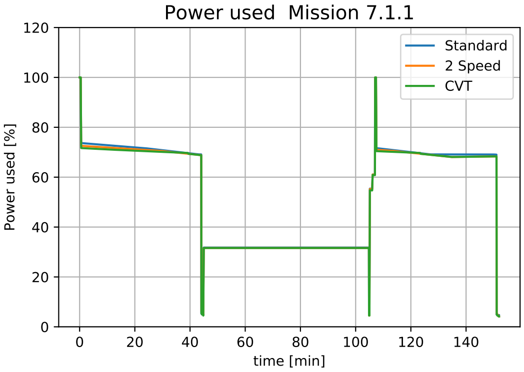


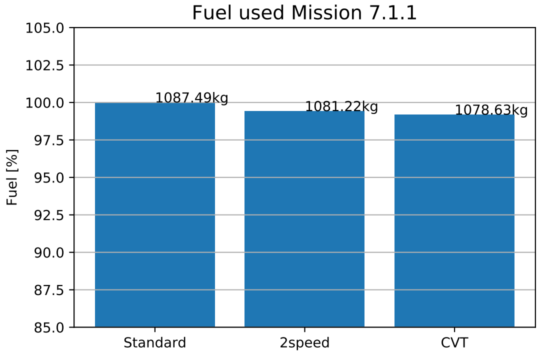
Search and evacuation of victims with landing on the earth and unloading on the earth
Take off at 1000m with 500kg equipment. Then climbing to 1500m and cruising 200km with 275km/h. Descending to 1100m and cruising 60min with 110km/h. Descending to 1000m and hovering while loading 5 PAX, 100kg each. Climbing to 1500m and cruising 200km with 275km/h to the hospital.

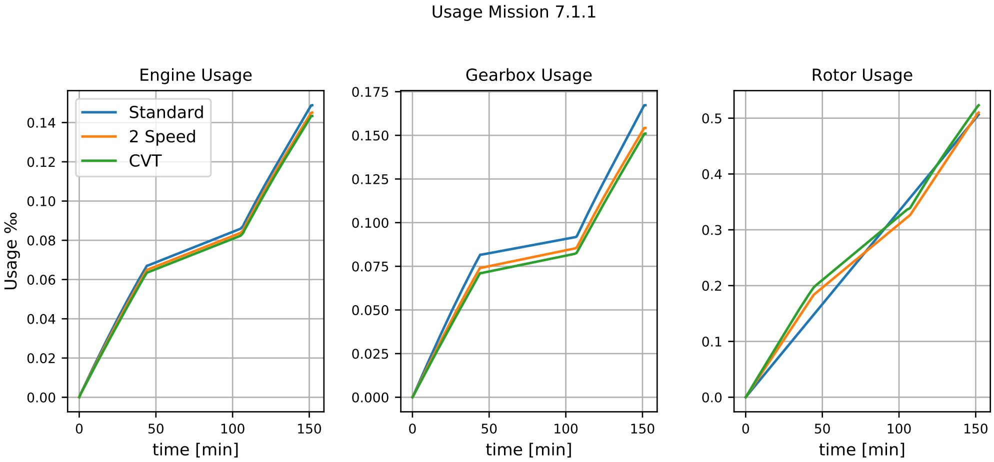






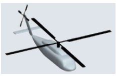




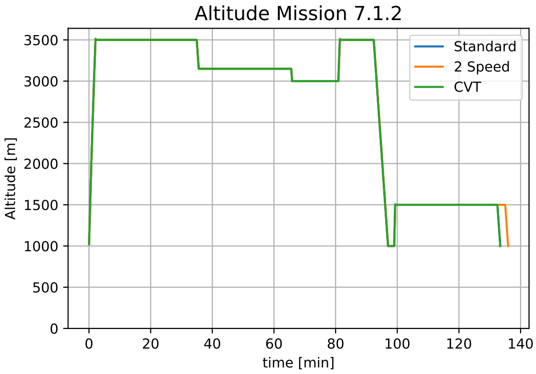


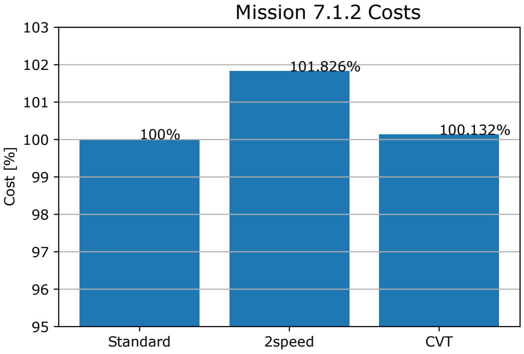
SAR

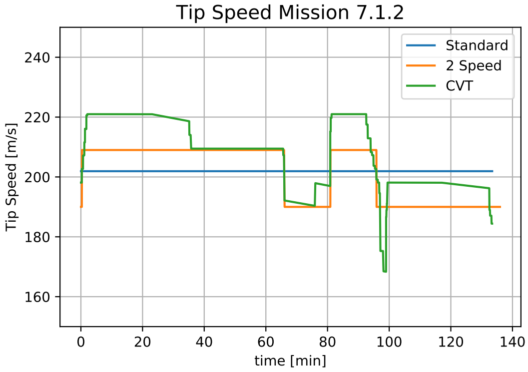
Mission 7.1.2

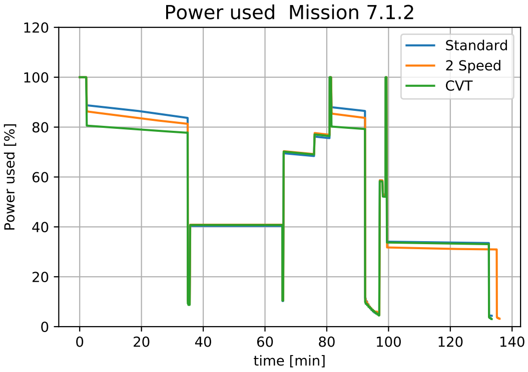


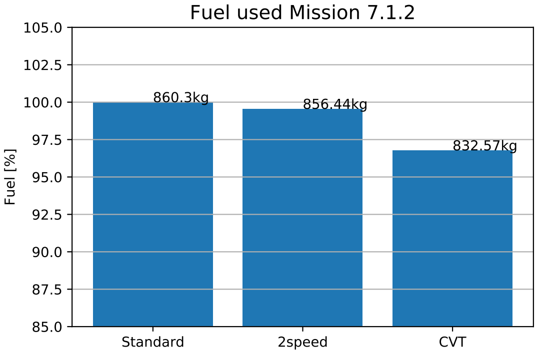
Search and evacuation of victims inside the fuselage with lifting and (or) unloading with the help of a winch
Take off at 1000m with 500kg equipment. Then climbing to 3500m and cruising 150km with 275km/h. Descending to 3150m and cruising 30min with 100km/h. Descending to 3000m and hovering while loading 5 PAX, 100kg each. Climbing to 3500m and cruising 50km with 275km/h to the hospital and descending to 1000m. Then climbing to 1500m and cruising home 100km with optimum speed.

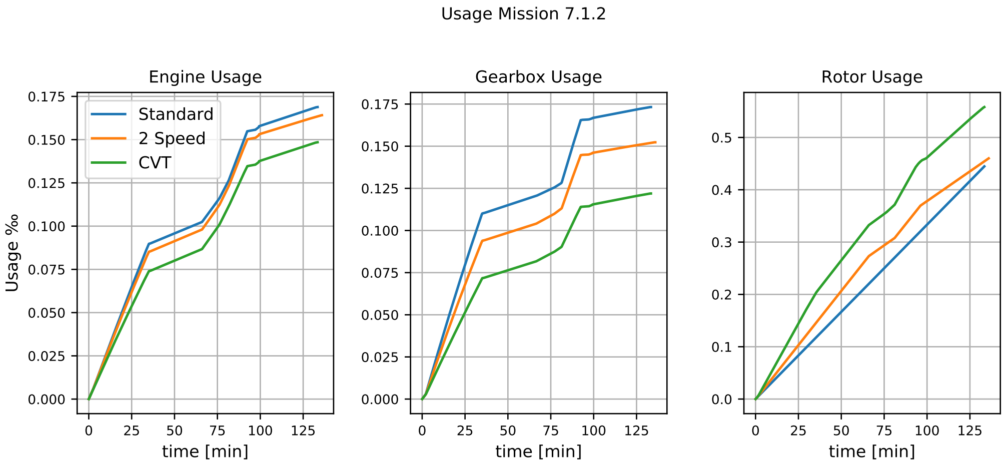






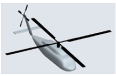




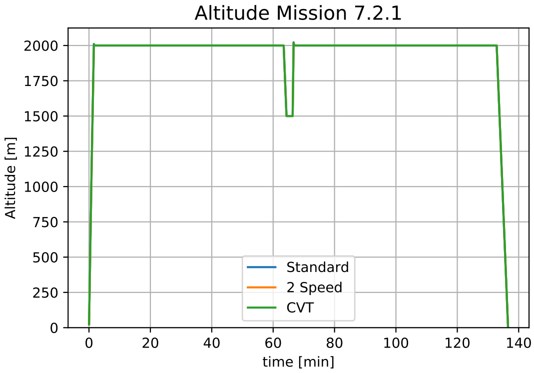


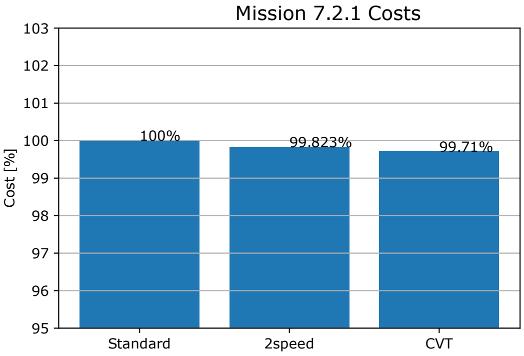
SAR

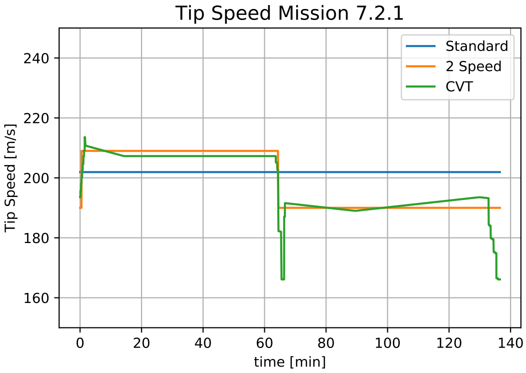
Mission 7.2.1

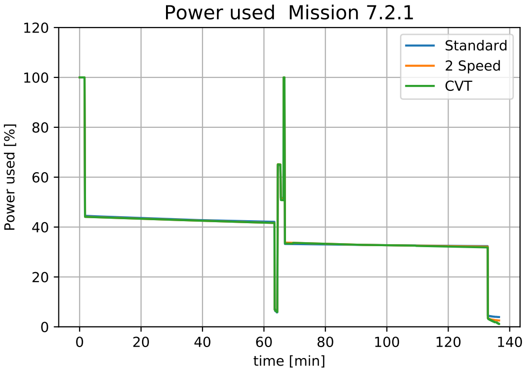


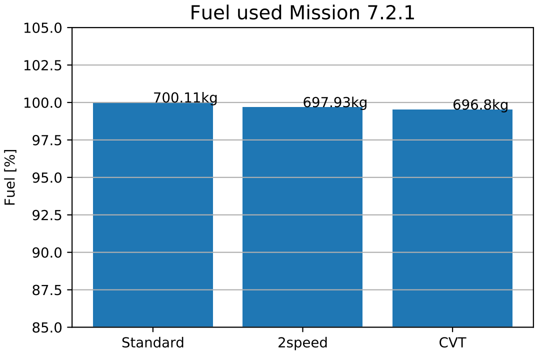
Transportation of emergency rescue team with landing on the earth and unloading on the earth
Take off at 0m 11 PAX, 100kg each. Then climbing to 2000m and cruising 200km with optimum speed. Descending to 1500m and hovering while 11 PAX are unloaded, then climbing to 2000m and cruising back with optimum speed.

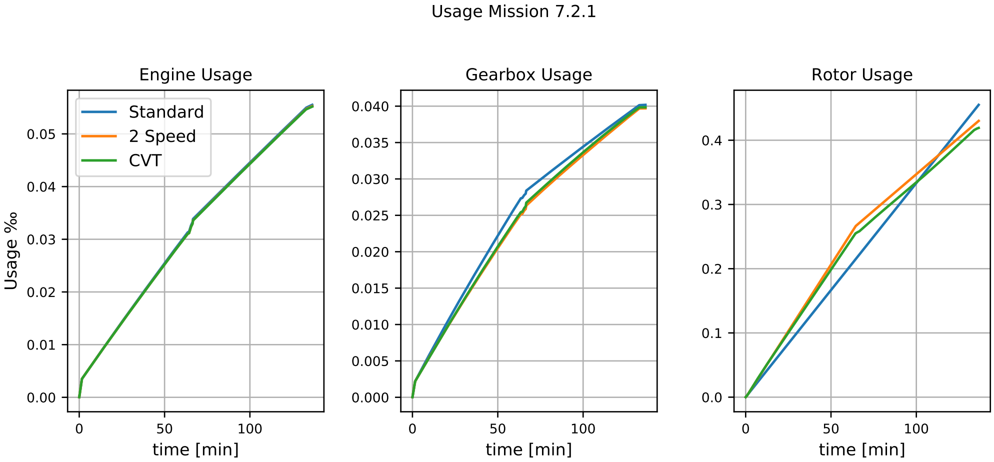












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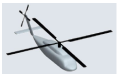
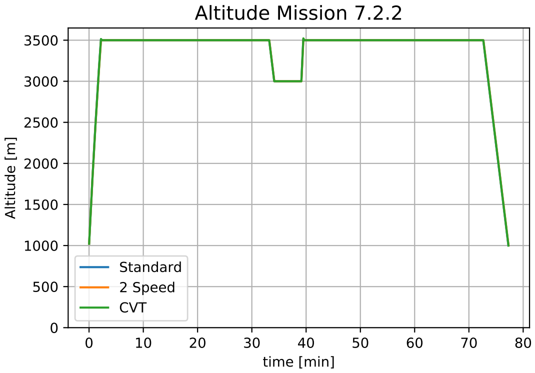
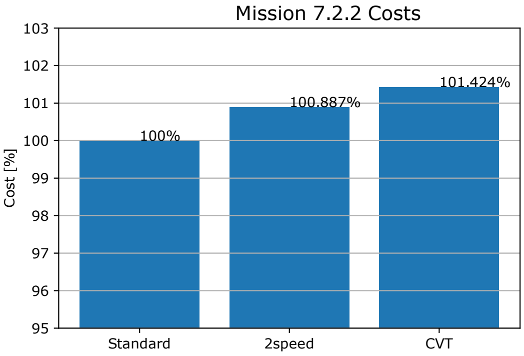
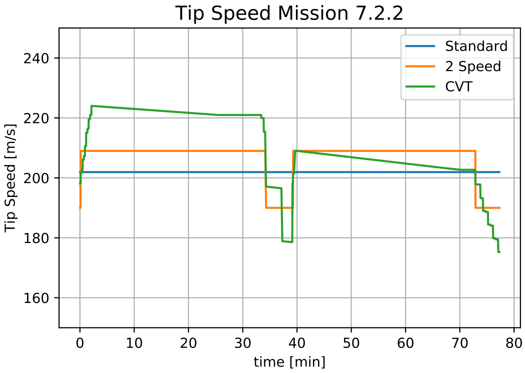
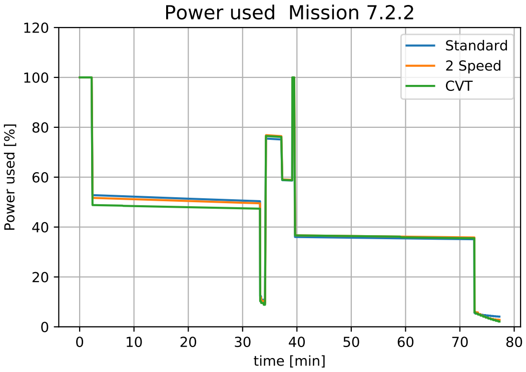


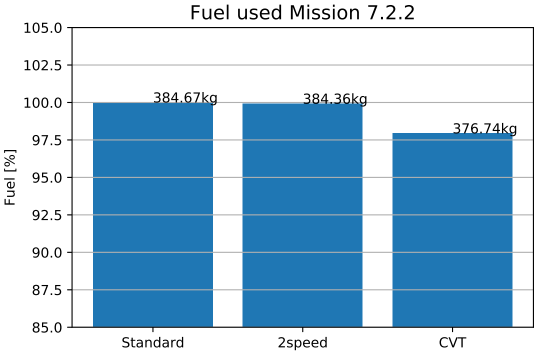
Transportation of emergency rescue team inside the fuselage with lifting and (or) unloading with the help of the special lifting-and-lowering devices
Take off at 1000m with 11 PAX, 100kg each. Then climbing to 3500m and cruising 100km with optimum speed. Descending to 3000m and hovering while 11 PAX are unloaded, then climbing to 3500m and cruising back with optimum speed.

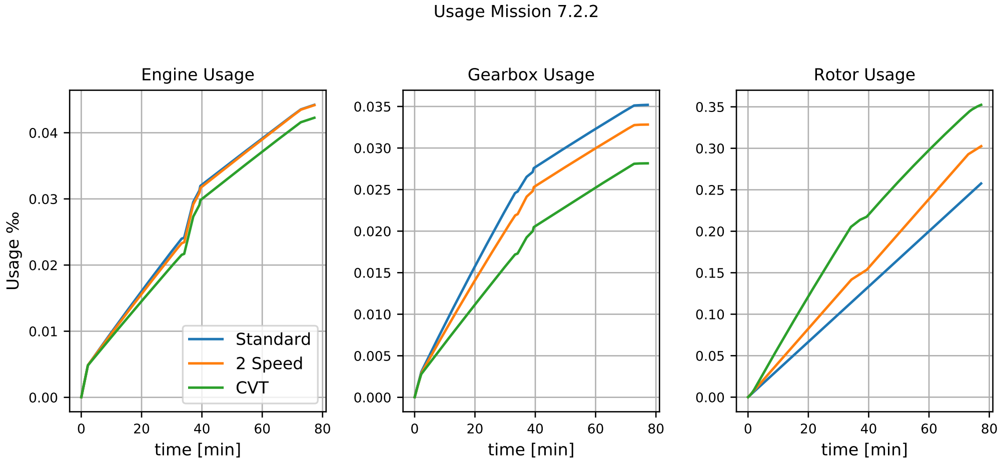












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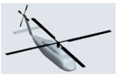
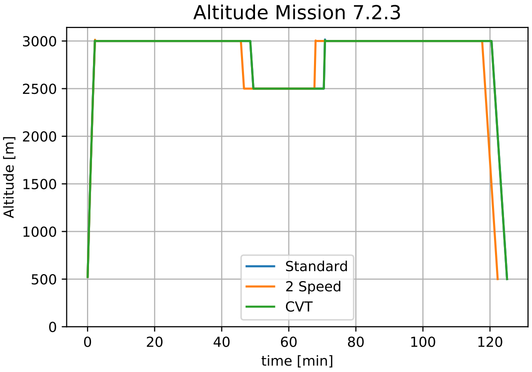
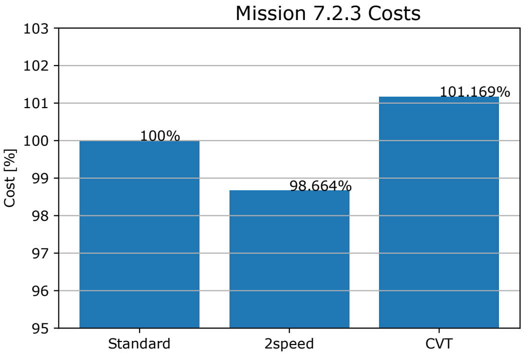
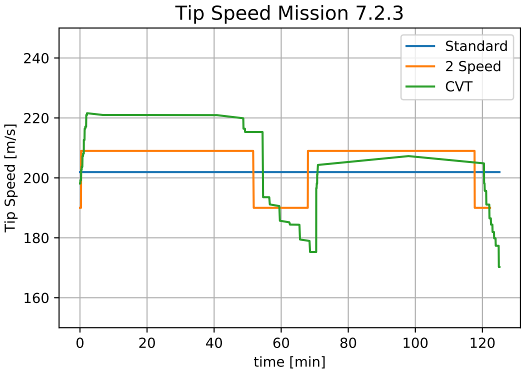
Mission 7.2.3

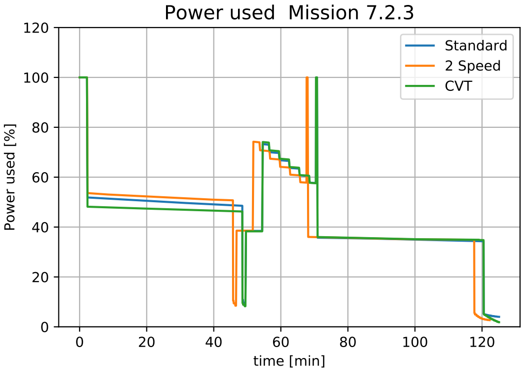


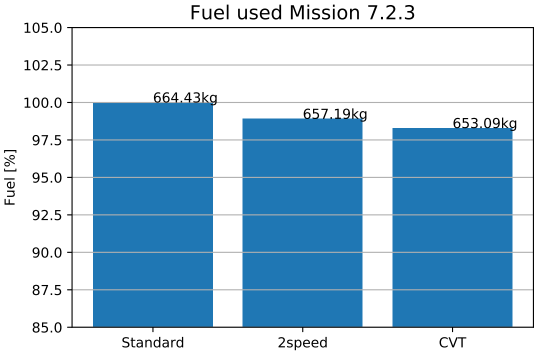
Transportation of emergency rescue team inside the fuselage with parachute landing
Take off at 500m with 11 PAX, 100kg each. Then climbing to 3000m and cruising 150km with optimum speed. Descending to 2500m and hovering while 10 PAX jump out on parachutes in teams of two, then climbing to 3000m and cruising back with optimum speed.

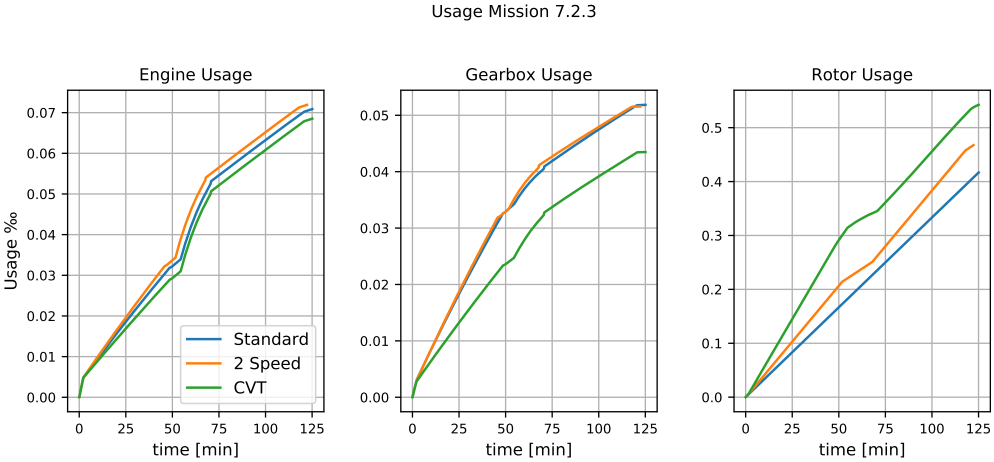












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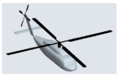
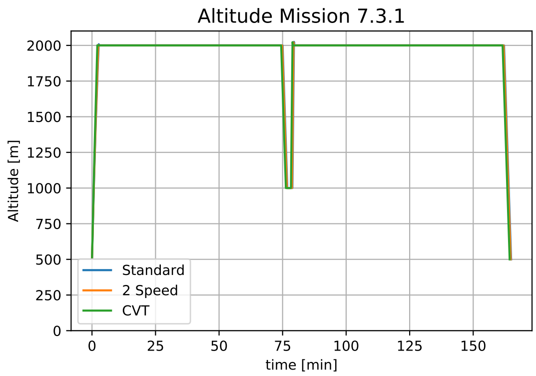
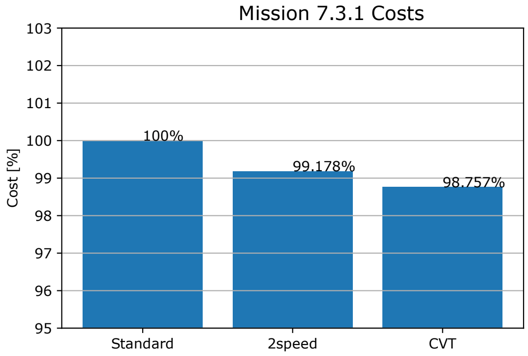
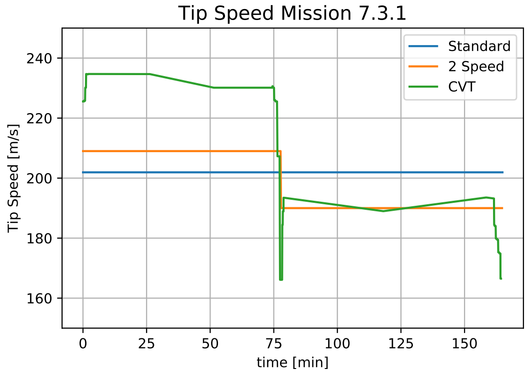


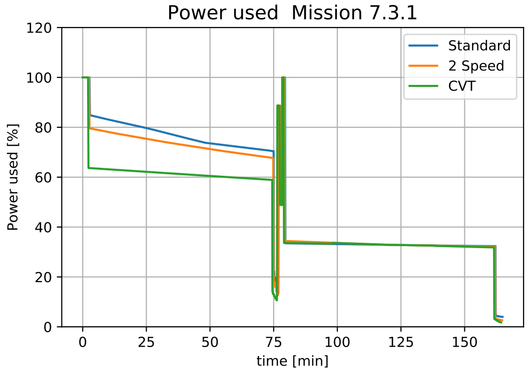
Transportation of the cargo inside the fuselage with loading on the earth and unloading on the earth

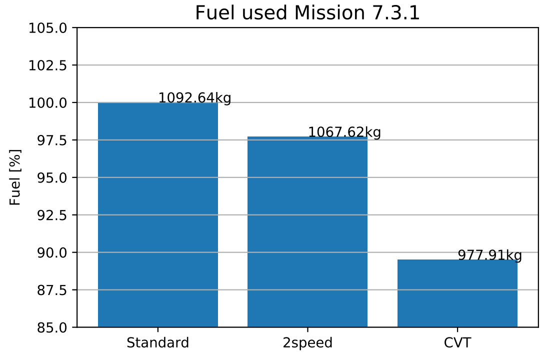
Take off at 500m with 3000kg cargo. Then climbing to 2000m and cruising 250km with optimum speed. Descending to 1000m and unloading with short hover. Then climbing again to 2000m and cruising back with optimum speed.

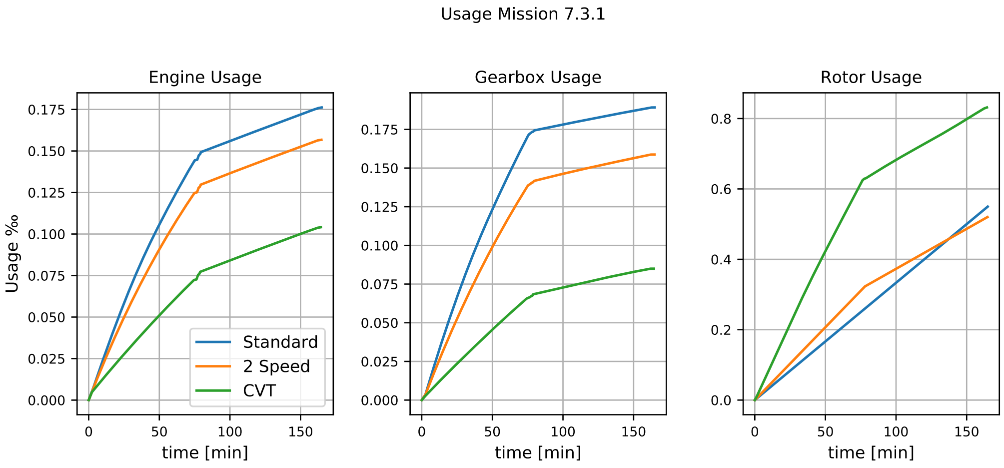












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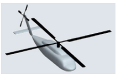
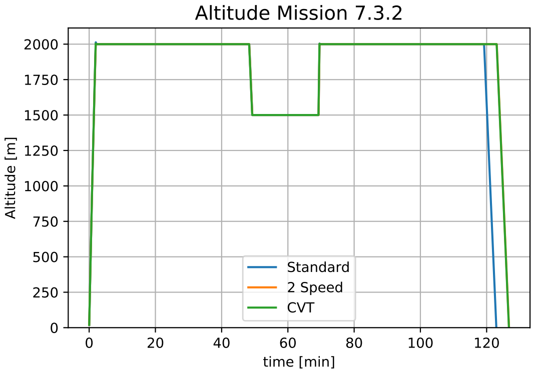
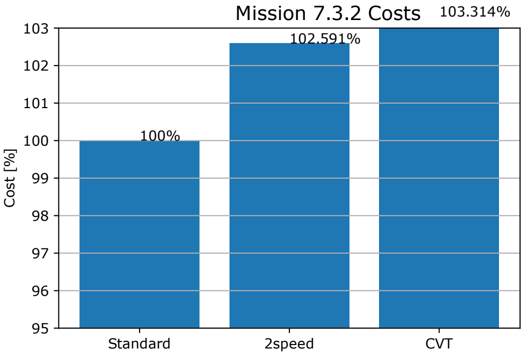
Mission 7.3.2

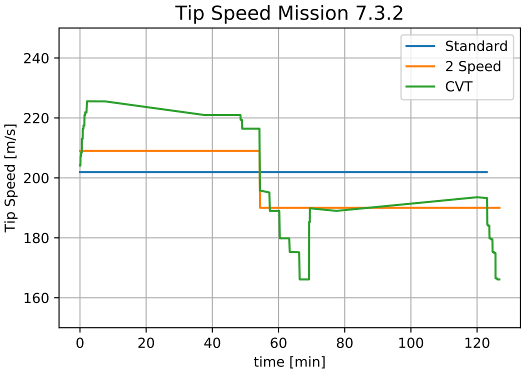


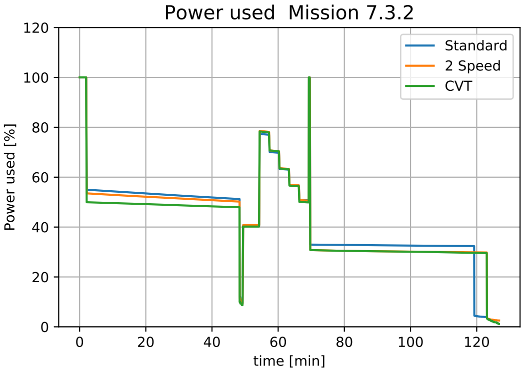
Transportation of the cargo inside the fuselage with in-flight parachute extraction

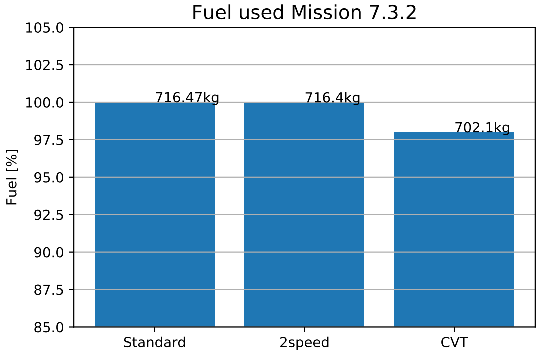
Take off at 0m with 2000kg cargo. Then climbing to 2000m and cruising 150km with optimum speed. Descending to 1500m and hovering while cargo is dropped out on parachutes in packages of 500kg, then climbing to 2000m and cruising back with optimum speed.

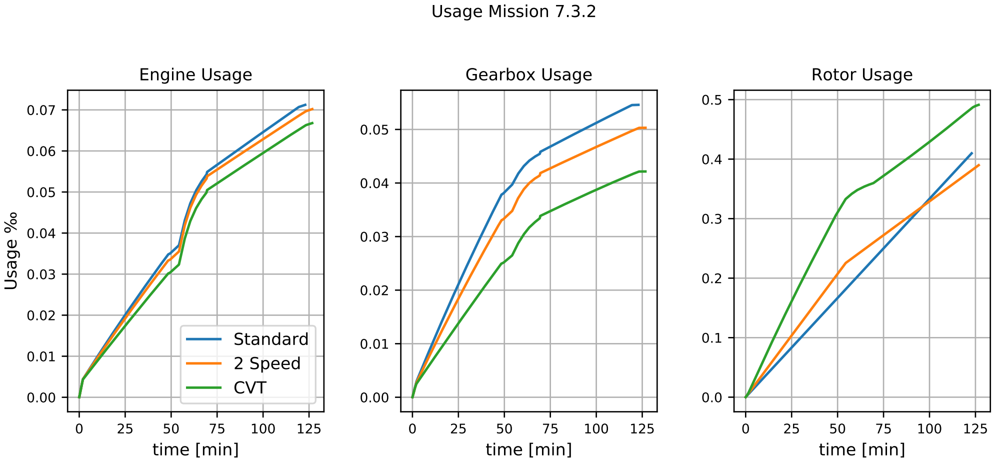












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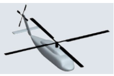
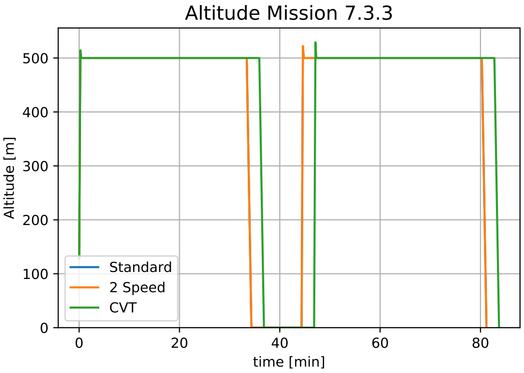
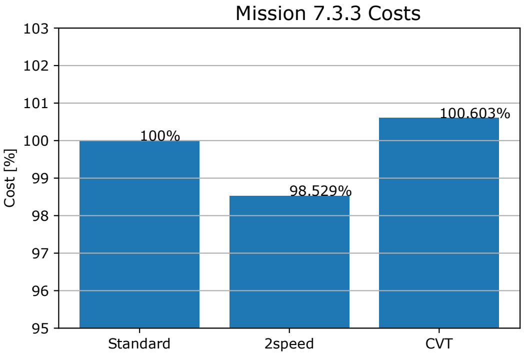
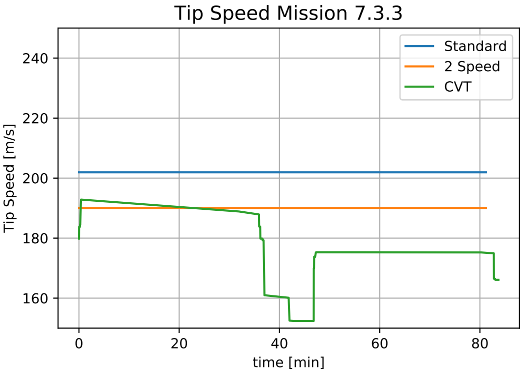
Mission 7.3.3

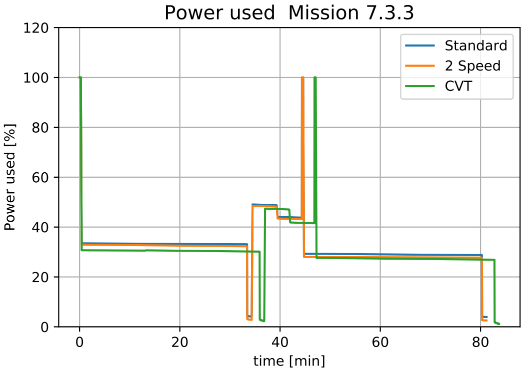


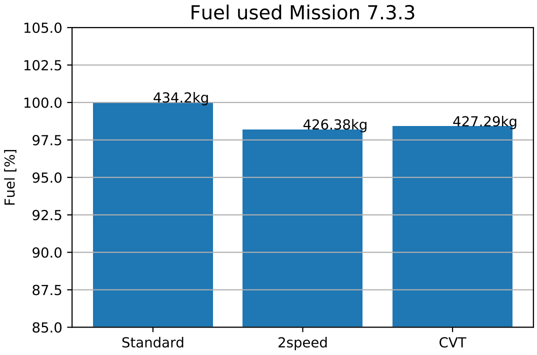
Transportation of the cargo inside the fuselage with in-flight dropping without parachutes
Take off at 100m with 500kg cargo. Then climbing to 500m and cruising 100km with optimum speed. Descending to 0m and hovering while cargo is dropped out near ground, then climbing to 500m and cruising back with optimum speed.

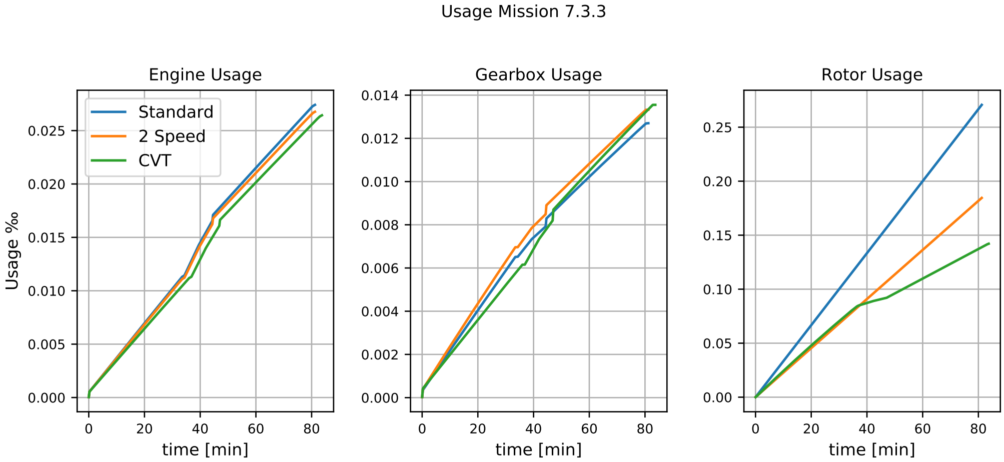












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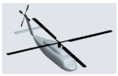
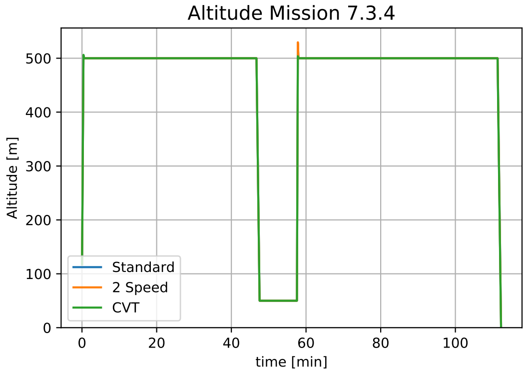
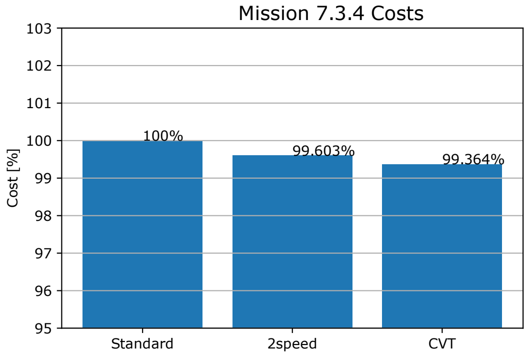
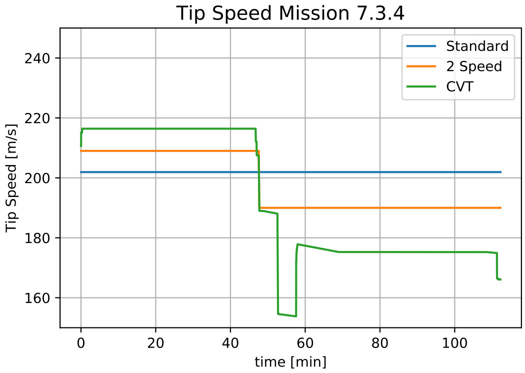
Mission 7.3.4

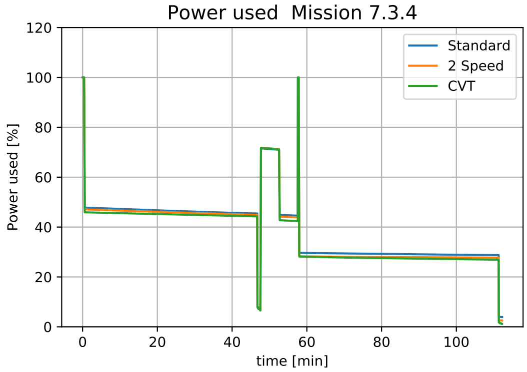


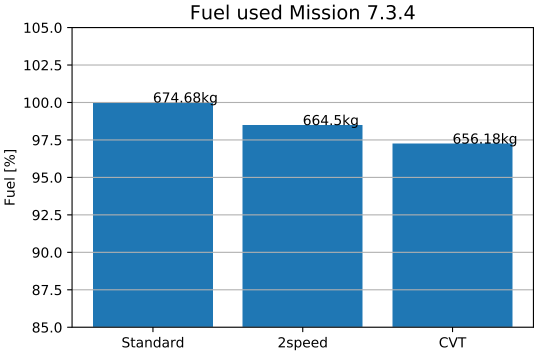
Transportation of the cargo inside the fuselage with lowering with the help of the special lowering devices (hoists)
Take off at 100m with 2500kg cargo. Then climbing to 500m and cruising 150km with optimum speed. Descending to 50m and unloading while hovering. Then climbing again to 500m and cruising back with optimum speed.

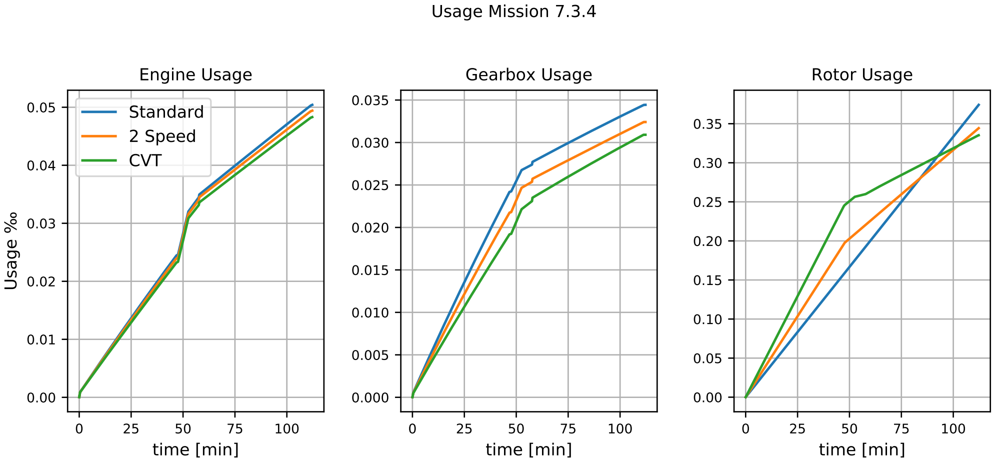












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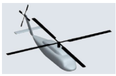
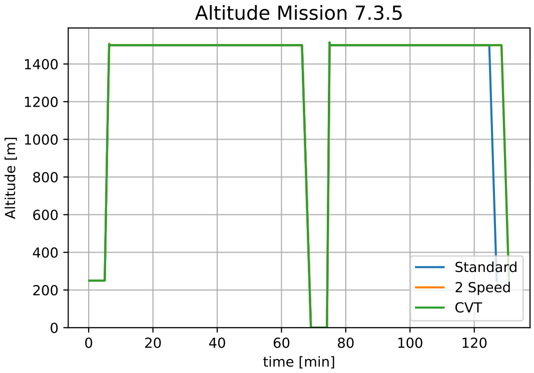
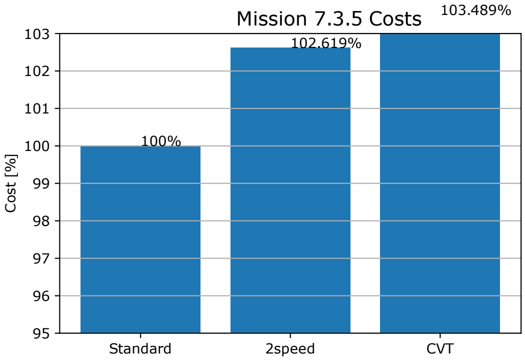
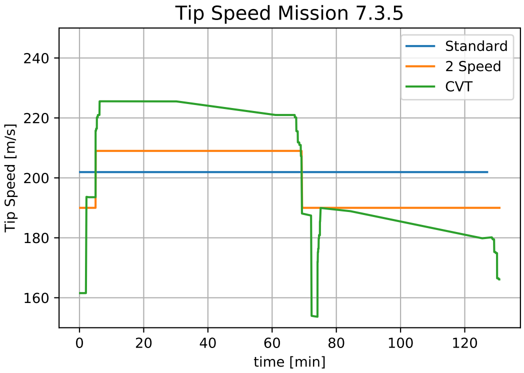
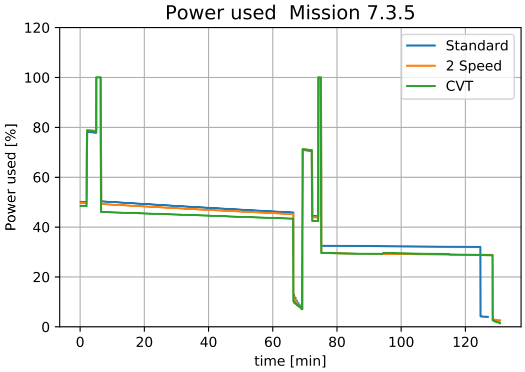


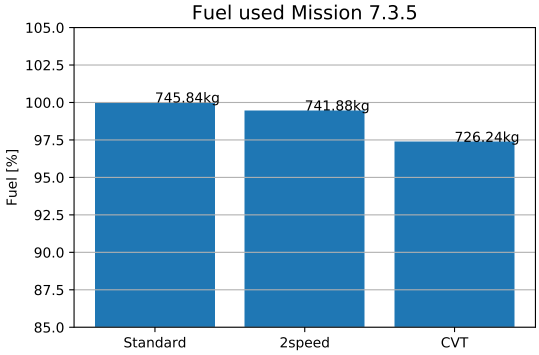
Transportation of the cargo on external sling
Take off at 250m and hovering near to ground to attach the 2500kg cargo. Then climbing to 1500m and cruising 150km with 150km/h. Descending to 0m and deattach cargo while hovering, then climbing again to 1500m and cruising back with optimum speed.

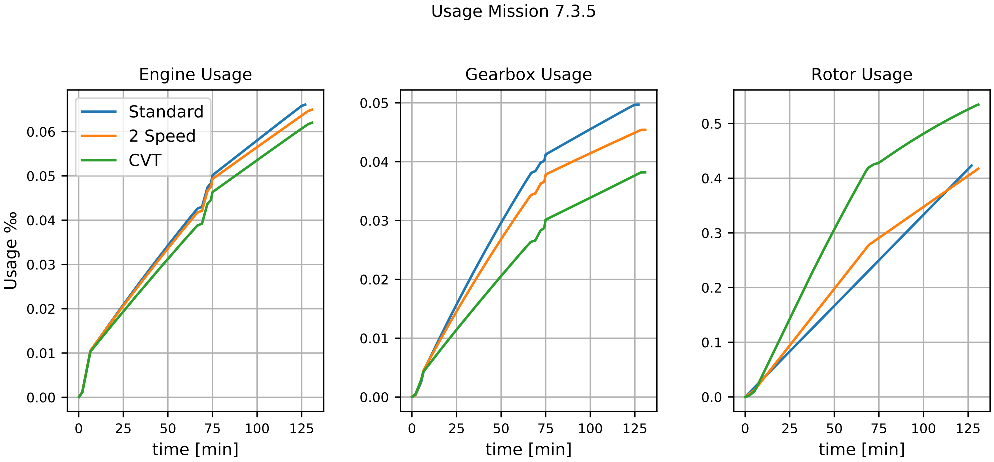












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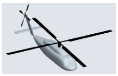
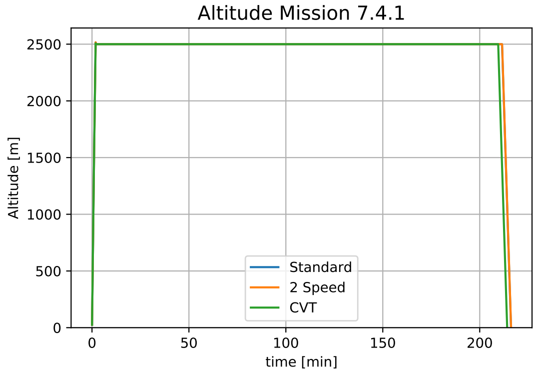
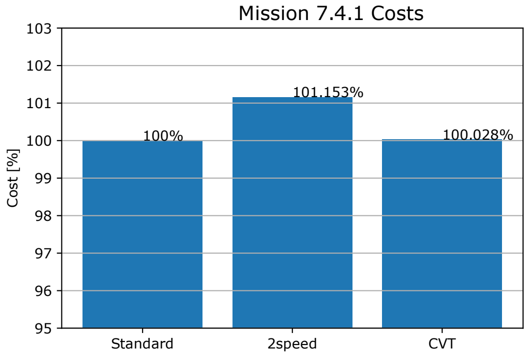
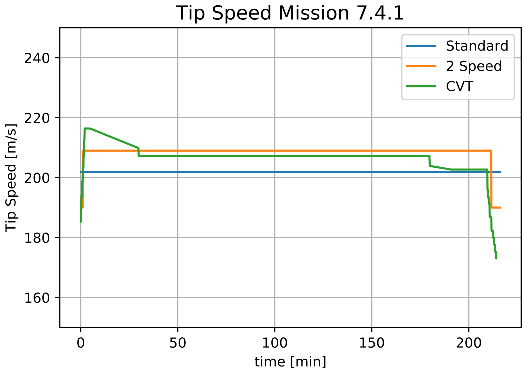


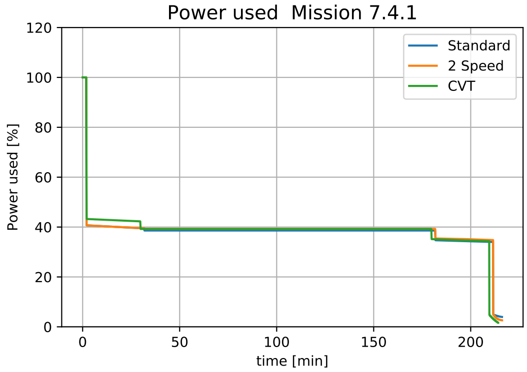
Patrolling flights

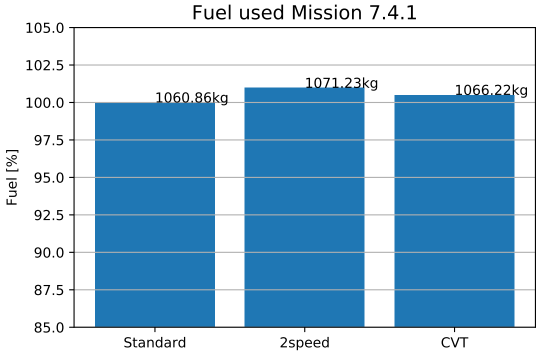
Take off at 0m with 300kg equipment. Then climbing to 2500m and cruising 90km to patrolling area with optimum speed. After cruising 2,5h with 100km/h, cruising back with optimum speed.

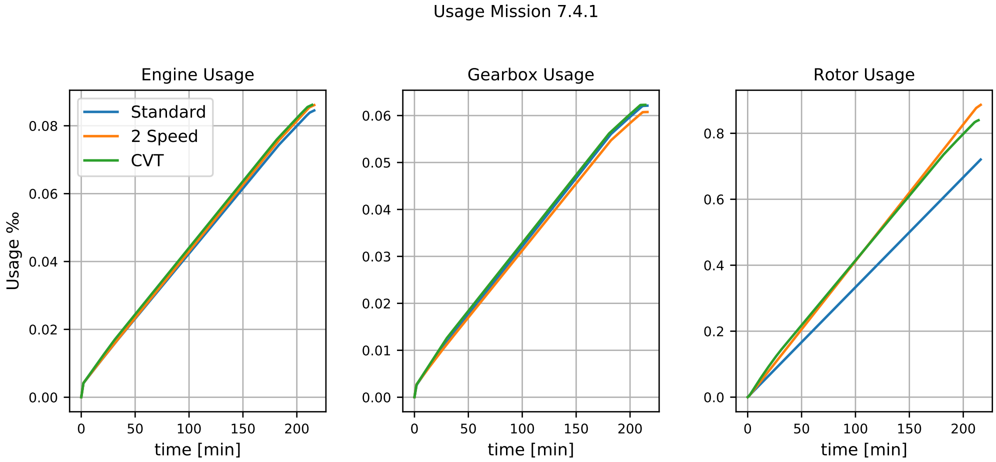






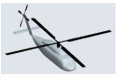






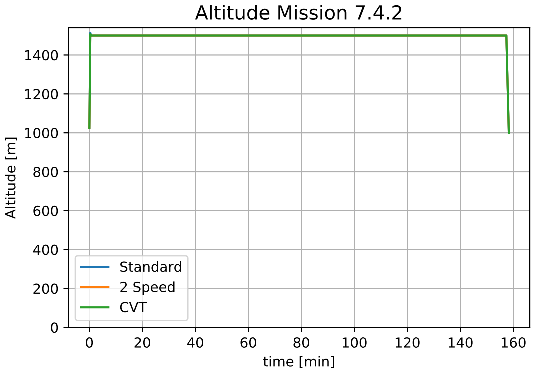
SAR

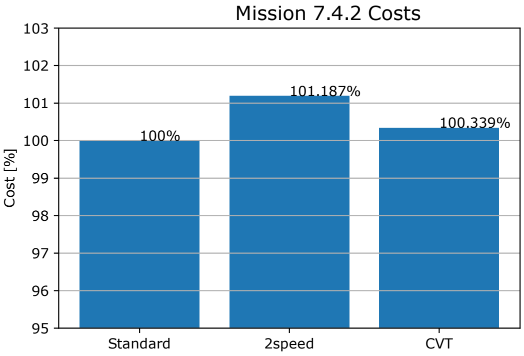
Mission 7.4.2

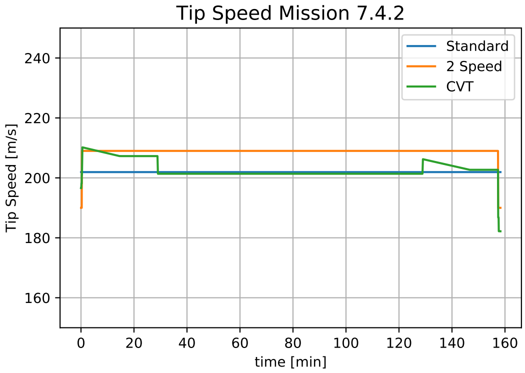


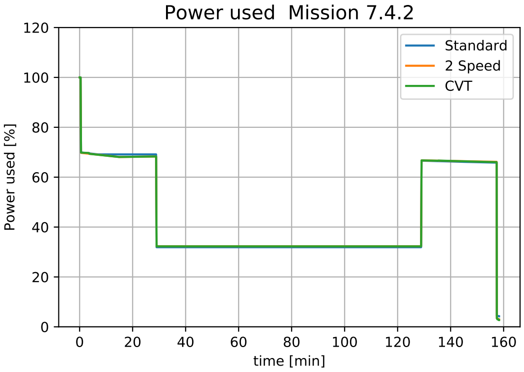
Search for objects

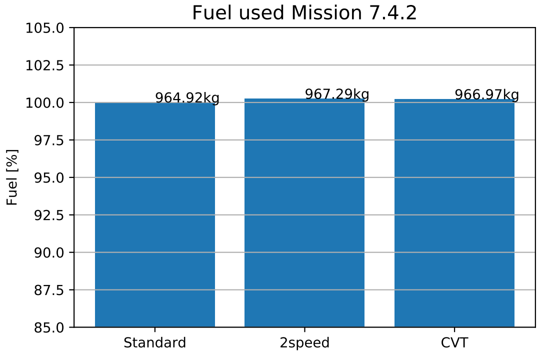
Take off at 1000m with 300kg equipment. Then climbing to 1500m and cruising 130km to searching area with 275km/h. After cruising 100min with 160km/h, cruising back with optimum speed.

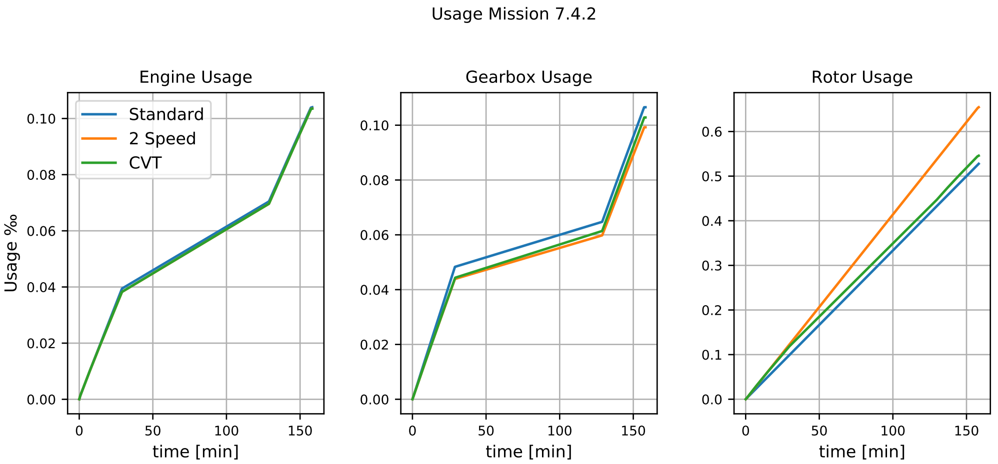












Chapter 5

Discussion

5.1 Comparision of the Transmission Technologies

The first part of the discussion compares pros and cons of the different transmission technologies in verious missions.

Mission 1.1.2 reveals that the two rotor speeds of the two-speed transmission can be either lower or higher than the optimum speed in a mission. This leads to no improvement of the fuel consumption over the standard transmission, whose rotor speed happens to be near the optimum for this specific mission.

Missions 1.3.1 and 1.3.2 of the oil and gas industry show, that when the helicopter is operating near the performance limit with standard configuration, the fuel savings can be up to 15% with CVT, when compared to a standard transmission. This is due to the lower power usage enabled by the variable rotor speed. These fuel savings do also reflect on the mission costs, but owing to the small share of the fuel costs on the overall costs it only amounts to about 2 per cent.

If the mission profile does not encourage a big tip speed deviation from the standard speed, no fuel or cost savings from the rotor speed variaton can be expected. On the contrary, there even is some negative influence on the costs due to the weight penalty of the CVT or two-speed transmissions. This can lead to an increase in costs of the CVT, when compared to the standard configuration. This behaviour can be seen in mission 1.2.1. In this mission one can also see a big discrepancy of costs. Due to the lower flight time of the 2 speed transmission, the costs are much lower. The lower flight time can be explained by the rough discretization of the input data and the resulting higher flight speed. It is possible that very different optimum speed values are selected even with small deviations of the mass, since the speed is not interpolated. The difference between two points in the velocity matrix is $3.6 m/s$. It leads to a higher flight speed and consequential a lower flight time. This can be seen also in missions 7.2.3, 7.3.2 and 7.4.1. However the lower flight speed still leads to a lower fuel consumption.

The impact of higher rotor speeds on the depreciation and overhaul costs can be seen in missions , 5.2.1 and 5.2.2. The increase in rotor tip speed of about $20 m/s$ yields in a 30% increase of rotor usage during this mission. Increase of the rotor speed leads to an increase of the depreciation and overhaul costs of the rotor. The rotor speed increase in turn leads to a decrease of the power demand. For this reason the engine and gearbox depreciation costs also decrease. The rotor depreciation costs have a higher influence on costs, than the fuel costs, engine and gearbox depreciation costs. Therefore the higher rotor usage of the CVT can result in higher overall costs.

The construction sector (Section 4.4) shows an improvement of the fuel consumption in almost every mission. In this industry sector the missions are rather short but have a high proportion of rotor speed variation. The biggest advantages of the CVT compared to standard are when the helicopter is flying fast, on high altitudes with high payloads. In these flight conditions the optimum CVT rotor speed is quite high, compared to the rotor speed of the standard configuration. If the CVT is compared to the reference rotor speed of the UH-60A of $221m/s$, the savings shift to lower loads and speeds [7].

5.2 Mission Performance

The results show, that there still is scope for improvement in the calculation method of the fixed speed. The study of the results reveals, that at low required power the determined speed is very efficient. One possible improvement in the speed calculation could be weighting according to fuel consumption instead of time. However, this would need to be investigated in a further study. The calculated fixed speed is 200m/s, about 10 % below the reference speed of the UH-60A. This may be efficient, but in reality it would cause problems, because the performance data of the helicopter, such as service ceiling, climb rate and maximum hovering altitude decrease strongly with the tip speed.

The validation shows that the calculation model for the speeds of the two-speed gearbox gives good results. The fuel saving compared to the two-speed gearbox assumed in [7] is 2 percentage points. However, even this calculation model could be improved by the different weighting, mentioned above. The spread of the CVT is between 1.42 and 1.57, depending on the industry sector, which is a very promising range. Garre [8] calculated a spread of 1.5 for the UH-60A in order to achieve power savings. In [12] variators were designed for a spread of 2. Due to the fact, that the power flow in the variation path depends on the spread [14], a reduction of the spread could enable a better performance of the CVT. This could lead to an decrease of the mass penalty and so to a mass efficient usage of the CVT technology.

The results show that a two-speed transmission is not a viable solution for a normal helicopter, like the UH-60A. Advantages of such a transmission are more likely to be seen with large differences between the two rotor speeds. For example a tilt rotor aircraft could be predestined for this with its two distinct operation modes. In order to be able to make a reliable statement, further calculations need to be made on this subject.

The increase in performance can be seen in an increase of the flight envelope. The service ceiling and the rate of climb were evaluated. In addition to the calculated performance-optimal speeds for each sector, Table 5.1 also shows the values for the reference speed.

It can be seen that in terms of climb rate and service ceiling only the CVT has potential for performance improvement. With this transmission variant, the service ceiling can be increased by 16.8 % compared to the reference speed, which could bring great progress especially for supply and rescue operations in the mountains. Also a slightly higher rate of climb could be observed with the CVT, but the advantages only become interesting in higher altitude.

Performance Data				
Helicopter Type: UH-60A				
	*Service Ceiling [m]	deviation from Ref. Speed [%]	**Climbrate [m/s]	deviation from Ref. Speed [%]
Oil and Gas Producing Industry				
Two Speed	3413	-14.65	10.95	-4.45
Single Speed	2904	-27.38	9.67	-15.62
Construction				
Two Speed	2909	-27.26	9.38	-18.15
Single Speed	1904	-52.34	6.59	-57.50
Search and Rescue				
Two Speed	3160	-20.98	10.04	-12.39
Single Speed	2904	-27.38	9.67	-15.62
CVT	4672	+16.83	11.48	+0.17
Ref. Sp. (221 m/s)	3999	-	11.46	-

*Service Ceiling: at MTOW with optimum flightspeed
**Climbrate: at MTOW in 1000m MSL with optimum flightspeed

Table 5.1. *Influence of the tip speed on the performance data*

5.3 Mission Costs

On the whole, the cost calculation model seems to be consistent with real life data. The simulation tool estimates the average cost of one flight hour in the UH-60A ”Black Hawk” to about 6000$, which corresponds very well with the cost shown in [13].

Overall the costs remain mostly the same compared to a helicopter equipped with a standard gearbox. However the helicopter equipped with a CVT has got a higher performance. The changes in costs are negligible at about ±1%. The reason for this is that the savings due to lower fuel consumption are outweighed by the higher production costs of the CVT transmission.

If the main rotor rotates at a higher speed, the rotor will wear out faster and the depreciation and overhaul costs will increase accordingly. Depending on the mission, the rotor usage, with variable rotor speed, can be up to two times greater than the standard usage. In contrast to this the gearbox wear is reduced at higher rotor speeds, as it depends primarily on the transmitted torque. The engine usage solely depends on how much power is used. Since the CVT uses up to 20% less power than the standard transmission the engine usage can be a lot lower. In total the Depreciation and Overhaul costs, when using a variable speed transmission, will be a bit lower than with a standard gearbox.

Together the fuel, depreciation and overhaul costs amount to about 30% of the total costs of one flight. The rest of the flight costs are shared between the crew costs, maintenance costs and indirect costs. Since these cost shares increase as the flight time progresses, according to our simulation the cost-optimal flight speed is near the top speed of the helicopter. This of course only applies if the flight is over a defined distance. If the flight time is specified instead of the distance that has to be flown, the cost-optimal flight speed is the same as the power-optimal one that was calculated in section 2.2.

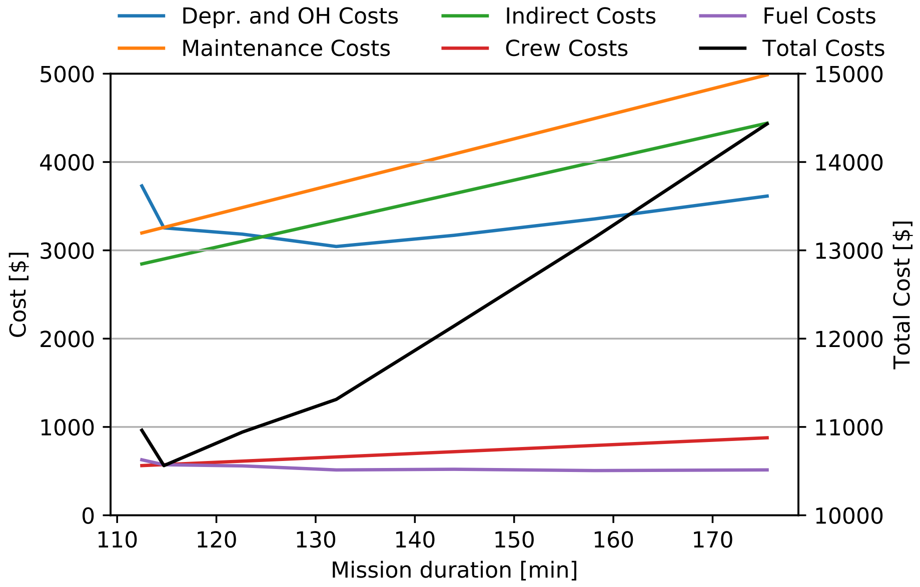


Figure 5.1. *Course of the different cost shares over the flight duration*

In figure 5.1 the different cost shares in relation to the flight time are shown for one mission. This mission represents a cargo flight. the key data of the mission is:

- take-off at $0m$ with $1000kg$ payload,
- climb to $1500m$,
- cruise for $500km$ with flight speed varying between 155 and $295km/h$,
- descent to $0m$,
- landing.

The flight time is plotted on the x-axis. An increase in flight time is equivalent to a decrease in flight speed. It is evident, that the Depreciation and overhaul costs are at their minimum at a flight time of about 130 minutes and the minimum fuel costs are at 150 minutes. They however have only a very small influence on the total costs and are overshadowed by the maintenance, indirect and crew costs. For this reason the minimum costs equate to a very high flying speed. The total costs only begin to rise again when the speed is near the maximum speed of the helicopter. At this point, a sharp increase of the Depreciation and overhaul costs is obvious. Nevertheless a further investigation would be necessary, because the cost factors which influence the time-dependent costs are adopted from the Cost report of Zhuravlev [17] and have not been examined in detail. Especially the maintenance hour costs have a high impact on about 70% of the costs, that are only time-dependent. If these turn out to be lower, the Rotor tip speed based costs would have a higher impact on the total costs and the optimum flight speed may shift to a slower value.

A comparison of the total costs between the three transmission types can be seen in figure 5.2. It shows that the rotor speed for optimum fuel usage can differ from the rotor speed for minimum costs. The mission used for the cost comparison requires almost no rotor speed variation. The lower rotor speed of the standard gearbox yields lower depreciation costs that have a bigger influence on the costs, than the fuel. So there is a discrepancy between ecology and cost efficiency.

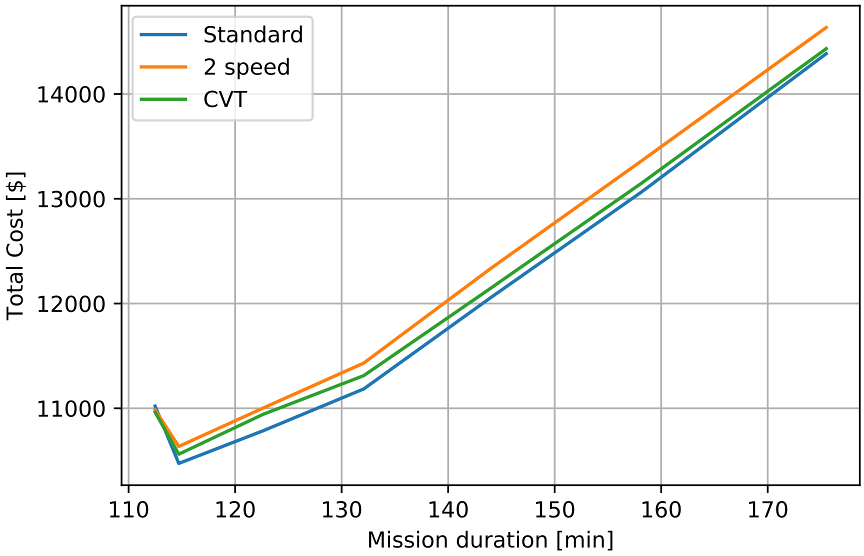


Figure 5.2. *Cost Comparison of transmission types*

This means that the control of the variable rotor speed would have to be based either on the minimum fuel usage or the minimum cost. Something similar to the cost index used by the flight management system of big passenger aircraft could be implemented for this. This would take into account if the pilot wants to fly more fuel efficient or more cost efficient.

Chapter 6

Conclusions

- The flight envelope increases when using a CVT. The service ceiling can be increased up to 17% over the reference transmission. Also an increase in climb rate and flight speed is possible with a CVT.
- The CVT has advantages over the Standard configuration at high speeds and high altitudes or with big payloads, due to a lower required power. Missions with a higher tip speed variation lead to higher fuel savings over standard configuration. If no RPM variation is necessary, there is no gain or even a penalty when using a CVT.
- Emergency operations were not taken into account when choosing the optimum rotor speeds. The rotor speed can be too low to ensure safe Autorotation. This is especially true for hovering, where the power-optimum rotor speed is low.
- A spread φ between lowest and highest rotor speed of 1.5 is enough for every considered industry sector. This shows that the research into the design of a CVT which has been conducted to date is valid. To enable performance gains and cost savings, minimizing of the additional transmission mass is necessary
- The calculated optimum fixed rotor speed for the standard transmission is significantly lower than the reference speed of $221 m/s$. Altough this leads to lower fuel consumption and costs, it also results in significantly poorer flight performance.
- A Two speed transmission can lead to improvements in the fuel usage and cost during a mission, if the two possible rotor speeds reflect the variation in rotor speed well. The two rotor speeds can also be higher and lower than the optimum speed, which leads to a higher fuel consumption. Advantages of a 2 speed gearbox are more likely to be seen with large differences between the two rotor speeds, which for example would be required for a tilt rotor aircraft.
- Mission costs are mostly affected by the flight time, so the cost optimum flying speed is near the maximum speed. Because of this, the fuel savings that are possible with a CVT only show a small impact on the overall costs. In turn the rotor depreciation and overhaul costs have a high influence on the costs. This can yield lower overhaul costs of the CVT, compared to reference speed due to lower possibler rotor speed.
- The strong dependence of costs on flight time means, that the cost optimum flying speed is not the speed that uses the least fuel, so there is a discrepancy between cost and CO_2 savings. This is also true for the rotor speed of the CVT. It has to be controlled either with regard to minimum fuel usage or minimum cost.

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