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Towards greener aviation : a comparative study on the substitution of standard jet fuel with algal based second generation biofuels

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TOWARDS GREENER AVIATION

A COMPARATIVE STUDY ON THE SUBSTITUTION OF STANDARD JET FUEL WITH ALGAL BASED SECOND GENERATION BIOFUELS

By

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AUTHOR'S DECLARATION

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Abstract

The negative environmental impact of the aviation industry, related mainly to the gaseous emissions from turbine exhausts, is increasing with the increased demand on travel. In addition to the adverse environmental effects, the currently used aviation fuel is posing economic burdens on the air transport sector, with the increase in crude oil prices. Therefore, the aviation industry is investigating the potential of substituting the currently used aviation fuel with alternative fuels- mainly with those derived from second generation biofuels. Of all available sources of second generation biofuels, numerous studies indicate that those derived from algae seem to be the most promising, in terms of providing a viable and sustainable alternative to fossil fuels. This study explores the feasibility of microalgal jet fuel, taking into consideration technological, environmental and economic aspects. The results indicate that the viability and sustainability of microalgal jet fuel greatly depend on the technologies and inputs used during the different production stages of microalgal fuels. Provided certain conditions and characteristics are present, microalgal jet fuel has a realistic potential to provide the economic and environmental benefits needed to substitute conventional fuels.

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Dedication

I would like to dedicate this thesis to my religion Islam which provides me with the power and patience to carry out such a research, and to all Muslims out there who are working hard to improve their communities and who are trying to make a difference in this world, by spreading the true colours of Islam.

This work is also dedicated to my family especially my grandparents, Fathi, Mona and Mouzaya, my parents Abdul-Majid and Aicha and my brothers and sisters, Mohamad, Bilal, Mona, Soha and Hiba who believed in me and gave me the courage to start and stay on this path.

Last but not least, I would like to dedicate this research to my wonderful husband, Mohamad. You are my gift from Allah, I could have never achieved this work without you. You have been with me every step of the way, through the bad times and the good times. May Allah bless us and keep you for me.

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Acronyms

AHP	Analytic Hierarchy Process
ASTM	American Society for Testing & Materials
ATM	Air traffic management
EUETS	European Union Emissions Trading Scheme
FT	Fischer Tropsch
GHG	Greenhouse gas
GREET	Greenhouse Gases Regulated Emissions and Energy Use in Transportation
HRJ	Hydro-renewable jet fuel
ICAO	International Civil Aviation Organization
IATA	International Air Transport Association
LTO	Landing and take-off cycle
PBR	Closed photo-bioreactor
PBRF	Closed photo-bioreactor with freshwater and fertilizers
PBRW	Closed photo-bioreactor with wastewater
RWP	Raceway pond
RWPF	Raceway pond with freshwater and fertilizers
RWPW	Raceway pond with wastewater
ULS	Ultra-low sulphur jet fuel
WWTP	Wastewater treatment plant

Chapter 1: Introduction

Algae have long been associated with harmful algal blooms, which can lead to degradation and eutrophication of aqueous media [Heisler *et al.,* 2008]. Previously, eutrophication was part of the natural process of aging of aqueous media such as lakes, which could take hundreds or even thousands of years to occur [Anderson *et al.,* 2002]. Today, the degradation of fresh and marine waters is accelerating as a result of the added nutrients from human activities [Burkholder, 2000]. Agricultural runoff, contamination with sewage and animal manure, and the expansion of the aquaculture farms contribute to the increased level of nutrients, such as nitrogen and phosphorus, which are responsible for harmful algal blooms [Anderson *et al.,* 2002].

More recently, a positive association has surfaced, linking algae with fuel production [Singh & Gu, 2010, Schenk *et al.,* 2008, Mata *et al.,* 2010, Brennan & Owende, 2010]. Algae are known for their high lipid content, which makes them potential candidates for substituting fossil fuels [Meier, 1955]. Furthermore, algae grow at a fast pace, providing all year-round supply of feedstock [Singh & Gu, 2010]. Therefore, there is a great interest directed towards algal fuels, and more specifically towards microalgal fuels [Brennan & Owende, 2010, Mata *et al.,* 2010]. One of the industries which is intensively researching the capabilities of microalgae as a fuel source is the aviation industry [Hileman *et al.,* 2009]. The aviation industry is hopeful to find in second generation biofuels, including microalgal derived fuels, environmental and economic benefits related to reduced greenhouse gas emissions and reduced jet fuel costs [IATA, 2009c].

Advocates see in algae not just a source of energy, but also a prospective contributor to CO_2 sequestration [Mata *et al.,* 2010]. Sceptics, on the other hand, view algal derived fuels as just a new trend, which will eventually prove to be unsuitable and unsustainable [Reijnders, 2008a]. Therefore, this study aims at bringing together the available literature review concerning microalgal biofuels and their use in the aviation industry, and analyzing these data based on three important sustainability criteria. The goal is to check whether microalgal jet fuels can be considered as technologically feasible, environmentally sustainable and economically viable.

Through this inquiry the opportunities and challenges of biofuel adoption in the aviation industry are presented, especially those derived from microalgae. The latest information on the economic, environmental and technological considerations of this fuel were evaluated and assessed, in order to make an objective conclusion concerning the current viability and feasibility of microalgal jet fuel. This study can be of great interest to the aerospace industry, as it can present an overall picture of the status of microalgal jet fuel. Also, it can be of great interest to the business community, which is looking for new projects which can provide both environmental and economic benefits. Moreover, policy makers can also make use of such an inquiry, as they are responsible for enforcing stringent environmental regulations and for subsidizing new alternative fuel projects.

Chapter two provides background information related to the transport sector, conventional jet fuel and the development of biofuels, from first generation biofuels to second generation biofuels, including microalgal fuels. Chapter three lays down the stages of microalgal jet fuel production and the different technologies used in each stage. Also in chapter three, conventional jet fuel production is briefly explained. Chapter four gives a brief introduction into the decision making tool used, including its application in the environmental field, and the different steps which constitute the analytic hierarchy process. Chapter five explains the tailored methodology used in this study in order to carry out the assessment of the data obtained from the literature. As for chapter six, the analysis of technological data is presented, along with the matrices, the results and the discussion related only to the technological considerations of the various aviation fuels under consideration. Like chapter six, chapter seven and eight provide similar type of analysis and information, related to the environmental and economic considerations of the aviation fuels considered, respectively. Chapter nine consists of combining the results of chapters six through eight, in order to obtain an overall picture concerning the viability of microalgal jet fuel. The overall conclusions and recommendations are provided in chapter ten.

Chapter 2: Background

Today's economy greatly depends on the ability to cross countries' boundaries and to move people and goods [Patil *et al.*, 2008, Penner *et al.*, 2000]. This ability is an essential part of the economic development and global trade [Khan *et al.*, 2009, Penner *et al.*, 2000]. Therefore, the transport sector is one of the fastest growing sectors consuming 26% of the global energy demand [Metz *et al.*, 2007, Rothengatter, 2010]. The number one choice to provide energy for the transport sector has always been petroleum sources [Malca & Freire, 2006], since they have optimal characteristics in terms of energy content, performance, ease of handling and price [Hemighaus *et al.*, 2006]. The transport sector, which uses liquid fuels will be responsible for an 80% increase in the global liquid fuels consumption by 2030, and its consumption of liquid fuels, will increase from 51% in 2006 to 56% in 2030 [EIA, 2009]. At present, the transport sector is the major consumer of global oil demand (30%) [Gouveia & Oliveira, 2009]. This consumption is expected to increase at a rate of 1.3% per year until 2030 [SC, 2008].

The increased demand on transportation has been attributed to several reasons, such as population growth, increased income, increased motorization, increased demand on tourism and decreased transportation cost and time [Rothengatter, 2010]. The dependence on non-renewable energy sources such as coal, oil and gas has created a global concern for energy security [Omer, 2008, Hemighaus *et al.*, 2006]. Energy security has also been jeopardized by the availability of most of the petroleum reserves in politically unstable areas [Shephard & Walck, 2007]. This fact has led to fluctuations in crude oil prices over the past years from $28/ barrel in 2003 to $147/ barrel in 2008 [Lior, 2010], and it has led to disruptions in oil supplies due to political crises such as the Arab-Israeli war in 1973 [Bauen, 2006, IEA, 2001].

In addition, fossil fuel sources are non-renewable. Thus, a cheap supply of oil will not be available for an unlimited time [Gouveia & Oliveira, 2009, Wardle, 2003]. Also, as time passes by, the energy input required to obtain and process petroleum fuels will exceed the energy output obtained from these fuels [Turtona & Barreto, 2006]. Moreover, the combustion of petroleum products such as oil is associated with the emission of greenhouse gases (GHGs) which contribute to global warming [Omer, 2008], predicted to be able to increase the global average temperature by as much as 6°C in the long term [Gopinathan & Sudhakaran, 2009]. Since 1970, global emissions of GHGs from the transport sector have increased by 120% [Metz *et al.,* 2007]. All of these negative aspects of petroleum fuels contribute to its weakened sustainability [Brennan & Owende, 2010].

The transport sector can be divided into several subsectors including road transport, marine transport, air transport and rail transport [Metz *et al.*, 2007]. Road transport accounts for the largest share of energy use (77%), emitting about 18% of global CO_2 emissions [Rothengatter, 2010]. As for air transport, it consumes about 13% of the energy used in the transport sector [IATA, 2009b] and emits 3% of global CO_2 emissions [Anger & Kohler, 2009, Scheelhaase *et al.*, 2009, Solomon & Hughey, 2007]. Even though air transport currently plays a small role in emitting greenhouse gases, it is receiving a great amount of attention due to the fact that this percentage is expected to increase with the growing demand on aviation, and due to the likely decrease in the use of fossil fuel sources in other sectors, as the world heads towards renewable energy sources [Solomon & Hughey, 2007].

2.1 Introduction to air transport

Air transport plays an important role in the economic development, by carrying about 2.3 billion passengers yearly [ICAO, 2010, Macintosh & Wallace, 2009]. Passenger air traffic is expected to keep increasing by 4.7-5.2% per year, over the coming 10 to 15 years [ICAO, 2010]. Air transport has witnessed the fastest growth rate among all transport subsectors, and this growth is expected to keep increasing in the coming years, as the demand for travel continues to grow [Whitelegg & Williams, 2000]. The aviation industry consists of aircraft and engine manufacturers and operators, fuel providers, airports and airport infrastructures [Solomon & Hughey, 2007]. Moreover, air transport contributes to 8% of the global Gross Domestic Product by transporting people and goods all around the world in a timely manner [ATAG, 2002, IATA, 2007b]. While air transport might contribute to the global economic development, this increased demand on aviation is associated with concerns such as environmental sustainability [Akerman, 2005, Owen *et al.*, 2010].

In the beginning of air transport, both gasoline and kerosene were used as fuels, because of their availability. After a while, gasoline (the lighter fuel) appeared to be unsuitable, as it tended to evaporate at high altitudes and cause deterioration of engine components [Maurice *et al.,* 2001]. Today, the dependence of aircraft is on kerosene, which meets operational demands [Wulff & Hourmouziadis, 1997]. Kerosene is mainly produced from conventional petroleum or crude oil. Kerosene is a complex mixture of hydrocarbons, and it has a boiling point ranging between 145 and 300°C [Tesseraux, 2004]. Each hydrocarbon molecule has its own chemical and physical characteristics such as boiling temperature, freezing temperature, density, specific energy and energy density, depending on the number of carbon atoms and on the bonds formed between these atoms [Hileman *et al.,* 2009].

Aviation can be divided into two categories, either commercial or military aviation [Penner *et al.,* 2000]. The main focus of this study is on civil aviation, which consumes 80% of the fuel used in aviation [Brasseur *et al.,* 1998]. Kerosene-type jet fuel will be referred to as conventional jet fuel, in this study. The specifications for conventional jet fuel have been established by the American Society for Testing & Materials (ASTM) [Maurice *et al.,* 2001]. A typical composition of conventional jet fuel can be described as 20 percent normal paraffins, 40 percent isoparaffins, 20 percent naphthenes, and 20 percent aromatics. The fuel's hydrogen content ranges between 13.4 and 14.1% by mass [Brasseur *et al.,* 1998]. Neither halogenated compounds nor metals are allowed as additives to the fuel [Tesseraux, 2004]. However, metal contaminants such as iron, zinc, and copper might be present (in small ppb range) due to possible leaching from plumbing and storage systems. Moreover, requirements for conventional jet fuel specify a maximum freezing point of -47 °C in order to be suitable for long, low-temperature and high-altitude flights [Penner *et al.,* 2000, Lee *et al.,* 2010]. Also, the fuel may contain up to 0.3% sulphur by weight. However, in reality the level of sulphur is usually less than 0.1% [Metz *et al.,* 2007], and in the range of 0.04 and 0.05% [Brasseur *et al.,* 1998].

2.2 Air transport and environmental impacts

As noted earlier, the increased demand on aviation is linked to an increase in the environmental impacts of aviation. Today, more attention is being directed towards aviation's emissions, because aircraft fly several kilometres above the earth's surface (in the troposphere or stratosphere), while other natural and anthropogenic sources produce their emissions at the earth's surface [Penner *et al.,* 2000]. It is worthy to note that most aircraft emissions occur at the troposphere level. As such they have the ability to induce serious environmental damage [Lee *et al.,* 2010, Forster *et al.,* 2006]. However, the aviation industry is working towards reducing its environmental impacts through new policies, technologies, infrastructures and improved efficiencies. Moreover, there is a trend to promote environmental sustainability in all air transport activities, and to adopt the concept of green aviation [CCS, 2009].

2.2.1 Emissions from air transport

Emissions from air transport have been taken into consideration since the late 1960s and early 1970s, following the commercial interest in supersonic aircraft (the Concorde), which is thought to be able to induce environmental impacts on the stratosphere [Lee *et al.,* 2010]. Emissions from aircraft depend on several factors such as aircraft efficiency, engine type, engine load and fuel composition [Tesseraux, 2004]. Compressed intake air which is the working fluid is mixed and burned with fuel in the combustor section. As a result, energy is produced from the combination of oxygen atoms in the air with carbon and hydrogen atoms in the fuel [Eberhard & Brewer, 2005]. The main GHGs emitted from the combustor exhaust are carbon dioxide and water vapour, with the exact proportions depending on the specific fuel carbon/hydrogen (C/H) ratio [Brasseur *et al.,* 1998]. These emissions contribute to global warming by preventing the infrared radiation from leaving the earth's atmosphere, which eventually leads to higher global temperatures [Lee *et al.,* 2009]. Carbon monoxide (CO), nitrogen oxides (NO_x), soot/particulates and a large number of organic compounds constitute the secondary products of aircraft exhaust emissions [Tesseraux, 2004]. The concentration of secondary products in the jet exhaust highly depends on the design of the combustion chamber [Brasseur *et al.,* 1998].

Carbon dioxide, which is the most important greenhouse gas emitted worldwide, is one of the primary products of kerosene combustion, with the amount of CO_2 emitted depending on the carbon content of the fuel [Penner *et al.,* 2000]. Today, air transport contributes to 3 % of total anthropogenic emissions of CO_2 [Anger & Kohler, 2009], which is approximately 1,468 million tonnes per year [IATA, 2004]. In 2050, air transport's contribution to global anthropogenic CO_2 emissions is expected to reach 7% [Penner *et al.,* 2000], and it is expected to be among the most important contributors to global warming [Whitelegg & Williams, 2000]. Moving to another combustion by-product, nitrogen oxides are emitted due to high combustion temperature and high pressure [Wardle, 2003]. The emission indices of NO_x range between 5 and 25 g of NO_2 per 1 kg of burned fuel [Penner *et al.*, 2000]. Although the proportion of total anthropogenic NO_x emissions is only 1.3% [IATA, 2004], it is assumed that NO_x, emitted from air transport, can have a greater impact on the climate than ground level emissions of NO_x, which are more subject to mixing and turbulences [Kivits *et al.*, 2010]. Moreover, studies show that NO_x emissions from aircraft are contributing to higher ozone levels (an important GHG) in the upper troposphere and lower stratosphere [Forster *et al.,* 2006]. According to calculations, a 6% increase in the ozone concentration, during the summer time, in the principal air transport traffic areas, can be detected [Whitelegg & Williams, 2000]. In addition to the warming effect from ozone creation, NO_x emissions are thought to have the ability to participate in the destruction of methane in the atmosphere, thus contributing to a cooling effect [Green, 2009, Penner *et al.*, 2000]. Moreover, the warming potential of NO_x is expected to be greater than its cooling potential [IATA, 2004].

2.2.2 Standards for air transport emissions

Aircraft emissions are subject to standards set by the International Civil Aviation Organization (ICAO), which is an agency established by the United Nations to oversee and cooperate the efforts related to the international civil aviation [ICAO, 1997]. Engine emission standards are present in the Annex 16 of the Chicago convention held by the ICAO, which took place in Chicago in 1944 [ICAO, 1944]. These standards tackle only the landing and take-off (LTO) cycle of aircraft; thus, they do not address aircraft emissions at high altitudes [Gopinathan & Sudhakaran, 2009, Lior, 2010]. Although these standards aim to limit emissions during the LTO cycle, they can also help decrease exhaust emissions at altitude. The regulated emissions include hydrocarbons, NO_x, CO and smoke number [Tesseraux, 2004]. It is noticeable that the standards do not tackle CO_2, water vapour or SO_2 emissions. As for SO_2 emissions, they are limited by the sulphur content specification, which is present in the ASTM standard for jet fuel (less than 0.3% mass) [Hileman *et al.*, 2009], while water vapour is limited by the standard's requirement for the fuel hydrogen content to be between 13.1 and 13.4% by mass [Penner *et al.*, 2000].

2.2.3 Environmental initiatives and improvements

2.2.3.1 Technological improvements

As a result of the growing demand on flying, and the increased contribution of aviation to GHG emissions, the air transport sector is aiming to achieve a green aircraft industry, by reducing its carbon footprint through several initiatives at the technological, operational, infrastructure, policy and fuel levels [CCS, 2009]. In the past years, aircraft emissions have been reduced due to technological advancement, which has lead to more efficient fuel combustion [Penner *et al.,* 2000, IATA, 2009a]. The amount of fuel burned per seat in today's new aircraft is 70% less than the amount of fuel burned in early aircraft, in the 1960s, due to the advancement from early turbojet to high bypass ratio turbofan engines [Brasseur *et al.*, 1998, Edwards *et al.,* 2004]. It is anticipated that an additional 15 to 20% fuel efficiency can be achieved with newer aircraft designs [Dagget *et al.,* 2007, Metz *et al.*, 2007], and that the emissions per aircraft can be reduced by 20 to 35% [IATA, 2009a]. Some of the new technologies include innovative plane designs, lighter composite materials, new engine advances [IATA, 2009b] and improved airframe technology [CCS, 2009].

2.2.3.2 Operational improvements

Moreover, operational measures can be adopted to reduce the inefficiencies in aircraft fuel consumption [Green, 2009]. It has been identified that there are at least 6% inefficiencies in aircraft operations, which can be improved [IATA, 2009b]. Examples include reducing aircraft’s non-essential weight, carrying a full passenger load per aircraft [IATA, 2009a, CCS, 2009], taxiing with a single engine, optimizing cruise speed and altitude [IATA, 2004], following more direct routings, eliminating stacking before landing and eliminating holding before take-off. Such measures are anticipated to be able to reduce fuel burn by 2-6% [Green, 2009]. In 2008, improved operational measures were able to cut 11 million tonnes of CO_2 emissions from aviation [IATA, 2009b].

2.2.3.3 Infrastructural improvements

At the infrastructure level, 12% inefficiencies have been identified in air transport. The key to an improved infrastructure, which can limit aircraft emissions, is mainly through a more efficient air traffic management (ATM) [CCS, 2009]. The ATM consists of improving en-routes and airport infrastructure, and it sometimes includes the omission of national boundaries such as the single European sky initiative [IATA, 2009b, Green, 2009]. The single European sky initiative can save approximately 350,000 wasted flight hours per year, which is equivalent to 25 million tonnes of CO_2 emissions [IATA, 2004]. The application of a more efficient ATM can be achieved in a short period of time, at a global level, and can achieve a 10% reduction in aircraft fuel combustion [IATA, 2009a, Green, 2009]. Other infrastructural improvements can be carried out at the level of surveillance, navigation and communications.

2.2.3.4 Policy initiatives

At the policy level, several options can be implemented to help reduce the carbon footprint of the aviation sector. Among these options is the inclusion of the aviation sector in an emission trading scheme and the internalization of external costs of the aviation sector, by including the cost of emissions from aircraft [Rothengatter, 2010]. It is expected that an international cap on CO_2 emissions will be applied by 2020 on all airlines [IATA, 2009b]. This cap should be reduced after a period of time, in order to aim for lower CO_2 emissions [Rothengatter, 2010]. At the policy level, it is very important to ensure a global sectoral approach [ICAO, 1997]. This global sectoral approach should follow up on the Kyoto protocol initiative, in order to reduce aviation emissions, which are produced over several countries, and which do not abide by national boundaries [Scheelhaase & Grimme, 2007]. The global sectoral approach prevents the overlapping and conflicting regional and national policies [IATA, 2009a]. Also, it is crucial for the applied policies not to lead to what is called "carbon leakage", where emissions are not reduced, but produced in other locations, where such environmental policies do not exist [CCS, 2009].

Concerning the emission trading scheme, it is a cost effective method to cut down on emissions, whereby a specified authority sets a market for emission trading [Anger *et al.*, 2008]. The emission quotas can be distributed by the authority through auctions to airlines [IATA, 2004]. Auctioning quotas might lead to an increase in prices and to the domination of market by large airline companies, where those which pay more will have higher quotas [Rothengatter, 2010]. Another possibility is to distribute the quotas free of charge based on previous emissions of airlines (Grandfathered method), which can bring negative consequences to those airlines that have been improving their emission efficiencies in the past [Anger & Kohler, 2009]. Last but not least, is to distribute the quotas based on the airline's emission efficiencies in comparison to the sector's average emission efficiencies (Benchmarked method) [IATA, 2009b].

Another possible policy which can reduce the emissions of the aviation sector is the internalization of aviation external costs. It is similar to the polluter-pays principle. The internalization of aviation external cost is a mechanism for transport demand management, whereby the pollution cost is made transparent and carried out by the polluter. There are several methods which can be applied to internalize external costs in the aviation sector. Among these are charges on fuel, charges on seats or tickets, charges on aircraft landing or charges related to the levels of emissions [Whitelegg & Williams, 2000]. Such charges will lead to an increase in tickets' prices, which will eventually lead to a decrease in the demand on aviation. As such, fewer flights will take off, and less emission will be produced [IATA, nd]. Studies have shown that the most efficient method is to apply charges based on emission levels, since such charges will avoid competitive distortions between airlines.

2.3 Alternative jet fuels

Another constituent of green aviation is the adoption of alternative fuels [Kivits *et al.,* 2010], which is the main focus of this inquiry. When considering alternative fuels, several factors should be taken into consideration, in addition to the fuel's environmental impacts. Among these factors are the cost of fuel production, the sustainability of the fuel supply and the safety and reliability of the fuel [Hill *et al.,* 2006]. Among the considered alternative fuels for aviation are the ultralow-sulphur jet fuel, synthetic fuels derived from the Fischer-Tropsch (FT) synthesis, biofuels and cryogenic fuels [Kivits *et al.,* 2010].

2.3.1 Ultralow-sulphur jet fuel

Starting with the first option, the ultralow-sulphur (ULS) jet fuel is derived from conventional petroleum sources such as crude oil. The only difference between ULS jet fuel and conventional jet fuel is that the sulphur content of ULS jet fuel can reach a maximum of 0.0015% by mass [Hileman *et al.,* 2010], whereas in conventional jet fuel, the maximum sulphur content is 0.3% [Brasseur *et al.,* 1998]. ULS jet fuel emits less SO_x emissions than conventional jet fuel. ULS jet fuel offers a better thermal stability than conventional jet fuel, which leads to a decrease in the corrosion of engine components and reduces the need for maintenance. Moreover, ULS jet fuel is technologically and economically viable. However, one important issue with UlS jet fuel is the fact that it produces more GHGs during its production than conventional jet fuel [Hileman *et al.,* 2010] .

2.3.2 Fischer-Tropsch synthetic fuel

Another alternative jet fuel can be derived from natural gas or coal through the FT synthesis [Dagget *et al.,* 2007, Edwards *et al.,* 2004]. The feedstock type does not affect the characteristics of the final product (jet fuel), in terms of compatibility with aircraft and in terms of combustion emissions, but it does affect the production cost and the overall life-cycle GHG emissions. The FT synthesis depends on high temperature, pressure and catalysts to produce bio-synthetic gas [Lee *et al.,* 2009, Zinoviev *et al.,* 2010]. The bio-synthetic gas is later transformed into liquid fuels, from which jet fuel can be obtained [Dagget *et al.,* 2007]. The production of FT synthetic fuel emits more GHG emissions than the production of conventional jet fuel, unless it was coupled with biofuels, as an additional feedstock to coal or natural gas. On the other hand, FT synthetic fuel has negligible amounts of nitrogen and sulphur, unlike conventional jet fuel [Edwards *et al.,* 2004, Hileman *et al.,* 2010].

2.3.4 Cryogenic fuel

Cryogenic fuels, such as liquid hydrogen, are present in their gas phase at normal ambient conditions and can be stored in their liquid forms at low temperatures or high pressures [Maurice *et al.,* 2001]. These alternative fuels offer the great advantage of having a low to zero carbon content, but their large-scale adoption is still hindered by technological and economic barriers [Lior, 2010]. The adoption of hydrogen fuel, for example, can reduce CO_2 emissions from aircraft, but on the other hand, it can lead to an increase in H_2O emissions from aircraft, which are responsible for contrail formation [Akerman, 2005]. Moreover, the adoption of cryogenic fuels will require vast modifications in airport infrastructures and aircraft components [Kivits *et al.,* 2010]. Therefore, cryogenic fuels are seen as a long term solution to the environmental impacts induced by air transport [Dagget *et al.,* 2007].

2.3.5 Biomass-derived fuels

Other alternative jet fuels can be derived from biomass, known as bio-jet fuels [Hileman *et al.*, 2010]. The air transport sector is showing a great interest in biofuels, in the hope to make a transition from non-renewable to renewable energy resources [Rajagopal *et al.*, 2009]. The air transport's interest in biofuels has both environmental and economic motives such as securing a source of fuel that can be available at an acceptable price from domestic sources and that has lower environmental impacts than conventional jet fuel [Lee *et al.*, 2009]. However, adopting biofuels in the aviation industry has to comply with several environmental, technological and economic criteria [Stratton, 2010]. Biofuels used in aviation should have lower GHG emissions on a life-cycle basis than conventional jet fuel, and not just during the combustion phase [Kivits *et al.*, 2010]. Most importantly, to be able to adopt them in air transport without delays, biofuels need to be suitable as drop-in fuels, which can be used with the existing infrastructure.

This thesis focuses on the use of biofuels, in aircraft. Biofuels are expected to become a major component of the fuel supply for the aviation industry, as they are anticipated to require only minor changes to the industry's infrastructure [Dagget *et al.*, 2007]. In addition, more and more policies around the world are encouraging and requiring blending mandates of biofuels and conventional fuels, in the transport sector, and soon these mandates will be applied to the air transport sector as well [Rajagopal *et al.*, 2009]. Therefore, it is crucial to assess the economic, technological and environmental feasibility of the adoption of biofuels in the aviation industry in order to identify the opportunities and challenges [Papalexandroua *et al.*, 2008].

2.4 Biofuels

As a general definition, biofuels consist of solid, liquid, or gaseous fuel derived from biomass [Goldemberg *et al.*, 2001, Patil *et al.*, 2008]. Biomass consists of green plants' organic material produced through photosynthesis by converting sunlight, carbon and water into energy in the form of chemical bonds. Biofuels derived from vegetable oils had been employed prior to the industrial revolution in the 19^{th} century. The first known feedstocks were peanut, hemp, corn oil and animal fats [McKendry, 2002]. By the mid- and late 1800s, the interest in biofuels had dropped, due to the production of cheap petroleum-based fuels, which helped the growth of the industrial revolution, by powering factories and automobiles [Wik, 1962].

The renewed interest in renewable energy resources and in biofuels in particular has been mainly attributed to the 1970s oil crises [Songstad *et al.*, 2009]. Also, as fossil fuel resources are proving to be unsustainable, biofuels are seen as a potential answer to the sustainable energy quest. Based on the feedstock and the production technology used, biofuels can be divided into two types; first and second generation biofuels [Naik *et al.*, 2010, Sims *et al.*, 2010]. First generation biofuels are obtained from edible feedstocks or food crops containing sugars, starches or vegetable oils [Sims *et al.*, 2010], or from industrial, agricultural, forestry and household wastes, which are biodegradable. First generation biofuels also refer to those biofuels obtained from traditional technologies yielding ethanol, biodiesel and biogas [Brennan & Owende, 2010]. Biofuels offer many economic and environmental advantages [Naik *et al.*, 2010]. The most important environmental advantage of biofuels is the ability to recycle CO_2 emissions [McKendry, 2002]. The carbon absorbed during feedstock growth is emitted during combustion, unlike the use of non-renewable fossil fuels, where the fossilized carbon is re-introduced into the carbon cycle [Sims *et al.*, 2010]. Other advantages include the ability to increase domestic energy supply and the ability to be blended with fossil-based fuels [Naik *et al.*, 2010].

2.4.1 First generation biofuels

First generation biofuels such as ethanol and biodiesel are produced at a large commercial scale, which means that the production technology of first generation biofuels is mature and well established [Sims *et al.*, 2010]. The call to adopt first generation biofuels as a replacement for fossil fuels, in the transport sector, has been met by scepticism, concerning their ability to reduce GHG emissions; thus, their ability to limit global warming [Goldemberg *et al.*, 2001, Reijnders & Huijbregts, 2009]. Taking a life-cycle assessment perspective, some first generation biofuels are shown to increase GHG emissions [Mata *et al.*, 2010], due to their need for intensive fertilization, which emits GHGs such as N_2O. Also, first generation biofuels depend on machinery and energy for cultivation and transportation, which consume fossil fuel resources; thus, produce GHG emissions [Schenk *et al.*, 2008]. The production of first generation biofuels can account for 10% of life-cycle GHG emissions, whereas the combustion of biofuels can emit about 90% of their life-cycle GHGs [IEA, 2004]. Moreover, land changes play an important role in determining the degree to which biofuels are carbon-neutral or not [Rajagopal *et al.,* 2009, Sims *et al.,* 2010]. For example, clearing rainforest regions to grow feedstock for biofuels can lead to an increase in CO_2 emissions, because forests tend to absorb more CO_2 than biofuel crops, which will eventually release the absorbed CO_2, once the biofuels are used [Schenk *et al.,* 2008].

Moreover, first generation biofuels have been produced from edible feedstock such sugarcane, corn, wheat, rapeseed and soybean [Reijnders & Huijbregts, 2009]. As such, large-scale production of biofuels from these food crops to cover the energy needs of the transport sector, has led to the controversy of food versus fuel. The fear is that biofuel crops will take over farmlands and increase food prices [Khan *et al.,* 2009, Sims *et al.,* 2010]. This controversial issue is especially frightening in developing countries, where favouring biofuel production over food production can have serious negative effects such as food shortages. Such impacts can have detrimental effects on developing countries, where famine and malnutrition already affect more than 800 million individuals [Schenk *et al.,* 2008]. This in addition to the concerns related to increased deforestation and threats on biodiversity, by converting forests into farmlands of monoculture crops. Other concerns with first generation biofuels relate to the competition of biomass with food crops on fresh water resources [Brennan & Owende, 2010, Naik *et al.,* 2010].

2.4.2 Second generation biofuels

As for second generation biofuels, they are mainly derived from non-food feedstocks [Mata *et al.,* 2010, Naik *et al.,* 2010]. Second generation biofuels can be derived from terrestrial sources such as woody and lingo-cellulosic plants or from aquatic sources such as algae [Singh & Gu, 2010, Sheehan *et al.,* 1998]. The quest for second generation biofuels was driven by the obstacles facing the large-scale adoption of first generation biofuels. Some of the benefits of second generation biofuels include higher energy yields per hectare than first generation biofuels, due to their faster growth rate and higher energy content, and to their ability to use poorer land quality. Also, second generation biofuels have the ability to reduce the dependency on imported oil and to diversify the energy supply. Most importantly, second generation biofuels do not compete with food sources and can offer a high potential for carbon fixation

[Brennan & Owende, 2010]. Also, second generation biofuels have the ability to increase income opportunities, especially in the agricultural sector [Singh & Gu, 2010].

Second generation biofuels are not widely available yet, because the conversion technologies from feedstock to desirable fuels are not cost competitive. However, it is expected that with the support of strong policies, second generation biofuels can surpass the current production capacity of first generation biofuels [Sims *et al.*, 2010]. The production of second generation biofuels is taking place mainly at a pilot scale level [Schenk *et al.*, 2008], providing less than 0.1% of global biofuel production. The interest in second generation biofuels is increasing with time as more advantages and benefits are being discovered, through research and development activities. The ultimate aim of research and development is to be able to produce sustainable and cost competitive biofuels, which can be carbon-neutral or carbon-negative [Cseke *et al.*, 2009], especially in terms of life-cycle assessments, to confirm that there is a valid basis behind the transition from first to second generation biofuels [Singh & Gu, 2010]. Among the most promising feedstocks for second generation biofuels are aquatic plants [Mata *et al.*, 2010].

2.5 Microalgae

There is a focus on aquatic biomass since the earth is mainly covered with water surface [Singh & Gu, 2010]. The focus is mainly on those fast growing organisms such as microalgae, which hold promising environmental and economic potentials [Velasquez-Orta *et al.*, 2009]. Microalgae, those 'miniature biochemical factories' [Patil *et al.*, 2008], are thought to be around since the beginning of life on earth [Sheehan *et al.*, 1998]. Microalgae are microscopic, unicellular and simple multi-cellular organisms [Singh & Gu, 2010]. These green organisms, which are rich in chlorophyll, contain carbohydrates, proteins and natural oils [Velasquez-Orta *et al.*, 2009]. They can be prokaryotic (lacking membrane-bound organelles), such as Cyanobacteria or they can be eukaryotic, such as green algae, red algae and diatoms, which have a high ability to retain lipids [Singh & Gu, 2010].

Microalgae depend on sunlight to convert carbon into organic matter, such as biofuels, foods (for zooplankton), feeds or "high-value bioactives" [Chisti, 2007]. These sunlight driven cells use solar energy for their growth along with carbon, and convert them into energy in the form of chemical bonds [IEA, 2004]. Microalgae are proved to grow at a faster rate than any other photosynthetic organism; thus, higher biomass yields can be obtained from microalgae than from terrestrial crops. They can complete a growth cycle in a period of time ranging from as short as 3.5 hours to few days [Cseke *et al.*, 2009]. Moreover, due to the simple development and structure of microalgae, they are able to grow in severe climates (extremophilic conditions) for long periods of time, as long as they are supplied with a source of light [Wulff & Hourmouziadis, 1997]. Microalgae can grow in aqueous media, including saline water and wastewater [Mata *et al.*, 2010, Cseke *et al.*, 2009] and on arid lands such as deserts, which are not suitable for agricultural crops, thus reducing the competition with food crops on arable lands, and reducing the need for freshwater resources. Furthermore, unlike terrestrial crops, microalgae do not need herbicides and pesticides during cultivation [Brennan & Owende, 2010].

Microalgae have been under research for more than sixty years [Tsukada *et al.*, 1977]. The concept of producing energy from microalgae is not new [Chisti, 2007]. The concept started with researchers trying to produce methane gas from cultivated algae in wastewater (source of nutrients) in the beginning of 1950s. As for the first large-scale culture of microalgae, it started in the early 1960s in Japan with the culture of *Chlorella* [Tsukada *et al.*, 1977]. Then the concept of producing energy from microalgae grew further with the energy crisis in the 1970s [Schenk *et al.*, 2008]. The interest in microalgae was further revealed by the government of the United States in the 1980 when the US Department of Energy initiated the aquatic species program, which aimed at producing transportation fuels such as biodiesel from microalgae, cultivated in ponds and fed with CO_2 from coal fired power plants [Solomon & Hughey, 2007].

This growing interest in microalgae, nowadays, is attributed to the increased need for alternative and renewable sources of energy, which can free the economy from its dependence on petroleum sources [Stratton, 2010] and which can tackle the concern of global warming [Cseke *et al.*, 2009, Wong, 2000]. An American study estimated that the energy per acre from microalgae can be thirty times greater than the energy per acre from terrestrial crops such as soybean [Singh & Gu, 2010]. Another study estimated that 61% of the US agricultural croplands would be needed to meet its transportation requirements when using palm oils, whereas only 3% would be needed when using microalgal oil [Chisti, 2008]. Microalgae have a high biomass production capacity and they can provide all-year-round supply of feedstock, unlike terrestrial crops which can be harvested once or twice a year [Chisti, 2008][Mata *et al.,* 2010].

2.5.1 Microalgae fuels

After cultivation, microalgae should be harvested and further processed to obtain the desired fuels. Different methods of harvesting are available, depending on the microalgae strain. After harvesting, microalgae are further processed, in order to obtain the desired microalgae components such as oil, protein and starch, which can be transformed into fuels [Schenk *et al.,* 2008]. Different processing methods can be applied known as biochemical or thermochemical processes [Naik *et al.,* 2010]. Choosing between these two processes depends on the type and amount of feedstock used, the type of fuel obtained, the cost, and the end use of the fuel produced [Brennan & Owende, 2010].

2.5.1.1 Biochemical conversion

Biochemical conversion includes anaerobic digestion, which produces methane from wet organic compounds such as microalgae in the absence of oxygen. A study was first published in the early 1950s, tackling the feasibility of producing methane from microalgae [Meier, 1955]. The study concluded that methane production from microalgae can be achieved due to their relatively high lipid, starch and protein content [Mata *et al.,* 2010]. Today, the production of methane from microalgae is not cost competitive with the methane produced from terrestrial crops, such as maize. Also through biochemical conversion, hydrogen (H_2) can be produced from microalgae. The photo-biological production of hydrogen from microalgae uses sunlight to convert water into hydrogen ions and oxygen atoms [Mata *et al.,* 2010]. Then, hydrogenase enzymes convert the hydrogen ions into H_2 [Brennan & Owende, 2010]. The process still needs bioengineering development to make it more efficient [Mata *et al.,* 2010]. Hydrogen from microalgae has a great advantage in the fact that the hydrogen does not accumulate in microalgal cells, but it is released into its gas phase [Mata *et al.,* 2010]. Also, another advantage is that hydrogen is a carbon-free fuel [Brennan & Owende, 2010, IATA, 2008].

The two most important alternative transportation fuels, biodiesel and bioethanol, can also be obtained through biochemical conversion. Ethanol can be produced through alcoholic fermentation, from biomass containing starch and sugars such as *C. Vulgaris* [Brennan &

Owende, 2010, Mata *et al.,* 2010]. Transesterification, another biochemical process can yield biodiesel or mono-esters through the chemical reaction involving triglycerides and alcohol [Chisti, 2008]. Biodiesel from microalgae has similar chemical and physical properties to petroleum diesel. On the other hand, microalgal biodiesel supersedes petroleum diesel by contributing to lower particulate, CO and hydrocarbon emissions during combustion [Schenk *et al.,* 2008]. However, microalgal oil is rich in polyunsaturated fatty acids which lead to fuel oxidation during storage, thus reducing the suitability of microalgal biodiesel. This problem can be overcome through hydrogenation of microalgal oil [Chisti, 2007].

Unfortunately, neither bioethanol nor biodiesel are seen as suitable alternative fuels for aviation [Hileman *et al.,* 2009]. Methane and hydrogen have been mentioned earlier as long term solutions to aviation's environmental impacts [Dagget *et al.,* 2007]. The physical and chemical properties of bioethanol make it unsafe for use in aircraft, as it has low energy density, high volatility and high flash points [Hileman *et al.,* 2009]. Moreover, bioethanol requires more space and weighs more than conventional jet fuel, to supply the same amount of energy [Dagget *et al.,* 2007]. The main obstacle for using biodiesel in aviation is its high freezing point which approaches 0˚C, far higher than the freezing point of conventional jet fuel which is -47˚C [Hemighaus *et al.,* 2006]. Additives can be used to reduce biodiesel's freezing point, but they can only reduce it by few negligible degrees Celsius. Therefore, currently biochemical conversion is not regarded as a reliable process to produce alternative jet fuel. Thermochemical conversion, on the other hand offers the potential of producing a new fuel from microalgae which can be suitable for use in aviation [Sims *et al.,* 2010].

2.5.1.2 Thermochemical conversion

Thermochemical conversion depends on heat to transform biomass into fuels [Brennan & Owende, 2010]. There exist several types of thermochemical conversion processes. Gasification transforms biomass at high temperatures, in the presence of water and oxygen into gases such as CO, H_2, CO_2, and CH_4 [Naik *et al.,* 2010]. Another thermochemical process can yield bio-oils from wet microalgae, known as thermochemical liquefication. Thermochemical liquefication employs low temperature (300–350˚C), high pressure (5–20 MPa) and a catalyst to make the transformation; thus, it is energy intensive [Brennan & Owende, 2010]. Pyrolysis, another conversion method, uses medium to high temperatures (350-700˚C) to transform biomass into bio-oil, syngas and charcoal under anaerobic conditions [Naik *et al.*, 2010]. However, bio-oils produced through pyrolysis cannot be directly used as fuels since they are acidic and unstable. Another thermochemical conversion process is known as hydro-processing, which consists of adding hydrogen while at the same time removing oxygen in the presence of catalysts [Amin, 2009]. Hydro-processing followed with isomerization and cracking leads to high quality fuels, which are rich in paraffins and suitable for the use in aircraft [Hileman *et al.,* 2010].

Since thermochemical routes can yield a range of long-chain hydrocarbons, which include biofuels suitable for aviation [Sims *et al.*, 2010], the main focus of this thesis was on microalgal fuels derived from microalgal oil through thermochemical processes. The aviation industry has shown a great interest in microalgal jet fuel as a potential alternative fuel [Kivits *et al.,* 2010]. The question is whether this source of fuel is economically competitive, technologically feasible and whether it is environmentally sustainable. Therefore, a thorough assessment needs to be conducted before adopting a new alternative source of fuel. Such an assessment can prohibit labelling any new source of energy as the ultimate solution before carrying out suitable analytical studies.

Chapter 3: An overview of fuel production considerations

3.1 Microalgal hydro-renewable jet fuel

3.1.1 Microalgae selection

As mentioned before, the first step to a successful production of microalgal fuel starts with the careful selection of microalgal strain [Brennan & Owende, 2010]. Supposedly, more than 50,000 strains of microalgae exist but only 30,000 strains have been characterized and studied [Mata *et al.,* 2010]. When biofuels are the end product desired, several aspects need to be tackled in order to choose the most productive strain. First of all, microalgal lipid content is the most important feature for biofuel production [Schenk *et al.,* 2008].When choosing the strain, one has to decide whether to go for the very high lipid content accompanied with low cell productivity or moderate lipid content accompanied with high cell productivity [Mata *et al.*, 2010], as these two characteristics are mutually exclusive in natural strains [Ratledge & Cohen, 2008]. Normally, microalgae can accumulate between 10%-50% of their dry weight in oil content [Chisti, 2007]. Oil accumulation higher than 50% is usually associated with low cell productivity [Schenk *et al.,* 2008].

3.1.2 Site selection

The next important step in microalgae cultivation is choosing the appropriate site. When assessing a potential site, several criteria need to be inspected and regulated. These criteria are divided between abiotic and biotic factors [Moheimani, 2005]. The abiotic factors, also known as the physical factors, are related to lighting, water, CO_2 and nutrients [Maxwell *et al.,* 1985]. Examples of the abiotic factors include the quantity and quality of light, the quantity and quality of the water supply, the water salinity, the amount of dissolved oxygen and carbon dioxide, the water pH, the surrounding climate including temperature [Maxwell *et al.,* 1985, Schenk *et al.,* 2008], the rate of evaporation and precipitation, and the availability of nutrients and carbon sources [Moheimani, 2005].

Researchers assert that both light and temperature play major roles in the productivity of microalgae [Mata *et al.,* 2010]. Strong and intense light can lead to a decrease in the efficiency of photosynthesis performed by the microalgal culture [Moheimani, 2005, Ginzburg, 1993]. This decrease in efficiency is known as photo-inhibition and it is described "as a loss of the photosynthetic capacity due to damage caused by high irradiance" [Moheimani, 2005]. Therefore, it is important to match the microalgal strain with the right location by considering the duration of sunlight per day [Ginzburg, 1993]. Concerning temperature, each microalga has its own optimum growth temperature which allows it to reach its maximum growth rate, but generally the optimal temperature to grow microalgae ranges between 20 and 30°C [Chisti, 2007]. It is thought that a decline in temperature can be tolerated by most microalgae strains, while an increase by only 2-4 °C from the optimal microalgal temperature can lead to a destruction of the culture [Chisti, 2007, Mata *et al.,* 2010].

Moreover, the land topography and geology also need to be carefully considered [Schenk *et al.*, 2008]. Enough space must be available to construct microalgae cultivation and production systems [Maxwell *et al.*, 1985]. Concerning the topography, land slope must be less than 10% and soil depth must be minimal to allow the construction of cost efficient, large cultivation systems. The selected land needs to supply the resources, required for the growth of microalgae such as carbon and water [Maxwell *et al.*, 1985]. Different strains of microalgae can grow in different aquatic media ranging from freshwater to sea-water, including brackish water [Ratledge & Cohen, 2008]. This characteristic can decrease the stress on freshwater [Maxwell *et al.*, 1985]. The use of saline water depends on the location selected, either next to coasts or nearby saline groundwater [Satyanarayana *et al.,* 2010]. On the other hand, the biotic factors include the presence of parasites and predators which can compete with microalgae, on nutrients [Moheimani, 2005, Mata *et al.*, 2010].

3.1.3 Microalgae nutrients

Nutrients are essential to obtain a significant amount of biomass from microalgae cultures. The nutrients needed are mainly inorganic compounds such as CO_2, phosphorus and nitrogen, [Chisti, 2006]. Providing these elements for microalgae cultures is generally considered to be inexpensive [Powell *et al.*, 2009]. Ninety percent of the hydrocarbons formed through microalgal photosynthesis are made from carbon, whereas the other 10% is constituted of hydrogen [Ginzburg, 1993]. Moreover, 50% of the dry biomass weight is attributed to carbon content [Patil *et al.*, 2008].

The source of this carbon, obtained by microalgae through biological uptake, is either from the 0.03% of carbon dioxide present in the atmosphere or from the flue gases of heavy industries and fossil fuel power plants, which are fed to microalgae cultures [Brennan & Owende, 2010]. However, when depending only on atmospheric CO_2, the productivity of microalgae will be very low and unsuitable for fuel production [Posten & Schaub, 2009]. Microalgae have a better ability to fix CO_2 than terrestrial crops, due to their faster growth rate. Unlike terrestrial crops, microalgae can grow on arid land; thus, they do not replace forests, which constitute an important carbon sink [Khan *et al.*, 2009]. It is recorded that 1 kg of microalgae can absorb about 1.83 kg of CO_2 [Chisti, 2007, Patil *et al.*, 2008]. The efficiency of CO_2 uptake by microalgae ranges between 30-99%, depending on the culture system, such as closed versus open system, and on the rate of culture mixing [Reijnders & Huijbregts, 2009]. This mechanism of CO_2 uptake allows the recycling of CO_2 [Mata *et al.*, 2010]. The CO_2 absorbed by microalgae during growth is re-emitted during microalgal biofuel combustion [Mata *et al.*, 2010]. In a one hectare area of cultivated microalgae, with a biomass productivity of $25g/m^2$.day, which has been attainable and maintained, approximately 500 kg of CO_2 can be absorbed [Schenk *et al.*, 2008].

The second most important nutrient is nitrogen, which comprises 10-13% of the organic dry weight of biomass [Posten & Schaub, 2009]. Another nutrient is phosphorus, an important constituent for cellular metabolism and regulation, which contributes to the production of enzymes and phospholipids in microalgae [Moheimani, 2005]. Phosphorus constitutes 1% of microalgae dry biomass weight [Powell *et al.*, 2009]. Therefore, a source of nitrogen and phosphorus should be added to the microalgae culture, in order to obtain high levels of productivity. Fertilizers can be used as a source of nutrients, as they contain nitrogen and phosphorus, and they are used to grow terrestrial crops [Posten & Schaub, 2009]. Another option, which can substitute the use of fertilizers, is to grow microalgae in wastewater instead of freshwater [Park *et al.*, 2011]. Wastewater can provide the needed nutrients for microalgae growth, since it can contain high concentrations of nitrogen and phosphorus [Pittman *et al.*, 2011].

3.1.4 Microalgae cultivation

To obtain high yields of biomass, microalgae cultures need to be provided with sufficient nutrients and growth stimulating factors [Schenk *et al.*, 2008]. Therefore, growing microalgae had to be shifted from natural ecosystems to sustained and controlled media, which can lead to maximal growth acceleration [Brennan & Owende, 2010]. In a well controlled culture, microalgal biomass can double within a period of 24 hours. Lack of monitoring and control of previously mentioned factors such as temperature, nutrients and pH can lead to a rapid deterioration of the culture and to contamination with other microalgal species, known as predators [Mata *et al.*, 2010]. Two options are available to maintain a controlled culture of microalgae, either open-culture systems such as lakes and ponds or closed-culture systems also known as closed photo-bioreactors [Grima *et al.*, 2003]. Open ponds are established outdoors while closed photo-bioreactors might be located indoors or outdoors [Reijnders & Huijbregts, 2009]. These artificial systems should mimic natural ecosystems, where microalgae usually grow and they should make use of the freely available sunlight [Solomon & Hughey, 2007], as such it is best to locate closed photo-bioreactors outdoors [Chisti, 2008].

3.1.4.1 Open ponds

Growing microalgae in open ponds has been known and practised since the 1950s [Goldman, 1979]. Open-culture systems can differ in size, shape, construction materials, mixing methods and inclination [Mata *et al.*, 2010, Moheimani, 2005]. Generally there are two types of open-culture systems, either natural waters such as lakes, lagoons and ponds or artificial ponds and containers [Brennan & Owende, 2010]. Most large-scale and commercial microalgae cultures in the United States, Japan, Australia, India, Thailand, China and elsewhere are grown in open ponds, since they are more cost efficient than closed-systems [Khan *et al.*, 2009]. Open ponds are simpler to establish and manage and they have a large production capacity, but lower than the production capacity of closed photo-bioreactors [Chisti, 2006]. Open ponds can serve for long periods of time, provided that the desired microalgal strain can be maintained [Khan *et al.*, 2009, Sheehan *et al.*, 1998].

In addition to the previously mentioned advantages, open ponds can be established in areas which are not suitable for agricultural crops; thus, they do not compete with food crops for land

[Brennan & Owende, 2010]. Also, they can be easily cleaned and maintained due to their large open surface area and they offer high potential for net energy production [Schenk *et al.,* 2008].

Open ponds have some disadvantages such as the need for energy to mix the nutrients and the need to keep the water level between 15 and 20 cm to allow sunlight penetration [Mata *et al.*, 2010]. Sometimes, the growth of a thick layer of microalgae on top of the pond might inhibit the penetration of sunlight into deeper water levels, thus reducing the productivity of microalgae [Brennan & Owende, 2010]. Moreover, open ponds are located outdoors, which makes them more vulnerable to weather changes, wide temperature ranges, evaporation, intensive lighting and to contamination from pathogens and parasites [Posten & Schaub, 2009]. Also, open ponds require a significant land space [Mata *et al.,* 2010].

On the long term, contamination of the microalgal culture might take over an open pond system [Reijnders & Huijbregts, 2009]. Therefore it is necessary to perform a cyclic process of cleaning and to re-inoculate the desired strain of microalgae every now and then [Schenk *et al.*, 2008]. Another way to prevent contamination consists of sustaining the microalgal culture in extremophilic conditions, which make the medium unfavourable for pathogens, thus allowing monoculture cultivation [Reijnders, 2008b, Yeang, 2008]. However, it is important to take into consideration that not all microalgae strains are capable of surviving in extremophilic conditions, such as in very high or low pH or in high salinity. It is worth mentioning that microalgae strains that are capable of surviving in harsh conditions normally have low oil yields [Yeang, 2008].

3.1.4.2 Closed photo-bioreactors

As mentioned before, open ponds, including raceway ponds, have several disadvantages such as occupying vast land spaces and being vulnerable to outdoor weather changes and to contamination [Chisti, 2008]. Therefore, other options to cultivate microalgae were introduced [Reijnders, 2008b]. Among these alternatives is the closed-system known as the closed photo-bioreactor (PBR), which is three-dimensional [Schenk *et al.,* 2008]. Closed photo-bioreactors have been intensively researched by the Japanese, French and German governments [Sheehan *et al.,* 1998]. Currently closed photo-bioreactors are deployed in pharmaceutical industries [IATA, 2007a].

There exist several types of closed photo-bioreactors such as tubular, flat-plated, rectangular, continued stirred reactors and many others. Tubular reactors are seen to be the most promising type of PBRs, for biofuel production [Demirbas & Demirbas, 2010]. Closed photo-bioreactors consist of highly transparent containers or tubes, made of plastic or glass and they have high mechanical strength and high durability [Mata *et al.,* 2010]. In a closed photo-bioreactor the desired microalgal strain is injected into transparent containers or tubes which allow the penetration of sunlight [IATA, 2007a, Moheimani, 2005]. Closed photo-bioreactors can either be placed outdoors to make use of cheap and available sunlight or they can be placed indoors and be artificially illuminated. However, artificial illumination is more expensive and it is not cost efficient for large scale biomass production [Chisti, 2008]. In addition to the microalgal culture, the containers or tubes are fed with water enriched with nutrients, and with CO_2 [IATA, 2007a]. It is important to prevent sedimentation, by creating a flow in the reactor either through a mechanical pump or an airlift pump [Chisti, 2006]. This adds to the cost of operating and maintaining the reactor [Yeang, 2008].

Closed photo-bioreactors offer many advantages such as water efficiency, by preventing evaporation [Posten & Schaub, 2009], energy and chemical efficiency, and a productivity that is higher than the productivity achieved in open ponds, taking into consideration the occupied land space [Reijnders & Huijbregts, 2009, Schenk *et al.,* 2008]. The cell densities in closed photo-bioreactors can reach as high as 20g/L [Posten & Schaub, 2009]. Moreover, closed photo-bioreactors aim at maximizing the photosynthetic efficiency of microalgae strains by providing a large surface area for sunlight distribution and by re-circulating the culture, nutrients and gases [Mata *et al.*, 2010]. Most importantly, closed photo-bioreactors protect microalgae cultures from contamination [Sheehan *et al.*, 1998, Yeang, 2008] and offer more control over the media characteristics such as temperature, dissolved oxygen and carbon dioxide concentrations and lighting exposure [Patil *et al.*, 2008]; thus, monoculture microalgae can be cultivated for extended periods of time [Chisti, 2007]. Due to the high ability to control media's characteristics in bioreactors, a wide variety of microalgae strains can be cultivated; thus, those strains which have high oil yields and little tolerance for extremophilic conditions can be used [Reijnders, 2008b]. Another advantage is the ability to easily clean the transparent materials used, such as tubes [Mata *et al.*, 2010].

Technological problems interfering with the widespread use of PBRs include microalgal growth on tube walls which prevents sunlight penetration, and difficulty to scale-up [Mata *et al.,* 2010]. Scaling-up closed photo-bioreactors can either be achieved with an increase in tubes diameters or length. The first option, can lead to an increase in dark areas in the tubes as more microalgae build up, resulting in a decreased light penetration [Xu *et al.,* 2009]. Increasing tube length can increase the residence time, such that the concentration of dissolved oxygen might reach super-saturation levels, thus inhibiting photosynthesis and leading to photo-oxidation [Chisti, 2007]. To prevent such an issue, a degassing zone must be incorporated into the design, where the microalgae culture can be aerated and oxygen can be removed [Chisti, 2006]. Moreover, due to the large surface area of the tubes, microalgae can be under intensive light. As such, a cooling system or a heat exchanger must be installed [Brennan & Owende, 2010, Moheimani, 2005]. Both closed photo-bioreactors and raceway ponds are considered technologically feasible to grow microalgae [Chisti, 2007].

3.1.5 Microalgae harvesting and drying

After cultivation, mature microalgal broth needs to be harvested and concentrated in order to be later processed into desirable end products [Brennan & Owende, 2010]. Unfortunately, due to the small size of microalgal cells, which ranges between 3 to 30 mm, and due to their low concentration in the medium or relatively high water content (80-90%), the harvesting procedure of microalgae can be challenging [Grima *et al.,* 2003, Patil *et al.,* 2008, Richmond, 2004]. Moreover, no one technique for harvesting microalgae can be considered as optimal for all strains and species [Packer, 2009, Schenk *et al.,* 2008]. The harvesting method varies according to strain features such as size and density and according to the quality of the final product desired [Brennan & Owende, 2010]. Many harvesting methods are applied in the field and each has its advantages and disadvantages [Mata *et al.,* 2010]. Examples of harvesting methods include sedimentation, filtration and centrifugation [Brennan & Owende, 2010, Mata *et al.,* 2010, Schenk *et al.,* 2008]. These harvesting techniques can be coupled with flocculation [Grima *et al.,* 2003].

Flocculation is a fairly widespread method, where polymers are used to bring together microalgae to form larger units, making them more easily harvested [Mata *et al.,* 2010, Schenk *et al.,* 2008, Richmond, 2004]. The efficiency of the flocculant used can be described in terms of the amount of flocculant needed to induce microalgal cells to coagulate as fast as possible [Richmond, 2004]. Researchers have recorded more than 80% efficiency using this method [Brennan & Owende, 2010]. The flocculants could either be inorganic chemicals (e.g., aluminum sulphate) or organic cationic polymer flocculants (e.g., Chitosan) [Schenk *et al.*, 2008]. When choosing between flocculants, it is crucial to consider the cost, toxicity and effectiveness of the flocculant, in addition to considering any harmful effects that the flocculant might induce on the end product, co-products or on the downstream processes [Grima *et al.,* 2003]. Flocculation is considered costly, but not as costly as centrifugation or filtration [Richmond, 2004]. Flotation on the other hand, does not require chemical addition to bring microalgae cells together; rather it uses air bubbles to bring microalgae to the surface of the medium [Brennan & Owende, 2010]. Naturally, there exist some microalgae strains which can perform flotation, with the increase of their oil content [Brennan & Owende, 2010]. However, little research has been conducted on flotation used for microalgae harvesting [Brennan & Owende, 2010].

The first issue concerning microalgae harvesting is related to the high water content of the biomass and to the small size of microalgae to be processed [Schenk *et al.,* 2008]. These facts, along with the necessity to match the right microalgal strain with its suitable harvesting method, if not taken into consideration, can lead to energy inefficient downstream processes, which could lead to further unnecessary costs [Schenk *et al.,* 2008]. Filtration, for example, is mostly suitable for relatively large microalgae which possess filaments [Brennan & Owende, 2010, Mata *et al.,* 2010, Schenk *et al.,* 2008]. Concerning filtration it is most used in laboratories and experiments, as it is slow and costly to maintain due to filter blockage with time [Grima *et al.,* 2003, Schenk *et al.,* 2008].

Moving to gravity sedimentation, a method widely used in algae farms, is considered, by itself, unsuitable when it comes to biofuel production from microalgae, as it needs large spaces and takes a great deal of time to separate the microalgae from the medium [Schenk *et al.,* 2008]. Sedimentation is especially used for considerably large microalgae, of sizes exceeding 70 mm [Brennan & Owende, 2010]. Concerning centrifugation, this method is seen to require plenty of energy and money to separate microalgae from the high water content [Packer, 2009, Schenk *et al.,* 2008]. In comparison to the other methods, centrifugation is regarded as an efficient technology that can separate microalgal biomass from the water content at a fast pace [Grima *et al.*, 2003]. Centrifugation consists of rapid sedimentation due to centrifugal forces, which can split the biomass from the liquid medium, depending on factors such as particle size and density [Richmond, 2004]. Centrifugation can achieve more than 95% of cell recovery [Uduman *et al.*, 2010]. It is mainly used to harvest microalgae with high value end products such as pharmaceuticals [Grima *et al.*, 2003].

As mentioned before, it is important to consider the right harvesting method which is suitable to the end product desired. One of the key criteria to be considered is the amount of acceptable moisture in the final product [Grima *et al.*, 2003]. The main goal of harvesting is to transform microalgal biomass from a total of 0.02-0.06% of solid matter into microalgal slurry that contains at least 2-15% of dry biomass [Singh *et al.*, 2011, Uduman *et al.*, 2010]. It is crucial to carry on with downstream processing as soon as possible, especially in warm climates, in order to preserve the usefulness of the biomass obtained. Similar to harvesting, downstream processing also depends on the final products desired. In this work, the interest is in obtaining biofuels from microalgal oils; thus, dehydration must follow the harvesting step, to reduce the moisture content of microalgal slurry [Grima *et al.*, 2003].

Several thermal drying methods have been applied to reduce the water content of microalgal biomass, including sun drying, spray drying and freeze drying, in addition to applying direct heat from fuel combustion [Brennan & Owende, 2010]. The least costly dehydration method is sun drying, mostly used for terrestrial crops [Richmond, 2004]. However, sun drying requires time and space [Brennan & Owende, 2010] [Li *et al.*, 2008], especially because microalgal biomass has a higher water content than terrestrial crops [Richmond, 2004]. Spray drying has been mostly used to obtain high value products such as pharmaceuticals, as it is an expensive method [Brennan & Owende, 2010]. Spray drying depends on droplets that are brought in contact with hot air to perform evaporation [Richmond, 2004]. Spray drying has the disadvantage of possibly destroying algal pigments. When the interest is in microalgal oil, it seems that freeze drying constitutes the most suitable dehydration method, as it facilitates oil extraction in the following processes [Grima *et al.*, 2003]. However, freeze drying is considered expensive for large scale biomass production [Brennan & Owende, 2010]. The use of heat from fuel combustion to dry microalgae seems to be the most suitable drying method, as long as the fuel source does not depend on non-renewable energy resources [Stratton, 2010].

3.1.6 Microalgal oil extraction

Once microalgal biomass has been dewatered and dried, oil extraction should take place [Mata *et al.*, 2010]. Oil extraction can either be performed mechanically by using cell homogenizers or ultrasound, or it can be performed in a non-mechanical way through the use of solvents [Brennan & Owende, 2010]. Homogenizers consist of applying high pressures to disrupt the cells. They are mainly applied for the extraction of proteins [Richmond, 2004]. Ultrasound can be used to disrupt microalgal cells by applying sonic waves at frequencies higher than 20 kHz [Packer, 2009]. Ultrasound has been mainly used in laboratories, because handling large volumes of microalgae requires high acoustic power [Richmond, 2004]. Another effective and less costly method to obtain the lipids from microalgae is through the use of organic solvents such as toluene, alkanes or alcohols, which lead to cell wall rupture [Richmond, 2004]. Although, the ultrasound technique is more efficient than solvents, it is still considered more expensive and more research needs to be conducted regarding its application on a large scale [Mata *et al.*, 2010].

3.1.7 Microalgal jet fuel production

The extracted oil is transported to a biofuel conversion facility. There are two main methods to obtain jet fuel from algae, either through the Fischer-Tropsch (FT) synthesis or through hydro-processing, which includes hydrogenation and hydro-cracking [Hileman *et al.*, 2010]. The Fischer-Tropsch synthesis produces a fuel known as synthetic paraffinic kerosene (SPK), whereas hydro-processing results in a fuel called hydro-processed renewable jet fuel (HRJ), with similar properties to conventional jet fuel [Stratton, 2010]. The Fischer-Tropsch synthesis is applied and has been established and certified as a technologically viable and safe process to produce jet fuel. In South Africa, a certified jet fuel is produced through the FT process by Sasol [IATA, 2007a]. Therefore, the FT process will not be discussed further long in this work. The focus is mainly directed towards the hydro-processing technology, which produces hydro-processed renewable jet fuels. Hydro-processing is an already existing technology that is widely applied in refineries [Kalnes & Marker, 2007]. Concerning biomass, the application of hydro-processing technology was first applied to produce green diesel, which is rich in isoparaffins, through catalytic saturation, hydrogenation, decarboxylation and hydroisomerization [Kalnes & Marker, 2007]. Hydro-processing of bio-oils can make use of already existing petroleum refineries [Bezergianni & Kalogiann, 2009]. This process is more desirable than transesterification which produces biodiesel because it can produce a higher quality diesel in terms of flow properties, blending readiness and storage stability [Kalnes & Marker, 2007, Naik *et al.,* 2010].

To produce hydro-renewable jet fuels (HRJ), the same process can be applied with more optimized conditions [UOP, 2008]. The original process yields 15% (in volume) of jet fuel as a co-product to green diesel, whereas the new and optimized process can yield up to 70% of high quality jet fuel known as HRJ with zero sulphur content [IATA, 2009c, UOP, 2008]. These optimized conditions can convert the carbon chain length of bio-oils and specifically microalgal oils, to a range of C10 to C14, which is suitable for application in the aviation industry [IATA, 2009c, UOP, 2008]. This reduction in carbon chain length requires a selective cracking step [Hileman *et al.,* 2010].

At first in the hydrogenation step, oxygen is removed from the microalgal oil which is then converted into long chain normal paraffins, propane, water and CO, through a reaction involving hydrogen addition [Range & Vanhaeren, 1997, IATA, 2009c, Zinoviev *et al.,* 2010]. In the next step, through isomerisation and cracking, the paraffins are transformed into isomers, isoparaffins, and cracked in the presence of a catalyst into small-molecular weight hydrocarbons, consisting of C10 to C14 carbon chain length molecules. These molecules constitute the HRJ fuel in addition to other products such as naphtha [IATA, 2009c]. The transformation of bio-oils, including microalgal oil, into HRJ requires inputs that are similar to the inputs used in petroleum refineries such as steam, natural gas, cooling water and electrical power [Kalnes & Marker, 2007]. The difference between HRJ and conventional jet fuel is that HRJ contains only paraffinic hydrocarbons, whereas conventional jet fuel contains about 60% of paraffinic hydrocarbons. Another difference is the high hydrogen to carbon ratio and zero sulphur content in HRJ, in comparison to conventional jet fuel [Hileman *et al.,* 2010]. Also, HRJ lacks aromatics which are present in conventional jet fuels with up to 25% in volume [Hileman *et al.,* 2010, IATA, 2009c]. The hydrogen needed for HRJ production can be obtained from natural gas and from some of the by-products obtained from hydrogenation and cracking [Kalnes & Marker, 2007].

3.2 Conventional jet fuel

Conventional jet fuel is mainly produced from crude oil [Hileman *et al.*, 2009]. The process of obtaining conventional jet fuel starts with oil exploration, followed by oil extraction, recovery and processing. Oil exploration has become a sophisticated procedure depending on satellite images which can recognize petroleum rich areas and reserves, and followed with land-based exploration, by drilling a limited number of wells. This method for oil exploration reduces unnecessary environmental impacts and allows an initial environmental assessment, before any major ecosystem disturbance [Borasin *et al.*, 2002]. In oil refineries, fractional distillation takes place in order to separate the oil into different compounds based on their different boiling point ranges [Hileman *et al.*, 2009]. Jet fuel is part of the kerosene produced from oil refining, obtained from the middle distillates [Koroneos *et al.*, 2005]. The refinement of crude oil today requires more complex and energy intensive operations than the refinement applied few years ago, because the quality of oil that is reaching the refinery today is lower than the quality of crude oil in earlier days [NETL, 2009]. Most of the conventional jet fuel is obtained directly from the first step of oil refining which is distillation. Additional steps can increase the yield of conventional jet fuel from the refined oil, such as catalytic cracking and catalytic hydro-cracking [NETL, 2009]. Conventional jet fuel undergoes hydro-treatment in order to reduce contaminants, by adding hydrogen to the fuel, which has the ability to remove sulphur content [Range & Vanhaeren, 1997, NETL, 2009]. Jet fuel is later transported in pipelines, stored and used directly in aircraft.

Chapter 4: The Analytic Hierarchy Process (AHP)

4.1 Background

The fundamentals of the Analytic Hierarchy Process were established by Thomas Saaty in the 1970s [Saaty, 1986]. The AHP is based on a mathematical arrangement consisting of "matrices and their right-eigenvector's ability to generate true or approximate weights" [Saaty, 1986]. Today, AHP is regarded as the most widely used tool for problems and decisions, involving multiple objectives [Dinh *et al.*, 2009, Shim, 1989]. The Analytic Hierarchy Process has been mostly useful for decision makers handling complex problems, entailing multiple and conflicting aspects. [Saaty, 1986, Vaidya & Kumar, 2006]. The "analytic" in AHP comes from the word analysis, which refers to breaking down an element into smaller parts [Forman & Grass, 1999]. This multiple criteria decision making tool can be applied in various fields in order to choose the best option among different alternatives, to resolve conflicts among politicians and other decision makers, or to allocate resources [Vaidya & Kumar, 2006]. The AHP is used, as a systematic approach, to fill the gap between facts, and values and attitudes of those judging these facts [Zhu & Dale, 2001].

The scientific community has shown its acceptance for this method, by applying it in different fields such as environmental and natural resources fields, which have found in AHP a reliable method for their analyses [Zhu & Dale, 2001]. To state a few, AHP has been used for land sustainability analysis, water resource planning, forest management and planning, environmental conflict analysis, and many other studies [Zhu & Dale, 2001]. All of these researchers have found in AHP a way to incorporate the diverse aspects, which can affect the environmental and natural resources, and to incorporate the different values that stakeholders assign for these aspects [Zhu & Dale, 2001].

4.2 Brief overview

The Analytic Hierarchy Process is made up of three important steps, which include "decomposition, comparative judgments and synthesis" [Saaty, 1986]. With decomposition, the goal, objectives, criteria and alternatives are identified and arranged in a hierarchical structure, such as pyramid [Zhu & Dale, 2001]. The general structure of AHP consists of the goal placed on top and the alternatives placed at the lower level, with criteria and sub-criteria in the middle [Saaty, 1987]. The goal, criteria and alternatives are linked together, in what are known as nodes and branches [Zhu & Dale, 2001]. Saaty suggested as a guideline not to exceed nine branches under one node, in order to reduce risks of inefficiency and inconsistency during comparison [Zhu & Dale, 2001].

Pair-wise comparisons are applied at each level of the hierarchy [Saaty, 1987]. First, the criteria are compared to each other, to determine their relative importance [Saaty, 1987]. The same principle is applied to the sub-criteria and alternatives [Zhu & Dale, 2001]. Therefore, "the principle of comparative judgments is applied to construct pair-wise comparisons of the relative importance of elements in some given level with respect to a shared criterion or property in the level above" [Saaty, 1987]. Matrices can be derived from the pair-wise comparisons [Vaidya & Kumar, 2006], which should be based on the best information available, including knowledge and intuition [Zhu & Dale, 2001]. The end result of the AHP can give weights to the alternatives, with respect to the criteria selected [Bodin & Gass, 2003]. Accordingly, the alternatives can be ranked from the best choice with the highest rank, to the worst choice with the lowest rank [Saaty, 1986].

4.3 Advantages and disadvantages of AHP

4.3.1 Advantages of AHP

- Ability to break down complex problems into simple parts, which can be processed more easily [Saaty, 1986].
- Ability to incorporate both qualitative and quantitative information into a structured but yet, flexible decision making process [Saaty, 1987].

- Acceptability in the international scientific community [Zhu & Dale, 2001].
- Easily understood and applied [Saaty & Vargas, 2001].
- Inconsistencies can be identified and corrected through the consistency index, which provides a reliable final conclusion [Pohekar & Ramachandra, 2004].

4.3.2 Disadvantages of AHP

- Time consuming, when a large number of alternatives and criteria is involved [Pohekar & Ramachandra, 2004].
- The need to reconsider the comparisons and weights assigned, when the consistency ratio exceeds 10% [Kablan, 2004].

4.4 The AHP process

The process begins by identifying the problem or goal [Papalexandroua *et al.*, 2008], then breaking down the problem/goal into factors which can influence the problem or goal [Vaidya & Kumar, 2006]. According to these factors, a hierarchy can be built, which contains the goal, criteria and/or sub criteria, and the alternatives considered (See Figure 4.4.1.) [Zeshui & Cuiping, 1999]. Pair-wise comparisons can then be carried out at each horizontal level of the hierarchy and in order to establish matrices [Saaty, 1986]. For "n" elements, the entries are arrayed in a square matrix of order "n" [Zeshui & Cuiping, 1999]. The entry of each matrix constitutes a ratio scale [Saaty, 1986]. The evaluation is carried out through the use of a 1-9 ratio scale, where "the scale assigns the intensity of importance of one criterion upon another" [Papalexandroua *et al.*, 2008], as shown in Table 4.4.1. The entries are obtained by comparing the elements in the left-hand column with the elements in the top row [Zhu & Dale, 2001]. When an element is regarded less favourably or less importantly than another, the entry takes the form of a fraction [Zhu & Dale, 2001]. Example: If A is strongly more important than B, then the entry of the cell which compares A to B is 5, whereas the entry of the matrix which compares B to A is 1/5. Moreover, the diagonal entries of a matrix hold the value 1, as each element is compared to itself [Vaidya & Kumar, 2006].

For each matrix, the consistency ratio can be calculated in order to check for inconsistencies [Saaty, 1986]. Consistency ratio is used in the AHP in order to reduce errors, resulting from subjectivity [Papalexandroua *et al.*, 2008]. Matrix $A = a_{ij}$, obtained from pair-wise comparisons is considered perfectly consistent when $a_{ij}a_{jk} = a_{ik}$, with i, j, k = 1, 2, …, n and $\lambda_{max} = n$, with λ_{max} being the principal eigenvalue of *A* [Zhu & Dale, 2001]. When the matrix is not consistent, the principal eigenvalue has a value which exceeds n [Saaty, 1987]. This difference between $\lambda_{max} > n$ and $\lambda_{max} = n$ allows the measurements of inconsistency [Saaty & Vargas, 2001]. Thus, the interest is in the consistency ratio, which is derived from the ratio of the consistency index for a particular matrix, to the average consistency index for random comparisons (Table 4.4.2), for a matrix of the same size of *A* (i.e., same number of n) (Table 4.4.2.) [Saaty & Vargas, 2001]. Starting with the consistency index, it is defined as $(\lambda_{max} - n)/(n-1)$ [Saaty & Vargas, 2001]. When a matrix is perfectly consistent, the consistency ratio is equal to zero [Saaty & Vargas, 2001]. On the other hand, usually the matrices derived from pair-wise comparisons are not perfectly consistent [Zeshui & Cuiping, 1999]. As such, the consistency ratio has a value which is greater than zero [Zhu & Dale, 2001]. The desired value of a consistency ratio is less than 0.1 [Saaty & Vargas, 2001]. When the value exceeds 0.1, pair-wise comparisons need to be re-assessed in order to reduce inconsistencies [Saaty, 1986].

The ranking of alternatives is based on the right eigenvectors. The principal eigenvector can be derived for each matrix [Zhu & Dale, 2001], and the priority or weight for each node (e.g., criteria or alternatives) can be established based on the right eigenvectors [Saaty, 1987]. The priorities consist of absolute numbers ranging from zero to one [Saaty, 1986]. The priorities are obtained by "raising the matrix to a sufficiently large power then summing over the rows and normalizing, to obtain the priority vector" [Zhu & Dale, 2001] (Appendix A). These priorities are called local priorities [Saaty, 1987]. Perform priority synthesis for all the criteria, sub-criteria and alternatives [Saaty, 1987]. There are two types of priorities. Local priorities are the weights obtained from the principal eigenvectors. Whereas, global priorities can be derived by multiplying local priorities by the weight of their corresponding node, in the level above [Zhu & Dale, 2001]. The first level of criteria has equal local and global priorities because the goal's priority is equal to one [Zeshui & Cuiping, 1999]. The sum of global priorities at each level is equal to one, and the sum of local priorities under one node is also equal to one [Saaty, 1987] (Figure 4.4.1). The goal of this step is to obtain the global priorities of all the elements of the hierarchy and most importantly to obtain the global priorities of the alternatives at the bottom level [Dinh *et al.,* 2009, Zhu & Dale, 2001], in order to be able to rank them from best to worst, according to their weights [Saaty, 1986].

Table 4.4.1.

The Fundamental Scale of Pair-wise Comparisons [Saaty & Vargas, 2001].

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one element over another
5	Strong importance	Experience and judgment strongly favour one element over another
7	Very strong importance	One element is favoured very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6 and 8 can be used to express intermediate values. Intensity of 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

Table 4.4.2

Average Random Consistency Index (R.I.) [Saaty & Vargas, 2001].

N	1	2	3	4	5	6	7	8	9	10
R.I	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

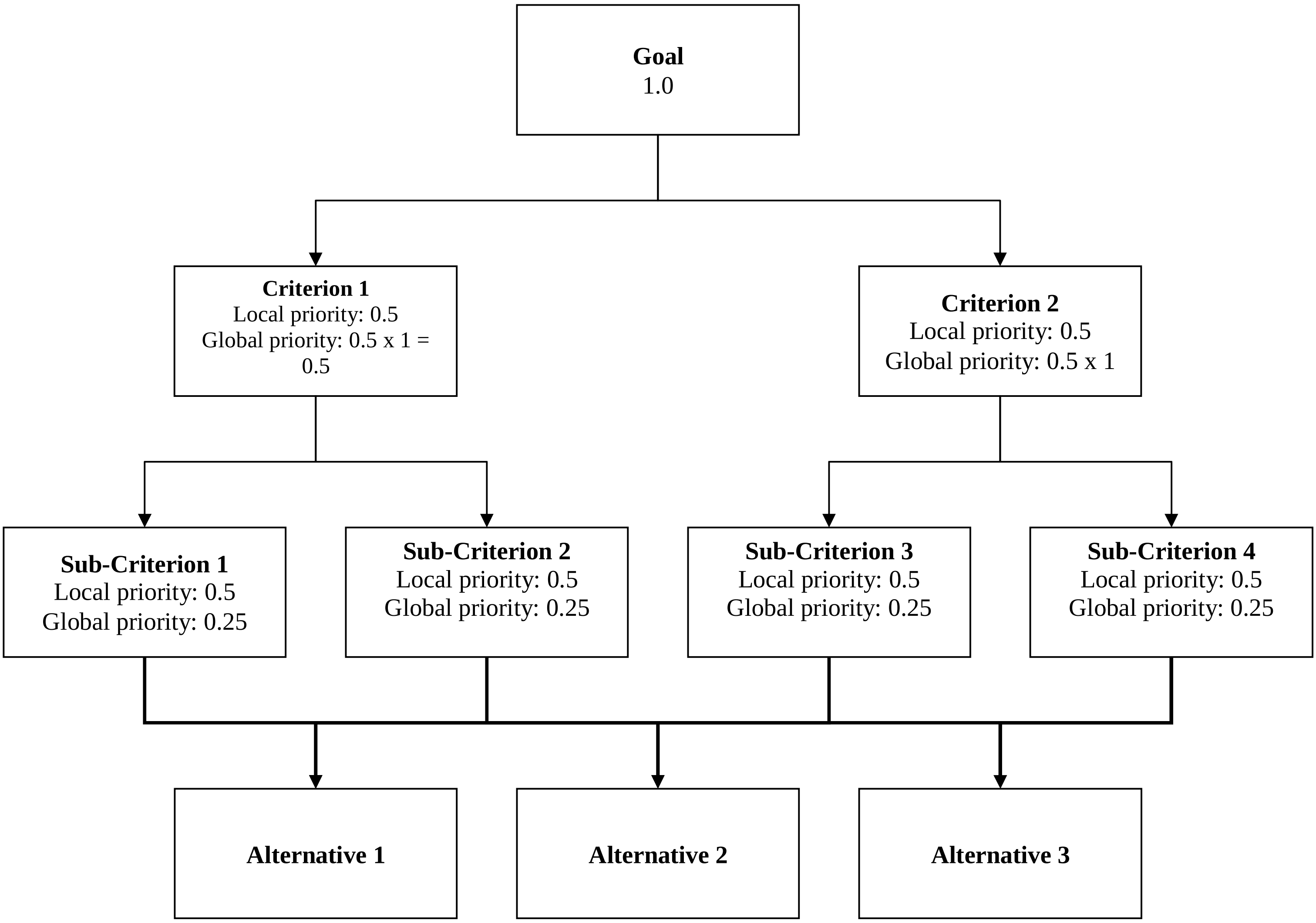

Figure 4.4.1. AHP hierarchy showing default priorities.

Chapter 5: Methodology

The goal of this study is to evaluate the economic competitiveness, technological feasibility and environmental sustainability of the production and use of microalgal hydro-processed renewable jet fuel (HRJ), one of many alternative aviation fuels, using the Analytic Hierarchy Process. Microalgal HRJ fuel has been receiving a great deal of attention from the aviation industry, as a renewable energy source that can replace conventional jet fuel [IATA, 2007a]. Therefore, an evaluation of the current status of microalgal HRJ fuel production and use is necessary in order for decision makers to have a complete picture that brings the economics, technology and environment into the equation. The aviation industry is being pressured into minimizing its environmental impacts [Wardle, 2003]. However, there should be no rush decisions to adopt a new fuel, without conducting the necessary assessments which can ensure its environmental sustainability [Hileman *et al.*, 2008]. Therefore, just because microalgal HRJ fuel comes from a renewable source of energy, this does not mean that its full life-cycle environmental performance is better than that of conventional jet fuel. AHP is the interlinked process that can bring economic, technological and environmental aspects together, with weights being assigned for each of these criteria [Papalexandroua *et al.*, 2008, Zinoviev *et al.*, 2010].

5.1 Data sources

The data used for the purpose of this study were obtained from three main sources; air transport technical reports, research theses and peer reviewed journals.

5.1.1 Air transport technical reports

The main reports used were published by the International Air Transport Association (IATA), which has many publications linking the aviation industry with alternative fuels; and by the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) [IATA, 2007a, IATA, 2008, IATA, 2009c, IATA, 2010, Stratton *et al.*, 2010]. Several flight trials using alternative jet fuels were cited in these reports, along with their technological performance and environmental impacts. The three main flight trials tackled in the reports which took place between 2008 and 2009, used hydro-renewable jet fuels produced through the UOP technology, by Honeywell, and were derived from several second generation feedstocks such as microalgae, camelina and jatropha. The airlines involved in these flight trials were Air New Zealand, Continental Airlines and Japan Airlines. From these flight trials, the information obtained was at the technological and environmental levels. In each flight trial, a 50-50% blend of HRJ fuel and conventional jet fuel was used in one of the engines. The duration of each flight was about two hours. Technological tests assessed engine performance and operability, whereas environmental tests measured emissions such as NO_x, HC and CO, in terms of grams of emissions per kilogram of burned fuel, during the LTO cycle [IATA, 2009c].

5.1.2 Research thesis

A master thesis by Stratton, from the Massachusetts Institute of Technology, included life-cycle GHG emissions from different aviation fuels. From this source, life cycle GHG emissions from both microalgal HRJ fuel and conventional jet fuel production and use were obtained and utilized in this study. Stratton used the Greenhouse Gases Regulated Emissions and Energy use in Transportation (GREET) framework, as the tool for his life cycle analysis [Stratton, 2010].

Technological considerations:

- Concerning conventional jet fuel, crude oil was assumed to be the source from which conventional jet fuel was produced.
- Microalgae were assumed to be cultivated in open ponds, fed with flue gas containing CO_2, from a nearby power plant.

Environmental considerations:

- Stratton's analysis focused on life-cycle GHG emissions, presented in terms of gCO_2 equivalents per unit of energy (lower heating value) consumed by aircraft (gCO_2e/MJ) [Stratton, 2010]. The GHGs tackled were CO_2, CH_4 and N_2O. The basis of GHG calculations depended on their global warming potential, which incorporates their radiative properties and their timescale removal from the atmosphere. The timescale chosen in Stratton's study was 100 years. Other important emissions such as NO_x, SO_x, soot and water produced during fuel combustion were not covered in Stratton's study

- In his study, Stratton tackled three scenarios; optimistic, pessimistic and base scenarios, for emissions. Our study reflected on the baseline scenario, rather than on the optimistic or pessimistic scenario.

5.1.3 Peer reviewed journals

5.1.3.1 AHP and biofuels

To the best knowledge of the author, only two studies have been conducted so far, using the AHP method to evaluate the sustainability and the feasibility of biofuel production [Dinh *et al.*, 2009, Papalexandroua *et al.*, 2008]. Papalexandrou, Pilavachi, and Chatzimouratidis, in 2008, evaluated the production of conventional (e.g., wheat) and second generation biofuels (e.g., waste wood), and their use in the European Union (EU) transport sector. Their main criteria analyzed were life-cycle GHG emissions, life-cycle energy consumption, the ability to substitute fossil fuels, and the cost of substitution. The study concluded that according to these criteria and among the alternatives considered, the best biofuel pathways using EU domestic sources include “bioethanol produced from wheat straw, syn-diesel produced from waste wood via black liquor, and bioethanol produced from wheat with process heat supplied from a combined cycle natural gas fired gas turbine with a combined heat and power scheme”.

Another study by Dinh, Guo, and Mannan, in 2009, aimed at evaluating the sustainability of biodiesel produced from different feedstocks, using the AHP method [Dinh *et al.*, 2009]. Among the raw materials considered were algae, soybean, jatropha, palm oil and rapeseed. Some of the criteria tackled included GHG emissions, land usage, water usage, total production cost, fuel cetane number and others. The study concluded that among the alternatives considered, and in relation to the criteria tackled, algae seem to be the best option for biodiesel production.

5.1.3.2 Other biofuel related themes

Other articles provided insight into the different criteria tackled in this study [Borowitzka, 1992, Brennan & Owende, 2010, Cherubini & Stromman, 2010, Clarens *et al.*, 2010, Collet *et al.*, 2011, Koroneos *et al.*, 2005, Lardon *et al.*, 2009, Stephenson *et al.*, 2010]. From these articles, issues related to raceway pond performance, closed photo-bioreactor performance, wastewater and freshwater consumption, fertilizer addition, energy consumption and others were obtained. Some of these articles provided a brief insight on the economic side of microalgae cultivation and production [Borowitzka, 1992, Collet *et al.,* 2011, Huntley & Redalje, 2006, Jorquera *et al.,* 2010, Schenk *et al.,* 2008].

5.2 Study assumptions

- Cultivated microalgae were assumed to be fed with flue gas containing CO_2, from a nearby power plant. This assumption was based on the fact that microalgae cannot reach the desirable production capacity by using atmospheric CO_2 by itself. It was also based on the fact that creating a pure CO_2 stream, containing 99% of CO_2, can result in much higher GHG emissions, than when supplying CO_2 from a nearby flue gas source [kadam, 2002].

- Similar to Stratton, the fertilizers used during microalgae cultivation in freshwater were nitrogen produced from ammonia, and phosphorus produced from superphosphate and potassium sulphate. Whereas the production of coagulants and solvents were not considered in the assessment [Stratton, 2010, Sturm & Lamer, 2010]. The processing facility of biomass was assumed to be located on the same site of microalgae cultivation, in order to be able to recycle the effluents [Patil *et al.,* 2008].

- Only conventional means for microalgae harvesting and oil extraction were covered in the scenarios, due to data availability. As such, microalgae were assumed to be harvested through flocculation followed by centrifugation [Schenk *et al.,* 2008, Stephenson *et al.,* 2010, Wijffels *et al.,* 2010], while oil extraction was assumed to be carried out using hexane solvent [Schenk *et al.,* 2008].

- After oil extraction, the left-over biomass was assumed to be sent to an on-site anaerobic digester rather than to a combustor, in order to preserve the nutrients in the microalgal meal [Gouveia & Oliveira, 2009, Stratton, 2010]. The coupling of microalgae cultivation with anaerobic digestion was first applied in 1957 [Collet *et al.,* 2011]. Biogas can be produced from the anaerobic digestion, and it can be used as an energy source for on-site needs, such as drying microalgal biomass [Gouveia & Oliveira, 2009, Stratton, 2010]. The nutrient rich-effluent can be recycled into the culture [Yang *et al.*, 2011].

- Conventional jet fuel was assumed to be produced from crude oil.

- The conversion of both microalgal oil and crude oil were assumed to take place in similar refineries with similar input and output [Kalnes & Marker, 2007, Wu *et al.*, 2009]. Thus, they were not considered in the analysis.

5.3 Alternatives

5.3.1 Alternatives overview

The alternatives were divided into five scenarios. Four of the alternatives refer to HRJ fuel obtained from microalgae and the fifth alternative refers to conventional jet fuel. The five alternatives are:

- Alternative 1: Raceway pond with wastewater source: RWPW.
- Alternative 2: Raceway pond with freshwater source: RWPF.
- Alternative 3: Closed photo-bioreactor with wastewater source: PBRW.
- Alternative 4: Closed photo-bioreactor with freshwater source: PBRF.
- Alternative 5: Conventional jet fuel: CVJF.

5.3.2 Alternatives description

The main stage of fuel production taken into consideration was the cultivation of microalgae and the extraction of crude oil. Moreover, concerning microalgae alternatives, RWPW, RWPF, PBRW and PBRF differed only in the cultivation stage of microalgae. After cultivation, downstream processes were the same from harvesting to oil extraction and jet fuel production. Concerning the differences, in two of the alternatives, RWPW and RWPF, microalgae were assumed to be cultivated in raceway ponds, with one using wastewater as the aquatic medium and the other using freshwater resources, accompanied with fertilizers. In the other two, PBRW and PBRF, microalgae were assumed to be cultivated in closed photo-bioreactors, with one using wastewater and the other using freshwater with fertilizers. The comparison between

RWPs and PBRs was carried out in this study, because of the lack of consensus within the scientific community on the optimum cultivation method [Brennan & Owende, 2010, Schenk *et al.,* 2008]. There are those who argue favourably for PBRs, such as Chisti, and there are those who view RWPs as the better alternative with all the years of experiments and experience supporting their position [Chisti, 2006]. The comparison between freshwater and wastewater was based on new studies, that concluded that microalgae cultivated in freshwater and depended on fertilizers appear to be environmentally unsustainable [Clarens *et al.,* 2010]. Conventional jet fuel scenario has been chosen as a benchmark, since it is the fuel which is widely used in aviation, today [IATA, 2010].

5.4 Criteria

The criteria tackled in this study were divided into three categories: the technological, the environmental and the economic criteria. These criteria reflect on the feasibility and sustainability of the alternatives compared [Zinoviev *et al.,* 2010].

The criterion technology was chosen in order to assess a basic reality of whether the alternatives studied are available, or will be available in the near future [Hill *et al.,* 2006]. The extent of the availability of the alternatives has an influence on whether each alternative is or will be a realistic contributor to jet fuels [Hileman *et al.,* 2009, Hill *et al.,* 2006]. Also, from technological considerations, the safety and reliability of alternative jet fuels can be detected.

The environmental criterion is very important and needs to be included, since the main objective, of finding alternative fuels, is to reduce the environmental impacts of the aviation industry [Hileman *et al.,* 2008, IATA, 2009c]. The environmental impacts of fuels are not just related to the combustion stage, but to the production stage as well [Stephenson *et al.,* 2010]. When possible, the environmental impacts of an alternative fuel should adopt the well-to-wake basis. Such an assessment has only been considered with relation to GHG emissions [Zinoviev *et al.,* 2010]. Other important environmental aspects include impacts on water consumption and water quality, production and use of fertilizers and pesticides, and impacts on land, which are rarely considered [Cherubini & Stromman, 2010, Sheehan, 2009, Dinh *et al.,* 2009].

The economic criterion is important because for any alternative fuel to be viable, it needs to be cost competitive with conventionally used fuels [IATA, 2008]. The economic aspect of any alternative studied constitutes a major influencing factor, for the success or failure of this alternative [Zinoviev *et al.*, 2010]. Along with the environmental reasons, researching alternative jet fuels stems from the need to reduce the economic fuel bill of aviation [Hileman *et al.*, 2008, IATA, 2007a]. Thus, in addition to environmental sustainability and technological viability, the economic competitiveness of the fuel constitutes a key player in determining its success [Hill *et al.*, 2006]. Most of the time, decision makers assign more weight and value to the economic side, rather than to the environmental or technological sides [IATA, 2008]. Therefore, an optimum environmental alternative might be existent, but its cost might be very high, making it undesirable to decision makers [IATA, 2008].

5.4.1 Technological

5.4.1.1 Fuel production capacity

The fuel production capacity is related to each stage of the fuel production process [Hileman *et al.*, 2009]. The technology to produce an alternative fuel might be established, but it might not have the capacity to produce large amounts of fuels. Scale-up from laboratory and pilot scale projects to large scale production is a major concern for alternative jet fuels [Papalexandroua *et al.*, 2008]. Also, production capacity is greatly related to the source of energy of the fuel, whether it is renewable or non-renewable, reflects its limited or unlimited availability [Hileman *et al.*, 2009].

5.4.1.2 Fuel compatibility with the present aviation system

This criterion is very crucial because it reflects on whether a fuel can be used in the near-term and whether it is a drop-in fuel which does not require major changes to the currently existing infrastructure such as transmission pipelines and storage tanks [Wardle, 2003]. Also this compatibility is reflected in terms of safety, where the fuel produced from the alternative source should have certain characteristics that ensure its safe usage especially in long and low temperature flights. Some of these characteristics include freezing point, flash point, lubricity and thermal stability [Hileman *et al.*, 2010].

5.4.1.3 Fuel readiness level

This criterion is directly related to the maturity of the alternative fuel [Hileman *et al.*, 2009]. Whether the technologies used to produce an alternative fuel are mature enough, can directly influence its ability to be produced on a large commercial scale [Nigim *et al.*, 2004].

5.4.1.4 Energy

The main aim from this criterion is to ensure that any alternative suggested will not require more energy input than energy output [Cherubini & Stromman, 2010, Chatzimouratidisa & Pilavachi, 2009, Collet *et al.*, 2011]. Thus, there is a need for any new alternative fuel to produce "net energy gain over the energy sources used to produce it" [Hill *et al.*, 2006]. As for the alternative fuels tackled, the interest was in both their specific energy and energy density, which was compared to the benchmark's specific energy and energy density. Specific energy is defined as the energy per unit mass, whereas energy density is defined as the energy per unit volume [Hileman *et al.*, 2010].

5.4.2 Environmental

5.4.2.1 Water

Few studies tackling alternative fuels include the impacts of fuel production and use on water resources. Water is an important aspect of environmental sustainability, as there is a fear that freshwater resources are being directed away from food crop cultivation to biofuel crop cultivation [Zinoviev *et al.*, 2010]. Therefore, the impacts on water quality and quantity should be included in such an assessment [IATA, 2009c]. It is important to differentiate between water consumption and water withdrawal [King & Webber, 2008]. Water withdrawal refers to the water withdrawn from an aquatic source, and later returned to the source [Wu *et al.*, 2009]. The returned water might not be of the same quality of the water withdrawn [Stratton, 2010]. Purposes for water withdrawal include systems' cooling. As for water consumption, which is the interest of this study, it refers to freshwater input minus water output which is recycled and reused [King & Webber, 2008, Wu *et al.*, 2009]. Water quality, on the other hand, was evaluated in terms of its potential to lead to eutrophication from nitrogen and phosphorus nutrients and in terms of presence of other contaminants such as suspended solids and hydrocarbons [Sheehan, 2009].

5.4.2.2 Air

The main emissions tackled were GHGs, which contribute to global warming [Dinh *et al.*, 2009, Macintosh & Wallace, 2009]. The number one environmental reason behind the search for alternative aviation fuels is the need to reduce GHGs from aviation [Hileman *et al.*, 2008]. Thus, it is important to consider GHG emissions from any alternative fuel suggested, and to compare them to the emissions of the benchmark fuel [Hileman *et al.*, 2009]. Approximately, 90% of the studies considering the environmental impacts of alternative energy sources include GHG emissions as their number one criterion for analysis [Cherubini & Stromman, 2010]. The main GHGs tackled in studies include CO_2, CH_4 and N_2O [Macintosh & Wallace, 2009]. The quantification of non-CO_2 is usually carried out using the global warming potential measurement, which can convert these emissions into CO_2 equivalents [Macintosh & Wallace, 2009]. During combustion, the quantities of GHGs emitted from biofuels and conventional fuels are very similar [Stratton, 2010]. Therefore, the emphasis here was on life-cycle GHG emissions, rather than on GHGs emitted during the combustion phase by itself [Hileman *et al.*, 2008]. In addition to CO_2, CH_4 and N_2O, other emissions produced during fuel combustion such as NO_x, CO, HC and smoke were tackled in this study.

5.4.2.3 Land

This sub-criterion was divided into two aspects. The first one was related to the magnitude of land needed, while the other one was related to the impacts induced on land from fuel production activities [Alabi *et al.,* 2009]. The size of land needed during cultivation of microalgae or extraction of crude oil is much larger than the area needed during other fuel production stages. Thus, the focus was on extraction and/or cultivation stages [Dinh *et al.*, 2009]. In addition to land usage, other impacts on land can include aesthetic impacts or impacts on the biodiversity of the area [Alabi *et al.*, 2009].

5.4.3 Economic

5.4.3.1 Fuel cost

The fuel cost is the most important economic aspect to be considered, as it directly reflects the ability of an alternative fuel to be competitive with the benchmark fuel [IATA, 2008]. When an alternative fuel has a much higher cost than conventional jet fuel, the aviation industry will not be encouraged to make the transition to the alternative fuel. The aviation industry is interested in reducing its fuel bill. Therefore even if an alternative fuel offered benefits at the environmental level, its cost still has a great impact on its potential to be adopted by the aviation industry.

5.4.3.2 Capital cost

This sub-criterion is an important aspect of economics, as it eventually affects the cost of fuel produced [Zinoviev *et al.*, 2010]. Capital cost was only evaluated for microalgal HRJ fuel alternatives, since conventional jet fuel already has the necessary facilities for its production. On the other hand, the commercialization of microalgal HRJ fuel greatly depends on the investors' ability to afford the capital cost of microalgal biofuel production facilities [Sims *et al.*, 2010]. Thus, CVJF was not part of this sub-criterion. Moreover, fuel refineries were not considered, because the current petroleum refinery infrastructure can be used for HRJ fuel production as well [IATA, 2007a]. The main issues tackled in this section were the capital costs of PBRs, RWPs and other infrastructural needs for the water, wastewater and CO_2 transportation [Sims *et al.*, 2010]. The harvesting equipments were not considered as it they are the same for RWP and PBR scenarios. Other capital costs include the cost of the initial microalgal culture. This cost is highly dependent on the specific strain; thus, it was not tackled. Moreover, the culture cost is the same for PBR and RWP scenarios; as such it does not affect the comparison in this study [Norsker *et al.*, 2011]. Due to the absence of CVJF in the pair-wise comparisons related to this sub-criterion, additional measures had to be taken, in order to compensate for this difference from a five order matrix to a four order matrix. This is further tackled in Appendix B.

5.4.3.3 Operating cost

In addition to the capital cost, operating cost constitutes an important aspect which is considered by those who are willing to fund alternative fuel production projects [Chatzimouratidisa & Pilavachi, 2009]. It is not enough for the capital cost to be acceptable, but also there is a considerable weight assigned for operating costs with any new and risky project [Sims *et al.,* 2010]. Operating cost differs between RWPs and PBRs and it is highly dependent on the technologies used to harvest microalgae and extract microalgal oil. Therefore, considerations for operating costs should be taken into consideration, early on in the process of developing microalgal biofuels. Due to the absence of CVJF in the pair-wise comparisons related to this sub-criterion, additional measures had to be taken, in order to compensate for this difference from a five order matrix to a four order matrix. This is further tackled in Appendix B.

5.5 Application of AHP

After identifying the criteria, sub-criteria, and alternatives, the hierarchy was built to represent these elements, as shown in Figure 5.5.1. The next steps consisted of comparing the alternatives to each sub-criterion and criterion, building matrices, deriving the right eigenvectors and the consistency ratio, prioritizing the alternatives and ranking them from best performance to worst performance. The process of deriving the right eigenvector from each matrix is presented in Appendix A. It is worth mentioning that there were five alternatives considered. Thus, when comparing the consistency index to the random consistency index in Table 4.4.2, the interest was in the consistency index corresponding to n= 5, which is 1.11, since the order of matrices in this study was equal to 5. Therefore, the consistency index for all matrices should be less than 1.11. After deriving the right eigenvector for each matrix, local and global priorities were calculated.

Since most of the data obtained from the literature were qualitative, the values assigned from pair-wise comparisons in the matrices were subjective to the author's knowledge, which is mainly based on the literature review conducted. Also, in addition to subjectivity, there was a higher risk of inconsistencies to occur, as the numerical values were derived from qualitative data; thus, the author was at risk of obtaining consistency indices exceeding the acceptable value of 1.11 or consistency ratios exceeding 0.1. Another issue was the possibility that someone else assessing these data, might assign different values for the pair-wise comparisons. To overcome this subjectivity, perfectly consistent matrices were built, where matrix $A = a_{ij}$, obtained from pair-wise comparison, had $a_{ij}a_{jk} = a_{ik}$, with i, j, k = 1, 2, …, n and $\lambda_{max} = n$ [Zhu & Dale, 2001], and with the consistency ratio being equal to zero [Saaty & Vargas, 2001]. From these set of perfectly consistent matrices, alternatives were ranked based on their performance, in relation to criteria and sub-criteria. However, these matrices reflected on ideal situations and did not represent realistic scenarios. Therefore, the author introduced errors into the matrices, by deriving two sets of matrices from the perfectly consistent matrices.

The first set of matrices consisted of reducing the entries, in each matrix, to their minimum possible values. Therefore, if another researcher were to assign these values, he/she would not assign a value which is lower than this minimum. For example, if one wanted to assign a value for pair-wise comparison between CVJF and PBRF in terms of fuel readiness level, one would not assign a value which is less than " very strong important", which refers to 7, but one might assign a value ranging between 7 and 9.

The second set of matrices consisted of increasing, the entries in each matrix, to their maximum possible values. Therefore, if another researcher were to assign these values, he/she would not assign a value which is greater than this maximum. For example, if one wanted to assign a value for pair-wise comparison between RWPs and PBRs in terms of production capacity, one would not assign a value which is higher than "strong important", which refers to 5, because both RWPs and PBRs still face obstacles in their production capacity, although currently RWPs produce more biomass than PBRs.

It is worth mentioning that the errors were only introduced to the values which were higher than 1, in the perfectly consistent matrices. When comparing A to B, if A is more important than B, then the value of this pair-wise comparison would be greater than 1, whereas the value of pair-wise comparison of B to A would be less than 1, because it represents the reciprocal of the value assigned to the pair-wise comparison of A to B, as $a_{ij} = 1/a_{ji}$. Therefore, it would be sufficient to modify the values which are greater than 1, as this would reflect also on the values which are less than 1. The errors introduced ranged between −20% and +40%, depending on each pair-wise comparison characteristics.

After deriving these set of matrices which take into consideration minimum, maximum and baseline values, the ranking of the alternatives corresponding to each of these scenario was compared. If the ranking of alternatives changed from one scenario to another, this means that the perfectly consistent matrices cannot be assumed as the baseline scenario, and that they differ from the realistic ranking of alternatives, which can be calculated by others. However, on the other hand, if the ranking of the alternatives from all three scenarios were identical, then it can be said that even with the presence of subjectivity, in the assigned numerical values of the pair-wise comparisons, the overall picture and the overall performance of alternatives can be derived from any of these scenarios and the assessment can be carried out using the perfectly consistent matrices.

The comparison between minimum, maximum and perfectly consistent matrices showed similar results and similar ranking of alternatives. Therefore, the analysis was based on values derived from the perfectly consistent matrices. As such, only perfectly consistent matrices were included in the main text, whereas maximum and minimum matrices were included in Appendix C.

5.6 Software

Matrix Laboratory (MATLAB) was used as a tool to calculate matrices and derive the right eigenvectors, principal eigenvalues and consistency indices.

5.7 Sensitivity analysis

5.7.1 Equal weight for technological, environmental and economic criteria

Among the three main criteria considered, technological, environmental and economic, no prioritization was made. The three criteria were judged to have the same importance. Thus, the weight of the goal, 1, was divided equally between the three criteria, and each received a weight of 1/3. The reason behind the lack of prioritization in this case was to establish a base-case without any subjectivity factor.

5.7.2 Environmental priority

In the second case, the priority and higher weight was given to the environmental criterion. As such the environmental criterion was assigned a weight of 0.5 out of 1.0, whereas each of the technological and economic criteria was assigned a weight of 0.25 out of 1.0. The reason behind this prioritization is related to the motive of the aviation industry to reduce its environmental impacts and further its quest for transport fuels, which can induce less environmental impacts than conventional jet fuel [Hileman *et al.*, 2010]. Also, in the environmental criterion, higher weights were assigned to both sub-criteria air and water. Therefore, the sub-criterion air was assigned a weight of 0.4, the sub-criterion water was assigned a weight of 0.4, whereas the sub-criterion land was assigned a weight of 0.2. The focus nowadays from the scientific community is on the contribution of various energy sources and fuel consumption activities to global warming through emissions of GHGs. This sub-criterion is very important to see whether the alternative fuel can reduce the carbon footprint of aviation. However, it must not be forgotten that water resources can also be affected by global warming, and that many countries are suffering from water shortages. Thus, the impacts of a new alternative fuel on water consumption and on water quality must be a priority as well, in addition to GHG emissions.

5.7.3 Economic priority

The higher weight among the three main criteria was given to the economic criterion. As such the economic criterion was assigned a weight of 0.5 out of 1.0, whereas each of the technological and environmental criteria was assigned a weight of 0.25 out of 1.0. The reason behind this choice is the fact that most decision makers and investors put a higher weight on the cost of any new project. The search for alternative fuels in the aviation industry is highly driven by the increasing cost of conventional jet fuel [Hileman *et al.*, 2008]. Moreover, the success of any new alternative fuel depends on its cost competitiveness with the conventional fuel used [Dinh *et al.*, 2009]. The higher weight among the sub-criteria was assigned to the fuel cost, as this cost is directly related to the cost competitiveness of the fuel in the market. Therefore, the sub-criterion fuel was assigned a weight of 0.5, whereas the sub-criteria capital and operating costs were assigned similar weights of 0.25, each.

In Table 5.7.1, there is a short list of references which have used the AHP method to evaluate the technological, environmental and economic considerations of energy related issues. The table provides an overview of the comparisons of these three aspects with relation to each other.

Table 5.7.1

The Weights of Technological, Envionmental and Economic Criteria, in Relation to Each Other, Obtained from Other Sources.

Reference	Technological	Environmental	Economic
Talinli *et al.*, 2010	Low to moderate imporatnce	Moderate to high importance	Low to moderate importance
Papalexandrou *et al.*, 2008	Case 1 : Moderate importance	Low importance	High importance
	Case 2 : High importance	Low importance	Low importance
	Case 3 : Low importance	High importance	Low importance
Dinh *et al.*, 2009	Moderate importance	High importance	High importance

5.8 Limitations

The full and accurate implementation of the comparative methodology adopted in this study faced many obstacles, such as scarcity of information, lack of quantitative data, lack of process-specific data [Dinh *et al.*, 2009], lack of consensus among the scientific community and lack of experience in terms of large scale production of microalgal HRJ fuel [Yang *et al.*, 2011]. Lack of quantitative data can be explained by the fact that the required data are mainly available for site specific trials and assumptions. Therefore, they are highly dependent on locations and technologies used. As such, no particular values can be used, but the overall conclusions from such studies were taken into consideration to fulfill the purpose of this inquiry [Cherubini & Stromman, 2010]. When faced with contradicting information or uncertainties, sensitivity analyses were conducted by taking two scenarios into consideration, and building a matrix for each scenario, to check whether such a difference can impact the overall performance of alternatives, in relation to the criterion tackled [Papalexandroua *et al.*, 2008]. Due to lack of information related to new technologies, some of the technologies discussed in previous chapters were not included in the assessment. The scenarios and technologies described in each of the alternatives have been chosen either because there were enough scientific data available on these particular technologies, or because they were the most widely used technologies in the field. The study was not intended to promote any of the scenarios chosen, but to present, understand and realize the different aspects, which can affect microalgal HRJ fuel's success or failure.

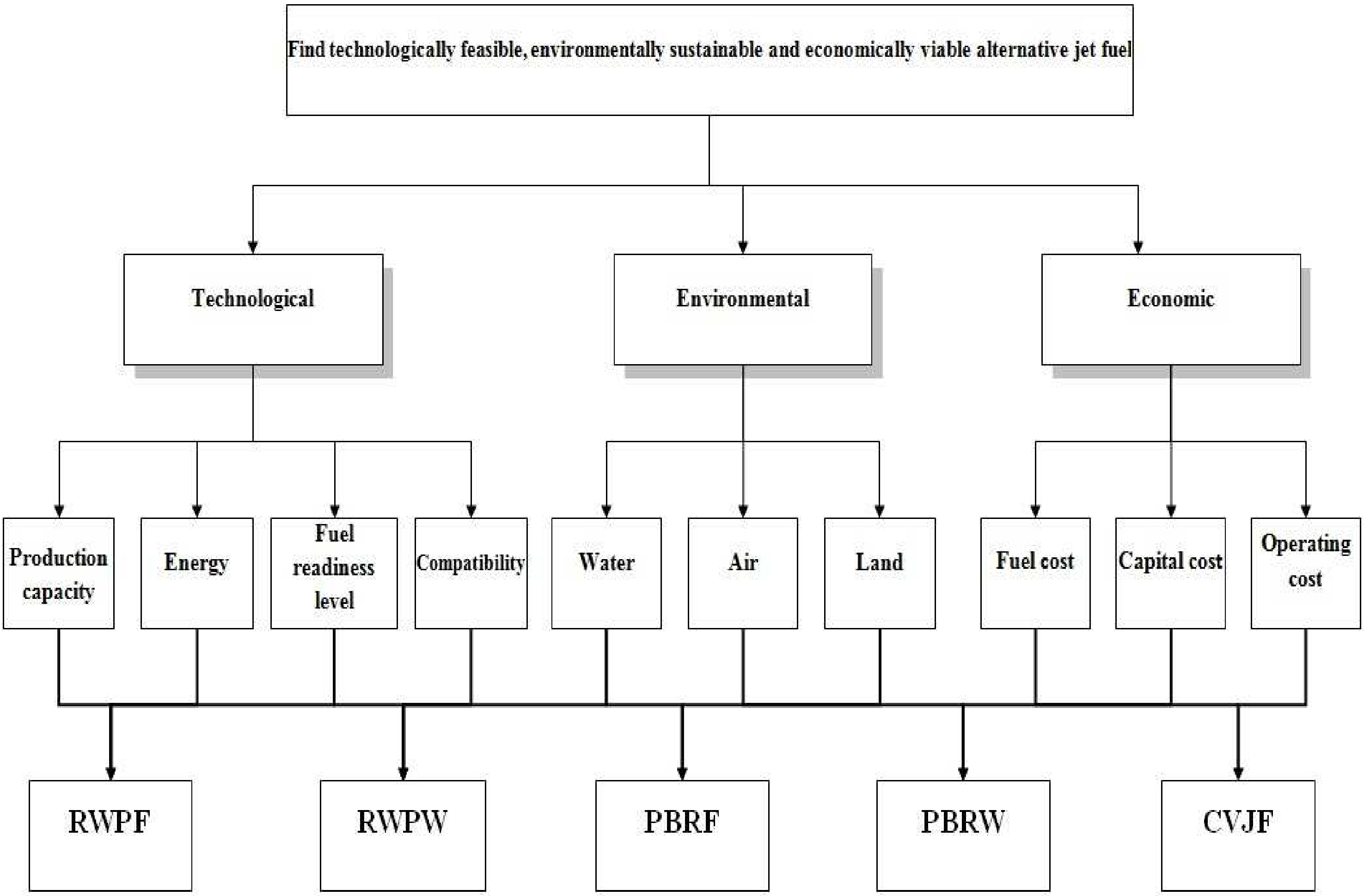

Figure 5.5.1. The hierarchy of microalgal HRJ and conventional jet fuel.

Chapter 6: Technological considerations

6.1 Production capacity

6.1.1 Analysis

The first criterion measuring the technological feasibility of the alternatives studied was the production capacity of each fuel. Production capacity refers to the potential amount of jet fuel, which can be obtained from each of the identified alternatives [Hileman *et al.,* 2009]. The production capacity of microalgal HRJ fuel is greatly related to the amount of microalgal biomass which can be produced, and to the oil content of microalgae strains [Stratton, 2010]. The capacity of refineries to transform oil into jet fuels is not considered, since petroleum refineries and bio-oil refineries have the same capacity [IATA, 2007a].

RWPs have lower volumetric productivities than PBRs [Borowitzka, 1992]. Also, RWPs are limited to certain strains of microalgae, which can grow in extreme conditions, and which might not have high lipid content [Schenk *et al.*, 2008]. Moreover, RWPs require larger surface area than PBRs, and they have poorer gas/liquid mass transfer and lower final microalgal density [Jorquera *et al.,* 2010, Patil *et al.,* 2008]. Microalgae cultivated in RWPs have the ability to reach and maintain productivities of 25grams of microalgal cells per square meter per day [Lee, 2001, Patil *et al.,* 2008, Schenk *et al.,* 2008, Lardon *et al.,* 2009, Pienkos & Darzins, 2009]. Such productivity in RWPs can yield around 26t/ha/year of microalgal biomass [Pittman *et al.,* 2011].

PBRs, on the other hand, can lead to the production of microalgal biomass ranging between 5-10grams of microalgae per litre of culture, and around 48grams of microalgal cells per square meter per day [Chisti, 2007, Pienkos & Darzins, 2009]. PBRs have a larger production capacity than RWPs, as they have a better capacity to capture light and they use land space more efficiently [Jorquera *et al.*, 2010]. However, PBRs are difficult to scale up and maintain [Mata *et al.*, 2010, Munoz & Guieysse, 2006], and until now, commercial scale production of algae and microalgae in PBRs has only been used for high-end products, such as pharmaceuticals [Borowitzka, 1992, IATA, 2007a]. Whereas for biofuel purposes, microalgae cultivated in PBRs are still mostly at the laboratory and pilot-scale levels [Brennan & Owende, 2010].

Moreover, currently more microalgae are cultivated and produced from RWPs than from PBRs [Schenk *et al.*, 2008].

Currently the production capacity of conventional jet fuel far exceeds the four other scenarios, which depend on microalgae [IATA, 2007a]. This high production capacity of CVJF is strengthened by the fact that, conventional jet fuel has been meeting the needs of aviation fleet for more than fifty years [Hileman *et al.,* 2009]. The global production of conventional jet fuel is estimated to use more than 854 million barrels of crude oil, per year [Wardle, 2003]. However, it is important to take into consideration that conventional jet fuel is obtained from non-renewable resources of crude oil, while microalgal HRJ fuel is obtained from renewable resources (i.e., microalgae strains and species) [Chatzimouratidisa & Pilavachi, 2009]. Thus, on the long term less conventional jet fuel will be available [Luque *et al.*, 2008]. Biofuels from microalgae, on the other hand, are still at the level of experimental and pilot scale projects [Sander & Murthy, 2010]. Therefore, the quantity of microalgal HRJ fuel produced is currently very limited [IATA, 2010]. An overview of these comparisons is presented in Table 6.1.1.

Table 6.1.1

Overview of the Production Capacity of the Alternatives.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	Same production capacity.
RWPW & RWPF versus PBRF & PBRW	PBRs have higher production capacity than RWPs, but this production capacity is currently difficult to be achieved.
PBRF versus PBRW	Same production capacity
CVJF versus RWPW & RWPF	CVJF is produced at commercial scale & enjoys a mature technology, but it is derived from non-renewable source. Whereas, RWPs have low production capacity, but they are derived from a renewable source.
CVJF versus PBRW & PBRF	CVJF is produced at a commercial scale & enjoys mature technology, but it is derived from non-renewable source. Whereas PBRs currently cannot reach their high production capacity potential, but they are derived from renewable source.

6.1.2 Results

Table 6.1.2

Production Capacity Perfectly Consistent Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.000	1.286	1.286	0.143	0.095
RWPW	1.000	1.000	1.286	1.286	0.143	0.095
PBRF	0.778	0.778	1.000	1.000	0.111	0.074
PBRW	0.778	0.778	1.000	1.000	0.111	0.074
CVJF	7.000	7.000	9.000	9.000	1.000	0.663

Table 6.1.3

Ranking of Alternatives, Based Solely on their Production Capacity.

Alternative	Ranking
CVJF	0.663
RWPF	0.095
RWPW	0.095
PBRW	0.074
PBRF	0.074

Best

Worst

6.1.3 Discussion

The right eigenvector obtained from the perfectly consistent matrix of production capacity showed that the alternative CVJF has the highest weight among the alternatives considered. This result was expected, as the production capacity of CVJF, today, far exceeds the production capacity of the other alternatives considered. The two RWP alternatives have the same weight, because they have the same production capacity, as they both were assumed to use raceway ponds for microalgae cultivation. The same explanation can be given to the two alternatives of PBRs, where microalgae were assumed to be cultivated in closed photo-bioreactors. Therefore, in terms of production capacity, one can only judge that CVJF is the best alternative, but one cannot really differentiate between the technological performances of the other four alternatives, from which microalgal HRJ fuel can be obtained.

6.2 Fuel readiness level

6.2.1 Analysis

Fuel readiness level refers to the fuel's production state, whether it can be produced at a large and commercial scale, or whether it is still at the laboratory and pilot scale levels [Hileman *et al.*, 2009]. Concerning conventional jet fuel, it is and it has been produced at a large commercial scale, and it is the number one source of fuel for the air transport sector [IATA, 2007a]; thus, it received the highest weight among the alternatives considered, in relation to this criterion.

As for the four other scenarios, the readiness of microalgal HRJ fuel was compared based on the differences among these scenarios, thus based on microalgae cultivation stages. The harvesting and extraction of microalgal oil and the production of fuel from cultivated microalgae were assumed to be similar for all of the four scenarios related to microalgal HRJ fuel. Flocculation and centrifugation are known processes, which are widely applied in the industrial sector and in water treatment plants as well [Uduman *et al.*, 2010, Richmond, 2004]. Also, oil extraction through solvent use such as hexane is widely used and applied to extract fatty acids from different microalgae species [Grima *et al.*, 2003]. Therefore, these technologies can be considered as mature, and that they have no adverse effects on microalgal HRJ fuel productivity.

Moreover, hydro-processing of oil is not a new technology, and it is applied in oil refineries [Kalnes & Marker, 2007]. Hydro-processing has been extensively researched and it has been applied for the processing of vegetable oils [Hileman *et al.*, 2009]. The consensus among the scientific community is that hydro-processing can be carried out within the existing infrastructure of petroleum refineries [Bezergianni & Kalogiann, 2009]. Several companies are investing in hydro-processing technology, such as Nestle Oil and UOP, to produce paraffinic fuels, which can act as alternatives for conventional middle-distillate products, such as jet fuel. Thus, it is safe to say that hydro-processing is a known technology that has exceeded the pilot scale level, but it is still at a limited production scale, when it comes to bio-oil processing [Hileman *et al.*, 2009].

The concerns in terms of fuel readiness level are related to the first step of microalgal jet fuel production, which is microalgae cultivation. Open ponds are a well established technology that has been known and used since the 1950s [Tsukada *et al.,* 1977], whereas closed photo-bioreactors are still in their infancy stage [Schenk *et al.,* 2008]. It is true that closed photo-bioreactors are currently used for the production of high value products such as pharmaceuticals, but they are still far away from being used for the production of low-value products such as biofuels, due to their high capital and operating cost [Norsker *et al.,* 2011].

Moreover, another difference lies in the use of freshwater versus wastewater, during microalgae cultivation. This difference, gives the advantage in this particular criterion to the alternatives which depend on the use of freshwater during microalgae cultivation, which is associated with the use of fertilizers, which are readily available in the market and can be easily obtained [Mata *et al.,* 2010]; unlike the use of wastewater which necessitates the implementation of new infrastructure to transfer the domestically produced wastewater or industrial wastewater to microalgae cultivation sites [Pittman *et al.,* 2011]. In some cases, new microalgal cultivation projects can be located in already existent wastewater treatment facilities, but in most of the cases, new facilities need to be built, thus requiring new infrastructures [Pittman *et al.,* 2011]. An overview of these comparisons is presented in Table 6.2.1.

Table 6.2.1

Overview of the Fuel Readiness Level of the Alternatives.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	RWPF is more readily available than RWPW, which needs a new infrastructure to transport wastewater.
RWPW versus PBRF	RWPW has been applied for large scale production, but it needs infrastructure for wastewater. PBRF is still at pilot scale, but it uses fertilizers, rather than wastewater.
RWPW versus PBRW	RWPW has been applied for large scale production, whereas PBRW is still at pilot scale level.
RWPF versus PBRF	RWPF has been applied for large scale production, whereas PBRF is still at pilot scale level.

Alternatives compared	Comparison overview
RWPF versus PBRW	RWPF has been applied for large scale production and it depends on readily available fertilizers, whereas PBRW is still at pilot scale level and needs wastewater infrastructure.
PBRF versus PBRW	PBRF is more readily available than PBRW, which needs a new infrastructure to transport wastewater.
CVJF versus PBRW	CVJF is produced at a commercial scale, compared to the least available alternative for microalgal HRJ fuel.
CVJF versus PBRF	CVJF is produced at commercial scale, compared to the second least available alternative for microalgal HRJ fuel.
CVJF versus RWPW	CVJF is produced at commercial scale, compared to third least available alternative for microalgal HRJ fuel.
CVJF versus RWPF	CVJF is produced at commercial scale, compared to the most available alternative for microalgal HRJ fuel.

6.2.2 Results

Table 6.2.2

Fuel Readiness Level Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.111	1.889	2.000	0.222	0.135
RWPW	0.900	1.000	1.700	1.800	0.200	0.121
PBRF	0.529	0.588	1.000	1.059	0.118	0.071
PBRW	0.500	0.556	0.944	1.000	0.111	0.067
CVJF	4.500	5.000	8.500	9.000	1.000	0.606

Table 6.2.3

Ranking of Alternatives, Based Solely on their Fuel Readiness Level.

Alternative	Ranking
CVJF	0.606
RWPF	0.135
RWPW	0.121
PBRF	0.071
PBRW	0.067

Best ↓ Worst

6.2.3 Discussion

In terms of fuel readiness level, as it was expected, CVJF received the highest ranking, since it is already used in the aviation industry, whereas microalgal fuels derived from microalgae cultivated in closed photo-bioreactors were at the bottom of the ranking, because they are the least developed fuels, among the alternatives considered. Among the microalgal HRJ fuel alternatives, and in relation to each of the cultivation systems, those alternatives which were assumed to use freshwater and fertilizers, to grow microalgae, received higher weights than those which were assumed to use wastewater to grow microalgae. Thus, RWPF outperformed RWPW and PBRF outperformed PBRW, in regard to this sub-criterion. The wastewater supply, for microalgae cultivation, is less available than the freshwater supply, especially in terms of infrastructure and pipeline system readiness.

6.3 Compatibility with current aviation system

6.3.1 Analysis

Another important sub-criterion which falls under the technological considerations of jet fuel is the degree of compatibility of the fuel with current infrastructural system, which transports, stores and uses jet fuel. The fuel needs to be compatible with the already existing pipelines, airport fuelling systems, aircraft and engines [Hileman *et al.*, 2009]. It is very crucial for any alternative fuel to be a drop-in fuel, in order to be used directly without applying changes to the infrastructure [IATA, 2009c]. Otherwise, more time and money will be needed to incorporate the alternative fuel into the aviation system. The current infrastructure is built with conventional jet fuel in mind; thus, this fuel is very compatible with this infrastructure. The only negative drawback with using conventional jet fuel is its relatively high sulphur content, which requires cleaning of pipes after transporting conventional jet fuel, in order to avoid contamination of other low sulphur fuels transported in these same pipes, such as ultra-low sulphur diesel. [Hileman *et al.*, 2009].

Concerning microalgal HRJ fuel, it is considered synthetic paraffinic kerosene, which is free of sulphur and aromatic content [Hileman *et al.*, 2010]. HRJ fuel has a better thermal stability than conventional jet fuel, due to its high hydrogen to carbon ratio, and due to the absence of metals and nitrogen and sulphur elements, which lead to lower fuel system deposit. As such, HRJ fuel has a higher heat of combustion than conventional jet fuel, on a mass basis [IATA, 2009c, Naik *et al.*, 2010]. Microalgal HRJ fuel is considered a drop-in fuel, and it is compatible with the current infrastructure of aviation [IATA, 2007a]. The lack of sulphur makes microalgal HRJ fuel more attractive for pipeline transportation than conventional jet fuel [Hileman *et al.*, 2008]. Whereas the lack of aromatics reduces its chemical stability and requires the fuel to be blended with conventional jet fuel, to increase its aromatic content, and in order for the fuel to be in accordance with jet fuel ASTM standards [IATA, 2009c, Naik *et al.*, 2010]. Moreover, when compared to conventional jet fuel, HRJ fuel has a poorer lubricity, due to the absence of sulphur. But, lubricity can be easily adjusted with additives [Hileman *et al.*, 2009].

Therefore, flight trials conducted using HRJ fuel, produced through the UOP process had to be blended with conventional jet fuel, due to its lower density. The engines with blended fuel showed a better fuel efficiency than the engines with 100% conventional jet fuel [IATA, 2009c]. In general, no sign that HRJ fuel negatively impacted the engines was detected [Kivits *et al.*, 2010]. These successful test flights resulted in an order from the US Navy and Air Force of 600,000 gallons of HRJ fuel, produced through the UOP process [IATA, 2009c]. An overview of these comparisons is presented in Table 6.3.1.

Table 6.3.1

Overview of the Compatibility of the Alternatives with the Current Aviation System.

Alternatives compared	**Comparison overview**
RWPW, RWPF, PBRF, PBRW versus CVJF	The compatibility of CVJF with the current aviation system exceeds the compatibility of microalgal HRJ fuel which needs to be blended in order to be used in aircraft.

6.3.2 Results

Table 6.3.2

Compatibility with the Current Aviation System Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.000	1.000	1.000	0.333	0.143
RWPW	1.000	1.000	1.000	1.000	0.333	0.143
PBRF	1.000	1.000	1.000	1.000	0.333	0.143
PBRW	1.000	1.000	1.000	1.000	0.333	0.143
CVJF	3.000	3.000	3.000	3.000	1.000	0.429

Table 6.3.3

Ranking of Alternatives, Based Solely on their Compatibility with the Current Aviation System.

Alternative	Ranking	
CVJF	0.429	Best
RWPF	0.143	
PBRF	0.143	
PBRW	0.143	
PBRW	0.143	Worst

6.3.3 Discussion

Conventional jet fuel showed the best compatibility with the current aviation system and its infrastructure. Microalgal HRJ fuel derived from the other four alternatives is also compatible, but because it needs to be blended with conventional jet fuel in order to be safely used, microalgal HRJ fuel received a lower ranking than conventional jet fuel. All of the four alternatives of microalgal HRJ fuel received the same ratio scale in the matrix, because regardless of their differences in microalgae cultivation systems, the end fuel product, from all of the four alternatives, possesses the same qualities [IATA, 2009c, Naik *et al.*, 2010]. Therefore, their weights were also identical in terms of compatibility with the current aviation system. As such, one cannot compare the performance of the alternatives providing microalgal HRJ fuel, based solely on their compatibility with the current aviation system, because this particular sub-criterion does not take into consideration the differences between these alternatives.

6.4 Energy

6.4.1 Analysis

Starting with microalgal HRJ fuel, energy consumption greatly differs between the two cultivation methods, raceway ponds and closed photo-bioreactors [Stephenson *et al.,* 2010]. There is a scientific agreement that closed photo-bioreactors consume more energy than raceway ponds [Jorquera *et al.,* 2010, Stephenson *et al.,* 2010]. Energy consumption of closed photo-bioreactors can range between as low as 55W/m^3 to as high as 3000W/m^3, whereas energy consumption of raceway ponds can range between 0.04w/m^3 and 4W/m^3 [Packer, 2009]. In addition to consuming more energy than raceway ponds, closed photo-bioreactors are more likely to have a Net Energy Ratio (NER) that is less than 1 [Lardon *et al.*, 2009]. NER is defined as the total energy output in lipid and biomass over the total energy input to produce this biomass [Cherubini & Stromman, 2010, Jorquera *et al.,* 2010].

The highly controlled environment, in closed photo-bioreactors, requires high level of energy input, for mixing, degassing and cooling; all these features which insure the better productivity of closed photo-bioreactors require at the same time higher inputs of energy [Brennan & Owende, 2010, Chisti, 2006]. Closed photo-bioreactors can have NER that is greater than 1, but at a really high cost. This high cost can provide energy efficient pumping system to provide mixing for the culture, and energy efficient gas/liquid transfer [Brennan & Owende, 2010, Jorquera *et al.,* 2010]. Another difference between RWPs and PBRs lies in the harvesting stage. Microalgae cultivated in closed photo-bioreactors consume less energy during harvesting than microalgae cultivated in raceway ponds. In closed photo-bioreactors, microalgae are more concentrated in a given volume of culture, which facilitates their harvesting due to their low water content [Chisti, 2007].

Moreover, non-renewable energy input can be decreased by making use of microalgal slurry and by growing microalgae in wastewater rather than in freshwater [Stephenson *et al.,* 2010]. Concerning microalgal slurry, which is obtained after oil extraction, the residual biomass can undergo anaerobic digestion, in order to produce biogas and provide energy, which can be used onsite for downstream processes, such as microalgae drying [Collet *et al.*, 2011, Stephenson *et al.*, 2010]. In addition to the biogas, anaerobic digestion produces nutrient rich effluent, which can be recycled into the culture medium [Collet *et al.,* 2011]. Thus, reducing the need for fertilizers, in case of PBRF and RWPF, which in turn require energy to be produced [Clarens *et al.,* 2010]. These measures can greatly reflect the energetic performance of microalgal biofuels [Demirbas & Demirbas, 2010].

Moving to wastewater versus freshwater sources as aquatic media for cultivation, as mentioned before, in order to be able to grow microalgae in freshwater, fertilizers need to be added for nutrient supply such as nitrogen and phosphorus [Brennan & Owende, 2010]. This difference necessitates an additional energy input to produce the fertilizers [Lora *et al.,* 2010]. Thus, more energy is needed for microalgae cultivated in both RWPF and PBRF than for microalgae cultivated in RWPW and PBRW, respectively [Clarens *et al.,* 2010]. Another aspect manifests in the energy efficiency associated with wastewater remediation; in comparison to regular wastewater treatment plants (WWTP), less energy is needed to remove the same amount of nutrients when using microalgae to remediate the wastewater [Demirbas & Demirbas, 2010]. As for PBRs, According to one study, the amount of energy currently invested to produce biofuels from microalgae grown in closed photo-bioreactors far exceeds the amount of energy used to produce conventional fuel, even when using wastewater for microalgae cultivation [Stephenson *et al.,* 2010]. As such, PBRs were considered the worst option, in relation to this sub-criterion.

Concerning CVJF, the energy performance of crude oil extraction activities is dependent on the operations of each site [NETL, 2009]. But, in general, crude oil extraction is considered a mature technology, which can deliver more energy than it consumes [Stephenson *et al.,* 2010]; thus, its NER > 1. As for jet fuel production, crude oil refining and bio-oil refineries are considered similar [Hileman *et al.,* 2010, Kalnes & Marker, 2007]. It is true that HRJ refineries consume more energy than CVJF, for additional steps of cracking and hydrogen production, but when taking the time factor into consideration, the quality of crude oil is degrading with time, which means that more energy will be needed to produce the same amount of jet fuel produced today [NETL, 2009, Stratton, 2010]. As such, HRJ and CVJF refineries were assumed to consume comparable levels of energy [Stratton, 2010]. Thus, they were not included in this section. Moreover, according to Stratton, the production of HRJ fuel, from microalgae cultivated in freshwater with fertilizers, consumes less energy than the production of conventional jet fuel [Stratton, 2010]. Therefore, the performance of RWPW and RWPF with regard to energy is better than that of CVJF.

Comparing HRJ fuel with conventional jet fuel shows that HRJ fuel has a 2% higher specific energy than conventional jet fuel [Hileman *et al.*, 2009]. The higher specific energy of HRJ fuel implies that to fly a given distance, less weight of HRJ fuel is needed than that of conventional jet fuel. This reduction in fuel weight allows the aircraft to increase its payload, without the risk of exceeding the maximum takeoff weight. Moreover, HRJ fuel has a 3% lower energy density than conventional jet fuel, which reduces the maximum range of aircraft. This lower energy density, negatively affects the few worldwide flights, which need to have full fuel tanks [Hileman *et al.*, 2009]. An overview of these comparisons is presented in Table 6.4.1.

Table 6.4.1

Overview of Energy of the Alternatives.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	RWPF consumes more energy than RWPW because it depends on fertilizers during cultivation.
RWPW versus PBRF	PBRF consumes more energy than RWPW because PBRs are more energy intensive than RWPs and because PBRF depends on fertilizers during cultivation.
RWPW versus PBRW	PBRW consumes more energy than RWPW because PBRs are more energy intensive than RWPs.
RWPF versus PBRF	PBRF consumes more energy than RWPF because PBRs are more energy intensive than RWPs.
RWPF versus PBRW	PBRW consumes more energy than RWPF because PBRs are more energy intensive than RWPs. But, RWPF depends on fertilizers during cultivation.
PBRF versus PBRW	PBRF consumes more energy than PBRW because it depends on fertilizers during cultivation.
CVJF versus PBRW & PBRF	CVJF is more energy efficient than PBRs, but microalgal HRJ fuel has a higher specific energy than conventional jet fuel.

Alternatives compared	Comparison overview
CVJF versus RWPW & RWPF	RWPs are more energy efficient than CVJF, and microalgal HRJ fuel has a higher specific energy than conventional jet fuel.

6.4.2 Results

Table 6.4.2

Energy Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.500	4.000	3.500	2.500	0.254
RWPW	2.000	1.000	8.000	7.000	5.000	0.508
PBRF	0.250	0.125	1.000	0.875	0.625	0.064
PBRW	0.286	0.143	1.143	1.000	0.714	0.073
CVJF	0.400	0.200	1.600	1.400	1.000	0.102

Table 6.4.3

Ranking of Alternatives, Based Solely on their Energy.

Alternative	Ranking	
RWPW	0.508	Best
RWPF	0.254	
CVJF	0.102	
PBRW	0.073	
PBRF	0.064	Worst

6.4.3 Discussion

In terms of energy performance, RWP alternatives seemed to top the ranking of alternatives, with their low energy consumption during microalgae cultivation. This higher energy performance of RWP alternatives is also associated with the high microalgal HRJ fuel performance in terms of specific energy, in comparison to conventional jet fuel. RWPW exceeded RWPF in regard to this sub-criterion, due to its lower need for energy, as RWPF requires more energy input associated with fertilizer production and use during microalgae cultivation stage.

PBRs were at the bottom of the ranking because during microalgae cultivation, their energy output exceeds their energy input, which makes them energy inefficient. Similar to RWPW in comparison to RWPF, PBRW performs slightly better than PBRF, in terms of energy performance, because PBRW does not depend on fertilizers. However, the lack of need for fertilizer production and use by PBRW, does not overcome PBRW high energy requirements, which are mainly associated with highly controlled environments, during microalgae cultivation [Clarens *et al.,* 2010]. Although microalgal HRJ fuel produced from the two alternatives PBRs has higher specific energy than conventional jet fuel, their drawback in terms of high energy input, overcomes this advantage. Therefore, PBRs were ranked as the worst alternatives, with regard to this sub-criterion.

6.5 Overall technological considerations

6.5.1 Results

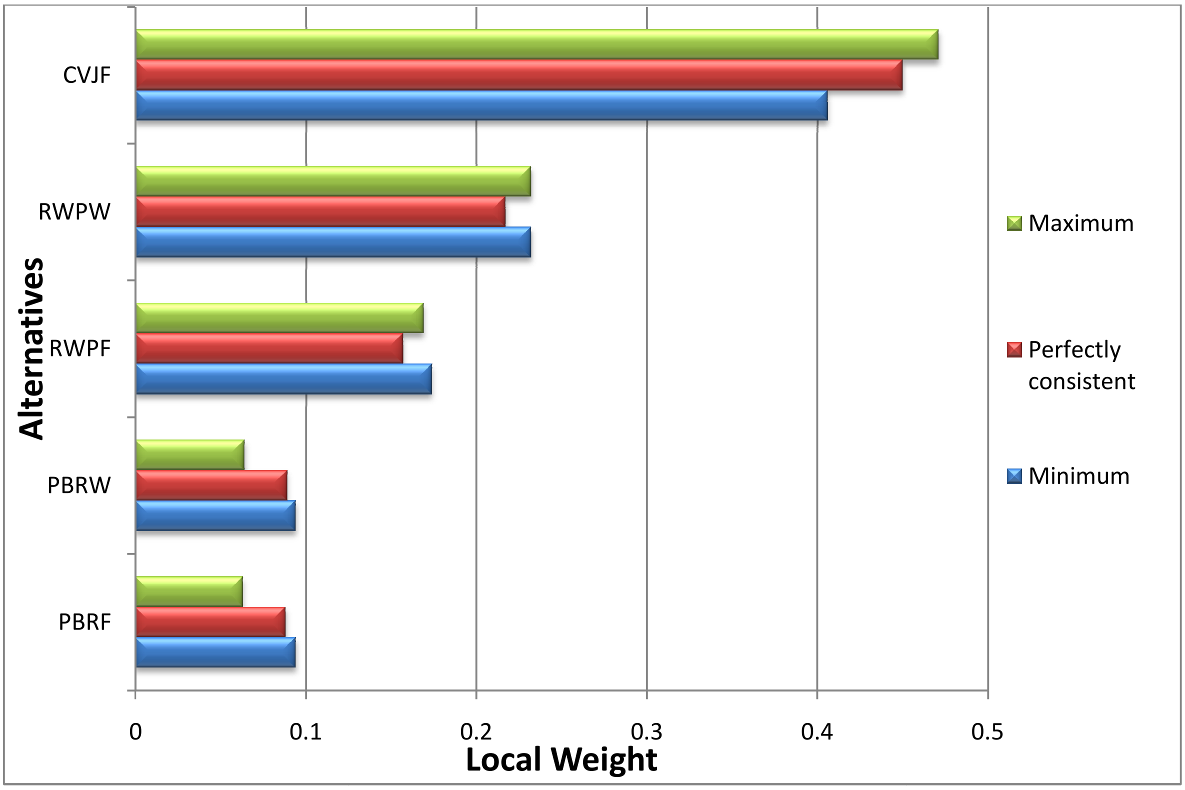

Figure 6.5.1 Overall technological considerations of the five alternatives, corresponding to maximum, perfectly consistent and minimum matrices.

6.5.2 Discussion

In all of the three scenarios; maximum, minimum and perfectly consistent matrices, when comparing the five alternatives, only in terms of technological considerations, CVJF seemed to be the best option. This result was expected, as CVJF is the benchmark, which is currently used in the aviation industry. Therefore, CVJF was expected to have the best technological performance among the alternatives, as it is derived from mature technology, and as it has been used in aviation for several decades. It is worth mentioning, that RWPs came next after CVJF, and specifically RWPW.

RWPW followed CVJF in terms of technological considerations, because raceway ponds have been used at a commercial scale, unlike PBRs, and because raceway ponds topped the energy sub-criterion ranking. Therefore, it is expected that microalgal HRJ fuel produced from RWPs and especially from RWPW, can improve its readiness level in the market in the coming few years, as it has the potential to compete, at the technological level, with CVJF [IATA, 2009c].

PBRs, on the other hand, seem far away from being technologically competitive with the other alternatives, due to the difficulties they face at the technological readiness level and at the energetic performance level as well. Therefore, microalgal HRJ fuel produced from PBRs, are not expected to be available at a large scale, in the near future. Rigorous research and development to improve the technological performance of PBRs still need to take place, in order for them to be competitive with CVJF production. Once, the technological performance of PBRs is improved, they are expected to exceed both CVJF and RWP technological performances due to their high production capacity potential [IATA, 2009c].

Although the weight of each of the alternatives differed between the three scenarios, this difference did not impact the overall technological performance of the alternatives considered. Also, it is worth mentioning, that in the maximum scenario, CVJF received the highest weight in comparison to the weight of CVJF in the other two scenarios, whereas PBRs received the lowest weight in the maximum scenario, in comparison to the weight of PBRs in the other two scenarios. This can be explained by the reciprocal values given to the pair-wise comparisons in the matrices. As the weight given to CVJF rises, in the maximum scenario, the weight of PBRs decreases, due to their reciprocal relationship.

Chapter 7: Environmental considerations

7.1 Water

7.1.1 Analysis

From production to use of fuel, the cultivation and extraction stages are considered to be the most water consuming stages [Schnoor *et al.*, 2008]. Starting with microalgal HRJ fuel, little quantitative data are available concerning water consumption during microalgal growth in both raceway ponds and closed photo-bioreactors [Clarens *et al.*, 2010]. Many researchers believe that the use of closed photo-bioreactors saves greatly on the use of water to grow microalgae, since they have a higher volumetric productivity; thus, closed photo-bioreactors need a lesser amount of water than raceway ponds, to grow the same amount of microalgae [Schenk *et al.*, 2008, Chisti, 2007]. Closed photo-bioreactors are thought to be able to consume 7 to 16 times less water than raceway ponds, depending on the type of the closed photo-bioreactors [Jorquera *et al.*, 2010].

However, scholars who have reached these estimates have failed to mention that in hot climates, closed photo-bioreactors tend to accumulate heat, where the temperature inside the reactors can reach 55°C [Mata *et al.*, 2010]. Thus, closed photo-bioreactors require as much water, for cooling purposes, as the water which can be lost through evaporation in raceway ponds [Demirbas & Demirbas, 2010, Alabi *et al.*, 2009]. In other climatic conditions, raceway ponds have the ability to outperform closed photo-bioreactors, in terms of water consumption, where the rainfall rate might exceed the rate of evaporation from raceway ponds [Stephenson *et al.*, 2010]. In such cases, raceway ponds can be replenished by the rainfall, whereas closed photo-bioreactors, which are closed systems, cannot benefit from such an advantage, and they end up consuming more water than raceway ponds [Stephenson *et al.*, 2010]. As such, the level of water consumption is highly dependent on the climatic conditions, and on the design of the cultivation system used [Mata *et al.*, 2010]. This uncertainty in water consumption during microalgae cultivation was tackled in this study, by building two matrices for the sub-criterion water. In one matrix, the consumption of freshwater in closed photo-bioreactors was assumed to be higher than that in raceway ponds, and vice versa.

Another aspect related to water consumption, during microalgae cultivation, is whether the spent medium is recycled into the culture or not. Studies have shown that the direct recycling of spent medium into the culture can negatively affect the growth and productivity of microalgae, due to the presence of some inhibitors, and particulate matter [Rodolfi *et al.,* 2003]. On the other hand, the lack of recycling of spent medium greatly affects the rate of fresh water consumption, thus making microalgal biofuels environmentally unsustainable [Stephenson *et al.,* 2010]. Therefore, from an environmental point of view, spent medium recycling is very important, especially if freshwater resources are used to grow microalgae [Clarens *et al.,* 2010]. Through flocculation and centrifugation, which are used to harvest microalgae, inhibitors present in the spent medium can be reduced, thus allowing the recycling of spent medium into the culture [Rodolfi *et al.,* 2003]. As for wastewater use, even when microalgae cultivation depends on wastewater resources, a relative amount of freshwater needs to be added to the culture, in order to prevent salt build-up, which can occur due to evaporation [Yang *et al.,* 2011]. However, the amount of freshwater added is not significant, and the use of wastewater to grow microalgae is thought to be able to reduce the life-cycle water consumption by as much as 90%, in comparison to the use of freshwater resources [Yang *et al.*, 2011].

Another difference between microalgal HRJ fuel alternatives refers to the type of water used during microalgae cultivation stage. As mentioned before, microalgae can either be cultivated in freshwater supplied with fertilizers or in wastewater, which contains the nutrients sufficient for microalgal growth [Sander & Murthy, 2010, Schenk *et al.*, 2008]. Wastewater used for microalgal growth can be supplied from many sources such as agricultural runoff or industrial and municipal wastewater [Demirbas & Demirbas, 2010, Khan *et al.*, 2009]. It is without a doubt that the use of wastewater to grow microalgae holds many environmental benefits [Brennan & Owende, 2010]. First of all, using wastewater to grow microalgae, instead of freshwater can reduce the pressure on freshwater resources [Brennan & Owende, 2010]. Also, degradation of freshwater through eutrophication, due to the release of wastewater into fresh aqueous media, can be reduced [Mata *et al.*, 2010, Pittman *et al.*, 2011].

The wastewater used to grow microalgae is rich in nutrients such as phosphorus and nitrogen [Schenk *et al.,* 2008, Pittman *et al.,* 2011]. These nutrients are the ones responsible for eutrophication of freshwater resources [Schenk *et al.,* 2008]. Microalgae consume these nutrients during growth, and provide oxygen for bacteria, to consume organic and inorganic compounds [Pittman *et al.,* 2011]. Therefore, the wastewater is said to undergo biological cleaning, which makes it safe for disposal in the ecosystem [Brennan & Owende, 2010, Khan *et al.,* 2009]. One study concluded that nitrogen and phosphorus can be removed with an efficiency of 72% and 28%, respectively, from wastewater, using the microalgal strain *C.vulgaris* [Mata *et al.,* 2010]. Another study researched the removal efficiency of nitrogen and phosphorus in urban wastewater, using the microalgal strain *S.obliquus,* and achieved a 98% elimination of phosphorus and a complete elimination of ammonium [Brennan & Owende, 2010].

In addition to reducing the risk of eutrophication [Pittman *et al.,* 2011], the coupling of microalgal growth and wastewater remediation has the ability to consume a reduced amount of freshwater than conventional wastewater treatment plants, to remediate wastewater [Clarens *et al.,* 2010]. Approximately, this combination can reduce 50% of the water consumed in regular WWTPs, in order to remove nitrogen and phosphorus, as they require significant freshwater inputs [Clarens *et al.,* 2010]. Experiments in this field have showed that microalgae are capable of maintaining an optimum growth and productivity while at the same time remediating wastewater [Brennan & Owende, 2010].

Since there was no scientific agreement regarding the amount of water consumed during microalgae cultivation [Mata *et al.,* 2010], it was hard to compare microalgae scenarios with CVJF. According to one study, most alternative fuels require more water to be produced than conventional fuel [Pate *et al.,* 2007]. However, when microalgae are cultivated in a way that is mostly dependent on wastewater, then the amount of freshwater needed, becomes very low, thus making it environmentally sustainable in terms of water consumption [Lardon *et al.,* 2009]. As such, the two alternatives RWPW and PBRW were assumed to behave more favourably in terms of water consumption, in comparison to CVJF. However, when comparing RWPF and PBRF, these two alternatives have the ability to consume more freshwater than CVJF, even with spent medium recycling [Lardon *et al.,* 2009].

Moreover, RWPF and PBRF were assumed to be supplied with freshwater coupled with fertilizers, during microalgae cultivation stage. Fertilizers need petroleum resources, which consume water, to be produced [Clarens *et al.,* 2010]. Although RWPF and PBRF have the ability to consume more freshwater than CVJF, it should be taken into consideration that the amount of water consumed in order to extract crude oil is increasing with time, as oil wells age [Elcock, 2010]. With time, the extracted oil becomes heavier and more viscous, and it requires the use of enhanced oil recovery technologies, which consume large amounts of water ranging between 2 to 350 gallons of water per gallon of oil extracted [Pate *et al.*, 2007]. To meet these high needs of water consumption, the industry tends to recycle the water output [Pate *et al.*, 2007]. However, according to one study, only 55% of the water output or produced water gets re-injected and reused for activities such as enhanced oil recovery [Khatib & Vebeek, 2003].

Concerning water quality, during crude oil extraction, water output can contain hydrocarbons such as naphthalene, metals such as zinc, suspended solids such as sands and clays, salt and traces of oil [EPA, 1993]. The treatment of water effluent is necessary before returning it back to the environment [Borasin *et al.*, 2002]. The main water effluent treatment consists of oil removal through gravity separators, where oil floats on the surface due to its lower density, in comparison to water [EPA, 1993]. More advanced treatments include gas flotation and filtration [EPA, 1993]. Other factors, which can influence water quality from crude oil extraction, include blowouts and spills, which can induce negative environmental effects on the aquatic environment [Borasin *et al.*, 2002]. As for microalgae cultivation, the water effluent is not seen to induce a significant impact on water bodies, upon discharge [Park *et al.*, 2011]. On the contrary, when wastewater is the influent used to grow microalgae, they can help improve the water quality; thus, water effluent can have a better quality than water influent [Park *et al.*, 2011]. It is worth mentioning, that the remediation of wastewater by using microalgae constitutes a secondary treatment [Yang *et al.*, 2011]. Thus, a tertiary treatment needs to take place, such as disinfection or filtration, after nutrient removal [Yang *et al.*, 2011].

When combining impacts on both water quality and quantity, CVJF was assumed to have more environmental impacts than the other four scenarios, especially that CVJF is expected to require more inputs from water and energy, with time, as fossil fuel resources become more difficult to obtain [EPA, 1993]. Therefore, water consumption and contaminants in water effluent will keep increasing, as crude oil extraction activities become more energy and water demanding. On the other hand, microalgae cultivation is expected to become more and more efficient with time, like any other biofuel production system [Jorquera *et al.*, 2010, Sims *et al.*, 2010]. An overview of these comparisons is presented in Table 7.1.1.

Table 7.1.1

Overview of the Alternatives in Relation to Water.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	RWPW uses and remediates wastewater, whereas RWPF depends on freshwater and fertilizers.
RWPW versus PBRF	RWPW uses and remediates wastewater, whereas PBRF depends on freshwater and fertilizers.
RWPW versus PBRW	Wastewater use and remediation in both scenarios. Water consumption rate is dependent on location.
RWPF versus PBRF	Freshwater use and fertilizer production and use in both scenarios. Water consumption rate is dependent on location.
RWPF versus PBRW	RWPF uses freshwater and fertilizers, whereas PBRW uses and remediates wastewater.
PBRF versus PBRW	PBRW uses and remediates wastewater, whereas PBRF depends on freshwater and fertilizers.
CVJF versus RWPW	RWPW has less impact on water quantity and quality than CVJF.
CVJF versus RWPF	RWPF has less impact on water quantity and quality than CVJF.
CVJF versus PBRW	PBRW has less impact on water quantity and quality than CVJF.
CVJF versus PBRF	PBRF has less impact on water quantity and quality than CVJF.

7.1.2 Results

Table 7.1.2

Option 1: Water Matrix (1), with RWPs Assumed to Consume less Amount of Water than PBRs.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.333	1.167	0.500	1.333	0.131
RWPW	3.000	1.000	3.500	1.500	4.000	0.394
PBRF	0.857	0.286	1.000	0.429	1.143	0.113
PBRW	2.000	0.667	2.333	1.000	2.667	0.263
CVJF	0.750	0.250	0.875	0.375	1.000	0.099

Table 7.1.3

Ranking of Alternatives, Based Solely on Water (1).

Alternative	Ranking
RWPW	0.394
PBRW	0.263
RWPF	0.131
PBRF	0.113
CVJF	0.099

Best → Worst

Table 7.1.4

Option 2: Water Matrix (2), with PBRs Assumed to Consume less Amount of Water than RWPs.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.438	0.904	0.290	1.117	0.115
RWPW	2.281	1.000	2.087	0.696	2.810	0.271
PBRF	1.106	0.479	1.000	0.347	1.511	0.134
PBRW	3.452	1.436	2.883	1.000	3.651	0.382
CVJF	0.895	0.356	0.662	0.274	1.000	0.098

Table 7.1.5

Ranking of Alternatives, Based Solely on Water (2).

Alternative	Ranking
PBRW	0.382
RWPW	0.271
PBRF	0.134
RWPF	0.115
CVJF	0.098

Best → Worst

7.1.3 Discussion

Due to the dependency of this sub-criterion on the climatic conditions of the location studied, two matrices were chosen to represent the two possible options. In the first matrix, RWPs were assumed to consume less amount of water than PBRs. Therefore, RWPW topped the ranking of alternatives, as it uses and remediates wastewater during microalgae cultivation. Also, in option 1, RWPF outperformed PBRF. In option two, PBRW topped the ranking, as it was assumed that PBRs consume less amount of water than RWPs. In both cases, the use of wastewater contributed to the high ranking of the alternatives RWPW and PBRW, which occupied the top two positions, as the use of wastewater during cultivation can reduce impacts on freshwater in terms of both quantity and quality. CVJF received the lower weight in both matrices, because the differences between option one and option two does not have an effect on the performance of CVJF in terms of water consumption and its potential to cause deterioration to water quality.

7.2 Air

7.2.1 Analysis

Carbon dioxide is the main GHG tackled when comparing fossil fuel resources with renewable energy resources [Brennan & Owende, 2010]. The main difference between these two sources is the fact that burning fossil fuels releases carbon which was previously sequestered [Cherubini & Stromman, 2010]. Therefore, the interest in biomass, and in this case in microalgae, is related to the ability of biomass to absorb atmospheric CO_2 and re-emit the same amount, when combusted [Stratton, 2010]. Thus, microalgae and other feedstocks are said to have a “biomass credit” which makes them more favourable than fossil fuels [Stratton, 2010]. However, life cycle emissions need to be considered because, the biomass credit by itself does not insure, lower life cycle GHG emissions [Stratton *et al.*, 2010]

Calculations by Stratton revealed that conventional jet fuel production and use can lead to 87.5 grams (g) CO_2e/MJ, whereas microalgal HRJ fuel production from RWPF, using freshwater and fertilizers, and combustion can lead to 50.7 5 grams (g) CO_2e/MJ [Stratton, 2010]. This indicates the possibility of reducing GHG emissions from the benchmark scenario, by almost 40%, even when using fertilizers. Although, uncertainties surround the calculations of GHGs, due to the unavailability of data surrounding N_2O emissions from cultivated microalgae [Stratton, 2010], it is safe to say that the use of wastewater instead of freshwater to cultivate microalgae has even a greater possibility to reduce GHG emissions [Clarens *et al.*, 2010, Demirbas & Demirbas, 2010]. In addition to the savings in GHGs produced during fertilizer production, RWPW has the additional advantage of reducing GHG emissions attributed to the energy needed to remediate wastewater in regular WWTPs, as microalgae cultivation coupled with wastewater remediation consumes less energy than regular WWTPs [Demirbas & Demirbas, 2010].

Moreover, as mentioned before, the energy consumed during microalgae cultivation in PBRs is more than the energy consumed during microalgae cultivation in RWPs [Jorquera *et al.,* 2010]. Thus, more GHG emissions were expected to be produced from PBR scenarios than from RWP scenarios [Stephenson *et al.,* 2010]. Also, in comparison to CVJF and according to one study, the amount of energy currently invested to produce microalgal fuels from PBRs is far greater than the amount of energy used to produce conventional fuel, and even when using wastewater, GHG emissions from PBRW still exceed GHGs from CVJF [Stephenson *et al.,* 2010]. Therefore, the global warming potential of PBR alternatives seems to be greater than that of the alternative CVJF [Stephenson *et al.,* 2010].

Another environmental advantage which can be associated with microalgae HRJ fuel scenarios is the production of on-site biogas through anaerobic digestion of microalgal meal, following oil extraction [Posten & Schaub, 2009]. This saving in GHG emissions can be applied to all four alternatives of microalgal HRJ fuel presented in this study. To start with, the presence of an anaerobic digester allows the recirculation of CO_2 into the culture medium [Posten & Schaub, 2009], where 40% of the biogas produced is composed of CO_2 [Stratton, 2010]. Moreover, the 60% of methane, present in the biogas, can be used for on-site energy and heat needs, which reduce the dependency on non-renewable energy resources; thus, reduces GHG emissions [Stratton, 2010]. In addition, the effluent released from anaerobic digestion is rich in nutrients, which can substitute the use of fertilizers, thus reducing GHG emissions from fertilizer production [Collet *et al.,* 2011, Stratton, 2010].

In addition to the life cycle GHG emissions, other emissions were measured during flight trials using HRJ fuel [IATA, 2009c]. The comparison between the emissions of 100% conventional jet fuel engines and the emissions of blended fuel engines show that the later produces less NO_x and smoke emissions [IATA, 2009c]. This reduction in emissions was expected as the blended fuel has a lower flame temperature than conventional jet fuel, due to its higher H/C ration [IATA, 2009c]. However, great uncertainties surround the measurement of NO_x emissions from jet engine exhausts [IATA, 2009c].

On the other hand, tests revealed an increase in both CO and HC emissions, when using blended fuel [IATA, 2009c]. This increase can also be explained by the reduction in the blended fuel flame temperature, as these emissions, unlike NO_x, tend to increase with decreasing flame temperature, where lower temperatures are more likely to lead to incomplete combustion and carbon oxidation [IATA, 2009c]. The increased levels of HC and CO emissions were still within the emission standards [IATA, 2009c]. An overview of these comparisons is presented in Table 7.2.1.

Table 7.2.1

Overview of the Alternatives in Relation to Air emissions.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	Less emission from RWPW, because it does not need fertilizers and it saves on energy needed to remediate wastewater using regular WWTP.
RWPW versus PBRF	PBRF produces more emissions, because it is energy intensive and depends on fertilizers, whereas RWPW leads to less emission, because it does not need fertilizers, and it saves on energy needed to remediate wastewater using regular WWTP.
RWPW versus PBRW	PBRW produces more emissions, because it is more energy intensive than RWPW.
RWPF versus PBRF	RWPF and PBRF are responsible for emissions from fertilizer production and use, but RWPF requires less energy than PBRF; thus, leads to less emission.
RWPF versus PBRW	PBRW consumes more energy and leads to more emissions than RWPF, even though RWPF contributes to emissions from fertilizer production and use.
PBRF versus PBRW	Both PBRF and PBRW produce considerable quantities of emissions because they are energy intensive, but PBRF emits more, because it uses fertilizers.
CVJF versus RWPW	RWPW produces less emission than CVJF, because RWPW is less energy intensive and contributes to energy saving by remediating

Alternatives compared	Comparison overview
	wastewater, which leads to less emission.
CVJF versus RWPF	CVJF is energy intensive; thus, CVJF leads to more emissions than RWPF.
CVJF versus PBRW & PBRF	CVJF is less energy intensive than PBRs; thus, CVJF leads to less emission than PBRs.

7.2.2 Results

Table 7.2.2

Air Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.531	3.683	3.100	2.580	0.251
RWPW	1.882	1.000	7.880	6.913	5.243	0.508
PBRF	0.271	0.127	1.000	0.946	0.597	0.066
PBRW	0.323	0.145	1.057	1.000	0.749	0.075
CVJF	0.388	0.191	1.675	1.335	1.000	0.101

Table 7.2.3

Ranking of Alternatives, Based Solely on Impacts on Air.

Alternative	Ranking
RWPW	0.508
RWPF	0.251
CVJF	0.101
PBRW	0.075
PBRF	0.066

Best

Worst

7.2.3 Discussion

Raceway ponds topped the ranking among the alternatives, in terms of environmental impacts on air, due to their lower energy needs, in comparison to the other alternatives. The highest score was for RWPW, which contributes to emission savings by reducing energy inputs associated with fertilizer production, and by reducing the needs for regular WWTPs to remediate wastewater. PBRs, on the other hand, received the lowest ranking, because they require high energy input, which leads to high gaseous emissions. Although, CVJF is usually regarded as a high contributor to GHG and other emissions, PBRs were still worst alternatives than CVJF, due to their energy inefficiencies during microalgae cultivation. It is true that microalgal HRJ fuel leads to less NO_x emissions during fuel combustion, but this advantage is very minor and does not allow PBR alternatives to outperform CVJF, in relation to this sub-criterion.

7.3 Land

7.3.1 Analysis

High impacts on land are recorded from the benchmark CVJF, as it requires oil exploration and extraction which can lead to deforestation, habitat destruction, blowouts and spills [Borasin *et al.,* 2002]. During oil exploration, heavy equipments are introduced, and during oil extraction, deep wells are excavated to obtain substantial amounts of oil, which can lead to ecosystem disruption and affect the biodiversity of the area [IATA, 2007a]. Oil spills on land lead to contamination of soil and nearby groundwater sources [Borasin *et al.,* 2002]. Moreover, oil exploration and extraction induce negative impacts on the aesthetics of the land [Borasin *et al.,* 2002].

On the other hand, the cultivation sites of microalgae can take place on arable and marginal lands [Schenk *et al.,* 2008]; thus, microalgae cultivation does not induce a major impact on land [Schenk *et al.,* 2008]. As such, the four alternatives of microalgal HRJ fuel have lower impacts on land than CVJF. It should be taken into consideration that the area needed to grow microalgae in RWPs, exceeds the area needed for an oil rig [Collet *et al.,* 2011]. When comparing microalgal HRJ fuel alternatives among each other, PBRs seem to have a lower impact on land than RWPs, because they can produce more microalgal biomass while occupying a smaller area [Chisti, 2006]. Moreover, PBRW has the least impact on land, because in addition to occupying less surface area, PBRW remediates wastewater [Park *et al.,* 2011], which reduces the need to build WWTPs, and it does not depend on fertilizers, which reduces the need to build fertilizer production facilities. An overview of these comparisons is presented in Table 7.3.1.

Table 7.3.1

Overview of the Alternatives in Relation to Land Impacts.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	RWPW has less impact on land than RWPF, because it does not need fertilizers, which use land space during production, and because it reduces the need for WWTPs, which also require land space.
RWPW versus PBRF	Although RWPW reduces the need for land for WWTP facilities, PBRF requires less area to produce the same amount of biomass as RWPW. But, PBRF requires fertilizers, which need land space to be produced.
RWPW versus PBRW	Both PBRW and RWPW reduce the need for land WWTP facilities, but PBRW uses land more efficiently than RWPW.
RWPF versus PBRF	PBRF uses land more efficiently than RWPF.
RWPF versus PBRW	RWPF requires fertilizers, which need land space to be produced, whereas PBRW uses land more efficiently than RWPF and reduces the need for WWTPs, which require land space.
PBRF versus PBRW	PBRF and PBRW use land efficiently during microalgae cultivation, but PBRW has the advantage of reducing the need for WWTPs, which require land space.
CVJF versus RWPW & RWPF	RWPs require more land for microalgae cultivation than CVJF for oil extraction, but RWPs can use arable land, while CVJF can have more impacts on land biodiversity and aesthetics.
CVJF versus PBRW & PBRF	PBRs use arable land and require little space, whereas CVJF can impact land biodiversity and aesthetics and require a significant land space for oil extraction.

7.3.2 Results

Table 7.3.2

Land Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.812	0.551	0.183	1.390	0.096
RWPW	1.231	1.000	0.620	0.205	1.822	0.116
PBRF	1.814	1.612	1.000	0.370	2.788	0.186
PBRW	5.455	4.880	2.700	1.000	8.509	0.537
CVJF	0.719	0.549	0.359	0.118	1.000	0.066

Table 7.3.3

Ranking of Alternatives, Based Solely on their Impacts on Land.

Alternative	Ranking
PBRW	0.537
PBRF	0.186
RWPW	0.116
PWPF	0.096
CVJF	0.066

Best → Worst

7.3.3 Discussion

PBRs topped the ranking among the alternatives considered, in relation to impacts on land, due to their ability to make use of insignificant space of arable lands to produce significant amount of microalgal biomass. PBRW, in particular, received the highest score, because in addition to the previously mentioned advantages, PBRW can remediate wastewater, which eliminates the need for regular WWTPs, which in turn require land space. Although, RWPW has the same advantage as PBRW, in terms of wastewater remediation, RWPW received a lower rank than PBRW and PBRF, due to its need for vast spaces, to be able to produce significant amounts of microalgal biomass. All of the four microalgal HRJ fuel alternatives exceeded CVJF, in regard to this sub-criterion, because they can depend on arable and marginal lands and because they do not induce significant damage on the land used during microalgae cultivation, unlike crude oil extraction activities.

7.4 Overall environmental considerations

7.4.1 Results

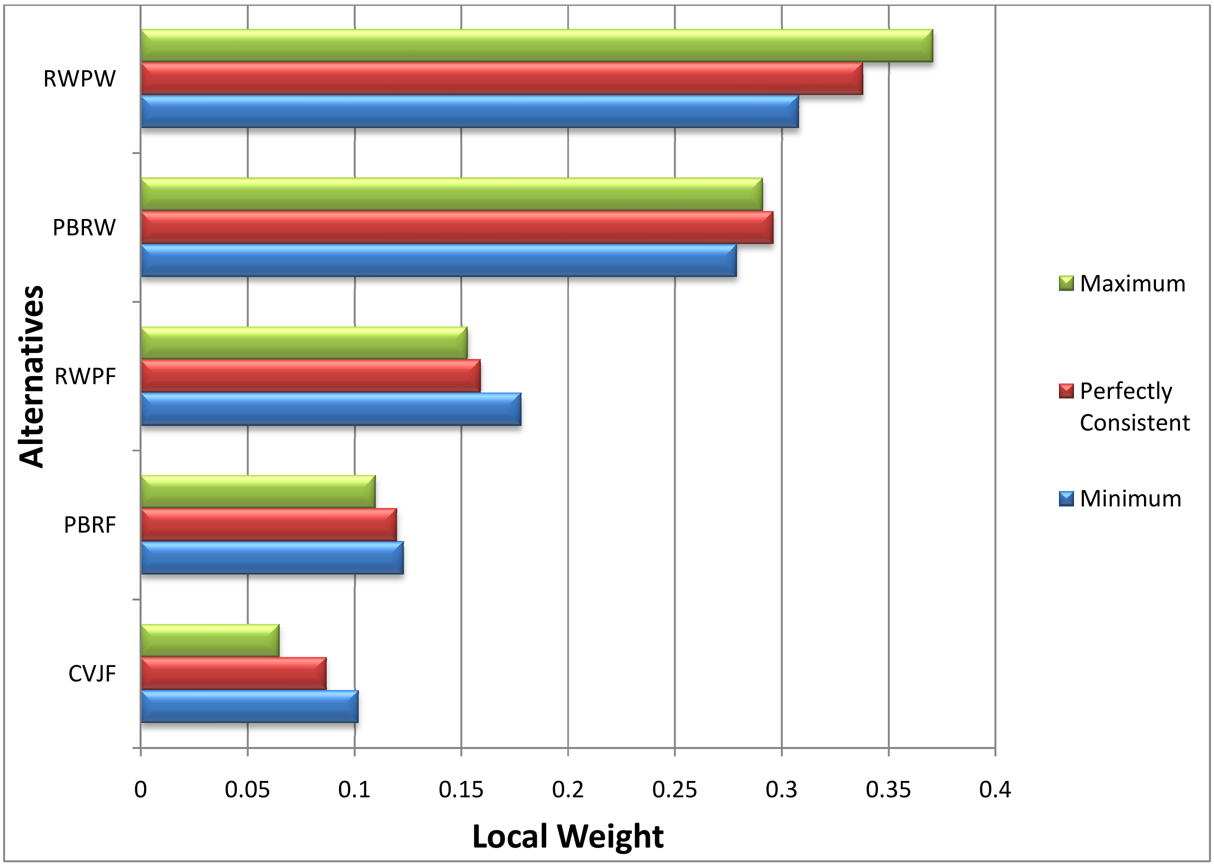

*Figure 7.4.1.*Overall environmental considerations (1) of the five alternatives, corresponding to maximum, perfectly consistent and minimum matrices, taking into consideration water matrix (1).

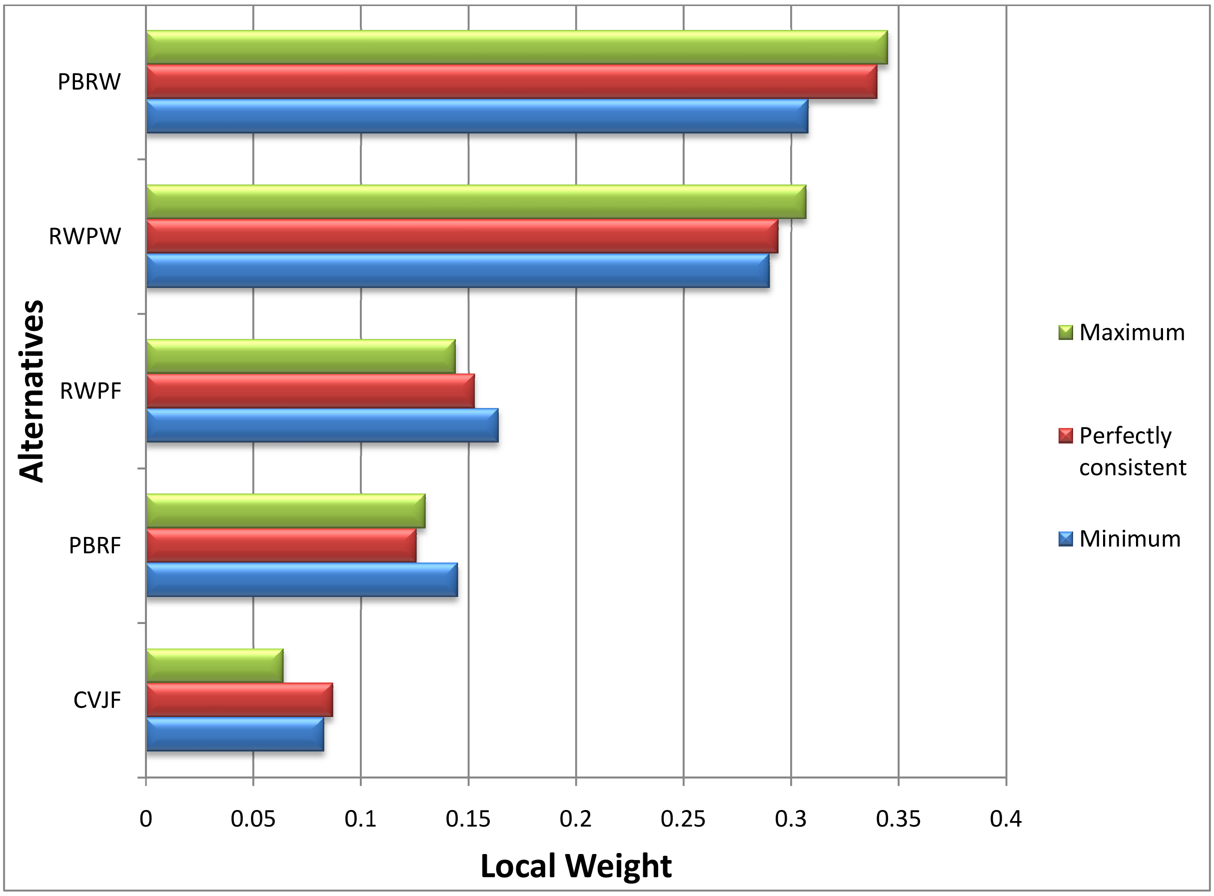

*Figure 7.4.2.*Overall environmental considerations (2) of the five alternatives, corresponding to maximum, perfectly consistent and minimum matrices, taking into consideration water matrix (2).

7.4.2 Discussion

The overall environmental considerations of the alternatives seemed to change with regard to changes in the first sub-criterion; water. From Figure 7.4.1, RWPW seemed to receive the highest ranking among the alternatives. Therefore, when RWPs were assumed to be more water efficient than PBRs, RWPW was able to exceed all the other alternatives, in terms of the overall environmental considerations. On the other hand, when PBRs were assumed to be more water efficient than RWPs, the overall environmental considerations were also affected, and PBRW topped the ranking, in this case. As such, this result clearly stresses on the importance of taking into consideration the location of microalgae cultivation, whether in hot or cold climate, in order to carefully choose the most suitable cultivation system, which is able to reduce overall environmental impacts. Therefore, no one particular system can be regarded as suitable for all locations.

In the two options considered, the first and second alternatives were always those alternatives which were assumed to use wastewater, during microalgae cultivation. Therefore, in addition to air emissions, impacts on water ought to be taken into consideration when assessing any alternative fuel, as the impacts on water can affect the overall environmental considerations and the ranking of alternatives. The environmental performance of the first two alternatives, in reference to both water options, was roughly close, whereas the environmental performance of the first two alternatives in comparison to the other alternatives was significantly distant. Therefore, using wastewater during microalgae cultivation can greatly enhance the overall environmental performance of alternative fuels.

When microalgae cultivation was combined with wastewater treatment, the environmental benefits can be seen at the water and air levels. Therefore, in the two scenarios, those alternatives which were coupled with wastewater treatment seemed to always stay as the top two alternatives. However, when the use of wastewater during microalgae cultivation was removed from the equation, and the comparison was limited to PBRF and RWPF, RWPF seemed to always perform better than PBRF, at the overall environmental level. In the first scenario, PBRF performed better only in terms of impacts on land, whereas in the second scenario, PBRF performed better in terms of impacts on land and water, in comparison to RWPF, but still PBRF did not manage to precede RWPF in the ranking, in either of the scenarios. This observation emphasized that the impact that PBRF induces on air is far greater than the impact that RWPF induces on both water and land combined. On the other hand, CVJF was ranked as the worst alternative in terms of environmental considerations, in reference to both water options. Although, CVJF scored better than PBRs in relation to the sub-criterion air, this was not enough to push CVJF ahead of PBRs, as it was the case for RWPF in comparison to PBRF.

Chapter 8: Economic considerations

8.1 Fuel cost

8.1.1 Analysis

It is true that the cost of conventional jet fuel today is much lower than the cost of the other alternative fuels considered in this study, but uncertainty plays a role in the future price of petroleum fuels [IATA, 2007a]. The cost of conventional jet fuel fluctuates with crude oil price fluctuations, and it is approximately 1.3 the cost of a barrel of crude oil [IATA, 2007a]. The price of conventional jet fuel cannot be maintained, as crude oil resources are limited and are being depleted [Luque *et al.,* 2008, Schenk *et al.,* 2008]. The quality of petroleum fuels is decreasing, which in turn increases the cost of extraction, refining and production [Hileman *et al.,* 2009, Schenk *et al.,* 2008]. The price of conventional jet fuel today is four times higher than the price of conventional jet fuel few years ago [Hileman *et al.,* 2008]. As the price of crude oil rises, the opportunity for other renewable sources of energy to be cost competitive and become commercially available, increases [Schenk *et al.,* 2008, Sims *et al.,* 2010].

The increased knowledge in the field of microalgae and the development of more efficient technologies for microalgae cultivation and harvesting are believed to be able to reduce the final cost of microalgal oil and fuel, to become competitive with the rising cost of crude oil [Schenk *et al.,* 2008]. The field of producing microalgae for biofuels is still in its early stages; thus, the cost of microalgal oil and fuel is based mainly on assumptions and extrapolations from pilot scale projects [Schenk *et al.,* 2008]. The main obstacle for microalgal biofuel commercialization is the high cost of oil feedstock stemming from high capital and operating costs [Li *et al.,* 2008, Sims *et al.,* 2010].

Jet fuel obtained from microalgae cultivated in PBRs is the most expensive fuel among the alternative fuels considered in this study, due to its high capital and operating costs [Huntley & Redalje, 2006, Jorquera *et al.,* 2010]. Many researchers agree that PBRs are still unable to produce microalgal biomass at a cost which can make the microalgal fuel competitive with other conventional fuels [Norsker *et al.,* 2011]. Today, the price of crude oil has exceeded $85/bbl [EIA, 2011]. In early phases of microalgal biofuels, researchers believed that microalgal oil can become cost competitive with crude oil at a price of $75/bbl [IATA, 2007a]. These assumptions were based on beliefs that microalgae can sustain biomass productivity at 60g/m^2.day with 50% oil content, thus producing oil at an average price of $75/bbl [Schenk *et al.,* 2008]. However, as years have passed by, these rates of productivities are still theoretical and today the price of crude oil has exceeded $75/bbl, and microalgal oil still has not reached economic viability [Schenk *et al.,* 2008].

There are diverse estimates considering the price of microalgal oil, ranging between $56/bbl to $378/bbl when cultivated in raceway ponds [Huntley & Redalje, 2006, Jorquera *et al.,* 2010], and not less than $379/bbl when cultivated in closed photo-bioreactors [Chisti, 2007, Jorquera *et al.,* 2010]. As for the cost of HRJ fuel from microalgae, the range is between $3 per gallon, which is considered optimistic, to $60 per gallon [IATA, 2009c]. Therefore, high uncertainties surround the price of HRJ from microalgae, and it seems that a realistic estimate cannot be reached, just by depending on pilot scale projects [IATA, 2010, Sims *et al.,* 2010]. An overview of these comparisons is presented in Table 8.1.1.

Table 8.1.1

Overview of the Alternatives in Relation to Fuel Cost.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	Fuel cost of RWPW and RWPF is approximately the same, because they use the same cultivation system. RWPW contributes to more economic benefits.
RWPW & RWPF versus PBRF & PBRW	Fuel cost of RWPs is better than that of PBRs, because RWPs are cheaper to build and operate, which leads to lower fuel prices.
PBRF versus PBRW	Fuel cost of PBRW and PBRF is approximately the same, because they use the same cultivation system. PBRW contributes to more economic benefits.
CVJF versus RWPW & RWPF	Fuel cost of CVJF, which is commercially produced, is much better than that of RWPs which is still very limited.
CVJF versus PBRW & PBRF	Fuel cost of CVJF, which is commercially produced, is far better than that of PBRs which is still mainly at laboratory scale.

8.1.2 Results

Table 8.1.2

Fuel Cost Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.909	1.364	1.273	0.182	0.110
RWPW	1.100	1.000	1.500	1.400	0.200	0.121
PBRF	0.733	0.667	1.000	0.933	0.133	0.080
PBRW	0.786	0.714	1.071	1.000	0.143	0.086
CVJF	5.500	5.000	7.500	7.000	1.000	0.603

Table 8.1.3

Ranking of Alternatives, Based Solely on Fuel Cost.

Alternative	Ranking
CVJF	0.603
RWPW	0.121
RWPF	0.110
PBRW	0.086
PBRF	0.080

Best → Worst

8.1.3 Discussion

Because CVJF has far better and cheaper fuel cost than microalgal HRJ fuel derived from either microalgae cultivated in RWPs or PBRs, CVJF topped the ranking, with regard to this sub-criterion. A huge gap can be noticed separating CVJF than the rest of the alternatives. RWP alternatives perform slightly better than PBR alternatives, but neither of them can be regarded as cost competitive with conventional jet fuel.

8.2 Capital cost

8.2.1 Analysis

There is an agreement that raceway ponds are less expensive to build than closed photo-bioreactors [Borowitzka, 1992, Collet *et al.,* 2011, Ratledge & Cohen, 2008], as ponds can be constructed from less expensive materials such as concrete and PVC, in comparison to transparent and resistant plastic or glass tubes used in closed photo-bioreactors [Jorquera *et al.*, 2010]. A major problem which is inhibiting the widespread adoption of closed photo-bioreactors is their high capital cost, which can be ten times higher than the cost of establishing open ponds [Brennan & Owende, 2010, Posten & Schaub, 2009, Schenk *et al.,* 2008].

Land cost should not be ignored when taking into consideration the capital cost of PBRs and RWPs. RWPs require more land area to produce the same amount of microalgae than PBRs; thus, RWPs need more land space, which means higher capital cost [Borowitzka, 1992]. On the other hand, the cultivation of microalgae in either PBRs or RWPs is expected take place on marginal and arid land, which is not expensive [Borowitzka, 1992, Li *et al.,* 2008].

In terms of wastewater versus freshwater, the capital cost includes the cost of infrastructure which is needed to transport the water [Clarens *et al.,* 2010]. This issue can be divided into two aspects. When depending on freshwater, site selection should take into consideration freshwater availability; thus, a nearby source of freshwater should be available, which reduces the infrastructure cost in terms of pipelines (e.g., length) [Sheehan *et al.,* 1998]. When using wastewater for microalgae cultivation, the source of wastewater might not be in the near vicinity of the facility; thus, infrastructural cost can be higher than the case of using freshwater resources to grow microalgae [Clarens *et al.,* 2010]. The pipelines might need to be of greater length and of greater durability in order to prevent leakage. However, this cost is eliminated due to the fact, that in the absence of a facility coupling microalgae cultivation with wastewater treatment, this wastewater would still need the infrastructure in order to be transported into a regular WWTPs [Pittman *et al.,* 2011]. In addition, the capital cost for microalgae cultivation facility using wastewater can omit the need to build a regular WWTP to handle this wastewater [Park *et al.,* 2011].

Another constituent of capital cost is the cost of pipelines which are intended for CO_2 transport. As mentioned before, in this study the source of CO_2 was assumed to be from a nearby power plant [Patil *et al.*, 2008, Posten & Schaub, 2009]. Thus, the cost of pipelines and infrastructure was not considered as significant [Posten & Schaub, 2009]. An overview of these comparisons is presented in Table 8.2.1.

Table 8.2.1

Overview of the Alternatives in Relation to Capital Cost.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	RWPW has a lower capital cost than RWPF, when taking into consideration the savings in capital costs needed to build regular WWTPs.
RWPW & RWPF versus PBRF & PBRW	RWPs have lower capital cost than PBRs.
PBRF versus PBRW	PBRW has a lower capital cost than PBRF, when taking into consideration the savings in capital costs needed to build regular WWTPs.

8.2.2 Results

Table 8.2.2

Capital Cost Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	Eigenvector
RWPF	1.000	0.500	3.000	2.500	0.268
RWPW	2.000	1.000	6.000	5.000	0.536
PBRF	0.333	0.167	1.000	0.833	0.089
PBRW	0.400	0.200	1.200	1.000	0.107

Table 8.2.3

Ranking of Alternatives, Based Solely on Capital Cost.

Alternative	Ranking	
RWPW	0.536	Best
RWPF	0.268	
PBRW	0.107	
PBRF	0.089	Worst

8.2.3 Discussion

Conventional jet fuel was not considered in this sub-criterion, due to the fact that its capital infrastructure and needs are already established and efficient, where mature technologies are used [Hileman *et al.*, 2009]. Thus, the capital cost of CVJF, currently, does not inhibit its production. As for the rest of the alternatives providing microalgal HRJ fuel, their capital cost was mainly attributed to microalgae cultivation facilities [Papalexandroua *et al.*, 2008, Sims *et al.*, 2010]. RWPW received the highest weight, because it benefits from two characteristics; the first characteristic is the lower capital cost of RWPs in comparison to PBRs, and the other characteristic is the savings in the need to build regular WWTPs to remediate wastewater. The second alternative RWPF was also based on RWP systems, due to the fact that RWPs are cheaper to build than PBRs. Whereas the third alternative was PBRW, because in comparison to PBRF, PBRW contributes to savings in the need to build regular WWTPs, whereas PBRF does not benefit from such an advantage, on the contrary PBRF requires fertilizers to be produced, which need additional capital cost for fertilizer production facilities to be built.

8.3 Operating cost

8.3.1 Analysis

Operating cost of PBRs exceeds the operating cost of RWPs, due to the highly controlled environment and the energy needed for mixing, pumping, cooling and degassing in closed photo-bioreactors [Borowitzka, 1992, Jorquera *et al.*, 2010]. The more closed photo-bioreactors offer controlled culture conditions, to increase productivity, the more they become expensive to operate [Jorquera *et al.,* 2010]. Some studies argue that the high cost of closed photo-bioreactors is offset by their high biomass productivity while occupying very little space [Borowitzka, 1992, Brennan & Owende, 2010, Schenk *et al.*, 2008]. But, the issue is that these high productivities of microalgae in PBRs have not been reached yet, outside of laboratories [Chisti, 2006]. However, researchers believe that there exists room for improvement for PBRs to become more cost efficient [Chisti, 2007, Norsker *et al.,* 2011].

Moreover RWPW and PBRW are more economically efficient than RWPF and PBRF, respectively [Khan *et al.*, 2009]. The use of wastewater to grow microalgae provides economic incentives in terms of providing nutrients, instead of purchasing fertilizers [Chisti, 2007, Demirbas & Demirbas, 2010, Khan *et al.*, 2009]. In terms of wastewater remediation, the economic benefits are solely at the RWPW level because it consumes less energy than regular WWTPs [Patil *et al.,* 2008, Pittman *et al.*, 2011], whereas PBRW does not provide such an economic incentive due to its higher energy needs in comparison to regular WWTPs [Goldman, 1979]. Moreover, making use of the by-products produced such as biogas and nutrient rich effluent from anaerobic digestion, can also make microalgae cultivation more economically attractive [Collet *et al.,* 2011, Demirbas & Demirbas, 2010, Satyanarayana *et al.,* 2010].

Concerning CO_2, as mentioned before, microalgae were assumed to be fed with a nearby source of flue gas, from a power plant emitting CO_2. The cost of this operation is mainly related to efficient mixing of the culture in order for microalgae to capture the CO_2 [Brune *et al.,* 2009, Schenk *et al.,* 2008]. However, the mixing is required for other reasons as well, such as nutrient recycling and prevention of microalgae settling [Schenk *et al.,* 2008]. Thus, the cost of mixing in relation to the CO_2 capture cost becomes negligible, because the cost of mixing is divided between several operations. In addition, if CO_2 was not being captured by microalgae, it would either induce adverse environmental impacts such as global warming or it would have to be captured by other form of techniques such as in deep geological wells or in oceans, which in turn have a relatively high cost and have the ability to increase the electricity bill by more than 30% [kadam, 2002]. As such, it is not only environmentally beneficial to use microalgae for CO_2 capture, but economic as well [Li *et al.*, 2008, Patil *et al.*, 2008].

The cost of microalgae harvesting was previously considered to be too expensive, for biofuel production purposes, but this perception has changed with the rising prices of petroleum fuels and with the better understanding of microalgae harvesting technologies [Posten & Schaub, 2009]. The cost of microalgae harvesting can range between 20-30% of total biofuel cost, due to the high water content [Mata *et al.*, 2010, Uduman *et al.*, 2010]. Flocculation followed by centrifugation, were the methods assumed to be used in this study, in order to harvest microalgae and minimize its water content. Centrifugation used as a first step can be very costly for biofuel production [Packer, 2009]; thus, it was assumed to be applied after flocculation which increases biomass density, especially that microalgae are very small in diameters. The coupling of these two techniques can increase the cost effectiveness of the harvesting process [Brennan & Owende, 2010].

When comparing the cost of harvesting and dewatering between RWPs and PBRs, it seemed that the cost of harvesting and dewatering of microalgae cultivated in closed photo-bioreactors is less than that in RWPs [Chisti, 2007, Norsker *et al.*, 2011]. Microalgal biomass is more concentrated in the former than in the latter and it has lower water content per volume harvested from closed photo-bioreactors [Posten & Schaub, 2009]. Thus, the energy needed to harvest the same amount of microalgae from closed photo-bioreactors is less than that needed to harvest microalgae from raceway ponds [Posten & Schaub, 2009].

Another important component of operating cost is labour cost [Chatzimouratidisa & Pilavachi, 2009]. Researchers describe microalgae cultivation and processing, and facilities' maintenance as labour intensive [Borowitzka, 1992]. During cultivation, monitoring is a crucial aspect which can determine early signs of culture collapse [Mata *et al.*, 2010]. Thus, constant monitoring is required, which in turns necessitates expenses related to personnel and expertise availability [Borowitzka, 1992]. An overview of these comparisons is presented in Table 8.3.1.

Table 8.3.1

Overview of the Alternatives in Relation to Operating Cost.

Alternatives compared	**Comparison overview**
RWPW versus RWPF	RWPW has lower operating cost than RWPF, which includes fertilizer use costs.

Alternatives compared	Comparison overview
RWPW & RWPF versus PBRF & PBRW	RWPs have lower operating costs than PBRs which offer more controlled environment during microalgae cultivation which in turn induces more expenses.
PBRF versus PBRW	PBRW has lower operating cost than PBRF which includes fertilizer use costs.

8.3.2 Results

Table 8.3.2

Operating Cost Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	Eigenvector
RWPF	1.000	0.500	3.000	2.500	0.268
RWPW	2.000	1.000	6.000	5.000	0.536
PBRF	0.333	0.167	1.000	0.833	0.089
PBRW	0.400	0.200	1.200	1.000	0.107

Table 8.3.3

Ranking of Alternatives, Based Solely on Operating Cost.

Alternative	Ranking	
RWPW	0.536	Best
RWPF	0.268	
PBRW	0.107	
PBRF	0.089	Worst

Conventional jet fuel was not considered in this sub-criterion, due to the fact that its operating cost does not currently hinder or impact its production potential and its availability in the fuel market [IATA, 2009c]. As for the rest of the alternatives which provide microalgal HRJ fuel, their operating cost was mainly focused on the microalgae cultivation stage, as they all share the same downstream processing stages. Also, the cultivation stage is regarded as the most influential stage on the end cost of the fuel produced [Sims *et al.*, 2010]. RWPW received the highest weight, because it benefits from two characteristics; the first characteristic is the lower operating cost of RWPs in comparison to PBRs, which are highly controlled, and require high operating cost, and the other characteristic is the lower operating cost to remediate wastewater, in comparison to regular WWTPs. The second alternative, RWPF, was also based on RWP systems, due to the fact that RWPs are cheaper to operate than PBRs. The third alternative was PBRW, which shares similar and high operating cost as PBRF, but it does not require the use of fertilizers.

8.4 Overall economic considerations

8.4.1 Results

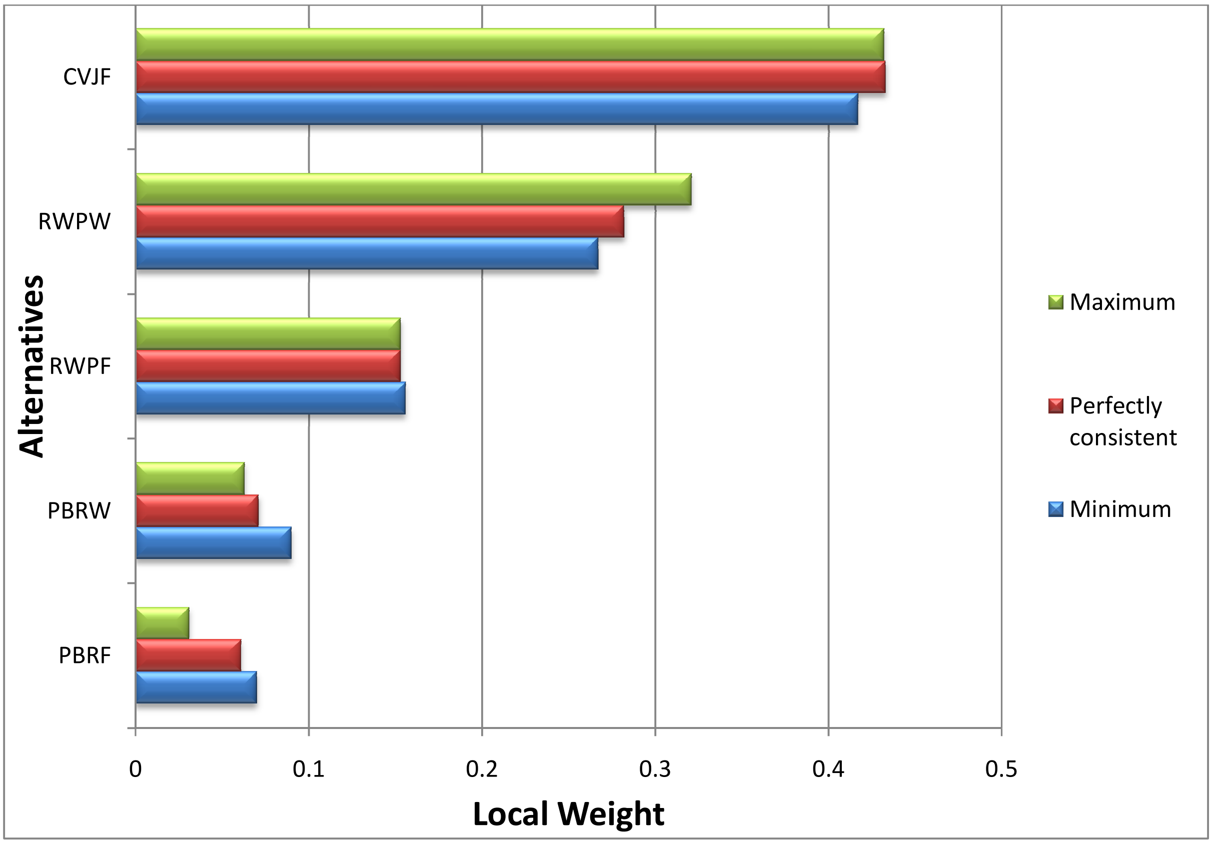

Figure 8.4.1. Overall economic considerations of the five alternatives, corresponding to maximum, perfectly consistent and minimum matrices.

8.4.2 Discussion

In all of the three scenarios; maximum, minimum and perfectly consistent matrices, when comparing the five alternatives, only in terms of economic considerations, CVJF seemed to be the best alternative. This result was expected, as CVJF is the benchmark, which is currently used in the aviation industry and as it is already cost competitive and commercially available, on a worldwide scale. Therefore, CVJF was expected to have the best economic performance among the alternatives, since it has been used in aviation for several decades.

Raceway pond alternatives came next after CVJF in terms of economic considerations, because unlike PBRs, RWPs have been applied at a commercial scale production level [Schenk *et al.*, 2008]. RWPW was the second best alternative, due to the many economic advantages which RWPW offers at both the capital and operating cost levels. The most important advantage which separates RWPW from the rest of microalgal HRJ fuel alternatives is its association with wastewater remediation. One can see that without wastewater remediation, such as in the case of RWPF, RWPs become significantly distant from being cost competitive with CVJF. It is true that RWPW offers many economic advantages over the other alternatives, but its fuel cost still does not allow it to currently compete with CVJF cost.

PBRs, on the other hand, are far away from being cost competitive with either RWP alternatives or CVJF alternative, due to the difficulties they face, mostly at the technological readiness level, which in turn reflect on their economic performance. The great advantage of PBRs is seen as their ability to offer highly controlled growth environment for microalgae during cultivation in closed photo-bioreactors. However, PBRs are still unable to offer this advantage and exceed the performance of other alternatives, due to the difficulties they face in maintaining this controlled environment at a large scale. Technological obstacles such as difficulties of scale-up and energy inefficiency greatly contribute to the fact that PBRs are still mainly at the laboratory level, which in turn contributes to their high cost.

Although the weight of each alternative differed between the three scenarios, this difference did not impact the overall economic considerations of the alternatives considered. Also, it is worth mentioning, that in the maximum scenario, CVJF received the highest weight in comparison to the weight of CVJF in the other two scenarios, whereas PBRs received the lowest weight in the maximum scenario, in comparison to the weight of PBRs in the other two scenarios. This can be explained by the reciprocal values. As the weight given to CVJF rises, in the maximum scenario, the weight of PBRs decreases, due to their reciprocal relationship.

Chapter 9: Overall technological, environmental and economic considerations

9.1 Base-case

9.1.1 Analysis

After deriving the matrices for each sub-criterion, the right eigenvectors were calculated, and the alternatives were weighted in relation to each sub-criterion and criterion. In the first weighting which refers to the base-case, all criteria were assumed to be of similar weight. This weight was derived by dividing the weight of the goal by the number of criteria involved. Therefore, each of the criteria, technological, environmental and economic received a weight of 1/3. The weights of criteria, as mentioned before, represent both their local and global priorities, because the goal's priority is equal to 1. Concerning the sub-criteria, the local priorities of each set of sub-criteria, under each criterion, are equal to 1, and the global priorities of all the sub-criteria are equal to 1. Therefore, the sub-criteria which fall under the environmental and economic criteria, each received a local priority which is equal to 1/3, and a global priority which is equal to 1/9. The sub-criteria which fall under the technological criterion, each received a local priority of 1/4, and a global priority of 1/12 (Check Figure 9.1.1.). The final weights of alternatives obtained correspond to their global priorities.

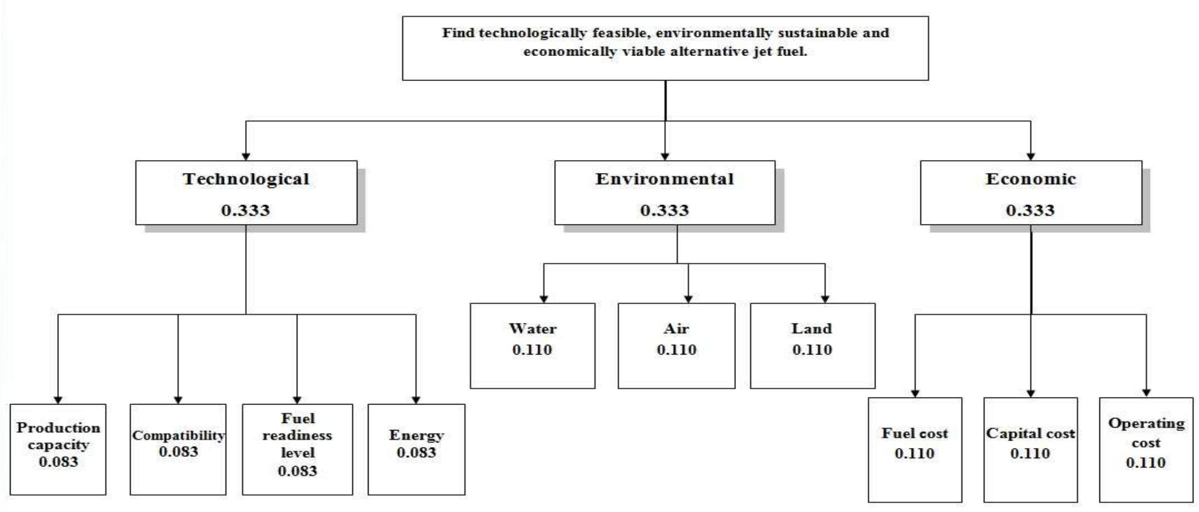

Figure 9.1.1. Base-case hierarchy.

9.1.2 Results

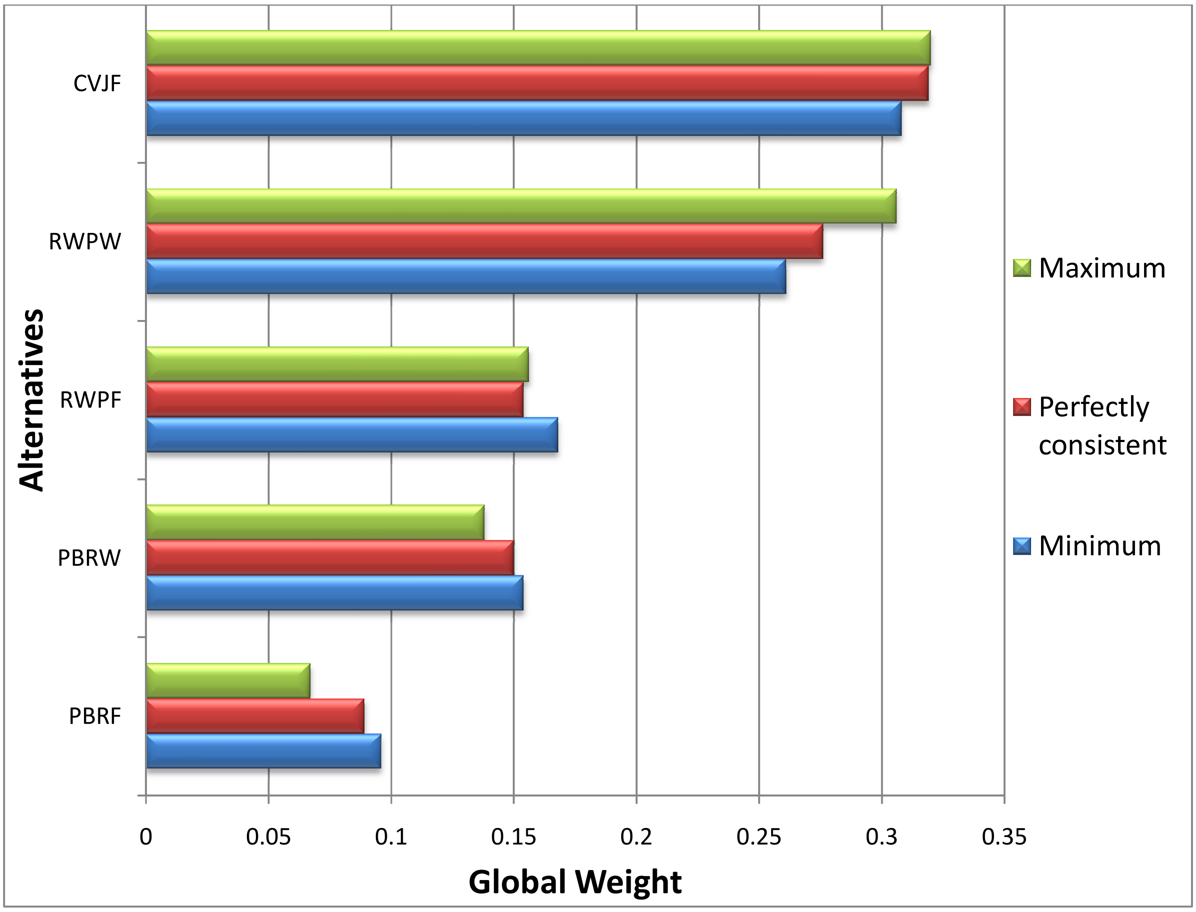

Figure 9.1.2. Overall considerations of the five alternatives, corresponding to the base-case scenario and taking into consideration water (1).

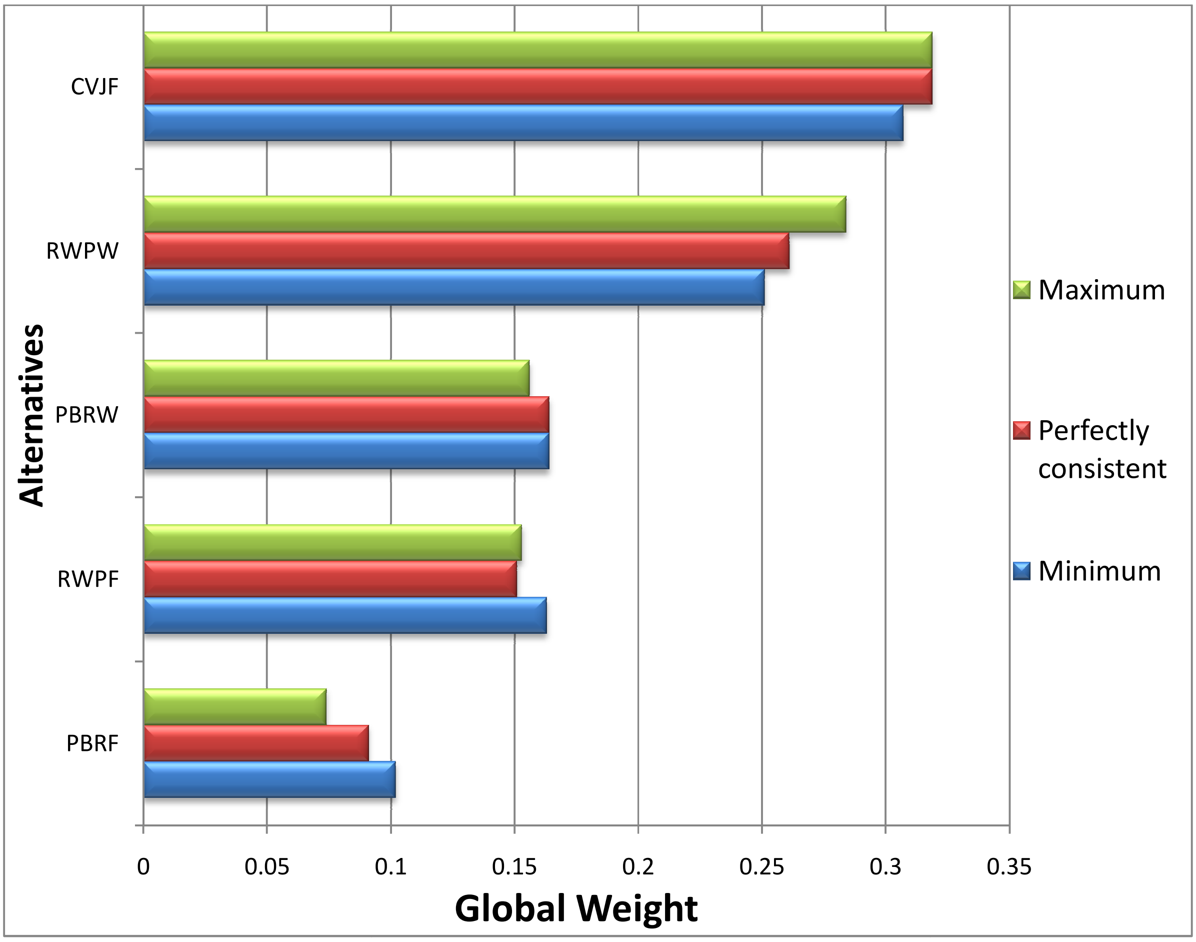

Figure 9.1.3. Overall considerations of the five alternatives, corresponding to the base-case, and taking into consideration water (2).

9.1.3 Discussion

Two types of results were obtained for the base-case, with each corresponding to the assumed water efficiency of closed photo-bioreactors and raceway ponds tackled in chapter seven under the environmental considerations. When all the criteria considered received the same weight of 1/3, the first alternative was CVJF in the two options of water (1 and 2). CVJF topped the ranking of alternatives, because at the technological and economic levels CVJF outperformed the other alternatives, due to its technological viability and commercial availability. Therefore, when giving similar weight and priority to all of the three criteria, no alternative for conventional jet fuel stands out. A decision maker might see that microalgal HRJ fuel alternatives are not yet capable of substituting CVJF, while providing environmental and economic advantages. In such a case, the decision might lean towards CVJF, until microalgal HRJ fuels can improve their overall performance. In all of the three scenarios corresponding to maximum, perfectly consistent and minimum matrices, CVJF was the number one alternative. Therefore, when adding errors to the perfectly consistent matrices and adopting realistic judgments, CVJF is considered the fuel of choice.

The second alternative obtained was RWPW, in all of the three scenarios and in relation to both water options. In this base-case, RWPW global weight was very close to that of CVJF. The difference between the overall performances of CVJF and RWPW (0.043) is much smaller than the difference between the overall performances of CVJF and the other alternatives (0.165-0.23). It is worth mentioning that these numbers (0.043 and 0.165-0.23) were calculated from the perfectly consistent matrices, taking into consideration water (1), and were used as an illustrative example. This high weight of RWPW was mainly due to its environmental benefits associated with the use of wastewater during microalgae cultivation, and due to the large scale application of raceway ponds. It is true that based solely on environmental considerations, as shown in chapter seven, RWPW can be considered as a better alternative than CVJF. But, due to the incorporation of other criteria such as technological and economic, RWPW was pushed behind CVJF. This small difference between these two alternatives might encourage stakeholders and decision makers to increase the research and development related to RWPW, in order to reduce this difference furthermore or maybe to reach a stage where RWPW can outperform CVJF.

Concerning the third alternative, a difference was noticed between the two results corresponding to Figures 9.1.2 and Figure 9.1.3, related to the difference assumed early on, in the water efficiency of closed photo-bioreactors and raceway ponds. This difference had an effect on the overall ranking of the alternatives, corresponding to this base-case. In Figure 9.1.2 which is related to water (1), RWPF was shown to be the third best alternative, whereas, in Figure 9.1.3 which is related to water (2), PBRW was shown to be the third best alternative. However, when looking back at the environmental considerations of these two alternatives (Figure 7.4.1 and Figure 7.4.2), PBRW was always a better alternative than RWPF. The reason behind being outperformed by RWPF in the first option (Figure 9.1.2), is the fact that in water

(1) PBRW had slightly better environmental impacts than RWPF, whereas in water (2), this environmental advantage of PBRW over RWPF was much higher.

Therefore, when combining the technological and economic considerations of these two alternatives with their environmental considerations (1), RWPF received the higher weight, because the advantage that RWPF has over PBRW, at the technological and economic levels, far exceeds the advantage that PBRW has over RWPF, at the environmental level. Whereas, when combining the technological and economic considerations of these two alternatives with their environmental considerations (2), PBRW received the higher weight, because the environmental advantage that PBRW possesses over RWPF, far exceeds the advantage that RWPF has over PBRW, at the technological and economic levels combined. To put these comparisons into a numerical context, perfectly consistent matrices were used for illustration. The global technological and economic weight of RWPF is equal to the local weights of RWPF corresponding to the technological and economic criteria, multiplied by the weights given for these criteria, which is 1/3. Therefore, RWPF has a global technological and economic weight which is equal to 0.102. The global environmental weight of PBRW corresponding to water (1) is equal to 0.09, which is less than the global technological and economic weight of RWPF, whereas the global environmental weight of PBRW corresponding to water (2) is equal to 0.111, which is more than the global technological and economic weight of RWPF.

The last alternative was always PBRF. Even when the water efficiency of closed photo-bioreactors was assumed to be better than that of raceway ponds, PBRF was not able to outperform RWPF. PBRF was outperformed by all of the alternatives, because at each of the technological, environmental and economic levels, PBRF was unable to compete with the rest of the alternatives. PBRF is still technologically unfeasible mainly due to its high energy requirements, environmentally unsustainable due to the high emissions which it produces during microalgae cultivation and economically unfeasible due to its high capital and operating costs. Therefore, major advancements are needed to improve the performance of PBRF at the technological, environmental and economic levels in order to be able to compete with the other alternatives.

From this base-case which reflects on the overall performance of conventional jet fuel and alternative jet fuels derived from microalgae, one can reach an important conclusion that a renewable source of energy is not necessarily a sustainable and viable source, to replace conventionally used fuels. The four alternatives derived from microalgae performed poorly in comparison to conventional jet fuel. Therefore, with regards to the weights assigned in this particular case, microalgal HRJ fuel cannot be considered as viable alternative to conventional jet fuel, yet.

9.2 Environmental priority

9.2.1 Analysis

As mentioned before, a sensitivity analysis was conducted in order to compensate for the subjectivity to the pair-wise comparison values. In this first sensitivity analysis, a higher priority was assigned to the environmental criterion. This was justified by the interest of the aviation industry to reduce its environmental impacts by adopting new alternative fuels [IATA, 2009c]. Therefore, the environmental criterion received a weight which is equal to 0.5, whereas each of the economic and technological criteria received a weight which is equal to 0.25. As for the environmental sub-criteria, water and air, they each received a local priority of 0.4 and a global priority of 0.2, whereas the sub-criterion land received a local priority of 0.2 and a global priority of 0.1 (Check Figure 9.2.1).

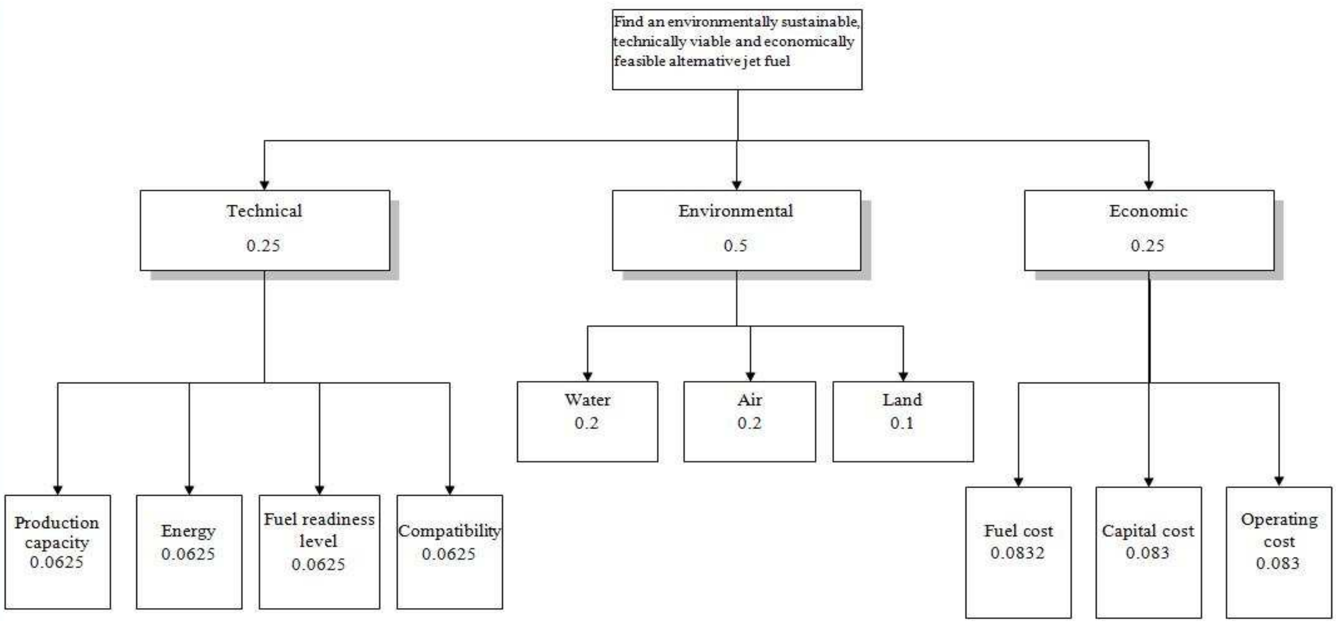

*Figure 9.2.1.*Environmenral priority hierarchy.

9.2.2 Results

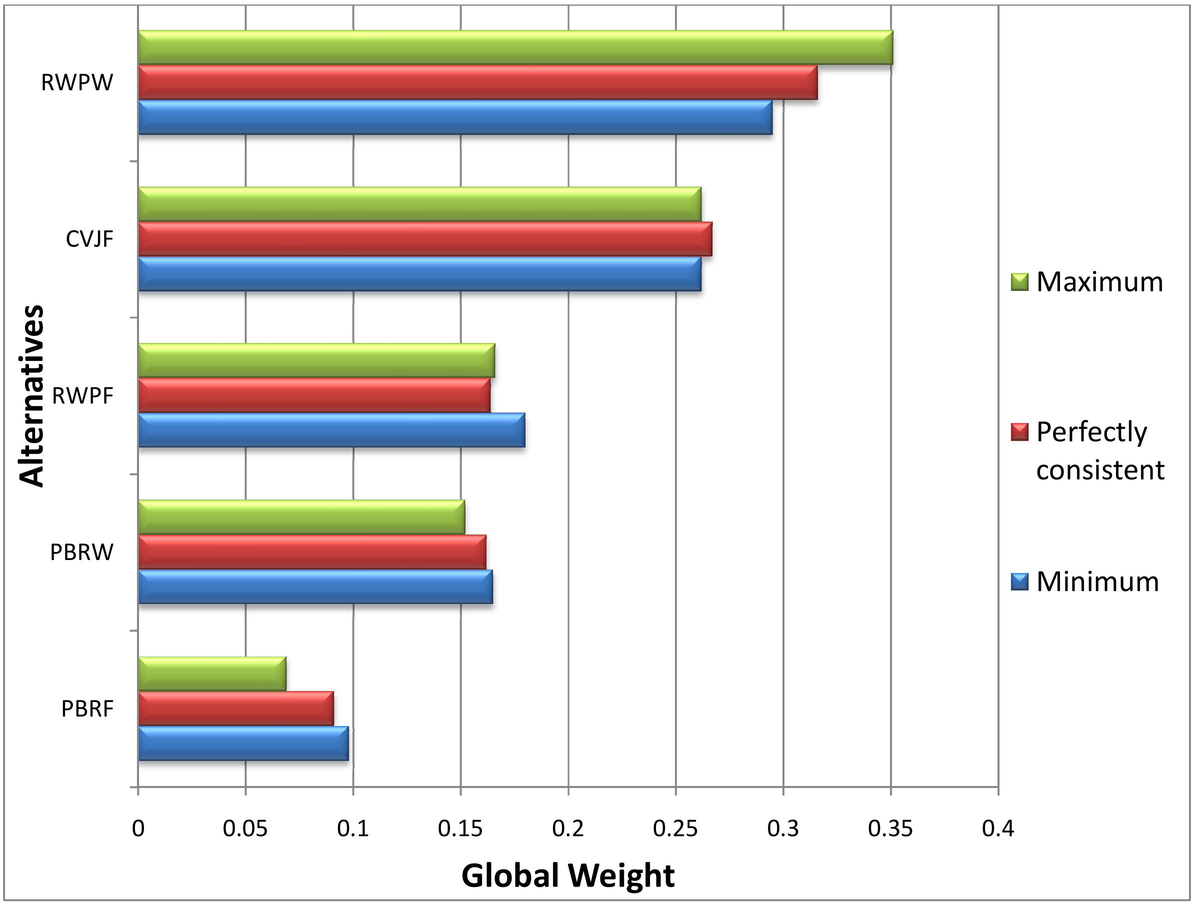

Figure 9.2.2. Overall considerations of the five alternatives, corresponding to the environmental priority case, taking into consideration water (1).

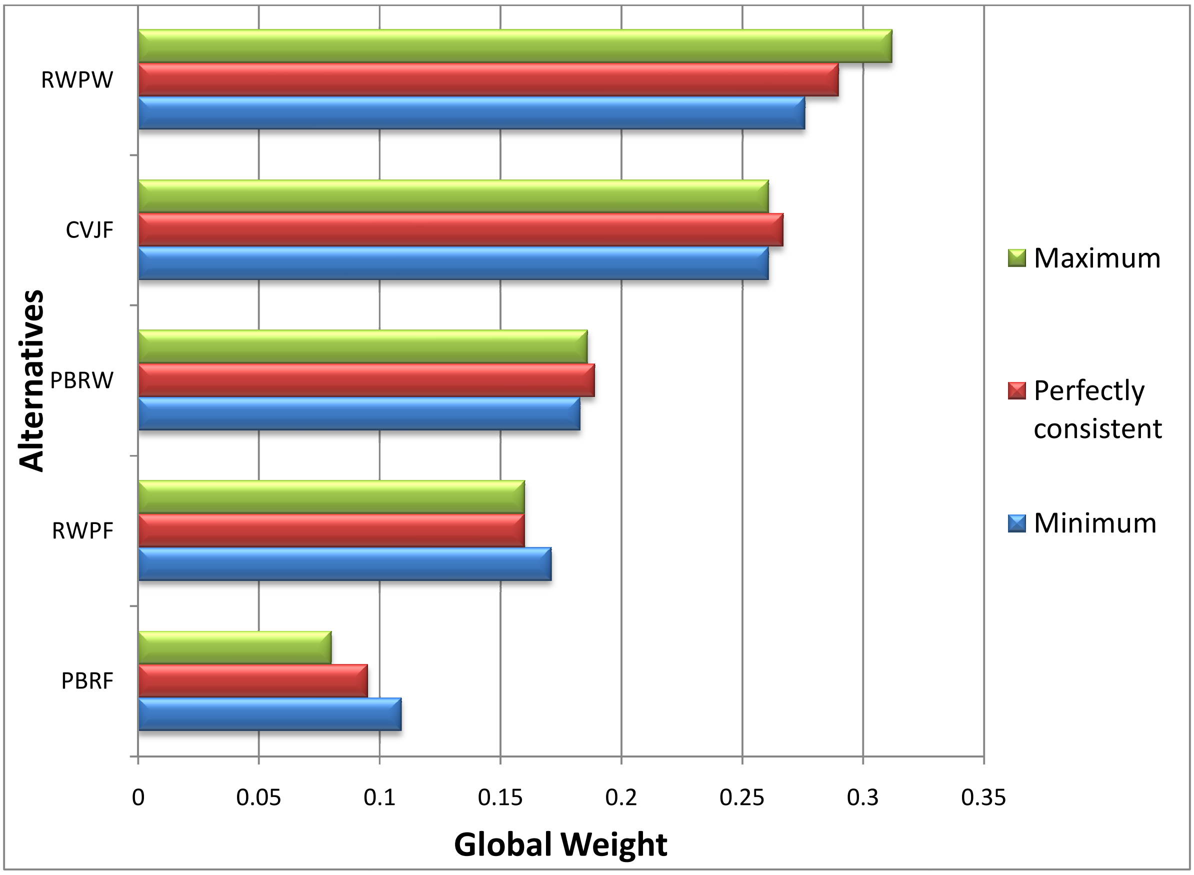

Figure 9.2.3. Overall considerations of the five alternatives, corresponding to the environmental priority case, taking into consideration water (2).

9.2.3 Discussion

When a higher priority was assigned to the environmental criterion, the ranking of alternatives changed in comparison to the base-case. RWPW managed to exceed the benchmark CVJF, in both of the options of water efficiency. However, due to the better performance of closed photo-bioreactors in terms of water consumption in water (2), RWPW received a slightly higher global weight in the overall performance (1), as shown in Figure 9.2.2, than that in the overall performance (2). Despite this difference in its final global weight, it is clear that RWPW would be the number one alternative for stakeholders who wish to focus their main interest on environmental sustainability.

As for the second alternative, CVJF was pushed back to the second place by RWPW. The reason behind this change can be explained by the fact that the technological and economic aspects of CVJF enabled it to outperform RWPW, in the base-case. However, when the environmental criterion was stressed, as in this case, the environmental advantages of RWPW exceeded the technological and economic advantages of CVJF, combined. To put it in a numerical context and taking into consideration the perfectly consistent matrices, the sum of the technological and economic global weights of CVJF is equal to the technological local priority of CVJF multiplied by the weight given to the technological criterion in this case, which is 0.25, plus the economic local priority of CVJF multiplied by the weight given to the economic criterion in this case, which is 0.25. As such, the global technological and economic weight of CVJF becomes 0.263, whereas the global environmental weight of RWPW is 0.316, which is more than the global technological and economic weight of CVJF.

Therefore, from an environmental point of view, the benchmark cannot be considered as the best aviation fuel. But, CVJF can be considered to be currently more environmentally sustainable than the other alternatives derived from microalgae, such as RWPF, PBRW and PBRF. Moreover, the distance between the weights received for both RWPW and CVJF seemed to be far less than the distance between the weights of CVJF and the other lower ranking alternatives.

Similar to the base-case, the third alternative differed between the two water options considered, in this environmental priority case. RWPF outperformed PBRW in regard to water (1), whereas PBRW outperformed RWPW in regard to water (2). Similar to the base-case, this difference stresses on the importance of including the impacts on water and the importance of taking into consideration the climatic conditions of microalgae cultivation sites. RWPF performed better than PBRW in relation to the technological and economic sub-criteria tackled in chapters six and eight. When PBRW outperformed RWPF in this environmental priority scenario, it indicated that when environmental sustainability is stressed, and with the suitable climatic conditions, PBRW with its lower global technological and economic weights can outperform the more readily available and cost-competitive alternative, RWPF.

Also, similar to the base-case, PBRF performed poorly in comparison to the other alternatives, because in addition to its inefficiencies at the technological level and its lack of competitiveness at the economic level, the assumed improved performance of closed photo-bioreactors in terms of water consumption (2) was not able to improve the position of PBRF in comparison to the other alternatives, even with the high environmental priority.

According to Harrison if an alternative jet fuel can be provided with a lower cost than conventional jet fuel or with more environmental advantages than conventional jet fuel, then its adoption in the aviation industry should take place [Harrison, 2008]. As such, while RWPW might have the potential to compete with CVJF, when stressing on environmental sustainability, the other microalgal HRJ alternatives seemed to be far from being competitive with CVJF.

9.3 Economic priority

9.3.1 Analysis

Another aspect of the sensitivity analysis consisted of giving the higher priority to the economic criterion, in comparison to the technological and environmental criteria. This high priority was justified by the weight and the high consideration that the stakeholders assign to the cost of any new alternative fuel [Harrison, 2008]. The economic criterion was assigned a weight of 0.5, whereas the technological and environmental criteria, each received a weight of 0.25. As for the economic sub-criteria, the fuel cost received the highest weight of 0.5, whereas each of the capital and operating costs received a weight of 0.25 (Check Figure 9.3.1). This higher weight assigned to the fuel cost can be explained by the aviation industry's interest in the final fuel cost, in comparison to the benchmark [IATA, 2010].

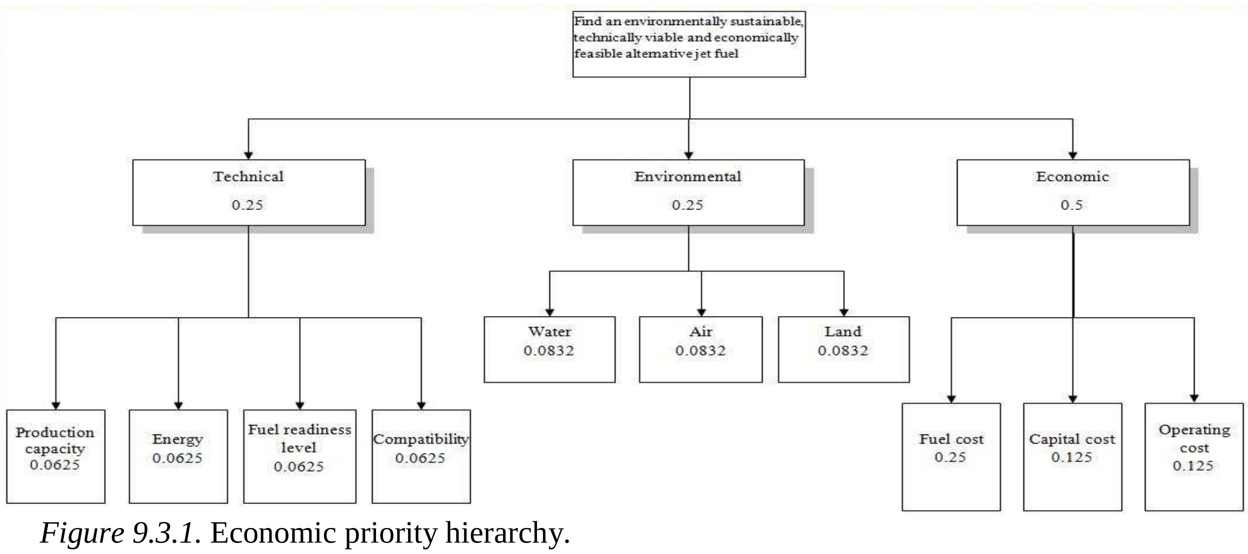

Figure 9.3.1. Economic priority hierarchy.

9.3.2 Results

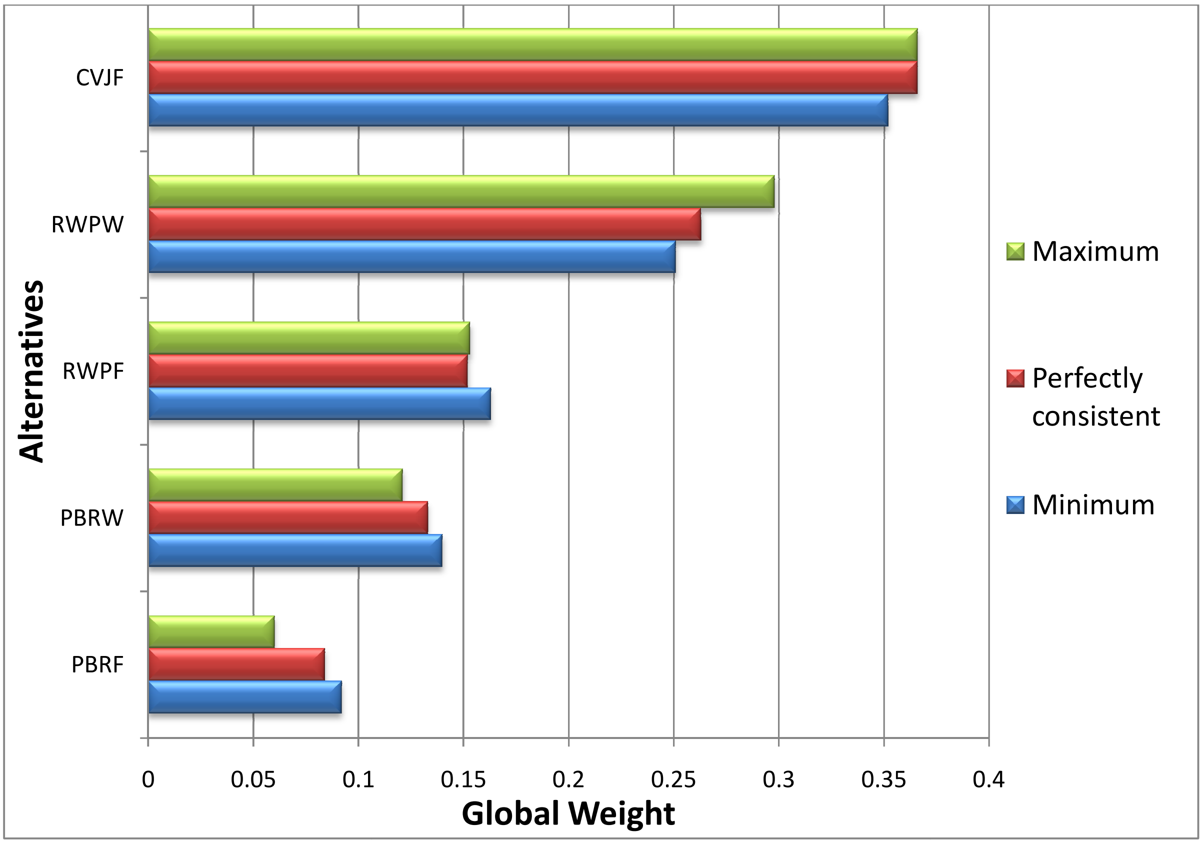

Figure 9.3.2. Overall considerations of the five alternatives, corresponding to the economic priority case, taking into consideration water (1).

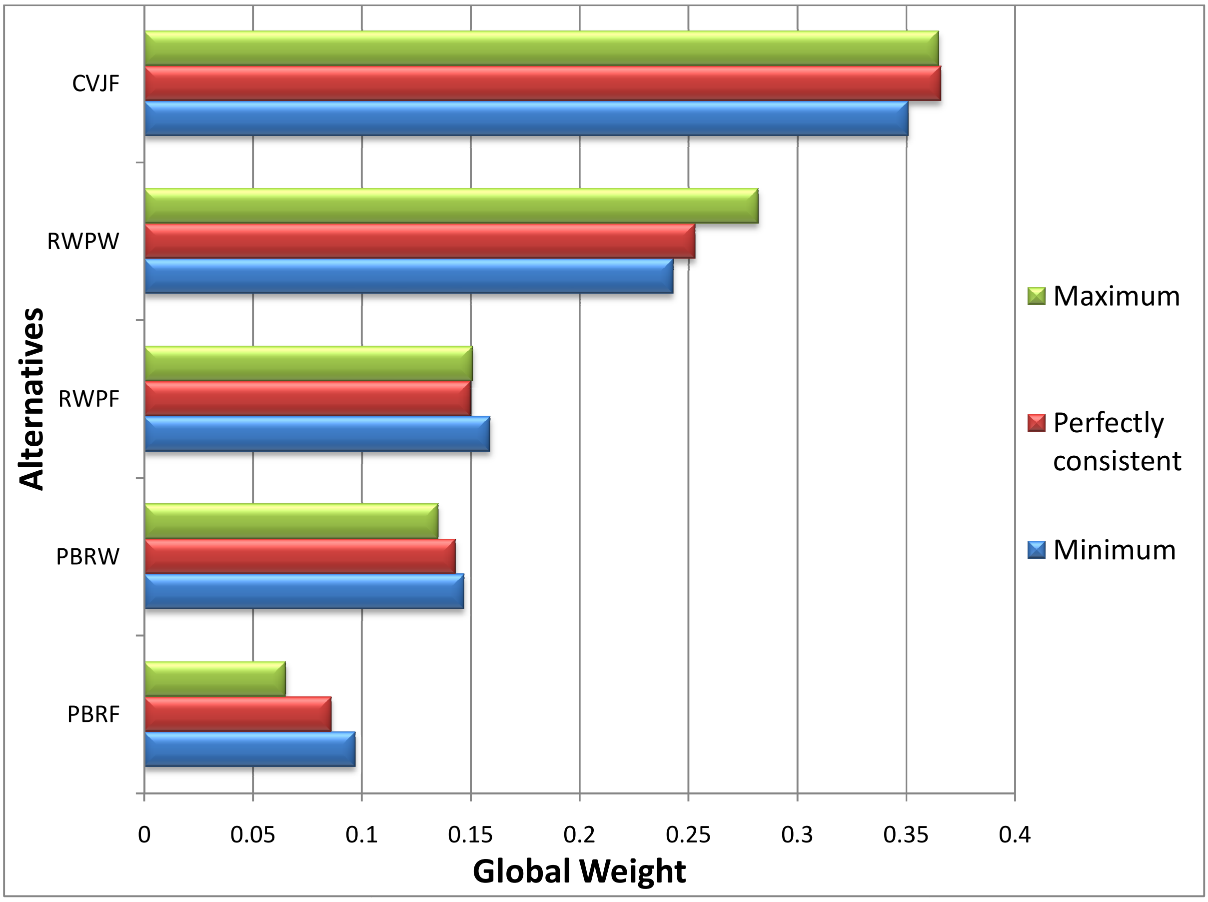

Figure 9.3.3. Overall considerations of the five alternatives, corresponding to the economic priority case, taking into consideration water (2).

9.3.3 Discussion

Giving the higher priority to the economic criterion lead to results which are similar to the ones obtained in the base-case. The benchmark CVJF topped the ranking of alternatives, in relation to both water options, followed by RWPW. However, in this case, the difference between the weights of each of the alternatives CVJF and RWPW (0.103) was more distinct than the difference observed in the base-case (0.033). It is worth mentioning that these numbers (0.103 and 0.033) were calculated from the perfectly consistent matrices, taking into consideration water (1), and were used as an illustrative example. Concerning CVJF, it received the highest ranking, because at the technological and economic levels, CVJF was found to be the best among the alternatives considered. Therefore, it would only be logical for the accumulation of the weights of these two criteria to present CVJF as the best alternative, especially with an increase in the weight of the economic criterion. Therefore, even if at the environmental level, CVJF was not the top alternative, the other two criteria were able to push CVJF to the top, in this case. To put this result in a numerical context and using the perfectly consistent matrices, it would be sufficient the subtract the global environmental weight of CVJF from its overall global weight corresponding to the high economic priority, to see that its global environmental weight is insignificant in comparison to the combined weight corresponding to the other two criteria. As such, the overall global weight of CVJF is equal to 0.366, whereas the global environmental weight of CVJF is equal to 0.0215, which corresponds approximately to 6% of its overall global weight.

The second position occupied by the alternative RWPW was mainly driven by the higher environmental advantages that RWPW offers in comparison to all the other alternatives, and to its higher economic and technological considerations in comparison to the other microalgal HRJ fuel alternatives. RWPW cannot be truly considered as competitive with CVJF at the economic level, but in comparison to the other microalgal HRJ fuel alternatives, RWPW performance was far better than them, which has lead to its closer weight to CVJF.

It is interesting to observe that in this higher economic priority case, the third alternative was the same in the two water options. Unlike the base-case and the environmental case, the assumption that closed photo-bioreactors have a better water efficiency than raceway ponds was not able to help the PBR alternatives, and in particular PBRW, to occupy the third alternative position. In both options, RWPW was ranked as the third alternative; thereby RWP alternatives outperformed PBR alternatives. This result can be explained by the fact that in the base-case and the environmental priority case, the environmental criterion had more weight than that in the economic priority case. In the base-case the environmental criterion was assigned a weight of 0.3 and the global priority of water was 0.09, and in the environmental priority case, the environmental criterion was assigned a weight of 0.5 with global priority of water being equal to 0.2, whereas in the economic priority case, the environmental criterion was assigned a weight of 0.25 with the sub-criterion water having a global priority of 0.075. Therefore, one can see that the enhancement that the improved water performance of closed photo-bioreactors had given to PBR alternatives and PBRW in particular in the base-case and the environmental priority case, did not have the same effect in this case. Thus, PBRW environmental weight was not able to outperform the higher economic and technological weight of RWPF. As such, PBRW was, in both options, ranked as the fourth alternative, followed by PBRF.

Chapter 10: Conclusion

10.1 Summary

Two types of fuels were considered in this study; the first one was the benchmark fuel known as conventional jet fuel and derived from conventional petroleum sources; i.e., crude oil, and the other type was microalgal hydro-renewable jet fuel, obtained from microalgae through the hydro-processing technology. These two types of fuels were divided between five alternative scenarios. The purpose of this study was to evaluate whether a technologically feasible, environmentally sustainable and economically competitive alternative fuel derived from microalgae can be provided to the aviation industry. The reason behind this choice was the lately great interest dedicated to microalgal jet fuel, from the aviation industry. This interest can be explained by the need to find biofuel sources, which are not derived from food crops. The interest in microalgae as a source of fuel is not just at the air transport level, other transport sectors are also showing interest in microalgae, where it is estimated that the US and EU are aiming to replace about 20% of transport fuels by 2020 with microalgal biofuels.

Several alternative scenarios were chosen to represent the different pathways through which microalgal HRJ fuel can be produced. Other pathways are available as many companies and research institutions are working on developing microalgal fuels. However, only few of these technologies were considered due to their widespread use, and due to the availability of information surrounding these particular pathways. It is worth mentioning that the performance of the alternatives considered are dependent on assumptions undertaken by researchers, such as those related to microalgal oil content and biomass productivity. Also, the results corresponding to microalgal fuels can differ when choosing other conversion routes.

The analytic hierarchy process (AHP) was used as the tool to analyze the data available on these two types of jet fuels. The analysis was mainly based on three criteria; the technological, the environmental and the economic. Mainly qualitative data were obtained, which necessitated the use of perfectly consistent matrices and the application of sensitivity analysis to compensate for subjectivity and to account for realistic views and opinions. In addition to the perfectly consistent matrices, two other matrices were derived for each sub-criterion, which represented maximum and minimum values possible for each pair-wise comparison. From the sensitivity analysis the ranking of the alternatives has slightly changed from one case to another, but the top two alternatives were always the same, CVJF and RWPW. Due to its better environmental performance, RWPW was only able to outperform CVJF in the higher environmental priority case, whereas in the other two cases, CVJF occupied the first position in the ranking of the alternatives. Therefore, the final result really depends on the decision makers and stakeholders, and their choice concerning their most important criterion. The other alternatives considered seemed unable to compete with either CVJF or RWPW, in any of the cases considered, as there is a gap noticed between the performance of CVJF and RWPW and the performance of the other alternatives, at the technological, environmental and economic levels.

It is important to note that the viability of microalgal HRJ fuel alternatives greatly depends on the inputs used, such as the type of water used during microalgae cultivation. RWPW was able to outperform RWPF due to the fact that RWPW depended on wastewater, whereas RWPF depended on freshwater input. Also, in other occasions, when closed photo-bioreactors were assumed to be more water efficient than raceway ponds, only PBRW was able to outperform RWPF; even with the poorer performance of PBRW in terms of technological and economic criteria. PBRF was not able to compete with either PBRW or RWP, due to the fact that it depended on freshwater resources for microalgae cultivation. Also, none of the microalgal HRJ fuel would have been able to compete with CVJF, if carbon sources were not provided from cheap waste streams. Therefore, one can see that coupling microalgal biofuel production with the use of waste streams constitutes a crucial requirement for the success of this fuel.

10.2 Adoption, commercialization and certification

It is clear that the adoption and commercialization of alternative jet fuels and specifically microalgal hydro-renewable jet fuel, are still facing many challenges. Most importantly, feedstock availability can be considered as the number one obstacle hindering the widespread adoption of microalgal HRJ fuel. Large scale production of microalgal biomass and microalgal oil has not reached the desired or needed level yet, due to difficulties still facing the producers at the technological and economic levels of microalgae cultivation and harvesting [Mata *et al.*, 2010]. Some of the issues affecting feedstock availability include the obstacle related to microalgae screening, and the identification of the right microalgae species for the right climatic conditions and the right cultivation systems. Although screening is performed by many institutions, there is an applied strategy which consists of not sharing the discoveries concerning the characteristics of different strains of microalgae, as part of an institution's intellectual property, which stems out of concern that competitors might make better use of such results. However, sharing such data is important in order to prevent repeated research and mistakes, which can only lead to more delays.

It is without a doubt that the main economic challenge of microalgal HRJ fuel manifests in the ability to make the transition from laboratory scale tests to a large commercialized scale. Private investors consider such projects to be very risky, especially that they cannot be provided with enough information, which can guarantee the success of these projects. Although raceway ponds have performed better over the years in regard to this aspect and in comparison to closed photo-bioreactors, the economics are still hindering early adopters from taking the risk of funding large scale production facilities. Therefore, governmental support needs to take place in order to ensure the competitiveness of microalgal oil with crude oil. Similar to first generation biofuels, which were supported by governments to reach their current commercial stage, second generation biofuels also need similar support at the level of research and development and pilot scale projects.

Other challenges are related to the hydro-processing stage of microalgal oil. As mentioned before, hydro-processing of bio-oils was first applied to produce, mainly, hydro-renewable diesel fuels in addition to obtaining a smaller fraction of hydro-renewable jet fuels. Additional steps need to be applied in order to produce hydro-renewable jet fuels in higher quantities than hydro-renewable diesel fuels. Therefore, the economics tend to increase when producing this higher fraction of hydro-renewable jet fuels, due to the need for additional steps of hydro-cracking and isomerization. Thus, the price of producing hydro-renewable jet fuel is higher than the price of producing hydro-renewable diesel fuels. Moreover, the amount of fuel needed to power the road transport sector is more than the amount of fuel needed to power the air transport sector. These two facts play a role in favouring the production of hydro-renewable diesel fuels over hydro-renewable jet fuels. To overcome such an issue, it is expected that as more bio-oils undergo hydro-processing in refineries, the production of hydro-renewable jet fuel increases. Moreover, another issue that needs to be tackled in order to increase the widespread production of hydro-renewable jet fuels is the certification of HRJ fuels, which are expected to take place in the coming year, with a maximum fuel blend percentage of 50%.

10.3 Recommendations and future work

It is worth mentioning that although several alternative pathways were considered in this assessment, they all relate to the same feedstock and to the same processing technology which is hydro-processing. Microalgal HRJ fuel is considered as part of the immediate solution to the environmental impacts of aviation, induced by the use of conventional jet fuel, as blended microalgal HRJ fuel can be used directly in the current aviation infrastructure. While many researchers believe in the ability of microalgae to offer considerable contribution towards environmentally sustainable biofuels, and others view in microalgae the ability to displace all liquid fuels obtained from petroleum, microalgae should not be the only feedstock considered and hydro-processing should not be the only technology considered. No one source and production process of alternative fuels can replace conventional jet fuel. Therefore, other alternatives should be considered, in order to provide a combination of the best performing alternative jet fuels to replace conventional jet fuel.

Also, the adoption of renewable alternative jet fuels constitutes one step among the many steps that are being researched and applied by the aviation industry to reduce its environmental impacts. The substitution of conventional jet fuel alone is not enough to significantly reduce the environmental impacts and GHG emissions, especially that during the life cycle of microalgal HRJ fuel, the carbon cycle is not considered to be neutral. Less emission on the overall life cycle is produced from microalgal HRJ fuel than from conventional jet fuel, but this step by itself is not enough to make a significant difference. Therefore, other long term carbon free alternative fuels should also be considered.

Many uncertainties still need to be tackled and addressed in order to have a more thorough understanding of the technological, economic and environmental considerations of microalgal biofuels. Among these uncertainties are those related to the lack of standardized method to account for life cycle GHG emissions. In this particular study, high uncertainties surround the calculation of quantities of nitrous oxides released during microalgae cultivation stage. Therefore, there is an urgent need to develop a standardized procedure, which can properly account for GHG emissions, and which can combine simplicity without scarifying the certainty of the results. Also, gaseous emissions produced during turbine fuel combustion need to be further addressed in order to understand the dynamics which affect the increase or decrease in the quantities of NO_x, HC, CO and smoke number emitted.

Another area which can be improved is the reduction in energy consumption during microalgae cultivation either in open ponds or in closed photo-bioreactors. Although open ponds consume much less energy than closed photo-bioreactors, there is always a room for improvement to make biofuel production less energy intensive. One suggestion consisted of using renewable energy sources instead of fossil fuel sources to power the microalgae cultivation site. Therefore, solar panels can be used for example to provide the required heat for the anaerobic digester or the energy needed for the harvesting steps of microalgae. However, when considering any renewable energy source to replace fossil fuels, it should be taken into consideration that the energy input needed to provide this renewable energy source should not exceed its energy output.

Even with higher alternative fuel prices, the aviation industry might be willing to commit to alternative fuels based on reduced environmental impacts and with the hope that as alternative fuel supplies increase, the price of fuels tend to decrease. However, the important questions become how long before the environmental benefits can be seen and measured and how long before the price of alternative fuels become bearable and acceptable. It is without a doubt that early adopters supported by governments need to take such a risk, as part of the learning curve of alternative aviation fuels.

All the ground tests and flight trials conducted aimed at assessing the feasibility and the environmental and economic performance of 50-50% HRJ fuel blends with conventional jet fuel. The process of alternative jet fuel certification is also concerned with the performance of 50-50% blended fuels. Once the certification of HRJ fuel, including microalgal HRJ fuel, is approved higher percentages of blended fuel need to be considered and assessed. These higher percentages might require alterations to the currently used infrastructure. But, it is important to start considering such higher percentages, as they may provide higher technological, economic and environmental benefits.

Concerning the results obtained from this study, they mainly reflect the current status of conventional and microalgal HRJ fuels. The technologies included in the analysis are based on their present status in the field. However, major advancements are expected to take place at the technological level, which can in turn affect the environmental and the economic aspects of fuels. Microalgal HRJ fuels are expected to become more efficient and more technologically attractive, whereas conventional jet fuels are expected to become less efficient. Therefore, such an assessment needs to be kept up-to-date, in order to account for any development which can generate different results according to new data, discoveries and achievements. Today the world is witnessing higher crude oil prices due to the political situations in the Arab world. Such situations, if persisted, can accelerate the adoption of alternative fuels.

Other issues which were not included in this work and need to be tackled include impacts of the transportation stage. Transportation of feedstock to refineries and of end-product fuels to airports and to other facilities needs to be addressed, as it can have significant environmental and economic impacts. Transportation was not considered in this study, because it is dependent on the location of microalgae cultivation sites, for example whether microalgal oil is imported from developing countries or produced in developed countries. Also, other site issues related to transportation are associated with the closeness of microalgae cultivation sites to the refineries. As mentioned before, petroleum refineries can be used to process microalgal oils into HRJ fuels. However, the location of petroleum refineries are set to be in relation to petroleum and crude oil sites, and microalgae cultivation sites might not be located in the proximity of these already existing refineries. Therefore, new refineries might need to be built, which can affect the overall performance of microalgal HRJ fuels.

Appendix A: Calculation of the right eigenvector

An example for calculating the right eigenvector of the perfectly consistent matrix of production capacity is provided below.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF
RWPF	1.000	1.000	1.286	1.286	0.143
RWPW	1.000	1.000	1.286	1.286	0.143
PBRF	0.778	0.778	1.000	1.000	0.111
PBRW	0.778	0.778	1.000	1.000	0.111
CVJF	7.000	7.000	9.000	9.000	1.000

Step 1: Squaring the matrix

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF
RWPF	5.002	5.002	6.431	6.431	0.714
RWPW	5.002	5.002	6.431	6.431	0.714
PBRF	3.889	3.889	5.000	5.000	0.555
PBRW	3.889	3.889	5.000	5.000	0.555
CVJF	35.004	35.004	45.004	45.004	5.000

Step 2: Summing the rows and the rows total

5.002 + 5.002 + 6.431 + 6.430 + 0.714 = 23.580

5.002 + 5.002 + 6.431 + 6.431 + 0.714 = 23.580

3.889 + 3.889 + 5.000 + 5.000 + 0.555 = 18.333

3.889 + 3.889 + 5.000 + 5.000 + 0.555 = 18.333

35.004 + 35.004 + 45.004 + 45.004 + 5.000 = 165.016

The rows total is equal to 248.842

Step 3: Normalizing by dividing the row sum by the rows total

Eigenvector	0.0948
	0.0948
	0.0737
	0.0737
	0.6631

This process must be repeated until the eigenvetor solution does not change from the previous one.

Appendix B: Calculations related to the economic criterion

In order to be able to use a five order matrix in regard to fuel cost and four order matrices in regard to both capital and operating cost, several steps had to be taken. The missing alternative in the four order matrices was CVJF. Therefore, in the right eigenvectors derived from capital and operating cost matrices, the fifth value which usually corresponds to CVJF was assigned a value of zero. As for the right eigenvector derived from the fuel cost matrix, the value obtained for CVJF was multiplied by one (assumed weight for fuel cost). This is justified by the fact that for CVJF, only one sub-criterion under the economic criterion was used to evaluate CVJF. And as mentioned before, the sum of the weights of sub-criteria under one node, in this case, one sub-criterion for CVJF should be equal to one. On the other hand, the other four alternatives were assessed based on three sub-criteria. The sum of the weights of the three sub-criteria is equal to one; thus, the weight for each sub-criterion was 1/3, corresponding to the base-case. The values of the right eigenvectors corresponding to the four alternatives were multiplied by the assigned weights of sub-criteria. After multiplying the weight of CVJF with one, and the weight of the other alternatives with the assigned weights of sub-criteria, the sum of the global priorities of the alternatives in relation to the economic criterion exceeded the maximum value which is one. Therefore, normalization had to be conducted in order to bring down the sum of the alternatives' global priorities to one. An illustration of this procedure is provided in the example below, taking into consideration the perfectly consistent matrices of the economic criterion.

Step 1: Assign values for pair-wise comparisons

Table A.1.1

Fuel Cost Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF
RWPF	1.000	0.500	3.000	2.100	0.167
RWPW	2.000	1.000	4.500	2.700	0.200
PBRF	0.333	0.222	1.000	0.500	0.111
PBRW	0.476	0.370	2.000	1.000	0.125
CVJF	6.000	5.000	9.000	8.000	1.000

Table A.1.2

Capital Cost Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW
RWPF	1.000	0.286	6.500	4.500
RWPW	3.500	1.000	9.000	6.000
PBRF	0.154	0.111	1.000	0.333
PBRW	0.222	0.167	3.000	1.000

Table A.1.3

Operating Cost Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW
RWPF	1.000	0.286	6.000	3.900
RWPW	3.500	1.000	8.000	5.900
PBRF	0.167	0.125	1.000	0.250
PBRW	0.256	0.169	4.000	1.000

Step 2: Derive the right eigenvector

Table A.2.1

The Right Eigenvectors of Fuel Cost, Capital Cost and Operating Cost Matrices.

Alternatives	Fuel cost: Eigenvector 1	Capital cost: Eigenvector 2	Operating cost: Eigenvector 3
RWPF	0.112	0.271	0.262
RWPW	0.175	0.594	0.587
PBRF	0.043	0.043	0.044
PBRW	0.068	0.091	0.106
CVJF	0.602	0.000	0.000

Step 3: Calculate the local priorities of the alternatives.

Table A.3.1

The Local Weights of Alternatives, corresponding to Fuel Cost.

Alternatives	Fuel cost Weight1	Eigenvector1	Weight1 x Eigenvector1
RWPF	0.333	0.112	0.036
RWPW	0.333	0.175	0.039
PBRF	0.333	0.043	0.026
PBRW	0.333	0.068	0.028
CVJF	1.000	0.602	0.602

Table A.3.2

The Local Weights of Alternatives, Corresponding to Capital Cost.

Alternatives	Capital cost Weight2	Eigenvector2	Weight2 x Eigenvector2
RWPF	0.333	0.271	0.088
RWPW	0.333	0.594	0.176
PBRF	0.333	0.043	0.029
PBRW	0.333	0.091	0.035
CVJF	0.000	0.000	0.000

Table A.3.3

The Local Weights of Alternatives, Corresponding to Operating Cost.

Alternatives	Operating cost Weight3	Eigenvector3	Weight3 x Eigenvector3
RWPF	0.333	0.262	0.087
RWPW	0.333	0.587	0.193
PBRF	0.333	0.044	0.014
PBRW	0.333	0.106	0.035
CVJF	0.000	0.000	0.000

Step 4: Calculate the local weights of alternatives and normalize.

Local weight = Weight1 x Eigenvector1+ Weight2 x Eigenvector2+ Weight3 x Eigenvector3

Table A.4.1

Local Weight of Alternatives and Normalized Local Weights of Alternatives.

Alternatives	Local weight	Normalized local weight
RWPF	0.213	0.152
RWPW	0.393	0.282
PBRF	0.085	0.061
PBRW	0.099	0.071
CVJF	0.603	0.432

Appendix C: Minimum and maximum matrices

B.1 Technol[ogy

B.1.1 Production capacity

Table B.1.1.1

Production Capacity Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.000	2.000	2.000	0.200	0.128
RWPW	1.000	1.000	2.000	2.000	0.200	0.128
PBRF	0.500	0.500	1.000	1.000	0.111	0.065
PBRW	0.500	0.500	1.000	1.000	0.111	0.065
CVJF	5.000	5.000	9.000	9.000	1.000	0.614

Table B.1.1.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Production Capacity Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.002	0	0

Table B.1.1.3

Production Capacity Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.000	5.000	5.000	0.125	0.136
RWPW	1.000	1.000	5.000	5.000	0.125	0.136
PBRF	0.200	0.200	1.000	1.000	0.111	0.038
PBRW	0.200	0.200	1.000	1.000	0.111	0.038
CVJF	8.000	8.000	9.000	9.000	1.000	0.653

Table B.1.1.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Production Capacity Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.370	0.093	0.083

B.1.2 Fuel readiness level

Table B.1.2.1

Fuel Readiness Level Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.100	1.500	2.000	0.250	0.140
RWPW	0.909	1.000	1.500	1.700	0.200	0.125
PBRF	0.667	0.667	1.000	1.100	0.167	0.088
PBRW	0.500	0.588	0.909	1.000	0.125	0.074
CVJF	4.000	5.000	6.000	8.000	1.000	0.574

Table B.1.2.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Fuel Readiness Level Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.006	0.002	0.001

Table B.1.2.3

Fuel Readiness Level Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	3.000	4.000	5.000	0.200	0.204
RWPW	0.333	1.000	2.500	3.500	0.167	0.106
PBRF	0.250	0.400	1.000	3.000	0.118	0.064
PBRW	0.200	0.286	0.333	1.000	0.111	0.037
CVJF	5.000	6.000	8.500	9.000	1.000	0.590

Table B.1.2.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Fuel Readiness Level Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.288	0.072	0.064

B.1.3 Compatibility with the current system

Table B.1.3.1

Compatibility with the Current System Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.000	1.000	1.000	0.500	0.167
RWPW	1.000	1.000	1.000	1.000	0.500	0.167
PBRF	1.000	1.000	1.000	1.000	0.500	0.167
PBRW	1.000	1.000	1.000	1.000	0.500	0.167
CVJF	2.000	2.000	2.000	2.000	1.000	0.333

Table B.1.3.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Compatibility with the Current System Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.000	0	0

Table B.1.3.3

Compatibility with the Current System Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	1.000	1.000	1.000	0.200	0.111
RWPW	1.000	1.000	1.000	1.000	0.200	0.111
PBRF	1.000	1.000	1.000	1.000	0.200	0.111
PBRW	1.000	1.000	1.000	1.000	0.200	0.111
CVJF	5.000	5.000	5.000	5.000	1.000	0.556

Table B.1.3.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Compatibility with the Current System Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.000	0	0

B.1.4 Energy

Table B.1.4.1

Energy Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.667	4.000	3.100	1.500	0.261
RWPW	1.500	1.000	7.000	6.000	3.000	0.448
PBRF	0.250	0.143	1.000	0.833	0.667	0.072
PBRW	0.323	0.167	1.200	1.000	0.833	0.088
CVJF	0.667	0.333	1.500	1.200	1.000	0.132

Table B.1.4.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Energy minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.051	0.013	0.011

Table B.1.4.3

Energy Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.222	6.000	4.000	3.000	0.219
RWPW	4.500	1.000	9.000	8.000	6.000	0.583
PBRF	0.167	0.111	1.000	0.400	0.400	0.040
PBRW	0.250	0.125	2.500	1.000	0.667	0.069
CVJF	0.333	0.167	2.500	1.500	1.000	0.089

Table B.1.4.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Energy Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.161	0.040	0.036

B.2. Environment

B.2.1 Water

Table B.2.1.1

Water (1) Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.500	1.100	0.667	2.100	0.171
RWPW	2.000	1.000	3.000	1.500	3.500	0.357
PBRF	0.909	0.333	1.000	0.500	1.100	0.126
PBRW	1.500	0.667	2.000	1.000	2.500	0.247
CVJF	0.476	0.286	0.909	0.400	1.000	0.099

Table B.2.1.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Water (1) Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.023	0.006	0.005

Table B.2.1.3

Water (2) Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.500	0.909	0.333	1.100	0.125
RWPW	2.000	1.000	1.700	0.833	2.500	0.263
PBRF	1.100	0.588	1.000	0.500	3.000	0.181
PBRW	3.000	1.200	2.000	1.000	3.500	0.338
CVJF	0.909	0.400	0.333	0.286	1.000	0.092

Table B.2.1.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Water (2) Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.074	0.018	0.016

Table B.2.1.5

Water (1) Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.200	2.000	0.333	3.000	0.119
RWPW	5.000	1.000	4.500	3.000	6.000	0.487
PBRF	0.500	0.222	1.000	0.250	2.500	0.084
PBRW	3.000	0.333	4.000	1.000	5.000	0.261
CVJF	0.333	0.167	0.400	0.200	1.000	0.049

Table B.2.1.6

Principal Eigenvalue, Consistency Index & Consistency Ratio of Water (1) Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.214	0.054	0.048

Table B.2.1.7

Water (2) Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.256	0.500	0.222	2.900	0.091
RWPW	3.900	1.000	2.900	0.500	4.900	0.291
PBRF	2.000	0.345	1.000	0.286	3.900	0.141
PBRW	4.500	2.000	3.500	1.000	6.500	0.431
CVJF	0.345	0.204	0.256	0.154	1.000	0.047

Table B.2.1.8

Principal Eigenvalue, Consistency Index & Consistency Ratio of Water (2) Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.148	0.037	0.033

B.2.2 Air

Table B.2.2.1

Air Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.667	3.500	3.000	2.000	0.262
RWPW	1.500	1.000	7.600	6.000	3.000	0.450
PBRF	0.286	0.132	1.000	0.909	0.400	0.066
PBRW	0.333	0.167	1.100	1.000	0.769	0.084
CVJF	0.500	0.333	2.500	1.300	1.000	0.138

Table B.2.2.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Air Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.036	0.009	0.008

Table B.2.2.3

Air Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.400	6.500	4.900	3.500	0.273
RWPW	2.500	1.000	9.000	7.500	6.000	0.515
PBRF	0.154	0.111	1.000	0.400	0.200	0.035
PBRW	0.204	0.133	2.500	1.000	0.455	0.063
CVJF	0.286	0.167	5.000	2.200	1.000	0.114

Table B.2.2.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Air Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.189	0.047	0.042

B.2.3 Land

Table B.2.3.1

Land Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.833	0.588	0.200	1.500	0.106
RWPW	1.200	1.000	0.833	0.222	1.600	0.127
PBRF	1.700	1.200	1.000	0.400	2.500	0.180
PBRW	5.000	4.500	2.500	1.000	7.000	0.514
CVJF	0.667	0.625	0.400	0.143	1.000	0.074

Table B.2.3.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Land Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.013	0.003	0.002

Table B.2.3.3

Land Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.400	0.286	0.145	3.500	0.072
RWPW	2.500	1.000	0.400	0.167	5.000	0.123
PBRF	3.500	2.500	1.000	0.250	6.500	0.214
PBRW	6.900	6.000	4.000	1.000	9.000	0.559
CVJF	0.286	0.200	0.154	0.111	1.000	0.033

Table B.2.3.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Land Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.262	0.065	0.058

B.3. Economic

B.3.1 Fuel cost

Table B.3.1.1

Fuel Cost Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.909	1.200	1.500	0.200	0.119
RWPW	1.100	1.000	1.300	1.200	0.222	0.122
PBRF	0.833	0.769	1.000	0.833	0.154	0.090
PBRW	0.667	0.833	1.200	1.000	0.167	0.096
CVJF	5.000	4.500	6.500	6.000	1.000	0.573

Table B.3.1.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Fuel Cost Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.015	0.004	0.003

Table B.3.1.3

Fuel Cost Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	CVJF	Eigenvector
RWPF	1.000	0.500	3.000	2.100	0.167	0.112
RWPW	2.000	1.000	4.500	2.700	0.200	0.175
PBRF	0.333	0.222	1.000	0.500	0.111	0.043
PBRW	0.476	0.370	2.000	1.000	0.125	0.068
CVJF	6.000	5.000	9.000	8.000	1.000	0.602

Table B.3.1.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Fuel Cost Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
5.114	0.029	0.026

B.3.2 Capital Cost

Table B.3.2.1

Capital Cost Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	Eigenvector
RWPF	1.000	0.667	2.500	1.500	0.264
RWPW	1.500	1.000	5.500	3.500	0.487
PBRF	0.400	0.182	1.000	0.833	0.104
PBRW	0.667	0.286	1.200	1.000	0.145

Table B.3.2.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Capital Cost Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
4.033	0.011	0.009

Table B.3.2.3

Capital Cost Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	Eigenvector
RWPF	1.000	0.286	6.500	4.500	0.271
RWPW	3.500	1.000	9.000	6.000	0.594
PBRF	0.154	0.111	1.000	0.333	0.043
PBRW	0.222	0.167	3.000	1.000	0.091

Table B.3.2.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Capital Cost Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
4.178	0.059	0.053

B.3.3 Operating cost

Table B.3.3.1

Operating Cost Minimum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	Eigenvector
RWPF	1.000	0.667	2.500	1.700	0.266
RWPW	1.500	1.000	6.000	4.000	0.502
PBRF	0.400	0.167	1.000	0.833	0.099
PBRW	0.588	0.250	1.200	1.000	0.132

Table B.3.3.2

Principal Eigenvalue, Consistency Index & Consistency Ratio of Operating Cost Minimum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
4.032	0.011	0.009

Table B.3.3.3

Operating Cost Maximum Matrix.

Alternatives	RWPF	RWPW	PBRF	PBRW	Eigenvector
RWPF	1.000	0.286	6.000	3.900	0.262
RWPW	3.500	1.000	8.000	5.900	0.587
PBRF	0.167	0.125	1.000	0.250	0.044
PBRW	0.256	0.169	4.000	1.000	0.106

Table B.3.3.4

Principal Eigenvalue, Consistency Index & Consistency Ratio of Operating Cost Maximum Matrix.

Principal eigenvalue (λ_{max})	Consistency Index (CI)	Consistency Ratio (CR)
4.237	0.079	0.07

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