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Future trends for biojet fuel and biosuccinic acid production in São Paulo state, Brazil

An agent-based modelling and simulation approach to explore institutional barriers and opportunities

Sebastiaan C.M. Fakkert

FUTURE TRENDS FOR BIOJET FUEL AND BIOSUCCINIC ACID PRODUCTION IN SÃO PAULO STATE, BRAZIL

An agent-based modelling and simulation approach to explore institutional barriers and opportunities

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Sebastiaan C.M. Fakkert

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Student number:	4248740
Thesis committee:	
prof.dr.ir. M. (Margot) Weijnen	chair
dr.ir. Z. (Zofia) Lukszo	first supervisor
dr. A. (Aad) Correljé	second supervisor
dr.ir. J.A. (John) Posada Duque	additional supervisor
ir. J.A. (Jorge) Moncada Escudero, PDEng	additional supervisor

TU Delft

EXECUTIVE SUMMARY

Research problem

Within the context of growing concerns about oil supply security and greenhouse gas emissions, both the aviation and petrochemical sector are exploring alternative feedstocks for the production of jet fuel and chemicals, respectively. In that light, research into bio-based jet fuels (biojet fuel) and bio-based chemicals has been accelerating in recent years. In the Horizontal Integration Project (HIP), to which this thesis is connected, a biorefinery concept was developed that proposes co-production of biojet fuel and biosuccinic acid from Brazilian sugarcane feedstock. Previous HIP research has concluded that the co-production of biojet fuel and bio-based succinic acid (a versatile platform chemical, from now on referred to as biosuccinic acid) in a sugarcane-based "biorefinery" could be a technically feasible and economically viable concept, and that sugarcane costs and technology investments are the major determinants for the concept's economic performance. Within this context, the state of São Paulo in Brazil was targeted as the most optimal location given its mature sugarcane market and social and institutional acceptance of renewables.

Yet, commercialization of this and similar biorefineries seems rather difficult. Despite substantial research in production technologies for biojet fuel and biosuccinic acid, commercial production of these products is still very minimal. Multiple industry actors and academia indicate that technical know-how is indeed not the main constraint for the commercialization of biorefinery concepts. Instead, two major barriers are often mentioned: *competition for sugarcane* and *government policies*. However, the existing body of scientific literature does not provide insight into how government policies might be affecting competition for sugarcane through influencing actors' behaviors. Therefore, a research was executed with the objective to analyze how government policies affect commercialization of biojet fuel and biosuccinic acid, within the context of sugarcane competition and international trade and to explore alternative policies.

In order to operationalize the research objective to be achieved, the following main research question was formulated:

Main research question

> "What set of policies can be recommended to increase the production of biojet fuel and biosuccinic acid, within the context of national and international competition between the road transport and sugar market?"

Methodology

In light of the intended local analysis of the sugarcane market, theory on complex adaptive systems was reviewed and applied to gain better understanding of how actors' behaviors and interactions give rise to the emerging key variables of interest that can be observed at the macro systems level. This analysis was complemented with theory on institutions and institutional economics, to study institutions at three levels: the level of government policies, the level of interactions between actors and the level of individual strategic decisions. Through combined application of both complex adaptive systems theory and institutional theory, a conceptual model for analysis was constructed, which served as the scientific research perspective.

Besides this theoretical basis, practical case-related data was gathered about the Brazilian sugarcane market as well as the HIP biorefinery concept. Then, through the application of the conceptual model of analysis on the case data, the biorefinery model was constructed through a process of conceptualization and was then implemented into an Agent Based computer simulation Model (ABM). This model allowed to explore how the external variables and policies influence the demand satisfaction for biojet fuel and biosuccinic acid in an iterative process. After the ABM model was found to sufficiently explain the emergent outcomes of interest, it was used in an extensive policy exploration in which policies were explored that might be able to increase the production of biojet fuel and biosuccinic acid in the period of 2015 until 2030.

Conclusions

i. **Actors' behaviors and interactions give rise to a dynamic sugarcane market**. Processing plants are the central player in the emergence of biojet fuel and biosuccinic acid production. Most plants have dual production technology for sugar and ethanol, and adjust how much sugarcane is used for each product through strategic decisions. Furthermore, car drivers' ability to switch between hydrous ethanol and blended gasoline gives rise to dynamics in ethanol price levels and processing plant' production decisions.

ii. **Sugarcane pricing and allocation are key factors** in the emergence of biojet fuel and biosuccinic acid production. Through the privately constructed CONSECANA-SP institution, sugarcane prices are directly linked to the profitability of ethanol and sugar. Sugarcane prices and the institutionalized interactions between suppliers and processing plants were found to have great impact on the emergence of biojet fuel and biosuccinic acid production.

iii. **Strong national and international competition** with the sugar and ethanol market is likely to be an unstable context for biojet fuel or biosuccinic acid to be commercialized. For both products, lower production was seen at times of high competition with the sugar market and ethanol exports, whereas high production was seen at times of low competition. The nexus between the domestic and foreign markets should be an integral part in the development of effective policies, in particular in the context of increasing adoption of bioethanol promoting policies worldwide.

iv. Exploration of the **2G bagasse-to-biojet technology showed positive results** for biojet fuel demand satisfaction. Even if ethanol support policies remain in their status-quo, nearly full biojet fuel demand satisfaction was observed, at the acceptable biojet fuel price of 1.65 R$/l. The fact that 2G bagasse-to-biojet fuel production is not sensitive to the average sugarcane price, could present a significant opportunity to increase biojet fuel production.

v. The multi-scenario experimental analysis that was performed showed that **current government ethanol-support policies hinder commercialization** of biojet fuel and biosuccinic acid production. Yet, the effectiveness of ethanol discouragement was found to be large affected by competition with the sugar market and foreign hydrous ethanol market. That is, even though domestic ethanol consumption is discouraged, sugar and ethanol production might be increased instead of biojet fuel and biosuccinic acid production, at times when demand for sugar or international hydrous ethanol trade is high.

Policy Implications and Recommendations

i. For biojet fuel, two different alternative policies were developed to explore how production can be increased up to 50% of the jet fuel demand in São Paulo state in the period 2015 until 2030: a price premium subsidy and a risk premium subsidy. For the base scenario (with a medium sugar price and foreign hydrous ethanol price), a price premium level of 2.5 R$/l is most effective, which corresponds to an average biojet fuel demand satisfaction of 54.5%, which is 45.5% lower than the demand target. Furthermore, the policy's effectiveness significantly decreases at times of high international trade (the most effective subsidy level is then 2 R$/l, which corresponds to an average demand satisfaction of

33.8%). The risk premium compensation subsidy was found not effective at all, also when combined with the price premium subsidy. In-depth research is needed to develop supply-side policies that specifically target the reduction of sugarcane costs for biojet fuel production, in the context of CONSECANA-SP. It can be recommended that a combination of decreasing ethanol support and subsidizing the biojet fuel price paid to biorefineries may be most effective to meet the demand target.

ii. For biosuccinic acid, as set of policies was explored that might be able to increase production of biosuccinic acid up to 50% of the estimated world demand in the period of 2015 until 2030. The same two types of policies were explored as for biojet fuel, and the insights gained were of similar nature as for biojet fuel. The biosuccinic acid price premium subsidy was found to be effective in increasing biosuccinic acid demand satisfaction, in contrast with the risk premium compensation subsidy, which had no significant effect at all. The most effective price premium level is 1 R$/kg, which corresponds to a demand satisfaction of 77.8%. This corresponds to a biosuccinic acid price of 1.2 R$/kg. Full average demand satisfaction is never achieved, which is likely due to the seasonality of sugarcane supply and processing. Similar to biojet fuel, policy effectiveness is largely influenced by competition with the sugar market and international hydrous ethanol trade. In case of high competition, a subsidy level of 1.5 R$/kg responds to a demand satisfaction of only 38.4%.

Recommendations to the aviation and chemical industry

i. The aviation industry is advised to **reconsider the production of 1G biojet fuel from sugarcane feedstock on its commercial feasibility**, as the research conducted in this thesis suggests poor potential for this production technology. Institutional aspects of sugarcane procurement should be an integral part of any feasibility study concerning the commercialization of 1G biojet fuel.

ii. Furthermore, the aviation industry is recommended to conduct further research into the **commercial potential of 2G bagasse-to-biojet fuel**, as this research indicated there might be large potential for this production technology.

iii. For the chemical industry, there **might be potential to use sugarcane for commercial production of biosuccinic acid**.

iv. Both industries should take notice of the **very dynamic nature of the sugarcane market**. Car drivers' consumption decisions and (inter) national competition between the sugar and ethanol market, are likely to be an unstable context for either 1G biojet fuel or biosuccinic acid to be commercialized.

Recommendations to the government of Brazil

i. If the government of Brazil would take a **standpoint of discouraging biojet fuel and biosuccinic acid production**, it might be most effective to maintain its current ethanol support, and to raise import taxes on hydrous ethanol.

ii. On the other hand, if the government of Brazil would take a **standpoint of stimulating biojet fuel and biosuccinic acid production**, for instance in the context of rising use of electric vehicles, price premium subsidies combined with ethanol discouragement may be an effective policy.

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Dear reader,

Months ago, I embarked on this research endeavor, not knowing what challenges and experiences where waiting for me. As with life, this thesis was a journey of self-discovery and development. Looking back, the research provided intense learning at both a professional and personal level. For me, it was a perfect blend of my passions for aviation, sustainability and learning. The research involved the application of new paradigms and ways of working for me, which would not have been possible without the support of my professional and personal circles.

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I hope you enjoy reading this thesis as much as I enjoyed writing it.

Sebastiaan Fakkert

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INTRODUCTION

> “Change is the law of life. And those who look only to the past or present are certain to miss the future”
>
> - John Fitzgerald Kennedy

Global oil consumption is increasing at a rapid pace and is expected to rise by 30% in the next 25 years (EIA, 2014). Meanwhile, there are growing concerns about oil supply security and foremost its environmental impacts and contribution to climate change through greenhouse gas emissions (GHG) (BNDES & CGEE, 2008; EIA, 2014; Royal Society, 2012; UNEP, 2011). The aviation and petrochemical sector combined accounted for about 16% of the world’s oil consumption in 2013 (Statista, 2016).

Although relatively small in terms of oil consumption and GHG emissions, the international aviation sector is continuously growing and is expected to grow with 4% annually, reaching 2.2 times more air passenger journeys in 2034 compared with today (IATA, 2015). Brazil is among the top growing aviation markets, with an annual expected growth of 4.4% in the next 20 years. Despite these positive market outlooks, the industry’s profitability and growth are structurally hampered by global events and oil price fluctuations. As a world average, aircraft kerosene accounted for over 30% of an airline’s operating costs in 2014, whereas in Brazil this was approximately 40% (IATA, 2014). On top of the costs element, the industry also receives increasing pressure from public opinion in the global climate change debate, pointing to its oil consumption and GHG emissions.

Meanwhile, also the global demand for chemicals and plastics – two other petroleum derivatives – continues to grow, while accompanied by the same environmental and supply security concerns as in other oil consuming industries (Chen & Patel, 2012; Nexant, 2014). Naturally, also the petrochemical industry’s profitability is very sensitive to oil price volatility. Yet, with main applications in construction, packaging, industrial production and automotive, chemicals and plastics have become indispensable in modern society (Nexant, 2014).

Within this context, research into bio-based jet fuels (biojet fuel) and bio-based products (mainly chemicals and plastics) has been accelerating in recent years. These efforts have focused mainly on three key production challenges: feedstock availability, chemical conversion technologies, and the economic and environmental performance according to sustainability standards (Eerhart, Patel, & Faaij, 2015; Weiss et al., 2012). Increased production of bio-based fuels and bio-based products requires delicate alignment of these three challenges.

While various technologies for the conversion of sustainable feedstocks into biojet fuel and bio-based products have been developed, their commercialization remains rather difficult. In addition, the well-known 'food vs. fuel' and 'land-use' debates have fueled sustainability concerns over feedstocks in recent years, mainly due to the fast growing bioethanol and biodiesel markets (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Wilkinson & Herrera, 2010). For instance, some claim that U.S. grown corn feedstock, which is processed into corn ethanol for road transport, has very poor, if not negative, sustainability advantages. On the contrary, although some sustainability concerns exist, Brazilian sugarcane feedstock has far better yields per hectare, lower impact on food security and lower GHG emissions than its U.S. counterpart (BNDES & CGEE, 2008; Kaup, 2015).

This homegrown sugarcane has been the backbone of Brazil's flourishing sugar and ethanol markets, which are in mutual competition for sugarcane feedstock at the national and international level. Since the government of Brazil initiated the PróÁlcool (pro ethanol) stimulation program in 1973, the Brazilian sugarcane based ethanol market has become the most successful producer, consumer and exporter of ethanol worldwide. In 2015, domestic ethanol and gasoline consumption were almost equal (UNICA, 2016). Hence, this unique market is by many seen as the most mature and integrated biofuel market nowadays (e.g. (Banse, van Meijl, Tabeau, & Woltjer, 2008; Sorda, Banse, & Kemfert, 2010)).

Sugarcane, however, is a very versatile feedstock that has the potential to be used for producing a wide variety of value-added products in addition to sugar and ethanol, among which aviation biojet fuel and bio-based chemicals (biochemicals). In this light, the *Horizontal Integration Project (HIP)*, to which this thesis is connected, aims to advance research on sugarcane based biojet fuel and biochemicals. The HIP is a joint venture of Dutch universities (TU Delft, WUR), Brazilian Universities (i.e. UNICAMP), various industry partners (e.g. BE-BASIC foundation, AirFrance-KLM, Delft Advanced Biorenewables BV (DAB) and research institutes. Previous HIP research has concluded that the co-production of biojet fuel and bio-based succinic acid (a versatile platform chemical, from now on referred to as biosuccinic acid) in a sugarcane-based "biorefinery" could be a technically feasible and economically viable concept, and that sugarcane costs and technology investments are the major determinants for the concept's economic performance. Within this context, the state of São Paulo in Brazil was targeted as the most optimal location given its mature sugarcane market and social and institutional acceptance of renewables.

However, a major barrier to overcome in the deployment of such biorefinery concepts is the aforementioned competition between sugar and ethanol markets for sugarcane. The aviation and chemical industry suggest that current policies of the government of Brazil incur preferential treatment for the sugar and ethanol market, and are thus hampering commercialization of sugarcane based biojet fuel and biochemicals (Boeing, Embraer, FAPESP, & UNICAMP, 2013; IATA, 2013). However, practical as well as theoretical insights into how these policies are hampering commercialization and how it could be increased form a major research gap in the existing body of literature.

The remainder of this introduction chapter is as follows. In the next two sections, both the developments in sustainable propulsion of aviation (1.1) and the production of biosuccinic acid (1.2) are discussed more thoroughly. Then, in section (1.3), existing production technologies as well as the HIP biorefinery concept of co-producing biojet fuel and biosuccinic acid are further explained. From there, the problem of growing competition for sugarcane feedstock and institutional barriers is presented, as well as the identified knowledge gap in the existing body of scientific literature (1.4). Finally, in section (1.5), the structure of the remainder of this thesis is explained and a roadmap is presented which intends to guide the reader throughout this thesis.

1.1 Sustainable propulsion of aviation: why and how?

Through a resolution in the International Air Transport Association (IATA) (which represents about 268 airlines worldwide), the aviation industry committed itself to have carbon neutral growth from 2020, and on the long term, achieve a reduction of 50% in carbon dioxide emissions by 2050 (IATA, 2013). But how? This seems a very daunting task, as there is general consensus among aircraft manufacturers and airlines that there is little to no opportunity left to increase operational and technical fuel efficiency for liquid fuel powered aircraft. Furthermore, other means of propulsion, such as electric or hydrogen based alternatives, are not expected to be available on the short to medium term (IATA, 2013). Hence, the aviation industry has set its focus on so-called ‘drop-in’ biojet fuels; pure or blended bio-based fuels that are compatible with existing aircraft and airport distribution systems and their performance standards (Boeing et al., 2013).

The development of drop-in fuels takes place on a global scale by research organizations, airlines, fuel producers, and aircraft manufacturers. Hupe (2012) indicates that between 2008 and 2012, annual biojet fuel initiatives rose from near zero in 2008 to over 300 in 2012. As to date, three different categories of biojet fuels have obtained ASTM certification (international standards for products and services): (1) Hydrogenated Esters and Fatty Acids (HEFA) (known from ‘frying fat’ fuel); (2) Fischer-Tropsch (FT) based on biomass and (3) renewable synthesized iso-paraffinic fuel (IATA, 2013). In the HIP project, a combination of ethanol-to-jet (ETJ) conversion technology (another type of production) and sugarcane feedstock was selected to have the lowest biojet fuel production price. ASTM approval for ETJ biojet fuel is expected on the short term (with 50 to 100 % blending), as final certification tests are currently being carried out and demo production facilities are being constructed (ASTM approval is expected in 2016) (BE-Basic Foundation, 2016). In light of Brazil’s national experience in sugarcane agriculture, the production and distribution of ethanol, its fast growing aviation market and its modern aviation industry with aircraft manufacturer EMBRAER, Brazil seems an attractive location to kick start aviation biojet fuel production (Boeing et al., 2013; Cortez et al., 2015).

1.2 Biosuccinic acid: a high-value platform chemical

Succinic acid is a high-value platform chemical used for a broad range of applications, stretching from niche applications to large applications, such as foods, pharmaceutics, industrial manufacturing (e.g. automotive) and cosmetics (Reverdia, 2010). It is also used as a raw material for several polymers. Today, succinic acid is predominantly produced from petroleum; a both costly and environmentally unfriendly method (Vaswani, 2010). Biosuccinic acid (succinic acid produced from biomass) has been selected by the U.S. Department of Energy as one of the most promising platform chemicals that can be produced commercially from biomass instead of petroleum (US Department of Energy, 2004). In that light, the production of biosuccinic acid (succinic acid produced from biomass) has the potential to tap a greater market for succinic acid and play a central role in the growing demand for chemicals.

Market researches indicate that the global biosuccinic acid market is expected to reach a total market volume of 710 kilo tons by 2020, by growing with an annual growth rate of 45.6% (AlliedMarketResearch, 2014; Dammer, Carus, Raschka, & Scholz, 2013).

1.3 The biorefinery concept: co-production of biojet fuel and biosuccinic acid

Existing processing plants in the Brazilian sugarcane market produce sugar and ethanol from sugarcane through so-called first generation (1G) pathways, meaning that these are produced from the starch (or sugar, as in the case of sugarcane) in edible feedstock (BNDES & CGEE, 2008). As aforementioned, 1G bio-based products are generally contested, for they are claimed to have an impact on food security, although many researches indicate sugarcane has by far the best environmental benefits compared to other 1G feedstocks (BNDES & CGEE, 2008; Lapola et al., 2010; Timilsina & Shrestha, 2011). Second generation (2G) pathways, however, are expected to have limited competition with food production or land-use. In 2G pathways, lignocellulosic biomass can be used to produce sugar and ethanol. Research into 2G feedstocks and conversion technologies has received much interest in recent years (e.g.(Amorim, Lopes, de Castro Oliveira, Buckeridge, & Goldman, 2011; M. O. S. Dias et al., 2011; Eerhart et al., 2015; Pereira, Maehara, Machado, & Farinas, 2015; Seabra, Tao, Chum, & Macedo, 2010)). This research has focused on techno-economic assessments on the use of sugarcane residues (bagasse, straw and tops) as well as other second generation feedstocks, such as forestry residues.

Figure 1 depicts the production flows of sugarcane in a highly aggregated manner. As can be seen from this figure, about 70% of crushed sugarcane is sugar juice, whereas the other 30% is so-called "bagasse"; a fibrous matter that is a side product of the crushing process (Amorim et al., 2011). Nevertheless, bagasse is a useful raw material for various applications. In existing processing plants, bagasse is solely used to produce bioelectricity to power the processing plant, and in the case of overproduction, is also sold to the electricity grid. Through a series of processing steps, the sugar juice is processed into sugar, hydrous ethanol, and anhydrous ethanol (a distilled version of hydrous ethanol, sold as gasohol after blending with gasoline). All of these processes are characterized as 1G pathways.

In the aforementioned HIP biorefinery concept, a variety of different configurations of feedstock, conversion technology and end-products are being developed. Such integrated co-production concepts have been praised for their economic benefits compared to stand alone facilities (OECD, 2014) and are often mentioned in the same breath with biobased economy and circular economy concepts. Biorefineries apply roughly the same strategy as in modern integrated petrochemical refineries, which produce a wide variety of value-added petroleum-based products (IEA Bioenergy, 2014). Through a full integral impact analysis, the co-production of biojet fuel and biosuccinic acid was selected as the most promising biorefinery concept in techno-economic feasibility (BE-Basic Foundation, 2016).

Such a biorefinery would produce biojet fuel from a combination of 1G and 2G pathways, while using sugarcane residues – stalks and straw usually left behind on the soil after harvest – for the production of bioelectricity. In this concept, the 1G pathway for biojet fuel production is the aforementioned ETJ pathway, for which ASTM approval is expected on the short term. In addition, biojet fuel would also be produced through a 2G pathway, by using bagasse as a raw material (as bioelectricity is then produced from trash). In this process, also several by-products, mainly Liquefied Petroleum Gas (LPG), Naphtha and Diesel are produced. In this thesis, the biorefinery concept is studied as an existing processing plant which upgraded its technology, so that it can also produce biosuccinic acid and biojet fuel (and some by-products) in addition to sugar and ethanol.

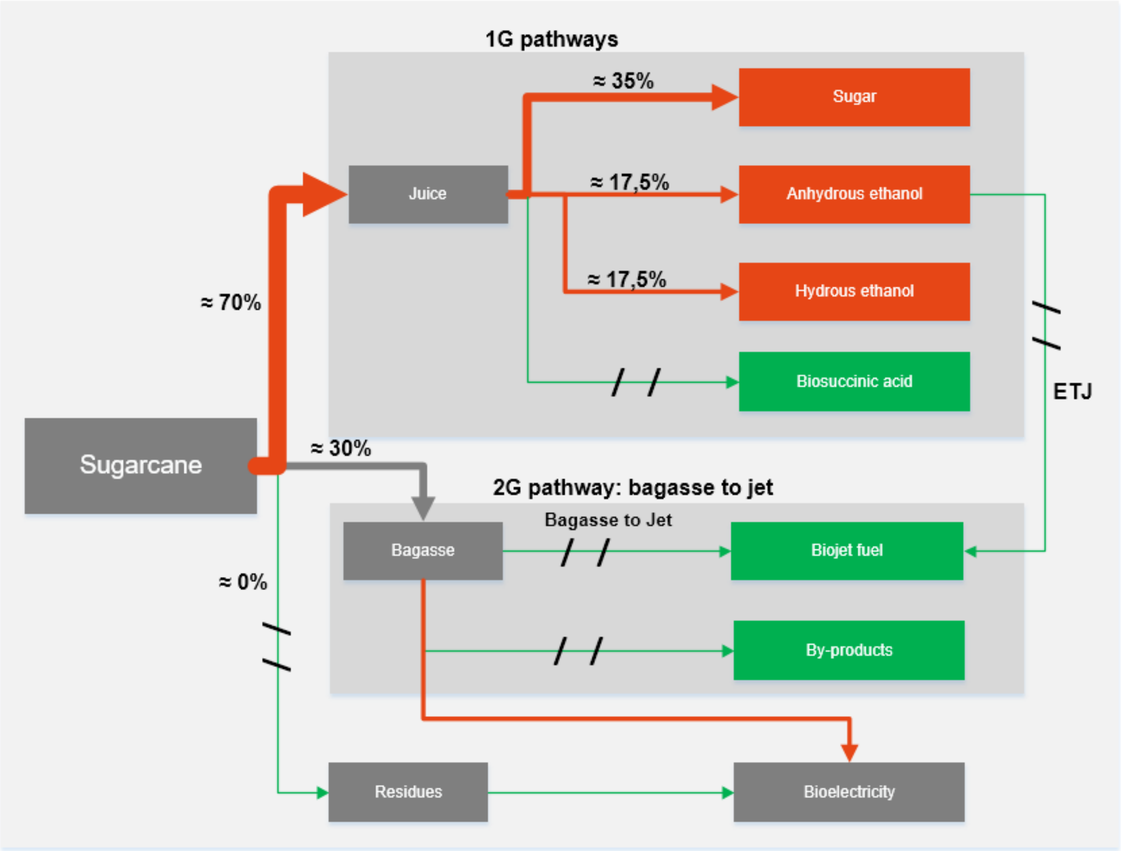


Figure 1: Key concepts, technologies and sugarcane flows

🟥 Technologies and products in existing processing plants - 🟩 Technologies and products proposed in the biorefinery - **/ /** non-used technology pathways - flow percentages are general estimates

1.4 The problem of growing competition for sugarcane and institutional barriers in commercializing biorefineries

As laid out in the previous sections, the academic community and industry have paid substantial attention to the development of technology for the production of other sugarcane-based products than sugar and ethanol. The HIP biorefinery concept – the biorefinery concept included in this study – proposes an innovative concept of co-producing biojet fuel and biosuccinic acid, which aims the needs of both industries.

Yet, commercialization of this and similar biorefineries seems rather difficult. This is reflected in the research problem: despite substantial research in production technologies for biojet fuel and biosuccinic acid, commercial production of these products is still very minimal. Multiple industry actors and academia indicate that technical know-how is indeed not the main constraint for the commercialization of biorefinery concepts.

Instead, two major barriers are often mentioned: competition for sugarcane and government policies.

First, many stress that competition for sugarcane – *which accounts for the majority of production costs* – is a major obstacle in commercialization (IATA, 2013). In existing sugarcane processing plants, sugarcane accounts for 50 to 70 % of the production costs of sugar and ethanol (Fava Neves, 2011; Kaup, 2015). In that respect, successful sugarcane sourcing is vital for achieving a plant's production targets. In addition, there is also competition for agricultural lands, as plants grow a substantial part of the needed sugarcane themselves by vertical integration strategies. Although a substantial stream of research has focused on current and future estimations of sugarcane cultivation costs, ethanol production costs, and sugar production costs, or a combination thereof, (e.g. (M. O. Dias et al., 2011; Jonker et al., 2015; van den Wall Bake, Junginger, Faaij, Poot, & Walter, 2009)), the reviewed literature lacks insights in sugarcane competition and how this might hinder the commercialization of biojet fuel and biosuccinic acid production.

In addition to the existing sugarcane competition, alternative users – such as the aviation and chemical industry in this thesis – suggest that government policies show a preferential treatment for the sugar and ethanol market, which have developed through very strong government regulation from the early 1970s on (Ferraz Dias de Moraes & Zilberman, 2014; Soccol et al., 2005). They pledge for a more 'level playing field'; a sugarcane market in which incentives for the production of biojet fuel and biosuccinic acid are more competitive (IATA, 2013). Although government influence has certainly decreased over time, still a limited number of policies, such as mandatory fuel blending, price control and taxation are claimed to have significant influence on the sugar and ethanol orientation of the sugarcane market (USDA, 2010). The interesting question which then arises, is *how current government policies affect this market behavior.*

Fortunately, these and other policy questions in the Brazilian case have received substantial interest from academia. Many scholars have analyzed the historical development of Brazilian sugarcane and ethanol policies. Whereas some provide merely an overview of Brazilian ethanol and/or U.S. ethanol policies (Nass, Pereira, & Ellis, 2007; Soccol et al., 2005), others have attempted to gain insight into the interrelation between ethanol policies and commodity prices (such as sugarcane and sugar), for example through time series analysis ((Sorda et al., 2010) (Schmitz, Schmitz, & Seale, 2003) (Balcombe & Rapsomanikis, 2008; Elobeid & Tokgoz, 2008; Rajcaniova, Drabik, & Ciaian, 2013; Serra, 2011)).

Figure 2 depicts the preliminary identified mechanisms in biojet fuel and biosuccinic acid commercialization. As can be seen from this figure, the hypothesized mechanism is such that biorefinery investments are lacking due to insufficient biojet fuel and biosuccinic acid demand, which in turn are a result of lacking biorefinery investments. In addition, biorefinery investments are also low as long as the relative profitability of sugar and ethanol is high.

Interestingly, all of these policy studies have analyzed market behavior at an aggregate, macro-economic level, and primarily from a neo-classical economics (NCE) perspective. This implies that they have failed to address how institutions (such as government policies) affect individual decisions of actors, such as sugarcane farmers, processing plants and car drivers. Yet, these individual production, consumption and investment decisions as well as the interactions between actors give rise to the production quantities that can be observed at the aggregate market level. The importance of understanding such 'local dynamics' and their relation to institutions is clarified in the following unique characteristics of the Brazilian sugarcane system.

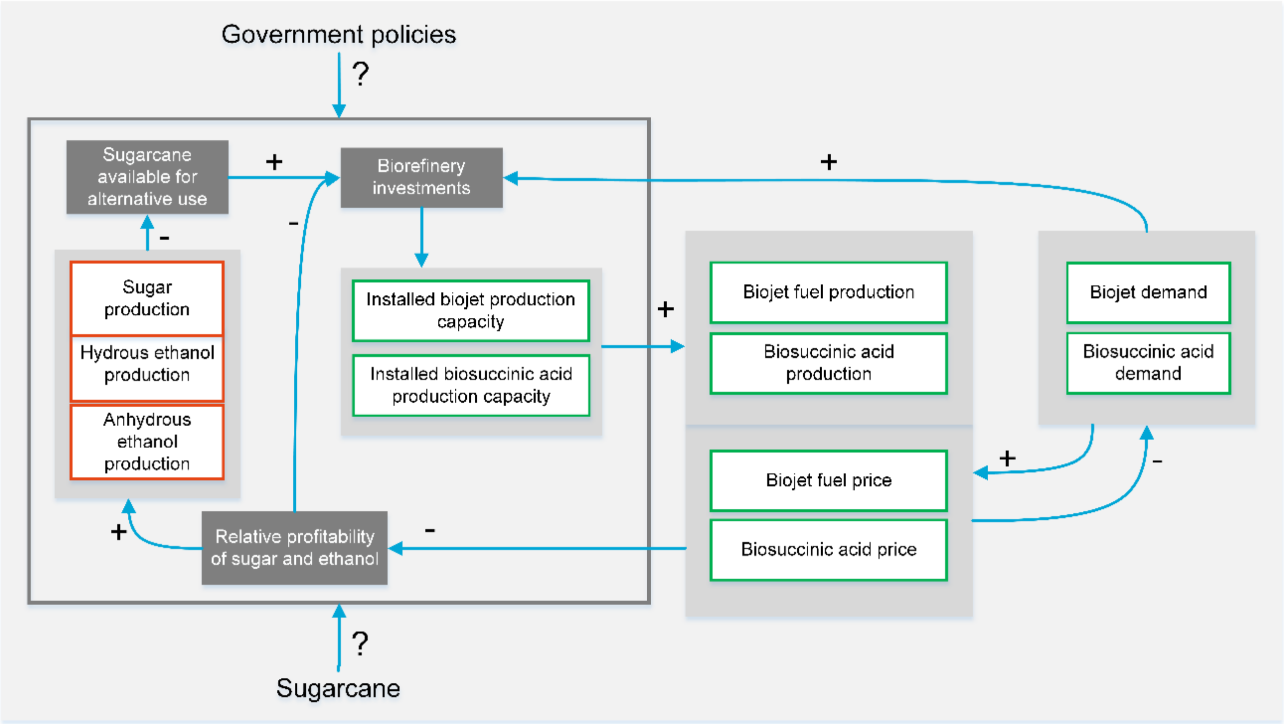


Figure 2: Preliminary identified mechanisms in biojet fuel and biosuccinic acid commercialization

First, sugarcane competition also takes place within processing plants. Most plants can co-produce sugar and both ethanol types, and typically adjust production quantities for each product in response to market prices (or other strategic motivations). Various scholars have focused specifically on analyzing these production strategies, sometimes referred to as 'sugarcane flexing' – a phenomenon that has also been observed for other 'flexible crops', such as soybeans, palm oil and maize, and in which plants can process crops info fuels, goods, feed and various materials (Borras, Franco, Isakson, Levidow, & Vervest, 2015; H. de Gorter, Drabik, Kliauga, & Timilsina, 2013; McKay, Sauer, Richardson, & Herre, 2015). Sugarcane flexing thus allows plants to maximize their total added value by altering production quantities. This is a strategy that shows large similarity with the one applied by oil refineries in the petrochemical industry (McKay et al., 2015; Star-Colibri, 2011). The adaptiveness of plants to market prices can create substantial dynamics, which should be taken into account in the design of effective policies.

Another factor are car drivers' fuel decisions. A substantial stream of research has analyzed fuel consumption in the Brazilian market (e.g. (de Freitas & Kaneko, 2011; Pacini & Silveira, 2011; Walter, Rosillo-Calle, Dolzan, Piacente, & Borges da Cunha, 2008)). All authors found that the diffusion of so-called Flex Fuel Vehicles (FFV's) from 2003 on has been the major driver for increased ethanol consumption over the last decade. Whereas drivers were previously 'locked in' to either hydrous ethanol or gasohol, depending on their type of car, FFV's provide car drivers the autonomous freedom to switch between hydrous ethanol and gasohol during every fill-up. Pacini and colleague add to this that fuel switching makes it challenging for governments to stimulate demand when production of ethanol is low (Pacini & Silveira, 2011). The combination of the aforementioned production strategies and fuel switching create substantial complexity.

Finally, the Brazilian sugarcane market cannot be merely studied in isolation, as international trade of sugar and hydrous ethanol have significant impact on production quantities and consumption in the domestic market. Given the fact that Brazil is by far the biggest sugar exporter in the world (with a total market share of about 21% (USDA, 2015b)) – sometimes referred to as 'the world's sugar bowl' –, it is generally the case that processing plants prefer sugar production (for export purposes) over hydrous ethanol production, when global sugar prices are high (Valdes, 2011). In addition, Brazil is also the second largest exporter of hydrous ethanol in the world, which has seen increasing foreign demand in the context of increasing biofuel promoting policies worldwide (USDA, 2015a). Therefore, depending on the perspective, international trade could present barriers as well as opportunities. For instance, processing plants could profit from increasing demand (and market prices) for a particular product. However, increased profitability of sugar and/or ethanol could make biorefinery investments less attractive.

The research presented in this thesis is therefore based on the recognition that, in order to advance insights in the commercialization of biojet fuel and biosuccinic acid in Brazil, it is imperative to study how government policies hinder this commercialization through influencing actor behavior. In order to do so, it is deemed necessary to acknowledge and understand the complexity of the Brazilian sugarcane market. Such a perspective could address questions such as: how do policies influence car drivers' fuel preference (and demand)? How do policies prevent processing plants from making biorefinery investments? And can sugarcane supply be regulated in favor of biojet fuel and biosuccinic acid production?

This thesis is partially related to a MSc thesis by (Armbrust, 2014), who conducted a research to explore factors for establishing a biojet fuel supply chain starting in Brazil. Armbrust (2014) developed an agent based model that "can be used to explore different scenarios in the field of biofuels, particularly when the market is characterized by flexible behavior on both the demand and supply side" (Armbrust, 2014). One of the major findings of Armbrust is that government policies are actually enforcing the advantage of the road transport sector in the competition for sugarcane. Therefore, Armbrust suggests that further research is required in institutional arrangements that *can successfully increase the supply of biojet fuel*. Since Armbrust's emphasis was on the aviation supply chain specifically, he did not include the production of biochemicals in co-production with biojet fuel in a biorefinery, nor did he include the influence of international trade. Furthermore, 2G pathways were also excluded from his research.

In conclusion, the existing body of literature has several shortcomings with regard to the research problem. First, although many authors recognize the competition between sugar and ethanol markets, only few have attempted to provide insight into its relation to government policies. Moreover, none of the reviewed authors (except for (Armbrust, 2014)), have incorporated actor heterogeneity in analyzing how government policies hinder the production of other products than sugar or ethanol. This presents a significant gap in the existing literature concerning the research problem.

Knowledge gap

Although the existing body of scientific literature partially addresses sugarcane competition as a major hurdle for the production of biojet fuel and biosuccinic acid, it does not provide insight into how government policies might be affecting this competition through influencing actors' behaviors.

Therefore, in this thesis a research is presented that analyzes how government policies affect commercialization of biojet fuel and biosuccinic acid, within the context of sugarcane competition and international trade.

1.5 Reading Guide – Roadmap for the reader

Part	Chapter	Content
I **Thesis definition**	1. Introduction	The research problem is introduced.
	2. Research Definition	A scientific research is defined based on the identified knowledge gap.
	3. Building a conceptual model for analysis	The conceptual model that was used to analyse the Brazilian sugarcane market is derived from various theories.
II **Biorefinery Model Development & Analysis**	4. Systems analysis of the Brazilian Sugarcane Market	The conceptual model for analysis is applied to the Brazilian sugarcane market and the results are presented in a system diagram.
	5. Conceptualizing the Biorefinery model	Based on the proceeding system analysis and research scope, the Biorefinery model is conceptualized.
	6. Biorefinery Implementation	The Biorefinery model is implemented in the NetLogo modelling environment to become a simulation model.
	7. Policy Exploration: The model in action	The Biorefinery model is used to explore the effects of Brazilian government policies on the emergence of biojet fuel and biosuccinic acid production.
III **Conclusions, Recommendations, Limitations & Reflection**	8. Conclusions & Recommendations	An answer is formulated to the main research question and the sub-questions, and recommendations for policy settings are given. The key limitations of the research are discussed and suggestions for future research are given.
	9. Research Evaluation	The research process is evaluated from the standpoint of the Author's experiences in executing the research.

2

RESEARCH DEFINITION

- TOWARDS EMERGING BIOJET FUEL AND BIOSUCCINIC ACID PRODUCTION

In this chapter, the previously identified problem is formulated into a clear and concrete scientific research. First, the research objective – to contribute to an increase of biojet fuel and biosuccinic acid production in Brazil – is formulated in section (2.1). Then, the main research question and sub-questions are presented that are used to operationalize this research objective (2.2). Finally, the research methodology that was used to answer the research questions is described in section (2.3).

2.1 Research Objectives and Scope

The objective of this research is to contribute to an increase of biojet fuel and biosuccinic acid production in Brazil, by providing insight into the role of government policies in hindering commercialization of this production, and to make policy recommendations to achieve commercialization in the existing context of national and international competition between the sugar and ethanol market. Hence, focus is on the exploration of policy settings under which biojet fuel and biosuccinic acid production by means of the HIP biorefinery concept could emerge.

Research objective

What: To contribute to an increase of biojet fuel and biosuccinic acid production in Brazil.
How: By providing insight into the role of current government policies in hindering commercialization of this production, and to make policy recommendations to achieve commercialization in the existing context of national and international competition between the sugar and ethanol market.

Thus, the scope of this research is both *diagnosis* – providing insight into how government policies affect the observed market behaviour –, as well as to *explore* a set of possibly effective government policies to change this market behaviour. The production of biojet fuel and biosuccinic acid is explored through the application of the HIP biorefinery concept, and therefore also includes 2G technology. The primary focus of the research is on the allocation and processing of sugarcane feedstock, and does not include detailed logistic challenges such as the creation of biojet fuel supply chains. The state of São Paulo was chosen as the geographical area of interest, aligned with the scope of the HIP project. São Paulo is among the states with the highest sugarcane yield per hectare and represents 55% of national sugarcane production, 64% of national sugar production, and 50% of national ethanol production (Ferraz Dias de Moraes & Zilberman, 2014; UNICA, 2016). Furthermore, it is in relative close vicinity to Guarulhos airport in São Paulo and Galeão airport in Rio de Janeiro, to which domestic aviation is limited in the research scope. Finally, Santos port is located in the state of São Paulo, which is responsible for about 70% of ethanol imports and exports (Valdes, 2011).

Within the scope of this research, sustainability is not explicitly included, although it is implicitly incorporated, for example, through limits on the available quantity of agricultural land (imposed through agricultural zoning) (Ministry of Agriculture, 2008). Although excluded, the author of this thesis takes notice of the controversy with which bio-based products have been surrounded in recent years; a partial result of the growing global interest in biofuels over the last decade. An extensive body of literature emerged that questions the actual sustainability of biofuels (mainly ethanol and biodiesel), in terms of environmental, social and economic value creation in agreement with the triple-bottom line of sustainability (WCED, 1987) ((e.g. (Goldemberg, Coelho, & Guardabassi, 2008; Smeets et al., 2008; Timilsina & Shrestha, 2011; Tsiropoulos et al., 2015; Wilkinson & Herrera, 2010). However, it should be mentioned that many researchers agree that Brazilian sugarcane ethanol has the greatest reductions in GHG emissions due to high crop yields and the use of bagasse for bioelectricity ((Lapola et al., 2010; Timilsina & Shrestha, 2011). From a social sustainability perspective, however, concerns exist about labor conditions and vertical integration diminishing family farming. Nevertheless, over recent years, more stringent sustainability regulations have been implemented, which include agricultural zoning and allegedly increased labor conditions and mechanization. In addition, with regard to the food and land debates, various scholars argue that 2G pathways – as explored in this thesis – could significantly reduce GHG emissions, due to higher yields per hectare (Timilsina & Shrestha, 2011). Therefore, the exploration of commercializing 2G pathways in this thesis, might present insights into how biojet fuel and biosuccinic acid production could be increased through more sustainable feedstocks.

2.2 Research Questions

In order to operationalize the research objective to be achieved, the following main research question was formulated.

Main research question:

Main research question

> “What set of policies can be recommended to increase the production of biojet fuel and biosuccinic acid, within the context of national and international competition between the road transport and sugar market?”

This research question is divided into the following six sub questions, which bring more structure in answering the research question.

Sub-questions:

1. What actors in the sugarcane market of São Paulo state are involved in the emergence of biojet fuel and biosuccinic acid production, and what rules adequately characterize the interactions between these actors?

2. What influence does international trade of sugar and ethanol has on the emergence of biojet fuel and biosuccinic acid production?

3. What is the effect of the introduction of the 2G bagasse-to-biojet fuel production technology on the production quantity of biojet fuel?

4. What effect do current policies of the government of Brazil have on the emergence of biojet fuel and biosuccinic acid production?

5. What set of policies can be recommended to increase the production of biojet fuel up to 50% of the jet fuel demand in São Paulo state in the period 2015 until 2030?

6. What set of policies can be recommended to increase the production of biosuccinic acid up to 50% of the estimated world demand in the period of 2015 until 2030?

2.3 Research Methodology

In this section, the research methodology that was applied to answer the main research question is discussed. The methodological design of the research is displayed in *Figure 3*, which illustrates the general research logic. An extensive justification for the use of the theory and methods mentioned here is provided in chapter **(**3**)**.

In light of the intended local analysis of the sugarcane market, theory on complex adaptive systems was reviewed and applied to gain a better understanding of how actors' behaviors and interactions give rise to the emerging key variables of interest that can be observed at the macro systems level. In addition, theory on institutions and institutional economics was applied to study institutions at three levels: the level of government policies, the level of interactions between actors and the level of individual strategic decisions. Through combined application of both complex adaptive systems theory and institutional theory, a conceptual model for analysis was constructed. This model is the scientific research perspective, which guided the author in answering the research questions.

Besides this theoretical basis, practical case-related data was gathered about the Brazilian sugarcane market as well as the HIP biorefinery concept. Then, through the application of the conceptual model of analysis on the case data, the biorefinery model was constructed through a process of conceptualization. This is a static model that includes the main actors and their interactions that can provide insight into how the key variables of interest observed at the macro level are 'generated' at the local level. Although useful for general understanding, a static model alone was deemed insufficient to answer the research questions, and in particular sub-question 2.

In order to gain insight in the link between policy inputs and the key outcomes of interest, the biorefinery conceptual model was implemented into an Agent Based Model computer simulation model (ABM), which allows to explore different system behavior and policies in an iterative process. In this process, multiple meetings were held with agricultural expert Mr. Pierossi, to gain additional insights on the model's scoping decisions and assumptions. An extensive motivation for the choice of ABM is provided in section **(**3.4**)**. After an iterative process of model verification and data analysis, the model was used to explore the influence of current government policies and to explore alternative policies in the context of competition with the sugar and ethanol market.

After the ABM model was found to sufficiently explain the emergent outcomes of interest, it was used in an extensive policy exploration in which a set of policies was developed that can be recommended to increase the production of biojet fuel and biosuccinic acid.

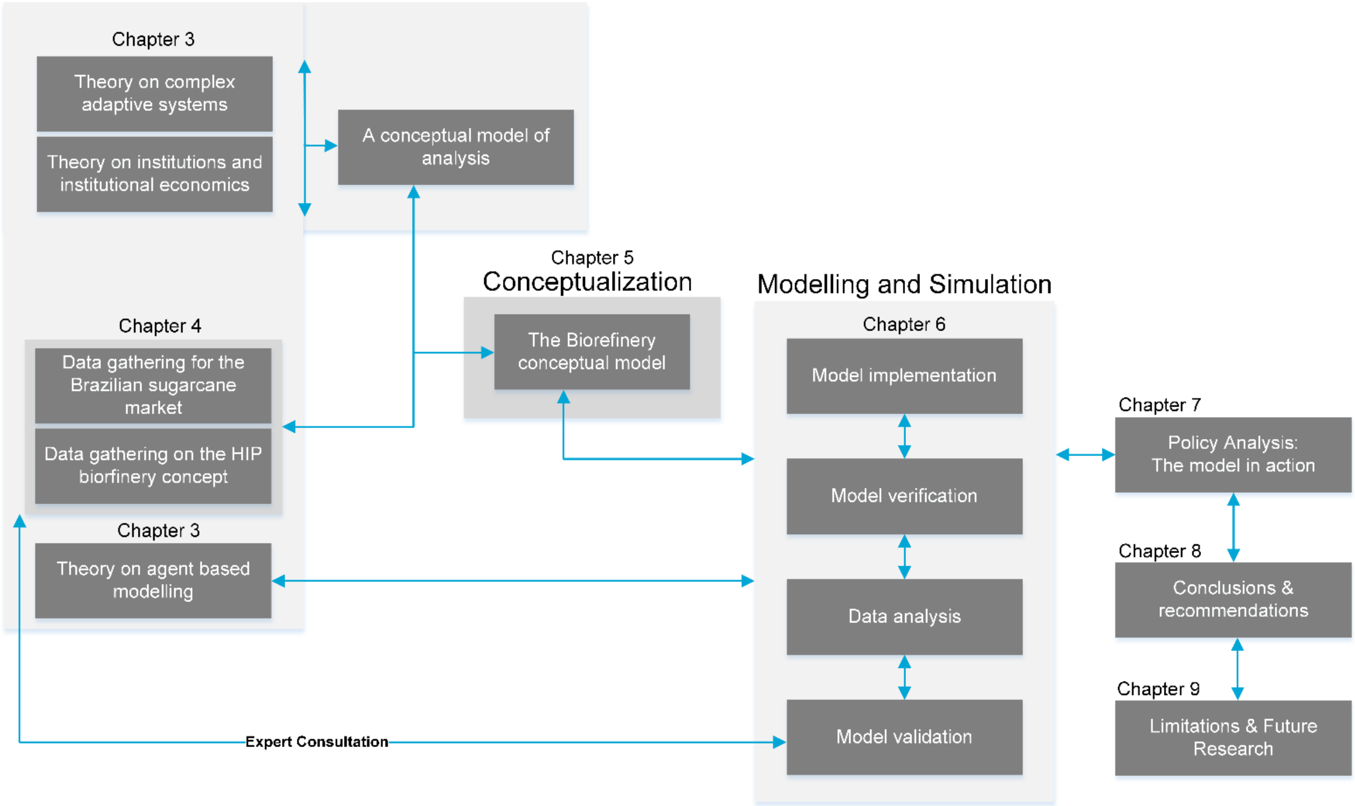


Figure 3: Methodological research design

3

THEORETICAL FOUNDATIONS
- BUILDING A CONCEPTUAL MODEL FOR ANALYSIS

This theoretical chapter presents the construction of a conceptual model which is the research perspective through which the Brazilian sugarcane market was analyzed. As such, it tells the researcher “what to look for’’ in the quest of answering the research questions. The first two sections depict the theoretical foundation of the conceptual model. First, section (3.1) presents the generative science perspective and complex adaptive systems that it relates to. Then, section (3.2) provides the institutional theories that were consulted to enhance the researcher’s capability to identify the social aspects and policies that can sufficiently explain the emergent behavior. Thirdly, the conceptual model is presented in section (3.3). Finally, a motivation for the use of the ABM framework as well as a general description of its modelling process are presented in section (3.4).

3.1 The Brazilian sugarcane market: a complex adaptive system

From the introduction in chapter (1), it was concluded that the problem of interest is a complex socio-technical problem and that previous research related to the problem has been conducted primarily from a, macro-level, top-down approach. This has been unsatisfactory in addressing the research problem. In that light, the need for a “bottom up” approach was emphasized. Therefore, in this thesis, an “elemental perspective” perspective was chosen.

The generative science perspective provides such an elemental perspective (Epstein, 2006). Within the generative science, actors are considered heterogeneous *‘agents’,* that is, they have their own unique local decision logic and rules of interaction. Thus, generativists contest macro-level approaches (such as general equilibrium economic models), which aggregate agents into several homogeneous pools and assume that they have individual rationality about macro-level equilibria. Instead, in the generative science, the heterogeneity and bounded rationality of actors play a central role. That is, they do not have unlimited information about the global level nor do they have infinitive computational power in decision making – they are just considered a bit more human. They make decisions according to simple rules, based on limited and local information. In the generativists’ perspective, a conceptual model is constructed about the interactions between agents at the local level, which are considered to generate or ‘grow’ an emerging pattern that is observed at the macroscopic system level. While doing so, focus is on the generative sufficiency of the conceptual model. This means that the model should allow to sufficiently explain macroscopic behavior, but does not have to be more extensive than needed. Systems studied in the generative science are often described as *complex adaptive systems (CAS’s)*. Among the different definitions that exist for CAS’s, (Holland, 1995) was found to provide the crispest definition as displayed in *Figure 4*.

Complex adaptive system

> “a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a complex adaptive system tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents”

Figure 4: A common definition for complex adaptive systems. Adopted from (Holland, 1995)

From the definition by Holland (1995) it thus follows that CAS’s consist of agents, interacting in a network of links and continuously adapting to the overall system behavior. Perhaps the usefulness of the CAS approach is illustrated best by assessing the characteristics of CAS’s mentioned by Lei, Bekebrede, and Nikolic (2010).

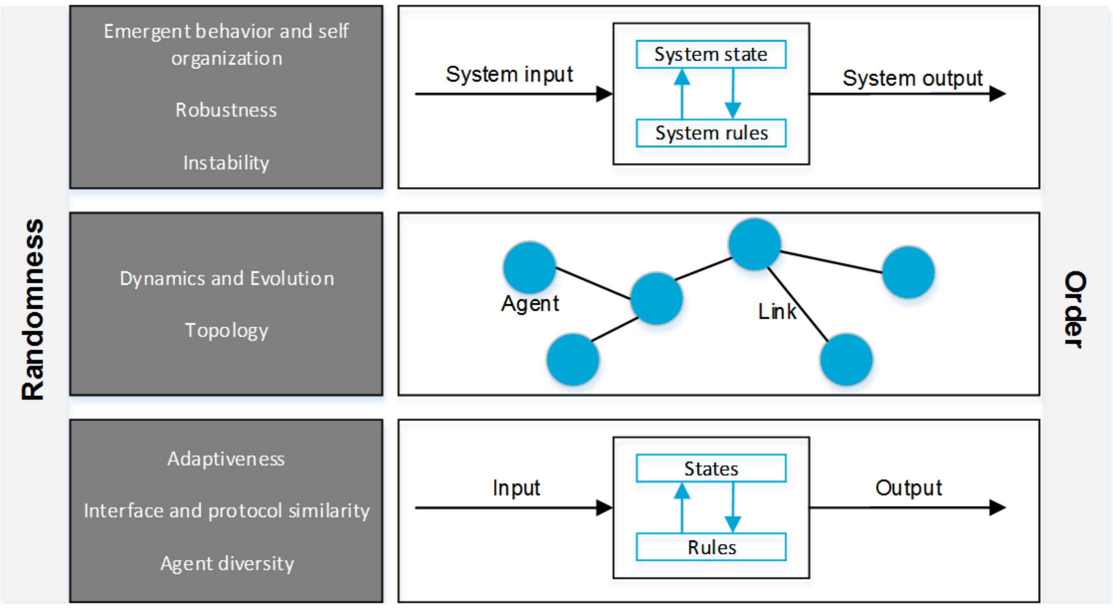


Figure 5: A conceptual framework of a complex system adaptive system – adopted and adjusted from (Lei et al., 2010)

At the **agent level**, there are three main properties: *adaptiveness*, *agent diversity* and *interface and protocol similarity* (*Figure 5*) *Adaptiveness* refers to an agent’s ability to change its behavior in accordance with its own internal states or surroundings. In the sugarcane system, for instance, car drivers base their decision to choose ethanol over gasohol or vice versa based on market prices and personal preferences (*agent diversity*). Logically, drivers with a preference for ethanol have different internal states than gasohol drivers. Furthermore, all agents share a common *interface and protocol*, being the manner in which they can communicate with each other. At the higher **network level**, agents are considered as a ‘web’ of structured interactions, having two main characteristics: (1) *dynamics and evolution*, and (2) *network topology*. Dynamics and evolution, for instance, can be seen in the interactions between farmers and processing plants. These interactions are not static, instead contractual relations have a limited duration and can be made between different sets of agents. Furthermore, the concept of *network topology* clarifies the relations and interdependencies that can be observed between elements in the sugarcane system. For instance, it seems likely that processing plants have a network of sugarcane suppliers to whom they are connected. The same could be expected for car drivers, which are likely to be “connected” to one or more fuel stations in their area.

Finally, the **system level** can be said to describe a whole entity, and therefore has a similar structure as an individual agent, but on a higher level of aggregation (Lei et al., 2010). At the system level, once can observe the previously mentioned emergent behavior and self-organization. This behavior is reflected in the *system output*, and results from the outputs of all agents at the agent level. However, a system output can simultaneously be an input for agents as well. For instance, the market price for hydrous ethanol is the result of a multitude of agent outputs, and therefore no single agent has full knowledge about what this market price will be before it undertakes any action (unless one agent or a group of agents has a monopoly). The system is self-organizing when it is able to change its output without any external input. An important additional notion here is that systems as well as agents can be *path dependent*. This means that over time they evolve in a certain way, which makes switching to another course rather difficult. One could argue that this is also the case in the Brazilian sugarcane market, where the market has been oriented on sugar and ethanol production since the 1970s. The system's robustness and instability express how resilient the system is and how sensitive it is to small changes in variables, respectively. Finally, the environment of a complex adaptive system is a combination of two extremes: perfect randomness and perfect order. In the former, not any causation can be found between events, whereas in the latter, events are perfectly predictable.

3.2 Operationalizing the institutional perspective

As became clear in the previous section, understanding interactions between agents is a key element in the application of CAS theory. Yet, it can be rather difficult to identify the interactions that support generative sufficiency. Interactions can however be identified and analyzed within the wider conception of institutions. Although maybe not obvious at first instance, there is an 'intimate relationship' between the agent concept discussed in section (3.1) and institutions (Correljé, Groenewegen, & Künneke, 2005). Denzau and North (1994) describe this relation as agents having (internal) mental models by which they interpret the environment, whereas institutions (external to the agent) are created by these same agents to structure and order the environment in which they operate.

Ghorbani (2013) emphasizes the usefulness of incorporating institutions in the analysis as she states that "besides providing social structure, incorporating institutions into ABM models helps develop more tangible assumptions about agent decision-making and behavior because we can take the influence of institutions in enabling or restricting those behaviors into account". In that light, theory on institutions and New Institutional Economics (NIE) was consulted to enhance the researcher's capability to identify and analyze the social aspects in the generativist perspective.

3.2.1 What about institutions?

The term institutions has seen increasing application in the social sciences in recent years (Ghorbani, 2013). Probably the most commonly used definition of institutions is provided by North (1990), who defines institutions as a set of humanly devised constraints that shape human interaction over time. North (1990) refers to these as "the rules of the game in a society" and distinguishes them in two major categories: *formal rules* (e.g. government regulations) and *informal* codes of behavior (e.g. norms and values). Additionally, their enforcement is a third dimension of the concept of institutions. North (1990) then argues that the sum of formal and informal institutions define the context in which human interaction in a society takes place.

Such institutions are not static, as if they would remain constant and unchanged over time. Instead, they are man-made, and are thus shaped over time by agent interactions, referred to as institutional change and reform. Within the stream of New Institutional Economics (NIE), substantial research has been performed on the process of institutional change (Correljé et al., 2005).

In this thesis, institutions were considered as existing explicit and implicit rules that shape and influence decisions by individual agents involved in the emergence of biojet fuel and biosuccinic acid production. In the next two sections, this definition is operationalized for application in this thesis, and the used elements of theory are presented.

3.2.2 Frameworks for institutional analysis

The Institutional Analysis and Development framework (IAD) and Actor-centered Institutionalism (ACI) framework are two commonly used models for the study of institutions. Both models underwrite the importance of bi-directional interactions between actors and institutions. That is, as aligned with North's definition of institutions, actors are influenced by institutions but also shape them over time. This dynamic nature of institutions makes it rather challenging to grasp how they relate to complex adaptive systems and the ABM paradigm (Ghorbani, 2013).

In that light, (Ghorbani, 2013) developed the "Modelling Agent Systems based on Institutional Analysis framework" (MAIA) – a conceptualization framework based on the IAD framework. A key concept in the MAIA framework is to accommodate the formalization of social structures in which agents operate. However, MAIA is not used in this thesis for primarily two reasons. First, although social structures will be modelled to some extent, the evolution or emergence of institutions is omitted from this research. Second, the use of MAIA may add additional complexity when used in parallel with the existing model of (Armbrust, 2014) – a major building block for this thesis.

Therefore, existing models are considered to have sufficient analytical capacity for the purpose of this research. For the construction of the conceptual model for analysis, the Williamson four-layer framework was used because of its relative simplicity yet conceptual richness (Williamson, 1998). In this section, it serves as a springboard to further specify what aspects of institutional economics were found useful for adoption in the conceptual model. The Williamson four-layer model is a widely used framework for institutional analysis in the field of economics (Williamson, 1998) (*Figure 6*).

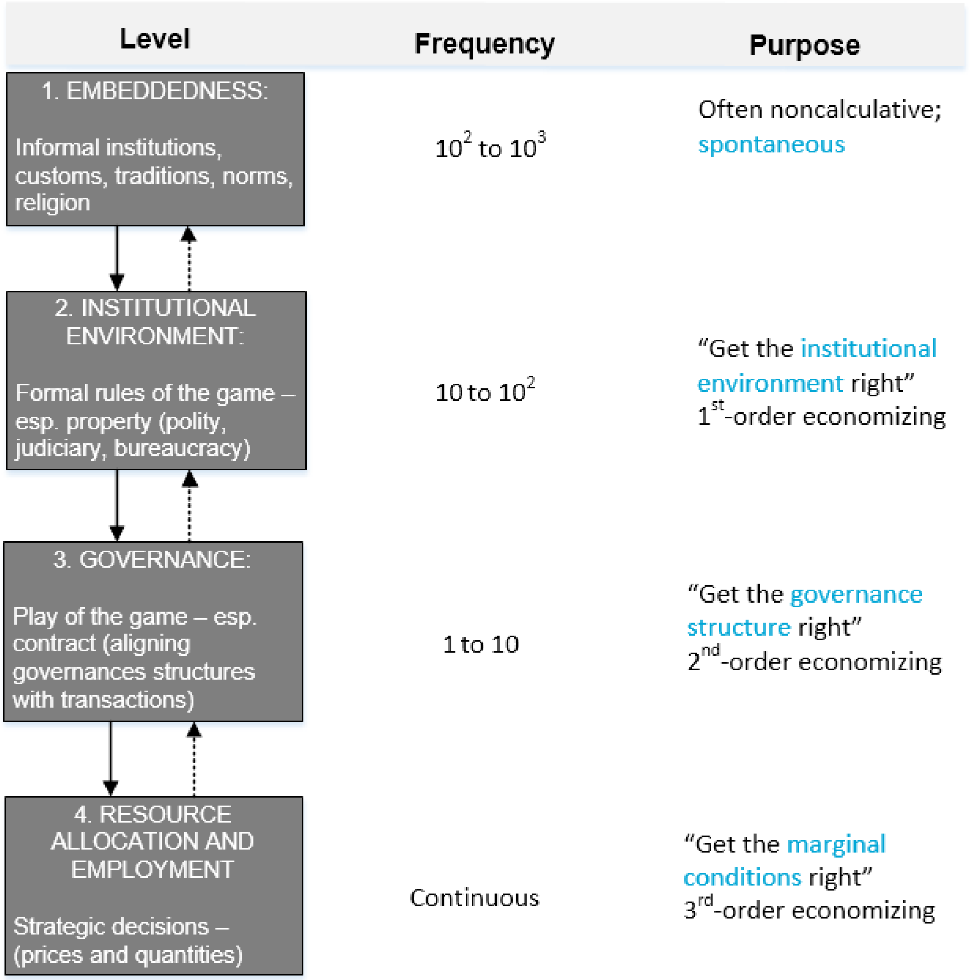


Figure 6: The four-layer model of Williamson. Adopted and adjusted from (Williamson, 1998)

As its name suggests, the model distinguishes institutions in four different layers, according to two criteria: *frequency of change* of the institutions and their *purpose*. The solid arrows mean that higher level institutions impose a constraint on lower level institutions. The dotted arrows express the hard to grasp influence of lower level institutions on higher level institutions.

Level 1: Informal institutions

The first level refers to informal institutions, such as customs, traditions, norms and religion, which change only very occasionally. It is mostly the domain of social sciences like anthropology, history and sociology (Correljé et al., 2005), but is also often referred to as "Original Institutional Economics", in which focus is laid on the embeddedness of informal institutions in individuals' behaviors. Logically, analysis of this level is quite descriptive in nature. Informal institutions are assumed to be constant over time, and are therefore omitted from the research scope and the conceptual model.

Level 2: Regulatory economics at the institutional environment

The second level refers to the institutional environment, which are the explicit formal rules of the game to which actors are supposed to oblige. As such, they form the boundaries of the economic system within which actors make their own decisions. For example, such rules can be bureaucracy-related or regulation through policies. In Neo Classical Economics (NCE), the institutional environment is included on a ceteris paribus basis: it is taken exogenous and assumed to remain constant over time

(Correljé et al., 2005). Focus is then on how a market behaves, given a certain institutional environment.

In this thesis, market regulations (as a type of formal institutions) are also taken exogenous. Therefore, only unidirectional interactions from formal institutions to agents are considered in this research. For regulations, a distinction can be made between *conduct regulation* and *structural regulation* (den Hertog, 2010). Through conduct regulation, governments exert influence on the behavior of producers (processing plants) and consumers (e.g. car drivers) in the market, whereas structural regulation concerns the market structure, such as the entry or exit of agents. The two main streams of regulatory economics in the literature were reviewed (public interest theory of regulation and private interest theory of regulation (den Hertog, 2010)), but are not used in this research, because the process of regulatory change is excluded from the research scope. Thus, in level 2 the perspective is to identify the different types of conduct and structural regulations used to regulate agent behavior at the agent level.

Level 3: Governance structures and transaction costs

The third level refers to relatively recent theoretical developments in governance structures and contracts used to coordinate economic transactions, often referred to as Transaction Costs Economics (TCE) (Williamson, 1998). At the governance level, actors are in pursue of finding the most optimal governance structure for their interactions in order to minimize production costs. For example, one could think about how processing plants govern their sugarcane supply chains. Insights in such governance mechanisms could reveal how sugarcane supply for biojet fuel and biosuccinic acid production is hindered.

From a NCE perspective, the costs of production are the only relevant costs in selecting governance structures, and transaction costs – the costs related to economic transactions, such as buying and selling – are neglected. However, in line with the NIE perspective, such transaction costs cannot simply be neglected, as actors have bounded rationality and operate in a complex market environment. In other words, they cannot be assumed to have full information about the governance decisions they make. For example, a processing plant has only limited information about the market prices of the products it produces. In fact, there are costs to the discover market prices. Furthermore, farmers are likely to negotiate with various buyers to supply their sugarcane, but they do not have full knowledge about what would be the most profitable deal or how to define the selling price (bounded rationality). Therefore, TCE studies the costs made in the transaction of goods and services. Or, as Williamson (1998) describes it: “transaction costs regard the firm not as a production function but as a governance structure”.

Such transactions are characterized by three main attributes: (1) *asset specificity*, (2) *frequency* and (3) *uncertainty*. (1) *Asset specificity* refers to the degree in which assets, such as harvest machinery or processing technologies are specific to a purpose. Thus, assets with a high asset specificity can only be used for one or a limited number of purposes – which is clearly the case for sugarcane farmers and processing plants, as is explained in chapter **(**4**)**. Two additional categories for asset specificity were found useful for this research: *site specificity* (geographical constraints) and *physical asset specificity* (equipment and machinery). In addition (2) *frequency* refers to the number of times that agents perform a certain transaction or contracts are made, which could address questions such as: how often do sugarcane farmers and processing plants negotiate? For how long does the farmer have contracted supply obligations? Finally, (3) *transaction uncertainty* refers to the degree of change in transactions and the disturbances to which they are subject, such as farmers making supply contracts with newly constructed processing plants. TCE then argues that agents are likely to develop the most optimal institutions/institutional arrangements to manage and reduce such transactions. In the level 3 perspective, the aim will thus be to identify different governance structures used in the sugarcane market and to gain insight into how they influence the key outcomes of interest.

Level 4: Strategic decisions at the operational level

Finally, at the fourth level, actors make continuous strategic decisions in their production processes, such as processing plants altering their production ratios in response to market prices of sugar and ethanol. This level has been of major interest to NCE, which analyzes production decisions as a production function, with price and output being the major decision variables. Although this approach might be somewhat applicable to processing plants, it is certainly not to autonomous car drivers making individual decisions about fuel consumption. For example, above the importance of cost competitiveness of hydrous ethanol and gasohol, such decisions also incorporate a selection of 'soft variables', such as fuel preference and a car driver's inclination to switch fuels. In that light, commonly used neo-classical theory on market economy (involving market equilibria of aggregated production segments) cannot provide the desired generative sufficiency. Instead, in this thesis, agents are modelled as heterogeneous entities that behave differently according their own characteristics.

3.2.3 The institutional perspective used

As aforementioned, in this research, institutions are considered as existing explicit and implicit rules that shape and influence decisions by individual agents involved in the emergence of biojet fuel and biosuccinic acid production. Mainly three types of constraints were analyzed: (1) existing government policies concerning the sugarcane market, (2) governance structures in sugarcane procurement and sugarcane pricing, and (3) strategic decisions of agents. It was assumed that enforcement of these rules is costless and agents always try to oblige to them. Furthermore, analysis of the development or change of existing institutions was omitted from the research scope. Instead, key focus was on the identification of these institutions, to analyze how these influence agent behavior and interactions in the sugarcane market, and how this could present barriers as well as opportunities for the emergence of biojet fuel and biosuccinic acid production. Furthermore, agents were assumed to be individual decision-making entities, and therefore inter organizational institutions (e.g. corporate values and standards) were omitted from the research.

The perspective applied for the first type of institutions – existing government policies –, concerned the identification of existing regulations for the sugarcane market of São Paulo state and to gain insights into how these regulations influence agent's behaviors and interactions. For instance, this allowed to answer questions such as how gasoline taxation influences the fuel consumption behavior of car drivers and production decisions of processing plants. Thus, the influence of existing policies was assessed by exploring different settings for these policies.

For sugarcane procurement and sugarcane pricing, institutions were defined as governance structures through which farmers and processing plants govern sugarcane supply and prices. These governance structures are both formal and informal aspects that describe the interactions between these agents. Incorporating such aspects in the analysis may reveal insights into how these could be barriers for the emergence of biojet fuel and biosuccinic acid production.

Finally, strategic decisions of agents concern individual behaviors of agents according to their heterogeneous characteristics. This means that agents are not necessarily expected to show similar behavior in similar market conditions, because each agent's different mix of characteristics may give rise to different outcomes among agents.

3.3 A conceptual model for analyzing the sugarcane market

Figure 7 depicts the conceptual model that was constructed from the previously elaborated theories and used for the analysis of the Brazilian sugarcane market in pursue of answering the modelling question. In this model, the generative science perspective was complemented with an institutional perspective to allow for studying how institutions are related to the different levels of the CAS.

Please note that, as previously mentioned, the highest institutional layer of the Williamson model was omitted from the model. As for level 3 (the institutional environment), only unidirectional influence of the institutional environment on agent behavior and interactions is included in the conceptual model. At this level, the government policies (a type of formal institutions) of the government of Brazil are located. The approach followed here is neither a purely NCE nor a purely NIE perspective. Namely, from a purely NCE perspective, the study of interest would be what effect government policies (e.g. market price control or mandatory fuel blending) would have on the aggregate market behavior, while assuming homogeneous and rational agents. However, in the proposed conceptual model, focus is on what effect these policies have on the individual decisions of actors as well as their governance structures. On the other hand, from a North oriented NIE perspective, key focus would be on the interactions between institutional layers (the embeddedness) and how actors influence and shape the institutional environment over time. However, the institutional environment will only be studied unidirectional – meaning that there is no feedback from the agent level to the institutional environment (institutional change and reform).

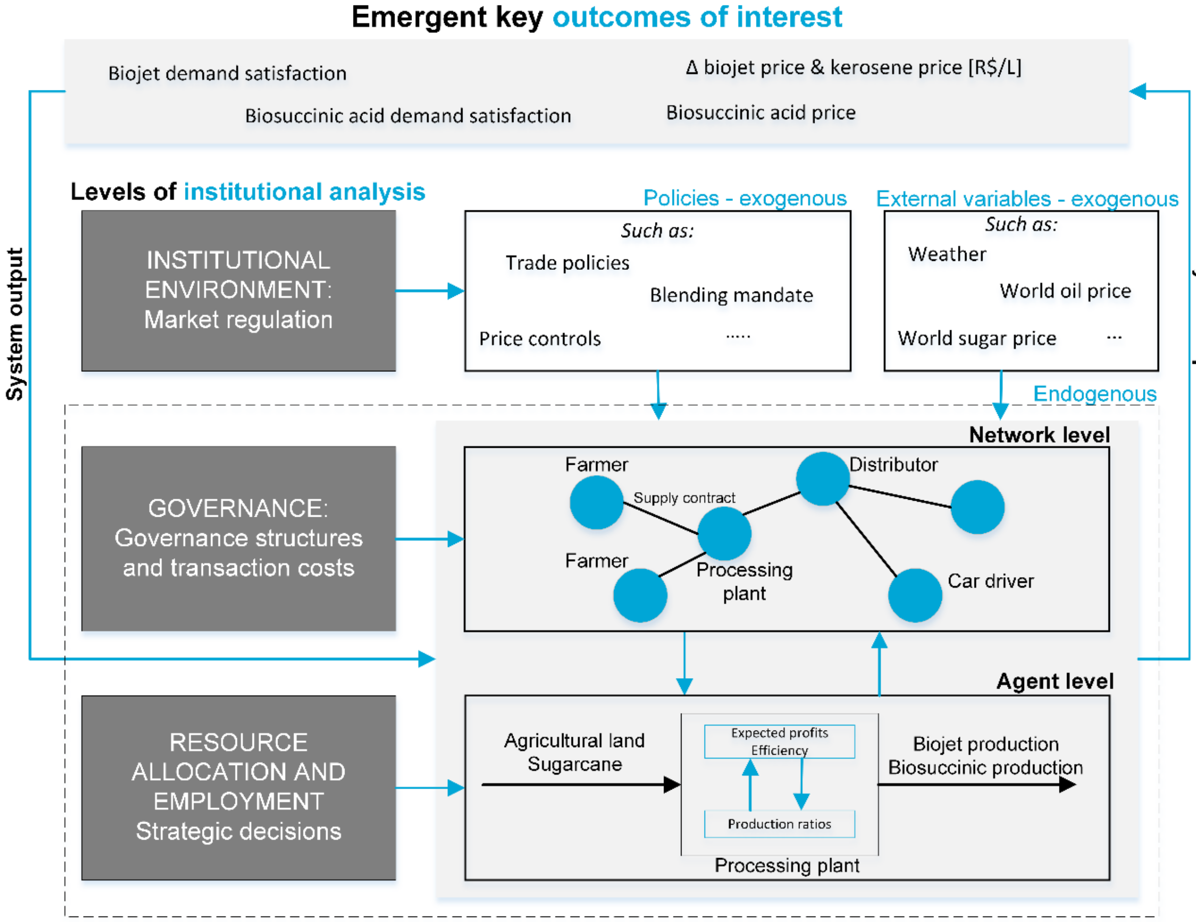


Figure 7: The conceptual model for analysis of the Brazilian sugarcane market

3.4 Using the agent-based modeling framework for modelling and simulating the sugarcane market

The previously constructed conceptual model tells *what* and *whom* to look for in explaining the emergent outcomes of interest. Through the application of the model on the Brazilian sugarcane market, valuable insights can be obtained in explaining how institutions at each of the three identified levels influence agents' decision-making and how actors interact. Accordingly, hypotheses can be formulated about how these interactions could grow the emergent outcomes of interest.

However, an analysis of the system in static state does not allow to fully exploit the potential of the conceptual model and to 'grow' the emergent key outcomes of interest from the generative science perspective. Moreover, given the author's ambition to explore different policies in an iterative process, computer simulation was chosen to be used as a "virtual laboratory" (Borshchev & Filippov, 2004; Robinson, 2004).

A variety of modelling paradigms available for computer simulation purposes. The natural choice for modelling from a complex adaptive systems perspective is the Agent Based Modelling (ABM) framework. A motivation for this choice and a comparison with other modelling paradigms is provided in section **(**3.4.1**)**. Then, in section **(**3.4.2**)**, the ABM framework that was applied in this research is further elaborated on.

3.4.1 Motivation for the ABM modelling paradigm and its limitations

There are four main modelling methods that are most often used for modelling and simulating systems: Computable General Equilibrium (CGE), System Dynamics (SD), Agent Based Modelling (ABM) and Discrete Event Simulation (DES) (Bonabeau, 2002; Borshchev & Filippov, 2004; Sterman, 2002; van Dam, Nikolic, & Lukszo, 2013). Their main characteristics are provided in *Table 1*.

Although CGE does allow for some policy exploration, it does not have the simulation capacity of SD, DES and ABM. SD, DES and ABM all allow for examining the interaction of things and how they relate to overall system behavior, but they fulfill significantly different purposes. In the case of SD, a high-level, top-down perspective is applied to identify and model feedback loops and causal relations. Therefore, in SD, homogenous objects represent a high-level of aggregation and there are no heterogeneous agents making decisions or whatsoever. DES is a combination of both high and low level modelling and can include agents making simple decisions. However, in DES it is rather difficult to include institutions of any type. The use of ABM allows to model relatively autonomous and heterogeneous agents that are acting in parallel, each of them having their own decision-logic and/or states and behaviors. In that sense, ABM is truly a bottom-up approach, in which a local view is applied to discover emergent properties at the macro level.

Although the application of ABM provides substantial advantages, it also comes – like any other simulation method – with various limitations. A universal observation, applicable to any modelling paradigm, is that the use of models in complex systems is always susceptible to criticism, as models are created from the point of view (carrying all limitations, biases, etc.) of the observer. In particular in ABM, stakeholder involvement throughout the modelling process is rather difficult. Therefore, it is advisable to do extensive expert validation. Another limitation of ABM is that parameterization of the model with real world data can be difficult, as the agent interactions can give rise to unforeseen behavior. Therefore, substantial attention should be paid to the calibration of soft variables, such as fuel preferences or risk aversion.

Modelling method	Level of modelling	Characteristics	Sources
Computable general equilibrium (CGE)	High level, top-down	Macro-economic analysis of market equilibria (e.g. supply and demand), linear analysis.	(Shiflet & Shiflet, 2014)
System Dynamics (SD)	High level, top-down	Feedback loops, causal relations, information and material flows, policy analysis in relatively closed systems.	(Borshchev & Filippov, 2004; Sterman, 2002)
Discrete Event Simulation (DES)	Both high & low level	Optimization of (Industrial processes, closed systems.	(Borshchev & Filippov, 2004)
Agent Based Modelling (ABM)	Bottom-up approach, local view	Agents with conditional rules, emerging behavior, policy analysis in less predefined systems.	(Bonabeau, 2002; van Dam et al., 2013)

Table 1: Assessment and comparison of simulation methods

3.4.2 The Agent-Based Modelling Framework

In this thesis, the ABM framework as described in (van Dam et al., 2013) was applied. In this section, a brief description of each step in this ABM framework and how it was applied in this thesis is provided. For a more detailed description of the ABM framework, readers are referred to (van Dam et al., 2013)

Step 1: Problem formulation and actor identification

Any modelling study starts with a thorough problem formulation and identification of actors related to this problem. In the ABM framework, one is particularly interested in identifying the observed emergent patterns and how they deviate from the problem owner's desired patterns. Furthermore, this step includes an extensive actor identification of other actors related to the problem and formulation of the researcher's role. This step was carried out extensively through a systems analysis, which is presented in chapter **(**4**)**.

Step 2: System identification and decomposition – identifying elements

The next step is to identify the internal structure of the system from a complex adaptive systems perspective, meaning that focus is on the identification of agents and states, behaviors and interactions, which collectively give rise to the emergent patterns of interest. A detailed decomposition is obtained through an iterative process of identification and structuring of research findings. The final decomposition is presented in chapter **(**5**)**.

Step 3: Concept formalization – reducing ambiguity

The third and fourth step concern the formalization of the model in order to eliminate ambiguity and to increase the level of detail. Formalization is the 'missing link' between a general, context dependent description and computer language. Thus, the primary purpose in this step is to gradually reduce ambiguity, for computers cannot handle this. In this thesis, both Unified Modelling Language (UML) and IDEF 0 are used. The UML approach allows to easily structure the specific states and actions of each agent and how these agents relate to each other. From there, IDEF0 – a function modelling method – is used to further structure specific action situations, in terms of the required inputs, controls, mechanisms and outputs. The model conceptualization is presented in chapter **(**5**)**.

Step 4: Model formalization – building a simulation storyline

After having narrowed down what objects and agents will be in the model, these findings have to be further specified into a narrative (or "storyline") of *who* does *what* and *when*, for the events in the simulation take place in a sequential order. It is therefore of great importance to make the model logic very explicit. It is very common in this modelling step to frequently iterate step 1 to 4, as formalization can give the modeler insight that model elements should be added or omitted. This is done by constructing the *model narrative* and the *pseudo-code*. Pseudo-code is a human-readable code which will provide an insight into the general algorithm of the model. Model formalization is covered in both chapter **(**5**)** and chapter **(**6**)**.

Step 5: Software implementation – from concepts to code

The actual software implementation is clearly distinguishable from the first four steps, as this merely concerns the transformation of the formalized model into computer code. There are various computer software or "modelling environments" available for modelling ABM's, such as *NetLogo*, Repast and custom code (van Dam et al., 2013). For this thesis, NetLogo was chosen as the preferred software – an open source software which is very popular among academics for its simplicity (Gilbert & Bankes, 2002). Although model verification in NetLogo can be challenging, there is a very active online support community for NetLogo, where guidance can be obtained. The source code of the Biorefinery model is not provided in this thesis, due to its very large size. The source code of the model is available upon request with the author or thesis supervisors.

Step 6: Model verification – was the model built right?

The primary purpose of model verification is to verify if the conceptual model was correctly translated into the model code. A common pitfall in any computer-based modelling paradigm, is to draw conclusions from an erroneously working model. Thus, focus was on finding structural mistakes in the NetLogo code. Four types of verification were used: (1) recording and tracking agent behavior, (2) single-agent testing, (3) interaction testing, and (4) multi-agent testing (van Dam et al., 2013). The model verification is addressed in the chapter **(**6**)**.

Step 7: Experimentation

After the conceptual model was implemented and verified, it was used for experimentation purposes. Through experimentation, insights can be gained about how the emergent outcomes of interest are grown. This requires a set of well-designed experiments, with clear information about the variables to be changed and hypothesis to be tested. Furthermore, decisions have to be made about the ranges for which values will be varied, as well as the number and length of simulation runs. The model experimentation is presented in chapter **(**7**)**.

Step 8: Data analysis

The simulation runs in NetLogo generate a tremendous amount of data. Although very useful to track real-time model behavior, the NetLogo graph interface is insufficient for in depth data analysis and the comparison of different simulation runs. Therefore, R statistics was used for data analysis, which is fully compatible with NetLogo and allows to process raw data and generate graphs and tables for documentation purposes (Rstatistics, 2016). Due to the author’s previous experience with the IBM SPSS statistical software, this was used for the statistical tests.

Step 9: Model validation – was the right model built?

Whereas model verification focusses on verifying the technical correctness of the model, model validation aims to validate whether the model can represent the real world system or hypothesized system. The biorefinery model consists of both type of system elements. For the former, literature desk validation was applied to validate whether the model behavior sufficiently corresponds to the real-world behavior. For the latter, expert validation was carried out to validate the correctness of the sugarcane procurement interactions and sugarcane pricing mechanism. Model validation is discussed in chapter **(**6**)**, as well in APPENDIX III.

Step 10: Model use

In the final step of the ABM framework, the simulation model is used for interactive exploration of model outcomes in order to gain insights into the research problem. In this thesis, step 7 and 10 were combined and presented in chapter **(**7**)**. That is, experiments were specifically designed related to the research questions, after which the outcomes were used to formulate recommendations for policy settings. Naturally, future users of the model can use it to explore other behaviors, within the model’s abilities.

II

Biorefinery model Development & Analysis

4

SYSTEMS ANALYSIS OF THE BRAZILIAN SUGARCANE MARKET

In this chapter, the conceptual model constructed in the proceeding chapter is applied to the Brazilian case. As such, this chapter is a systems analysis, in which the main focus is on the identification of actors, variables, and institutions. In section (4.1), an inventory is made of the actors relevant to the problem and these are analyzed in detail. Then, in section (4.2) an institutional analysis is presented that covers the three institutional layers of the conceptual model. Finally, the findings are presented in a system diagram in section (4.3) which serves as the foundation for the development of the ABM Biorefinery model from chapter five on.

4.1 Actor Identification and Analysis

4.1.1 Sugarcane Feedstock Production

The production of sugarcane in São Paulo has doubled over the last twenty years, as can be seen in *Figure 8*. The major factors which influence sugarcane production besides the amount of harvested area are producer-specific yields, land quality and weather conditions. Although there has been a general upward trend in sugarcane production, production quantities can still variate substantially due to variations in these factors. Due to a combination of lacking investments in sugarcane planting and cultivation, sugarcane yields dropped by almost 20% between 2009 and 2011. That is the lowest yield since 1995 (Kaup, 2015). Combined with the fact that sugarcane accounts for 50 to 70 % of the production costs of sugar and ethanol (Fava Neves, 2011; Kaup, 2015), variation in the production determinants generally induce substantial volatility in production quantities and market prices for sugarcane, sugar and ethanol. Although there has been a substantial reduction of sugarcane prices since the 1970s, the sugarcane farmers association (ORPLANA) indicates, however, that sugarcane prices have increased by 65 % over the last 7 years.

Sugarcane is generally produced by two main actors: (1) ‘independent’ third party suppliers which are not connected to a specific processing plant; and (2) processing plants that produce sugarcane themselves (or through farming companies that belong to the same business group) through a variety of vertical integration strategies. In recent years, the former accounted for about 30 – 40 % of total sugarcane production, while the latter accounted for about 70 – 60 % (Ferraz Dias de Moraes & Zilberman, 2014). Both are discussed in more detail in the following two sections.

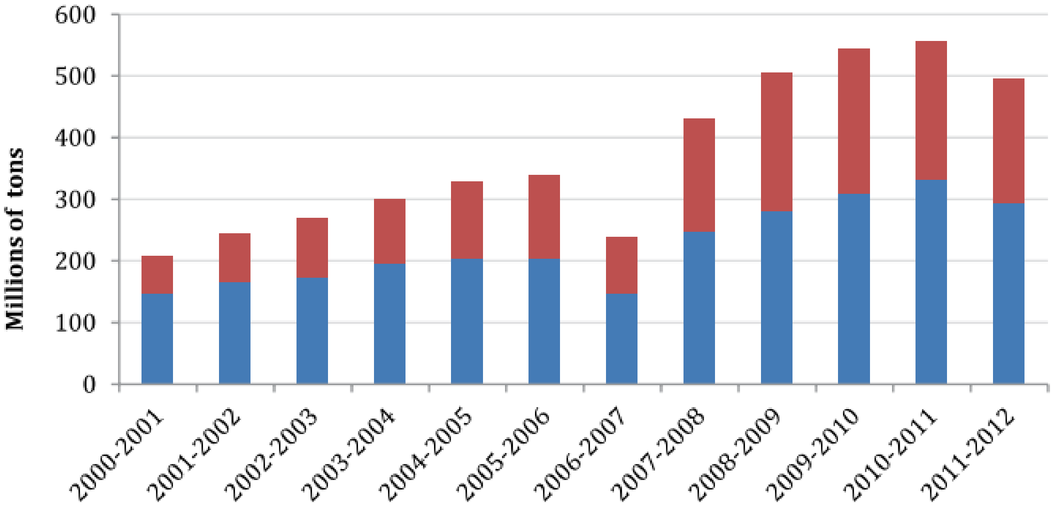


Figure 8: Composition of sugarcane production in the state of São Paulo 🟥 Sugarcane from independent suppliers 🟦 Sugarcane from processing plants (Ferraz Dias de Moraes & Zilberman, 2014)

Third party sugarcane suppliers

Independent, traditional, or *third party suppliers* (from now on referred to as suppliers) currently account for about 40 % of total sugarcane production in the state of São Paulo (Ferraz Dias de Moraes & Zilberman, 2014). These suppliers (around 11000 (UNICA, 2007)) do not have long-term affiliations with processing plants, and thus have the ability to choose the processing plant that they wish to supply their sugarcane to. However, geography is a limiting constraint, as it generally becomes economically unattractive for these suppliers to supply to plants further than about 30 – 50 kilometers away, because of increasing transportation costs and fast decrease in sugarcane quality after harvest. These factors can significantly reduce the number of plants that a supplier can negotiate supply contracts with (UNICA, 2007). Also, the concentration of processing plants in the suppliers' production region affects its bargaining position and choices (Ferraz Dias de Moraes & Zilberman, 2014). Land quantity varies a lot among third party suppliers and there is no typical profile for these actors, which can range from small family farmers to large agricultural corporations. Data from the Brazilian Sugarcane Growers Association of the Brazilian South-Central Region (ORPLANA) indicated that about 0.4 % of the total number third party suppliers accounts for 24 % of total sugarcane production, whereas 46 % of this number only accounts for 4.2 % of the total production. Prices for third party supplier sugarcane are generally determined through the CONSECANA-SP pricing mechanism, which was developed and implemented after deregulation of the sugarcane industry. This mechanism is further elaborated on in the institutional analysis.

Vertical integration of sugarcane production

As the sugarcane market revived from 2003 on, plants have increasingly adopted various vertical integration strategies to increase control over their supplies and assure themselves from a seasonal base quantity of sugarcane (Kaup, 2015). In addition, plants often achieve higher yields per hectare than suppliers, as they generally own more modern and efficient equipment. In São Paulo, vertical integration accounts for about 60 % of total sugarcane production (Ferraz Dias de Moraes & Zilberman, 2014). In particular in regions with a relatively high density of refineries per ha of land, fierce competition can exist. The predominant vertical integration strategy is to lease land (for a minimum of 5 to 6 years, the length of one growth cycle, and equal to 4 to 5 harvests) from *landowners*. This has resulted in an increasing competition for land, and land lease prices for sugarcane refineries have risen from an average of US $ 80 per hectare in 1995 to an average of US $ 230 per hectare in 2008 (Nassar, 2009; Novo, Jansen, Slingerland, & Giller, 2010). Novo et al. (2010) argue that this can be seen as a result of the sugarcane expansion, as they mention that sugarcane cultivation has been the only agricultural activity in most of the regions in São Paulo. This observation is of particular importance in light of the earlier mentioned geographical constraints of sugarcane procurement. This means, plants have become the fixed center of a network of close-by cultivation areas and independent suppliers, in which the value of these areas have increased tremendously over time (Fava Neves, 2011). Additionally, competition for third party supplier sugarcane increases with the concentration of processing plants in a particular area (Ferraz Dias de Moraes & Zilberman, 2014).

4.1.2 Ethanol and sugar production

The total quantity of sugarcane available to processing plants is often procured through a mix of supplied sugarcane and own production and is processed in two major products: ethanol (hydrous and anhydrous) and sugar. There are over 200 processing plants in São Paulo, of which the majority is individually-owned (Kaup, 2015). A distinction can be made between three types of processing plants: (1) *flex plants*; (2) *ethanol plants* and (3) *sugar plants*. Sugar plants have become rather unique in the state of São Paulo and are primarily located – in limited numbers – in the North-Eastern production region of Brazil. Therefore, sugar plants are not of further interest for this thesis. *Flex plants* have become the predominant type of processing plant in the state of São Paulo and most other states. Such plants have the technical and operational capability to co-produce ethanol and sugar. Production quantities of sugar and ethanol can be altered with a split of about 65 % to 35 %, usually changed on a monthly basis (Harry de Gorter, Drabik, & Just, 2015; H. de Gorter et al., 2013; McKay et al., 2015). This flexing strategy allows plants to improve their price risk management (Ferraz Dias de Moraes & Zilberman, 2014). On the contrary, *ethanol plants* – still about 100 in Brazil – can only produce hydrous and anhydrous ethanol. Therefore, one would expect different market responses of flex plants and ethanol plants. It is generally the case that flex plants prefer sugar production (for export) over hydrous ethanol production when global sugar prices are high (Valdes, 2011).

4.1.3 Domestic distribution

After deregulation of the market, government authorized *private distributors* have taken the role of distribution and blending. In fact, it is by law prohibited for processing plants to distribute fuels themselves (de Souza Siqueira Soares & Macchione Saes, 2014). Nowadays, there are about 200 authorized distributors nationwide. On their supply side, they negotiate with both plants to buy ethanol and with oil refineries to buy gasoline. According to the effective government blending mandate, they blend anhydrous ethanol with gasoline (27 % in 2016) into gasohol, which is subsequently traded with regional and local *retail agents*.

4.1.4 International trade of sugar and hydrous ethanol

The international trade in sugar and ethanol between the Brazilian market and other markets plays can have substantial impact on domestic market behavior.

Ethanol trade

For ethanol trade, between 90 and 97% of international ethanol trade is hydrous ethanol, which is – if required – generally distilled into anhydrous ethanol after import (Valdes, 2011). In 2009, Brazil was surpassed as the biggest exporter of hydrous ethanol by the United States. *Figure 9* shows how Brazilian ethanol exports have evolved over time. Export destinations for Brazilian ethanol have varied substantially over the years, as various new ethanol markets have arisen.

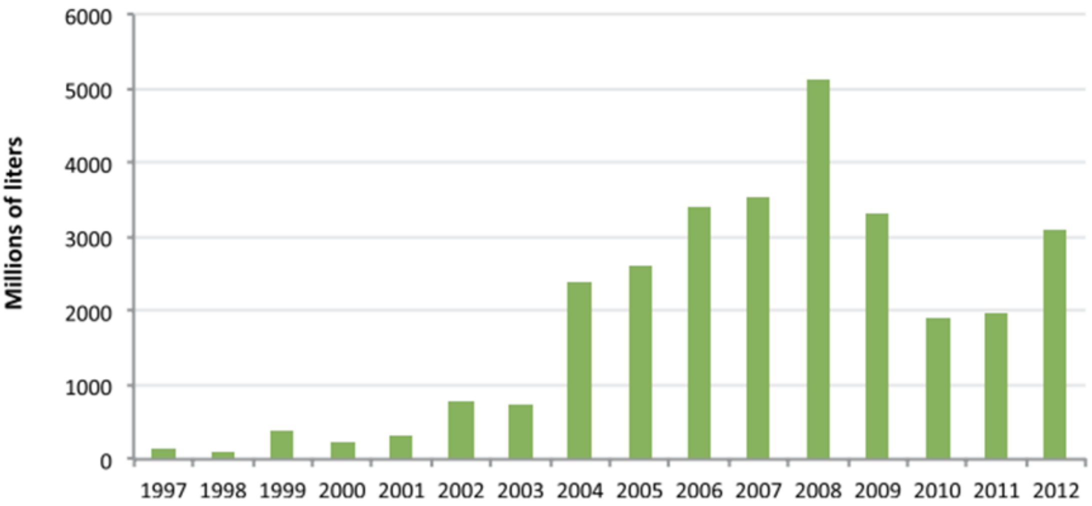


Figure 9: Brazilian ethanol exports between 1997 and 2012 (Ferraz Dias de Moraes & Zilberman, 2014)

In the 2014/2015 harvest year, main export destinations for hydrous ethanol were the United States, South Korea and Japan. Over 70 % of ethanol exports and imports are done through Santos Port in the state of São Paulo, as it has the largest infrastructures (pipelines, storage, and port facilities) (Valdes, 2011). On the contrary, ethanol imports have risen sharply from an average of 300000 liters in the period between 2004 and 2008, up to 3.1 million liters in 2009 and 22.2 million liters in 2010. With a share of 93 %, the U.S. has been the main supplier for Brazilian ethanol imports (Valdes, 2011). Although the U.S. and Brazil are the major producers and consumers in the world at the moment of writing this thesis, various researchers have indicated that the global ethanol market is expected to expand substantially in the near future (Sauer; Valdes, 2011). This directly related to the increasingly more stringent GHG reduction regulations worldwide.

Sugar trade

Brazil is also the biggest sugar producer and exporter in the world with at total market share of about 21 % – often referred to as 'the world's sugar bowl'. The main export destinations for Brazilian sugar in the 2014/2015 harvest year were China, Bangladesh and Algeria. Generally, flex plants choose to maximize their sugar production – and thus a reduction in ethanol production – with the intent to export (within the previously mentioned limits) if global sugar prices are high (Valdes, 2011). A phenomena that was one of the contributing factors in the decline of ethanol exports after 2008.

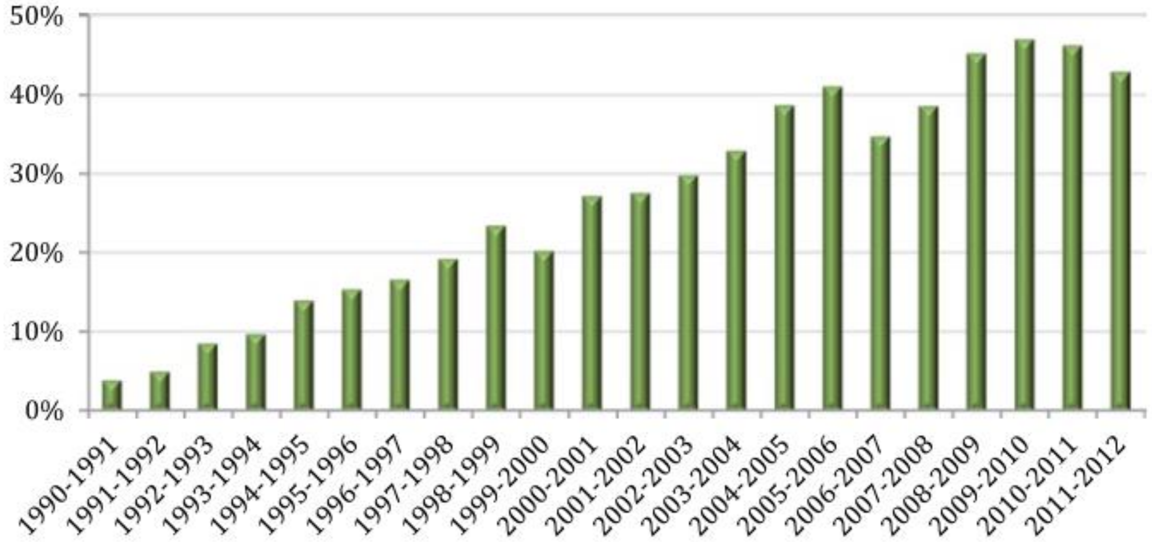


Figure 10: Brazilian share of the global sugar market between 1990 and 2012 (Ferraz Dias de Moraes & Zilberman, 2014)

International trade as a connector of markets

Trading streams have created a nexus between the Brazilian sugarcane market and other importing/exporting countries. For instance, it is generally seen that the domestic sugar and ethanol prices closely follow international sugar prices. Fuel and sugar exports are mainly done by *traders*, although some larger fuel distributors might be involved in trading hydrous ethanol as well (Valdes, 2011). Furthermore, Valdes (2011) indicates that export operations are highly diversified (in 2008 there were 153 registered exporters and 126 large firms responsible for 98 % of Brazil's ethanol exports). Traders can be seen as a mediating agent between the domestic market and foreign markets, while trying to make profits from price differences.

There are several major determinants for import and export flows. From the policy perspective, import and export tariffs are important assets to influence trading streams by adjusting the costs of imports and exports. Besides trading policies, transportation costs and exchange rates can largely influence cost-competitiveness of Brazilian ethanol in foreign markets (Crago, Khanna, Barton, Giuliani, & Amaral, 2010; H. de Gorter et al., 2013; Elobeid & Tokgoz, 2008; Valdes, 2011). For instance, Crago et al. (2010) indicates that at an exchange rate of US$ 1 = R$2.15, U.S. corn ethanol has a 15% lower price compared to Brazilian ethanol shipped to the U.S, even though Brazilian production price are lower.

4.1.5 Domestic consumers

The *car driver* market has experienced substantial change since the introduction of FFV's in 2003. Whereas drivers were previously 'locked in' to either hydrous ethanol or gasohol, depending on their type of car, FFV's provide car drivers the autonomous freedom to switch between hydrous ethanol and gasohol during every fill-up. Hence, FFV drivers have increased flexibility to fluctuations in fuel prices (H. de Gorter et al., 2013). As can be seen from *Figure 11*, the composition of car sales has changed tremendously over the years. Over 90% of cars sold in recent years are FFV's (Kaup, 2015). From a purely cost-benefit perspective, as a rule of thumb, FFV drivers will prefer hydrous ethanol over gasohol when the price difference is more than 30 % (Pacini, 2015; Pacini & Silveira, 2011; USDA, 2015a)). This is because hydrous ethanol gives lower mileage due to its lower energetic value. However, as both (Pacini & Silveira, 2011) and (Armbrust, 2014) have pointed out, car drivers' behavioral factors (such as individual fuel preference and inclination to switch fuels) make that there is no single dependent relation between fuel prices and demand.

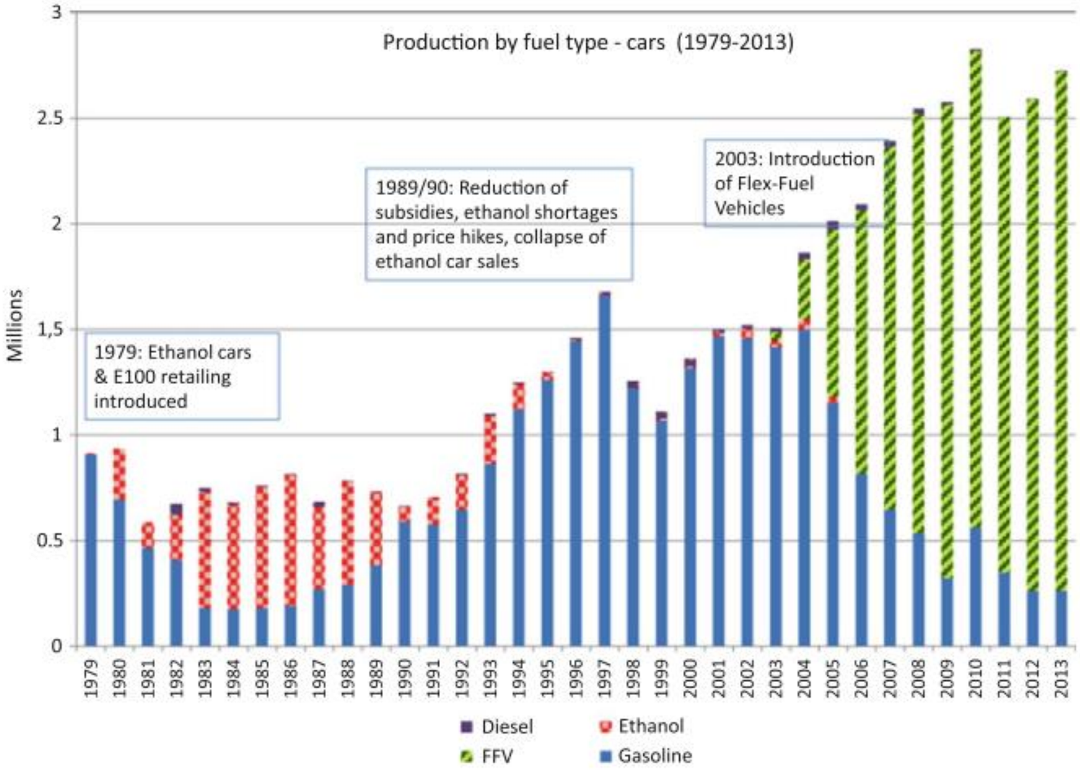


Figure 11: The composition of domestic car sales in Brazil over time since 1979

In contrast with hydrous ethanol imports, all *domestic sugar consumption* is met by domestic sugar production. Domestic sugar consumption summed about 11.3 million metric tons in 2014/2015, whereas sugar exports were about 18.3 million metric tons (USDA, 2015b).

Brazil has a fast growing *domestic aviation market*, which is the third biggest domestic market in the world by passengers carried. This is mainly a result of economic development. As can be seen from Figure 12, Brazilian domestic and international air travels grew 180% since 2002 and is expected to continue to grow with the country's economic development (Associação Brasileira das Empresas Aéreas, 2012).

Finally, the potential market for *biosuccinic acid* is substantial. As previously mentioned, succinic acid is a platform chemical with a wide variety of applications. Potential users of biosuccinic acid are food producers, pharmaceutical companies, cosmetic companies and a wide variety of industrial applications (AlliedMarketResearch, 2014).

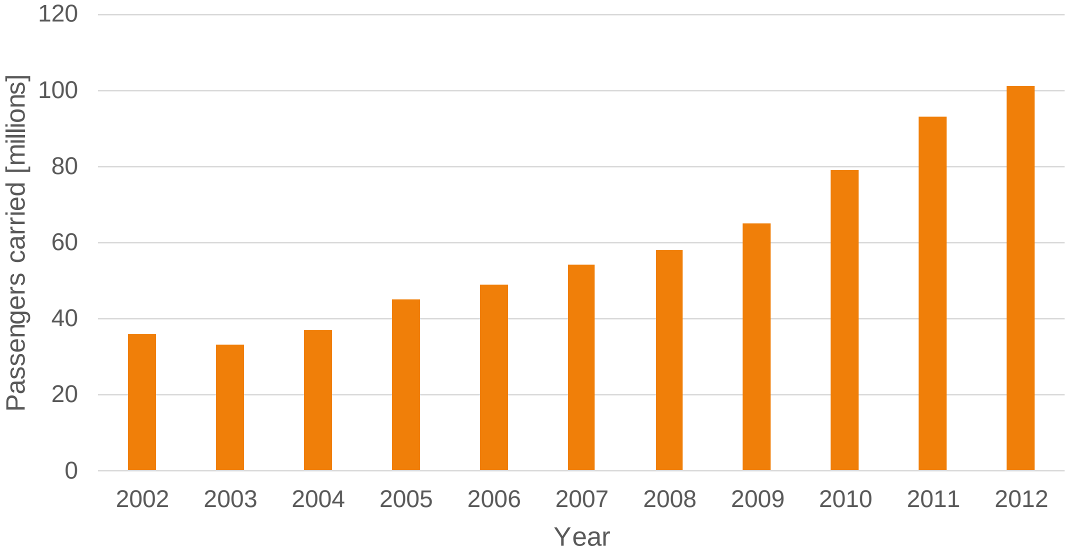


Figure 12: Passengers carried on domestic and international flights in Brazil (Associação Brasileira das Empresas Aéreas, 2012)

4.2 Institutional Analysis of the Sugarcane Market

4.2.1 Institutional environment: the formal rules of the game

As mentioned in chapter 1, the Brazilian sugarcane market experienced massive growth from the 1970s on due to very strong government control due to very strong government control (BNDES & CGEE, 2008; Nass et al., 2007; Soccol et al., 2005). Within the PróÁlcool program, initiated in 1975, a variety of policies were implemented with the aim to increase blending of gasoline with anhydrous ethanol, to be sold as gasohol ("or gasoline C") (Andrade & Miccolis, 2011; USDA, 2015a; Wilkinson & Herrera, 2010). These policies have been of major importance to the development and institutional change in the Brazilian sugarcane market and included both structure and conduct regulations. Market structure regulations included regulations such as the construction of ethanol distribution infrastructures and the construction and conversion of sugar mills (USDA, 2015a). In addition, a variety of market conduct regulations were used, such as financial incentives and loans, the blending mandate, fuel price controls and numerous tax credits and exemptions. With the deregulation of the market from the 1990s on, most PróÁlcool policies were abolished. Therefore, these are not incorporated in the succeeding analysis, as the major focus of this thesis is on the status quo in market regulation, rather than historical evolution of institutions (institutional change and reform). Nowadays, mainly conduct regulations are used to influence actors' behaviors, which are discussed in the following sections.

The blending mandate

The blending mandate dictates that no pure gasoline is allowed to be sold to any car driver in Brazil. The mandate specifies a fixed percentage of anhydrous ethanol that should be blended with gasoline by distributors (Sorda et al., 2010). Throughout the development of the market, altering the blending mandate has been one of the key policies to 'artificially' stimulate the demand of anhydrous ethanol. Whereas the blending mandate was 4.5% in 1977, it was increased over the years to reach 27% in 2016 (USDA, 2010). What is typically seen is that the government lowers the blending mandate when ethanol production is low (and prices high). Such increases in the blending mandate are always accompanied by technical studies to assess the impact on gasoline powered engines (due to the increased water content of gasohol) (USDA, 2010).

Gasoline prices

After deregulation of the oil industry in 1997, the Brazilian oil industry was no longer by law controlled by state-owned PETROBAS (Assunção, Pessoa, & Rezende, 2013). However, in practice, PETROBAS was still responsible for 96.6% of refining, 28.9% of distribution and 17.8% of retail in 2010 (ANP, 2010). As the government of Brazil is the largest shareholder in PETROBAS, it has a de facto monopoly over domestic gasoline prices at the refinery level and it uses this on a regular basis to influence domestic gasoline prices (Andrade & Miccolis, 2011; Ferraz Dias de Moraes & Zilberman, 2014). H. de Gorter et al. (2013) emphasize that through this domestic price regulation, gasoline prices are actually detached from world oil prices and thus naturally nearly eliminates gasoline price volatility (GTZ, 2008). Several researches have indicated the interrelation between gasoline prices and ethanol prices (e.g. (Ferraz Dias de Moraes & Zilberman, 2014; Serra, Zilberman, & Gil, 2011; USDA, 2015a)), showing that an increase of gasoline prices generally leads to an increase of ethanol prices. Then it follows that processing plants are in favor of higher gasoline prices. On the other hand, lower gasoline prices would increase gasohol consumption and decrease hydrous consumption (and price), decreasing profit margins for processing plants, urging some processing plants to export hydrous ethanol then foreign market prices are more favorable.

Domestic taxation

A complex taxation system that involves a variety of tax incentives are used to promote domestic ethanol consumption. These mainly focus on the promotion of (1) FFV adoption and (2) ethanol consumption. FFV adoption is promoted through lower taxes on FFV sales compared to gasoline powered cars FFV's. In 2015, both the aggregated fuel tax tariff and fix percentage tax showed a preferential treatment for ethanol consumption (USDA, 2015a). Aggregated tax for pure gasoline was 0.48 R$/l, whereas this was zero for hydrous ethanol. Furthermore, the fix percentage tax was 25% for gasoline, in contrast of 12% for hydrous ethanol.

Import and export tariffs

Import and export tariffs on hydrous ethanol can have substantial influence (besides the exchange rate and foreign hydrous ethanol price) on trading flows between the Brazilian sugarcane market and foreign ethanol markets. Ethanol exports seem to become increasingly important as the Brazilian government expresses its ambition to "transform ethanol into a freely traded global energy commodity" (USDA, 2010). The current import tariff for hydrous ethanol is set at 11.75%, and the export tariff was 20% in 2008 (Elobeid & Tokgoz, 2008).

Foreign market ethanol policies

The nexus between the Brazilian sugarcane market and foreign markets is – besides Brazilian import and export tariffs – also influenced by the developments in foreign markets' policies. Naturally, foreign markets also use import and export tariffs to influence domestic market behavior to some extent. In addition, policies of the Environmental Protection Agency (EPA) in the U.S. have had significant impact on U.S. ethanol demand. As will become clearer later, foreign policies are out of the scope of this research.

4.2.2 The Governance of Sugarcane Procurement

Vertical integration of sugarcane production

In section (4.1.1), it was explained that vertical integration accounts for about 60 % of total sugarcane production in the state of São Paulo and that processing plants predominantly rent lands from landowners for sugarcane production. TCE proves a valuable theory to analyze why vertical integration accounts for the majority of sugarcane production. First, the production of sugarcane involves highly specific machinery (physical specificity), that has little value for other agricultural purposes. In addition, it was stressed that the procurement of sugarcane involves a geographical restriction, often leading to a high concentration of sugarcane production and processing facilities in a certain region (site specificity). A unique characteristic of the Brazilian case is that the profitability of vertical integration largely depends on landowner lease rates, which on their turn are determined through the CONSECANA-SP system, as will be discussed in the next section.

CONSECANA-SP as governance of sugarcane transactions

Before deregulation, the government was heavily involved in sugarcane production through public and state-guaranteed loans and guaranteed remuneration of farmers (USDA, 2010). Yet, nowadays, the government does no longer set sugarcane prices. Instead, government involvement was replaced with a private pricing mechanism called CONSECANA-SP, which has been in effect since 1988 (Ferraz Dias de Moraes & Zilberman, 2014).

CONSECANA-SP is an initiative of both ORPLANA (the sugarcane growers association, to which most third party suppliers are connected) and UNICA (the sugarcane processing industry association, to which most processing plants are connected) and was created as a new sugarcane remuneration system. Furthermore, it provides minimum standards of interaction. The fundamental goal of CONSECANA-SP is to reduce the transaction costs of negotiations between third party suppliers and processing plants, and to share business risks, as both parties lack information about what the overall seasonal profitability of their activities will be. As depicted in *Figure 14*, the basic principle of the model is that the sugarcane prices paid to suppliers and land lease rates paid to landowners are based on the relative profitability of domestic and export sugar and ethanol sales.

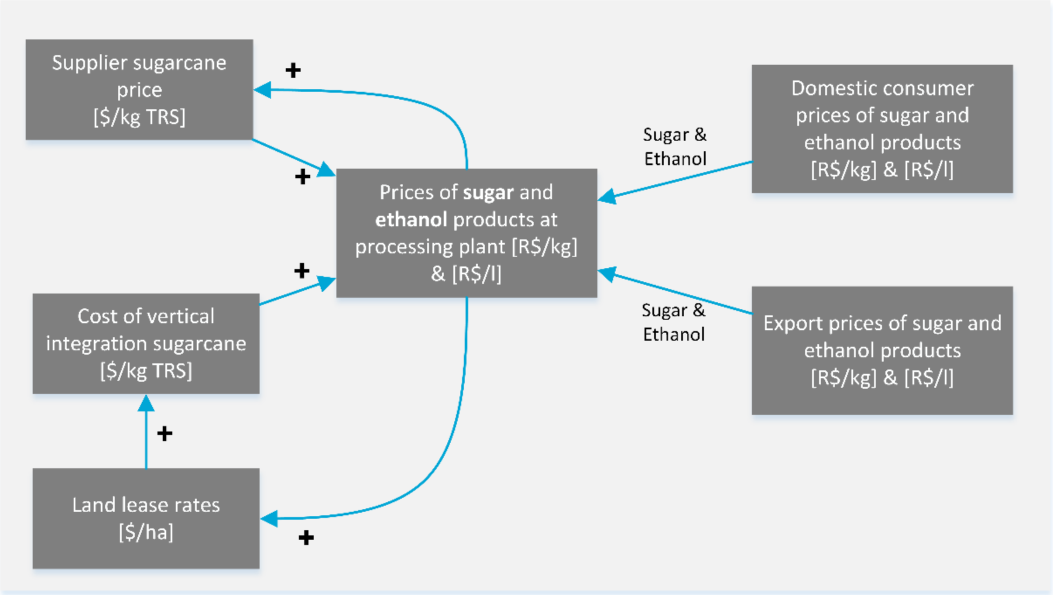


Figure 13: Sugarcane pricing market feedback through the CONSECANA-SP pricing mechanism

Due to the importance of the CONSECANA-SP mechanism in the succeeding conceptualization of the biorefinery model, the detailed principle of the model is explained here (*Figure 14*).

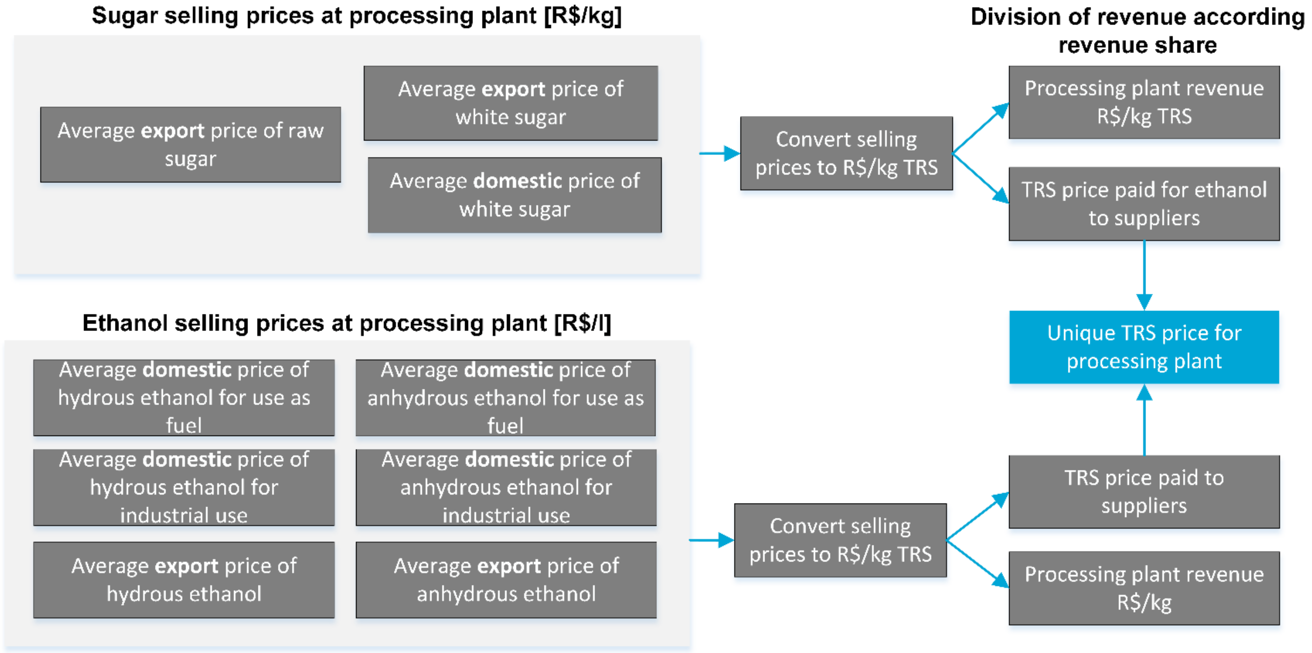


Figure 14: CONSECANA-SP pricing mechanism (CONSECANA-SP, 2006; Ferraz Dias de Moraes & Zilberman, 2014)

Through the CONSECANA-SP pricing mechanism, the base value of sugarcane is expressed by the Total amount of Recoverable Sugar (TRS) per ton of sugarcane. TRS expresses the sugar content that is used for sugar and ethanol production. In practice, this means that each truck of third party supplier sugarcane delivered to a processing plant, is checked on its TRS content through a series of tests. This is to establish how many kg of TRS is delivered. The remaining question is then; what is the price of 1 kg of TRS?

This price is linked to the average market selling prices of nine different products, over the period of one harvest season, as can be seen from *Figure 14*. These are the prices for which the processing plants sells the product to domestic distributors and trading houses. As an independent institute, the CEPEA (Center for Advanced Studies on Applied Economics) calculates, based on average industrial processing efficiencies, how much kilogram of TRS is required to produce 1 unit (kilogram or liters) of each of the nine products (for the specific conversion rates, please see APPENDIX II). This allows to convert the average selling prices (in R$/kg or R$/l) into R$/kg TRS. The CONSECANA-SP model then assumes that sugarcane accounts for 59.5% of the production costs of sugar, and accounts for 62.1% of ethanol production (CONSECANA-SP, 2006). Thus, remuneration to suppliers is done according to these percentages.

However, sugar sales and ethanol sales volumes obviously differ depending on the production ratios of processing facilities. Therefore, the TRS price is *unique* for each processing plant and based on weighing the product TRS price with the volumes of each product.

Implications of CONSECANA-SP for biorefinery investments

The CONSECANA-SP mechanism could have various implications for biorefinery investments, of which the most relevant ones are described here.

(1) CONSECANA-SP links sugarcane prices to the profitability of ethanol and sugar

Because TRS prices are based on sugar and ethanol prices, CONSECANA-SP directly links sugarcane prices to both the domestic and export selling prices of sugar and ethanol at the processing plant, meaning that any change in these selling prices is reflected to a somewhat equal change in sugarcane prices. This could create a major hurdle for the profitability of biojet fuel and biosuccinic acid production.

(2) Land lease rates are often based on TRS prices

Although the initial goal of CONSECANA-SP has been to govern the interactions and remuneration between third party suppliers and processing plants, TRS prices have also become the predominant component of land lease rates. Most lease rates are defined as a fixed percentage of the TRS price that the sugarcane produced on a landowners' land is worth (Sant'Anna, Bergtold, Caldas, & Grança, 2016). As such, CONSECANA-SP acts as a feedback mechanism, through which land lease rates are based on sugar and ethanol market prices. This feedback might partially explain the tremendous increases in land lease prices mentioned before.

(3) Supplier – biorefinery interactions might lead to increased transaction uncertainty

CONSECANA-SP has institutionalized most of the sugarcane transactions that take place in the sugarcane market. By doing so, it removed much of the transaction uncertainty of interactions between suppliers and processing plants. In that light, it seems unlikely interactions between suppliers, landowners and processing plants would remain the same in the case of biorefinery investments. For instance, it is unclear how the TRS price of a biorefinery could be determined, as the CONSECANA-SP mechanism does not yet include biojet fuel or biosuccinic acid in the TRS price calculation. Furthermore, if suppliers would have multiple processing plants in their area, they are in a stronger negotiation position and are likely to request at least the CONSECANA-SP TRS price for their sugarcane. Finally, the conversion of processing plant to biorefinery would involve substantial investment costs, which could endanger biorefineries' financial situations. In that light, suppliers and/or landowners may request an additional fee or guaranteed purchase to compensate for the higher transaction uncertainty.

(4) TRS prices could be favorable for 2G biojet fuel production

As aforementioned, TRS prices are only based on the sugar juice content of sugarcane, and not on its fiber content (bagasse). As was described in chapter 1, this bagasse is aimed to be used for 2G biojet fuel production in the HIP biorefinery concept. Hence, 2G biojet fuel production would not be linked to TRS prices and corresponding sugarcane prices. This may offer significant opportunities for the 2G bagasse-to-jet pathway included in this thesis. However, one must take into account that currently most processing plants use bagasse to produce electricity. Therefore, sugarcane trash would have to be used (and maybe other energy sources), to compensate for the lack of electricity production when bagasse would be used for 2G biojet fuel production instead of electricity.

4.3 Systems analysis

The observations made in the previous two sections are summarized in *Figure 15*. From this figure, it can be seen how the identified actors relate to the most important variables in the system. Furthermore, five subsystems are identified: (1) sugarcane procurement, (2) sugarcane processing, (3) road fuels distribution and pricing, (4) international trade, and (5) consumer markets. Moreover, the diagram depicts through which actors the key policies influence the main variables in the system. Dotted lines indicate interactions between actors, whereas solid lines indicate influences on variables.

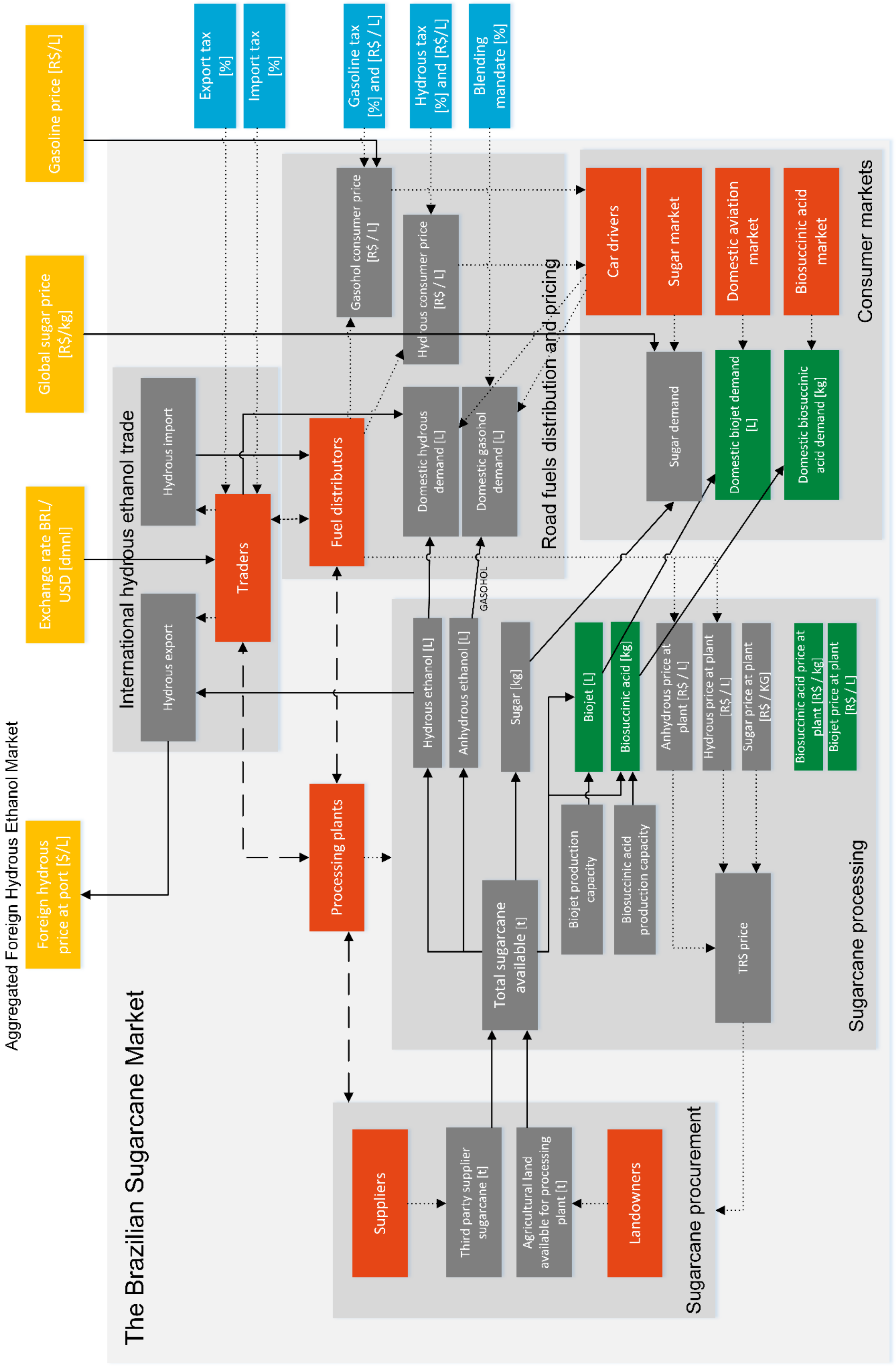


Figure 15: Systems analysis diagram of the Brazilian sugarcane market 🟧 Actors ◼ Key internal variables 🟩 Biorefinery variables of interest 🟦 Policy instruments 🟨 External variables

5

CONCEPTUALIZING THE BIOREFINERY MODEL

In the previous chapter, a systems analysis of the Brazilian sugarcane market was performed to identify the actors, key internal variables, policy instruments and external variables related to the key outcomes of interest. Based on these insights, this chapter presents the conceptualization of the Biorefinery model that was developed: an ABM model that can be used to simulate how the emergence of biojet fuel and biosuccinic acid production could emerge. This is done in three sections. First, the scope of the model, as well as the main assumptions are presented in section **(**5.1**)**. Within that context, the agents and their states and actions that were included in the model are summarized in a UML diagram (section **(**5.2**)**). Finally, a selection of most relevant actions are presented in section **(**5.3**)**. Please note that variables are written in `typewriter font` throughout this chapter.

5.1 Scoping the Biorefinery Model

From the previous systems analysis, it has become clear the Brazilian sugarcane system consists of a large variety of actors, policies and technologies. Yet, not all of these have to be included in the model's scope to answer the modelling question. Moreover, simply not everything can be included, as this would make the simulation too slow and complex to perform any meaningful analysis. Therefore, through the process of conceptualizing the agent based model, many boundary decisions and assumptions were made in order to develop a manageable simulation model. In this section, scoping considerations for each subsystem are discussed as well as the main assumptions. These are also presented at the end of each section in two summarizing tables. Some scoping decisions and key assumptions are also reflected on and questioned in a sensitivity analysis and meta-analysis in section **(**6.5**)**.

Sugarcane procurement and pricing: supplier contract negotiations are key

As aforementioned, suppliers and landowners are important actors in explaining the dynamics of sugarcane procurement. Yet, landowners were excluded from the model scope for several reasons. First, whereas supply contracts between suppliers and processing plants can change on a yearly basis, land lease contracts generally have a duration of at least 6 years (and are often extended to 12 years), which is the length of one full growth cycle (Sant'Anna et al., 2016). Therefore, it would be expected that less dynamics could be observed between processing plants and landowners as is the case between processing plants and suppliers. In particular when one takes into account the high site specificity and physical asset specificity of sugarcane growing. In that light, the creation and cancellation of contracts between landowners and processing plants were omitted from the model scope. Nevertheless, landowners are still included in the model as "semi-agents", which means that they have few internal states but cannot perform any action to change these states. This was done for two main reasons. First, it was convenient to include them for the distribution of land and clear visual separation between supplier sugarcane and sugarcane grown by plants on leased land. Second, as is described later in this thesis, a scenario was included in the model that allows to simulate how landowners would relate to the emergence of biorefineries if they would have variable contracts. However, by default landowners are connected to the same processing plant during the length of a simulation.

On the contrary, the interactions between suppliers and processing plants were modelled in great detail. This is in line with the observations that were made about the CONSECANA-SP system and its possible implications for the diffusion of biorefinery investments. Namely, it was argued that biorefineries might have to pay a higher TRS price to suppliers, to compensate for the increased transaction uncertainty that could result from a plant's transformation into a biorefinery. Furthermore, it was seen that CONSECANA-SP creates a direct link between the price of sugarcane paid to suppliers and the market selling prices of sugar and ethanol products. This calls for the inclusion of suppliers into studying sugarcane procurement dynamics. This is a different approach as chosen in the biojet model by (Armbrust, 2014), in which sugarcane supply was made an exogenous, constant variable that is equal to total sugarcane demand by processing plants (or: refineries in the biojet model). Therefore, sugarcane procurement nor pricing was not made a limiting constraint for the production of biojet fuel. However, in light of the research objective of studying sugarcane competition, such *sugarcane procurement and pricing dynamics are key*.

Therefore, a conceptualization was made to describe the annual supply contract negotiations between processing plants and suppliers. In this conceptualization, several key assumptions were made. First, it is assumed that there is a fixed total quantity of agricultural land used for sugarcane in the state of São Paulo. This seems reasonable, as multiple authors as well as expert Marcelo Pierossi have indicated that that the sugarcane market in São Paulo is highly saturated and expansion of sugarcane production mainly takes place nearby states. The total amount of land included in the model is assigned to suppliers as well as landowners, and this distribution will be made variable. Because this land is specifically used for sugarcane, suppliers nor processing plants that lease land can switch to other crops than sugarcane. This also seems unrealistic, given the high asset specificity of sugarcane growing and the fact that they are attached to a minimum of a 6 year growth cycle. By default 40% of the total land is assigned to suppliers and 60% to landowners. It should be noted that the quantity of assigned land is equal for individual suppliers or landowners, as scale differences among them are not of particular interest. On the contrary, focus is on the distribution of land between landowners and suppliers and how this relates to the average sugarcane price that is paid by each processing plants. Furthermore, it is assumed that all suppliers are a member as the vast majority of suppliers is (source: Marcelo Pierossi). This also means that the base price for sugarcane contracts is based on the TRS price of the specific processing plant. Finally, since key focus is on the allocation and the price of sugarcane, detailed logistics from supplier to processing plants (such as time of delivery) were omitted from the model scope. Instead, to simulate the distribution of sugarcane delivery quantities over the length of a harvest season, a normal distribution was used, as is described later.

Table 2: Main scoping considerations for sugarcane procurement

Main scoping considerations for sugarcane procurement

- Key focus is on supply contracts between suppliers and processing plants.
- Landowners are included as “semi-agents” to support the model’s working, but do not have any actions.
- Logistic specifics, such as moments of sugarcane delivery, are omitted from the model scope. Instead, a normal distribution was used to approach the seasonality of sugarcane production.

Table 3: Main scoping assumptions for sugarcane procurement

Main assumptions for sugarcane procurement

- There is a fixed total quantity of agricultural land used for sugarcane in the state of São Paulo.
- Processing plants do not own land.
- About 40 % (can be adjusted through the vertical integration rate, 40 % in the base scenario) of the total land is equally assigned to the suppliers.
- About 60 % (can be adjusted through the vertical integration rate, 60 % in the base scenario) of the land is equally assigned to the landowners.
- Both suppliers and landowners own their land over the entire simulation time.
- Suppliers nor landowners can switch to other crops than sugarcane.
- Suppliers sell all their sugarcane at once to a specific processing plants; they can only have one supply contract per season.
- The production costs of sugarcane grown by suppliers are not included. These costs are always present, regardless of with whom a contract is made.
- All suppliers are member of CONSECANA-SP, and therefore the base price for sugarcane is based on the TRS price of the processing plant.

Sugarcane processing: creating production dynamics

As became clear from the systems analysis in the previous chapter, processing plants play a central role in the competitive allocation of sugarcane for each product. This is done at two different dimensions. First, processing plants actively participate in sugarcane growing activities with the intend to maximize their sugarcane supply, considering that about 60% of the sugarcane produced in São Paulo is produced by processing plants by use of a vertical integration strategy. Second, it was discussed that flexing strategies allow plants to alter the amount of sugarcane used for sugar or ethanol production in response to changing market prices. In that light, it is desired to include processing plants in the conceptualization and develop a mechanism to describe strategic production decisions by processing plants. Based on the insights and biojet model that were developed by (Armbrust, 2014), the conceptualization of production dynamics were adopted from (Armbrust, 2014). For an extensive conceptualization of the sugarcane processing mechanism and motivation for its assumptions, one is referred to (Armbrust, 2014). Although the processing plant decision and production logic was largely adopted, several adjustments were made. First, whereas the biojet model only consists of flex plants, also ethanol plants were included in the biorefinery model. This was done because of the author's expectation that ethanol plants might give different dynamics to biorefinery investments and production. Second, sugarcane management was included in the production logic, to accommodate for the dynamics in sugarcane procurement and sugarcane supply distribution over the length of a harvest season. Furthermore, the production decision logic was extended with decision making rules for the production of biosuccinic acid and biojet fuel. Finally, a detailed investment mechanism was developed to simulate how the installed capacity of biojet fuel and biosuccinic acid production could evolve over time. This was deemed necessary to allow for the simulation of how processing plants could make biorefinery investment decisions, based on the average sugarcane price and profitability of biojet fuel and biosuccinic acid. Although it is advisable to for the reader to consult (Armbrust, 2014) for an extensive documentation of the assumptions in the production logic, the key assumptions are mentioned here for conceptual completeness and to assess whether they are still realistic within the scope of the biorefinery model.

First, processing plants do not have economies of scale. In reality, chemical conversion processes used in processing plants can have different economics depending on the quantity of sugarcane processed. Nevertheless, economies of scale effects were omitted from the model scope as these add a level of detail that is not deemed necessary to achieve the research objective. Namely, the key focus in the sugarcane processing subsystem is the allocation of sugarcane for each product, and not to optimize allocation taking into account economies of scale effects.

The second assumption concerns the sugarcane crushing capacity of processing plants. Crushing capacity relates to the first shared "crushing" step of sugar and ethanol production. Both sugar and ethanol production lines do have a limited production capacity which is between the previously mentioned production split of 40% and 60% of total crushed sugarcane. Although not explained in (Armbrust, 2014), processing plants have unlimited crushing capacity in the biojet model. This seems logical, as sugarcane supply was exogenous as well. In the biorefinery model, however, sugarcane supply was made endogenous, and thus it was reviewed whether the sugarcane crushing capacity still holds in the biorefinery model. The outcome of this review is that sugarcane crushing capacities of processing plants are assumed to be about equal to the amount of sugarcane grown in their catching radius. This implies that the crushing capacity is nor unlimited nor is it a limitation in sugarcane procurement. This assumption was made for several reasons. First, considering the geographical production clusters that have shaped over time in the sugarcane market, it seems unrealistic that a supplier would be located within the catching radius of a processing plant, if that particular plant would not have the crushing capacity to crush this sugarcane. Second, since in light of the observed highly saturated sugarcane market in the state of São Paulo, it was assumed that there are no entries or exits of processing plants. Therefore, all plants in the biorefinery model should have sufficient crushing capacity to crush the total amount of available sugarcane.

Table 4: Main scoping considerations for sugarcane processing (partially based on (Armbrust, 2014))

Main scoping considerations for sugarcane processing
• Production decisions by processing plants are based on profit estimations. • Processing plants have an investment mechanism to evaluate and decide for biorefinery investments. • Both flex plants and ethanol plants are included.

Table 5: Main assumptions for sugarcane processing (partially based on (Armbrust, 2014))

Main assumptions for sugarcane processing

- Plants have no knowledge about the production decisions of other plants; they have bounded rationality and can only respond to market prices at the aggregate market level.
- Sugarcane supply to a processing plant is distributed over the harvest season by a normal distribution.
- Plants have unlimited sugarcane crushing capacity, but do have restrictions on the amount of sugarcane that can be processed into each products.
- Plants do not have economies of scale; although production costs are unique for every plant, they remain constant regardless of production quantities.
- Plants always sell all their production.
- Plants have sufficient capital for biorefinery investments.

Road fuel pricing: matching supply and demand

In the preceding analysis of the car driver market in chapter 4, it was seen that car drivers generally base their fuel consumption decision on the price difference between hydrous ethanol and gasohol. The dynamics in these fuel prices are complex and difficult to simulate. Yet, if fuel consumption dynamics are to be included, it is imperative to include the pricing dynamics to which they influence and to which they respond. In that light, Armbrust (2014) developed a fuel pricing mechanism based on the principle of matching fuel supply and demand. This mechanism includes fuel distributors who are the price setters in the model; they determine the fuel price increment to the production prices of processing plants. By doing so, they can incentivize processing plants to increase the production of hydrous or anhydrous ethanol if the production of that particular fuel would be low. This mechanism was largely adopted in the biorefinery model, although several adjustments were made. As with the production decision logic, for an extensive explanation and justification for the mechanism, one is referred to (Armbrust, 2014).

Table 6: Main scoping considerations for road fuel distribution and pricing (partially based on (Armbrust, 2014))

Main scoping considerations for road fuel distribution

- Only the distribution of road fuels is modelled in detail.
- Distributors are responsible for all steps between sales at the plant and sales to car drivers.

Table 7: Main assumptions for road fuel distribution and pricing (partially based on (Armbrust, 2014))

Main assumptions for road fuel distribution

- There is no competition among distributors for fuel; total fuel supply (domestic production as well as imports) is equally distributed over the distributors.

- Distributors are focused on matching supply and demand and use pricing changes to achieve this goal, rather than profit maximizing.

International hydrous ethanol trade: connecting markets

In light of the research objective and the analysis performed in chapter 4, a mechanism was conceptualized to study the effects of international hydrous ethanol trade on the production and price levels in the Brazilian sugarcane market. As aforementioned, only international hydrous ethanol trade was studied, as this represents between 90 and 97% of ethanol trade (Valdes, 2011).

The key scoping decision regarding international hydrous trade was whether to model the foreign market endogenous or exogenous. Endogenous modelling might allow to simulate the effect of imports and exports on the foreign market price level and demand. In that case, the foreign market would need a pricing mechanism (perhaps similar to the domestic fuel distribution and pricing mechanism) as well as a demand mechanism to simulate how foreign demand would change in relation to the foreign hydrous price. However, in the biorefinery model, the foreign market was modelled exogenously for several reasons. First, in line with the research objective it is not of interest to study in detail the market dynamics in the foreign hydrous market. In fact, if one was to study those dynamics, it would likely be necessary to model the foreign market in the same level of detail as the Brazilian market, for it to generate meaningful outcomes. Furthermore, the key focus in the scope of this research is on the emergence of biojet fuel and biosuccinic acid production in the Brazilian market.

In that light, it was decided to model the foreign market as a semi-agent, which is representative of all aggregated foreign hydrous ethanol market. The hydrous ethanol price of this foreign market is then assigned as an external variable. Thus, it is assumed that foreign supply and demand are reflected in the foreign hydrous ethanol price at the foreign port. As a reference for shipping costs, the ethanol shipping costs from the U.S. to Brazil were used as an approximation. This seems valid as the U.S. is by far the biggest ethanol trading partner of Brazil. Another *trader agent* was conceptualized, which is the linking agent between the Brazilian market and foreign market. The trader has both an import and export mechanism, by which it imports or exports based on the price difference between the Brazilian hydrous ethanol price and foreign hydrous ethanol price, taking into account the exchange rates, import and export tariffs and logistics costs.

Table 8: Main scoping considerations for international hydrous ethanol trade

Main scoping considerations for international hydrous ethanol trade
• Foreign demand and supply and demand is not modelled, but reflected in the foreign hydrous ethanol price at the port. • All international hydrous trade is done by traders; plants or distributors cannot do international trade. • The foreign hydrous price is expressed in US Dollar ($), whereas all other prices in the model are expressed in Brazilian Real (R$).

Table 9: Main assumptions for international hydrous ethanol trade

Main assumptions for international hydrous ethanol trade
• Transportation costs to the U.S. are used as an approximation of foreign logistic costs. • Due to the volatility of exchange rates, the exchange rate used is based on a 5 year average between 2010 and 2015.

Consumer markets

From the proceeding systems analysis, it was seen that there are five consumer markets of interest in the Brazilian sugarcane market. Although all of these were included in the Biorefinery model, they are modelled in different levels of detail. Both car drivers as well as the two domestic airports are modelled as endogenous agents with their own states and actions.

The domestic fuel consumption was chosen to be modelled in high detail, in order to simulate the effect of fuel consumption dynamics on production decisions and market prices. For this purpose, the domestic car driver mechanism developed by (Armbrust, 2014) was entirely adopted in the biorefinery model. This mechanism allows to simulate the dynamics of car drivers' fuel demand. The switching behavior of car drivers is known to have significant impact on pricing and production dynamics, as most car drivers drive FFV's and thus have the ability to switch between gasohol and hydrous ethanol during every fill-up. For an extensive explanation and justification for the car driver mechanism, one is referred to (Armbrust, 2014). Domestic aviation was included through two airport semi-agents: Gaurulhos airport in São Paulo and Galeão airport in Rio de Janeiro, as aligned with the HIP project (BE-Basic Foundation, 2016). These airports have a fixed biojet fuel demand.

The remaining three markets: the sugar market, biosuccinic acid market and foreign hydrous ethanol market were modelled as "semi agents". Therefore, these markets only have few states and no actions through which they can influence these states. The domestic and foreign sugar market were modelled exogenously. This means that the global sugar price was chosen to implicitly reflect changes in sugar demand. This was considered to sufficiently express the influence of sugar prices on the processing plant's production decisions. Furthermore, the biosuccinic acid market was not modelled in detail and is only included through the biosuccinic acid price and demand. This was found sufficient within the research scope. Namely, focus is on the price level and demand at which biosuccinic acid production may emerge, and not changes in its market prices once a market would be established.

5.2 Agents, states and actions in the model

Figure 16 presents the UML diagram of all elements that were included in the biorefinery model, following the scoping and assumptions. As can be seen from the figure, a distinction is made between agents (active objects), semi-agents, passive objects and agent roles. In line with the conceptual model for analysis, agents are assigned a number of states as well as actions by which they can influence these states. Please note that for illustration purposes only the most important states and actions are mentioned in the UML. For a complete glossary of all variables in the model, one is referred to APPENDIX II.

As can be seen from the figure, both suppliers and processing plants can fulfill the role of sugarcane producer. Furthermore, a multitude of agents, representing different consumer markets can fulfill the role of consumer. As becomes clear from the UML, sugarcane is procured through negotiations with suppliers as well as through vertically integrated production. Then, sugarcane is processed into products by the processing plant, which owns a certain production technology. This production technology expresses what products a plant can produce. For instance, an ethanol plant does not own the production technology needed for sugar production. Production quantities depend on the production decisions of plants and the yields of its production technology. Processing plants have more actions than any other agents: five actions in total. Processing plants sell their products to distributors and traders, depending on which of the two agents can offer the highest price for its products. In the case of the distributor, gasohol (after blending) and hydrous ethanol are distributed to its connected car drivers. Traders will export hydrous ethanol from the processing plants if they can make profits. On the contrary, they can also import hydrous ethanol from the foreign market.

Sugarcane suppliers

The suppliers that were observed in the actor identification are adopted as agents in the biorefinery model. These suppliers have a certain quantity of `third party supplier land`, on which they produce `third party supplier sugarcane` every year, which they try to sell to processing plants close by after negotiation. The selection of the buying processing plant is done through the action "`negotiate third party supplier sugarcane contracts`", in joint participation of processing plants. Thus, suppliers only interact with processing plants. To reflect the aforementioned variation in production yields, each third party supplier has a random `sugarcane yield` and `TRS yield`.

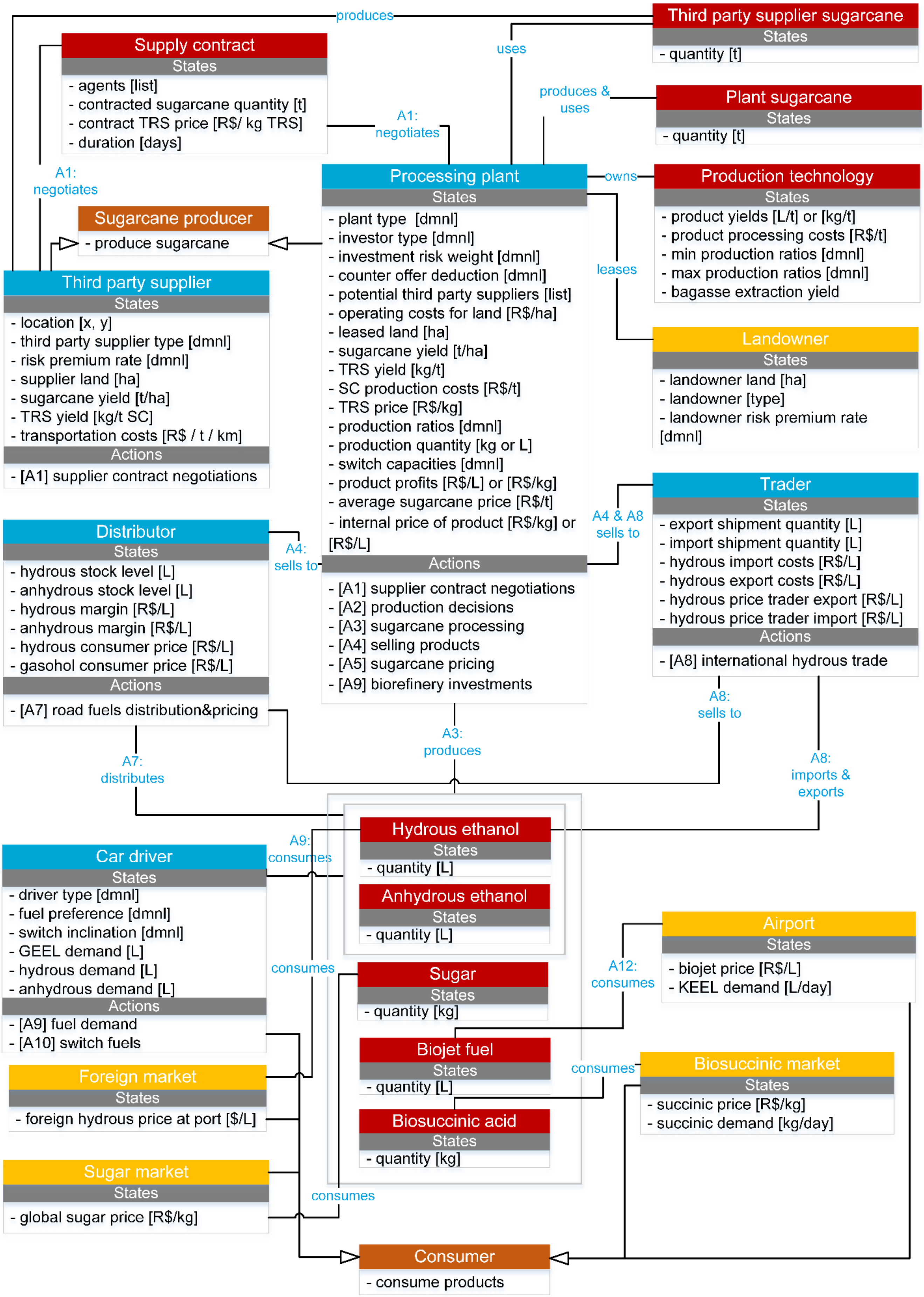


Figure 16: UML diagram illustrating the ontologies for 🟦 Agents 🟨 Semi-agents 🟥 Passive objects

🟧 Agent roles

Processing plants

The processing plant agents have the most extensive set of states and actions and are responsible for processing sugarcane into sugar, hydrous/anhydrous ethanol, biojet fuel and biosuccinic acid. Production quantities of each product depend on two main factors: the profitability of each product and the plant's production technologies, which are expressed through its `plant type`. As depicted in *Table 10*, four different plant types are included in the model, which express the different production technologies. It should be mentioned that a biorefinery does not necessarily have both 1G biojet fuel, 2G biojet fuel and biosuccinic acid production technology. Investment in each separate technology is done through the investment action described later.

Table 10: Plant types

Plant type	**Production technologies**		
	Sugar	Ethanol	Biojet/biosuccinic acid
1: "Ethanol plant"	No	Yes	No
2: "Flex plant"	Yes	Yes	No
3: "Partial Biorefinery"	No	Yes	Yes
4: "Full biorefinery"	Yes	Yes	Yes

Furthermore, each plant has individual yields for each of its production technologies (randomized around an average value). Finally, through the action "`plant market reaction`" plants adjust the quantity of sugarcane used for each product by adjusting the `sugar ratio`, `ethanol ratio`, `hydrous ratio`, `anhydrous ratio`, `succinic ratio` and `first generation biojet ratio`. Processing plants interact with a range of different agents: third party suppliers, distributors, traders and the external sugar market and biosuccinic acid market.

Distributors

As aforementioned, the domestic distributor mechanism developed by (Armbrust, 2014) was largely adopted in the biorefinery model, as the mechanism allows to model the dynamics in domestic fuel demand, which is a large determinant for overall system behavior. The conceptualization of this mechanism is briefly discussed here. For an extensive explanation and justification for the mechanism, one is referred to (Armbrust, 2014). The core activity of distributors is to balance domestic ethanol supply (from the processing plants and traders) and domestic demand for ethanol (by car drivers), as well as blending the anhydrous ethanol with gasoline into gasohol according to the effective blending mandate.

5.3 Actions in more detail – creating dynamics

In the previous section, the agents included in the model were introduced as well as their states. In this section, the actions through which the states can be changed are described in more detail. Due to the large number of actions in the model, only the most important ones are described extensively. For the actions not described in this chapter, a description is given in APPENDIX I. *Table 11* presents a brief overview of all actions in the model. Because the biorefinery base model and the biorefinery model are discussed in an integrated approach, specific biorefinery elements are mentioned in green throughout this section. Please note that the numbering of actions does not necessary imply a certain chronology; the actions are numbered for structuring purposes.

Table 11: Brief overview of actions in the model ■ described in this section, others are described in APPENDIX I

Action	Belongs to	Description
[A1]: supplier contracts negotiations	Plants and suppliers	Used to simulate annual sugarcane supply contract negotiations between plants and suppliers.
[A2]: production decisions	Plants	Used to simulate how plants change the amount of sugarcane used for each product in response to changes in market prices.
[A3]: sugarcane processing	Plants	Used to simulate sugarcane processing into products, taking into account the plant's production yields and decisions.
[A4]: selling products	Plants	Used to simulate sales between plants and distributors and between plants and traders, depending on the selling prices.
[A5]: sugarcane pricing	Plants	Used to simulate the pricing of sugarcane, taking into account the CONSECANA-SP system for the calculation of the TRS price, as well as the sugarcane mix (supplier or landowner).
[A6]: biorefinery investments	Plants	Used to simulate how plants could assess and decide on biorefinery investments.
[A7]: road fuels distribution & pricing	Distributors	Used to simulate the distribution and blending of fuels, as well as variations in market prices in response to supply and demand dynamics.
[A8]: international hydrous trade	Traders	Used to simulate imports and exports of hydrous ethanol, as a result of changes in foreign and domestic prices, import and export taxes and the currency exchange rate.
[A9]: fuel demand	Car drivers	Used to simulate the real fuel demand of car drivers, depending on their car driver type and daily GEEL demand.
[A10]: switch fuels	Car drivers	Used to simulate the dynamics in car driver fuel consumption, as a result of changes in market prices and personal characteristics such as fuel preference.

Action 1 [A1]: Supplier contracts negotiations

The yearly negotiations for supply contracts between suppliers and processing plants were conceptualized in accordance with the observed production clusters. As shown in *Figure 17*, each processing-plant is given a catching area, which is demarcated by the `catching radius`. Therefore, processing plants can only negotiate with suppliers that are located within the catching area. Naturally, suppliers which are located in the catching area of multiple processing plants, have more bargaining power as they can supply to more than one plant. To make an approximation for this kind of market density, the `inter cluster distance` variable can be used to simulate the relative distance between processing plants.

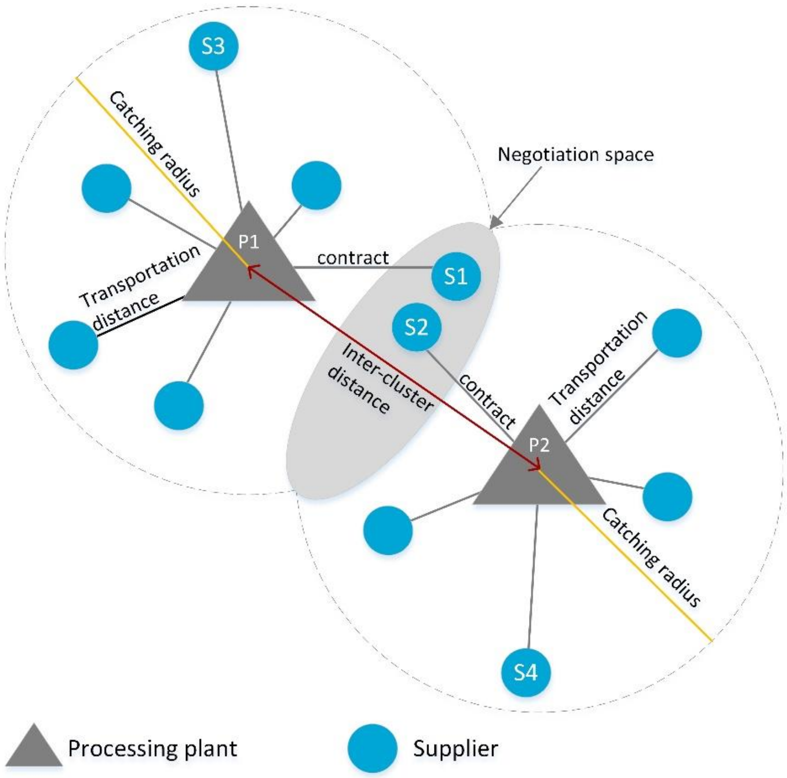


Figure 17: Spatial conceptualization of sugarcane sourcing from suppliers

An action was developed to simulate how such negotiations take place. An IDEF0 process diagram of this action is depicted in *Figure 19*. Furthermore, *Figure 18* provides guidance on how to read the IDEF0 diagrams used throughout this section.

Reading the IDEF0 diagrams

IDEF0 is a commonly used standardized method for modelling and structuring processes.

In this thesis, IDEF0 was applied in the following manner:

- Each complete IDEF0 diagram represents one action (e.g. A1).
- Each box represents a sub-process within that action (e.g. A1.1).
- *The inputs:* these variables are transformed into outputs by the sub-process.
- *The controls:* are the variables that control the sub-process and shape the outputs.
- *The outputs:* the output variables of the sub-process, which can also be an input for the next sub-process.
- *The mechanisms:* are the agents that carry out the sub-process.

Figure 18: Reading the IDEF0 diagrams (IBM, 2016)

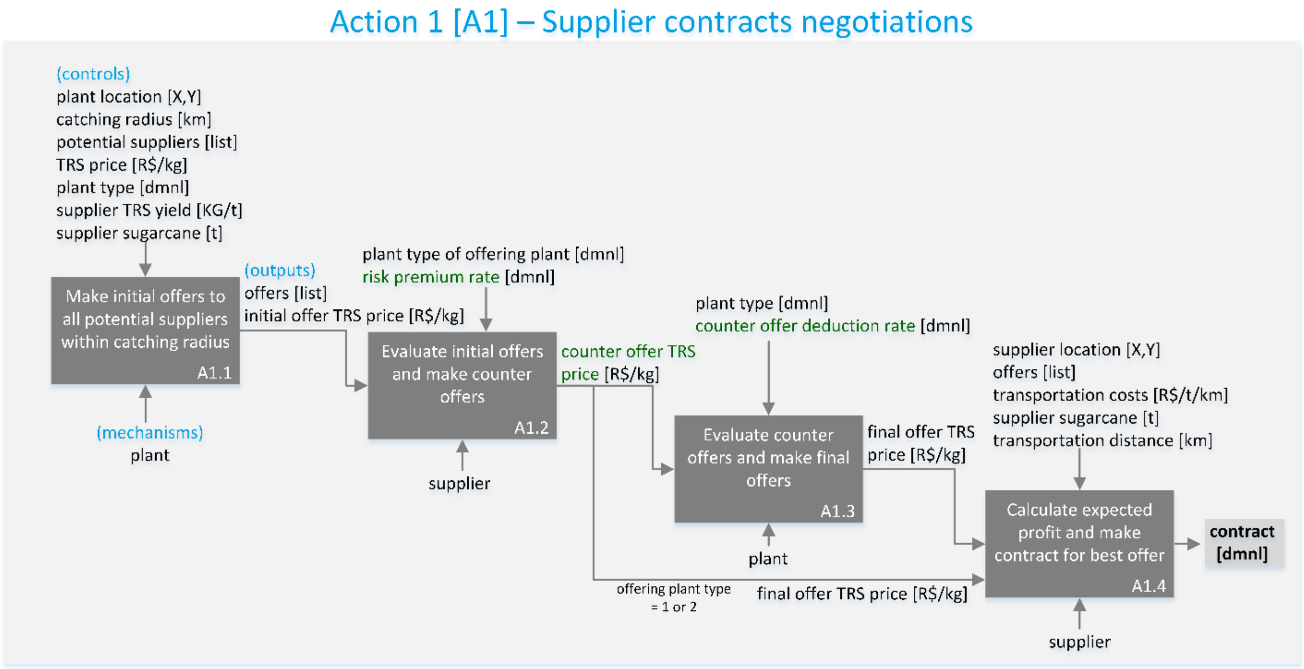


Figure 19: IDEF0 process steps in action 1 [A1] - supplier contracts negotiations

As can be seen from *Figure 19*, the negotiation process is divided in four steps.

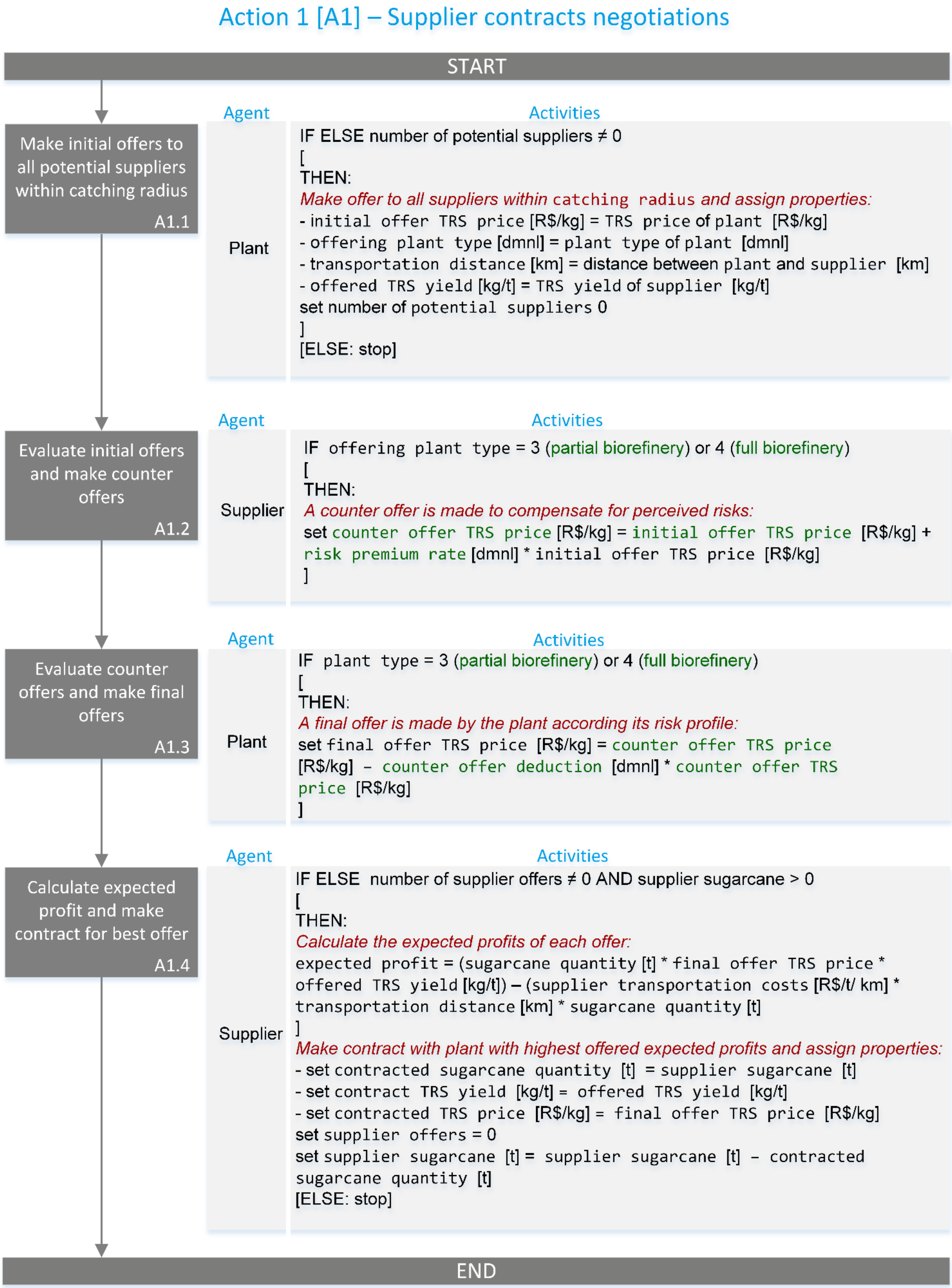
The activities carried out in each of these steps is provided in more detail in pseudo-code in *Figure 20*. The working of action 1 is as follows. At the start of each season, each plant makes an `offer` to all suppliers located within its `catching radius` (these are the `potential suppliers`) (A1.1). Such offers contains the `initial offer TRS price`, which is equal to the plant's own `TRS price`. This `TRS price` is the bottom price the plant has to pay through the CONSECANA-SP agreement. Then, each supplier evaluates the initial offers and makes a counter offer only if the `offering plant` is a biorefinery (`plant type` = 3 or 4) (A1.2). Through such a counter offer, the supplier attempts to account for the perceived risk of supplying to a biorefinery. Such risk perceptions, however, are not homogeneous among agents. Instead, suppliers can have different risk attitudes. To account for this heterogeneity, a distinction was made between three types of suppliers and processing plants: (1) risk avoidant, (2) standard, and (3) risk seeker (*Table 12*). With the definition of different supplier and processing plant types, a somewhat similar approach was chosen as done by (Kostadinov, Holm, Steubing, Thees, & Lemm, 2014). Depending on the risk attitude of the supplier, it increases the `initial offer TRS price` with the `risk premium rate`, which is then send to the offering plant as the `counter offer TRS price`.

Table 12: Supplier and processing plant risk attitudes and corresponding risk premium rate/counter offer deduction rate

Supplier or plant risk attitude [dmnl]	Risk premium rate [dmnl]	Counter offer deduction rate [dmnl]
1: risk avoidant	0.3	0.05
2: standard risk attitude	0.2	0.075
3: risk seeker	0.1	0.10

Subsequently, the biorefinery can make a `final offer` to the supplier, which is the `counter offer TRS price`, corrected with the `counter offer deduction rate`. As is the case with the suppliers, plants use this deduction rate to account for the perceived risks.

After all final offers have been made, each supplier makes a final decision about which plant to supply to, based on an expected profit calculation. The expected profit is based on the `final offer TRS price` and the `transportation costs`. As mentioned in Chapter **(**4**)**, suppliers are responsible for sugarcane transportation to the processing plant (unless individual agreements are made with the processing plant, however it is assumed that suppliers are always responsible for transportation). Therefore, `transportation costs` are taken into account into the expected profit calculation.



Action 1 [A1] – Supplier contracts negotiations

START

A1.1 Make initial offers to all potential suppliers within catching radius

Agent: Plant

```
IF ELSE number of potential suppliers ≠ 0
[
THEN:
Make offer to all suppliers within catching radius and assign properties:
- initial offer TRS price [R$/kg] = TRS price of plant [R$/kg]
- offering plant type [dmnl] = plant type of plant [dmnl]
- transportation distance [km] = distance between plant and supplier [km]
- offered TRS yield [kg/t] = TRS yield of supplier [kg/t]
set number of potential suppliers 0
]
[ELSE: stop]
```

A1.2 Evaluate initial offers and make counter offers

Agent: Supplier

```
IF offering plant type = 3 (partial biorefinery) or 4 (full biorefinery)
[
THEN:
A counter offer is made to compensate for perceived risks:
set counter offer TRS price [R$/kg] = initial offer TRS price [R$/kg] +
risk premium rate [dmnl] * initial offer TRS price [R$/kg]
]
```

A1.3 Evaluate counter offers and make final offers

Agent: Plant

```
IF plant type = 3 (partial biorefinery) or 4 (full biorefinery)
[
THEN:
A final offer is made by the plant according its risk profile:
set final offer TRS price [R$/kg] = counter offer TRS price
[R$/kg] – counter offer deduction [dmnl] * counter offer TRS
price [R$/kg]
]
```

A1.4 Calculate expected profit and make contract for best offer

Agent: Supplier

```
IF ELSE number of supplier offers ≠ 0 AND supplier sugarcane > 0
[
THEN:
Calculate the expected profits of each offer:
expected profit = (sugarcane quantity [t] * final offer TRS price *
offered TRS yield [kg/t]) – (supplier transportation costs [R$/t/ km] *
transportation distance [km] * sugarcane quantity [t]
]
Make contract with plant with highest offered expected profits and assign properties:
- set contracted sugarcane quantity [t] = supplier sugarcane [t]
- set contract TRS yield [kg/t] = offered TRS yield [kg/t]
- set contracted TRS price [R$/kg] = final offer TRS price [R$/kg]
set supplier offers = 0
set supplier sugarcane [t] = supplier sugarcane [t] – contracted
sugarcane quantity [t]
[ELSE: stop]
```

END

Figure 20: Agent activities for action 1 [A1]: third party supplier contracts negotiations

Action 2 [A2]: Plant production decisions

As mentioned in section (5.1), the production decisions of processing plants are of key influence on the production quantities for each product observed at the system level. The mechanism developed by Armbrust (2014) was largely adopted and slightly adjusted to be used in the biorefinery model. The conceptualization of action 2 (A2) is depicted in *Figure 21* and *Figure 22*. As can be seen from *Figure 21*, A2 consists of three subsequent steps of which the final output are the production ratio for each product. In this mechanism, processing plants are assumed to be able to adjust their production ratios once per month (the `production evaluation frequency`). The main principle of A2 is that the production ratios of sugarcane used for each product are adjusted based on future profit estimations for each of these products. In the first step (A2.1), the `internal price` and `profit` for each product are calculated. These depend on the `average sugarcane price`, the `processing cost` for the particular product and the product prices for which the plant sells the products (`product price at plant`).

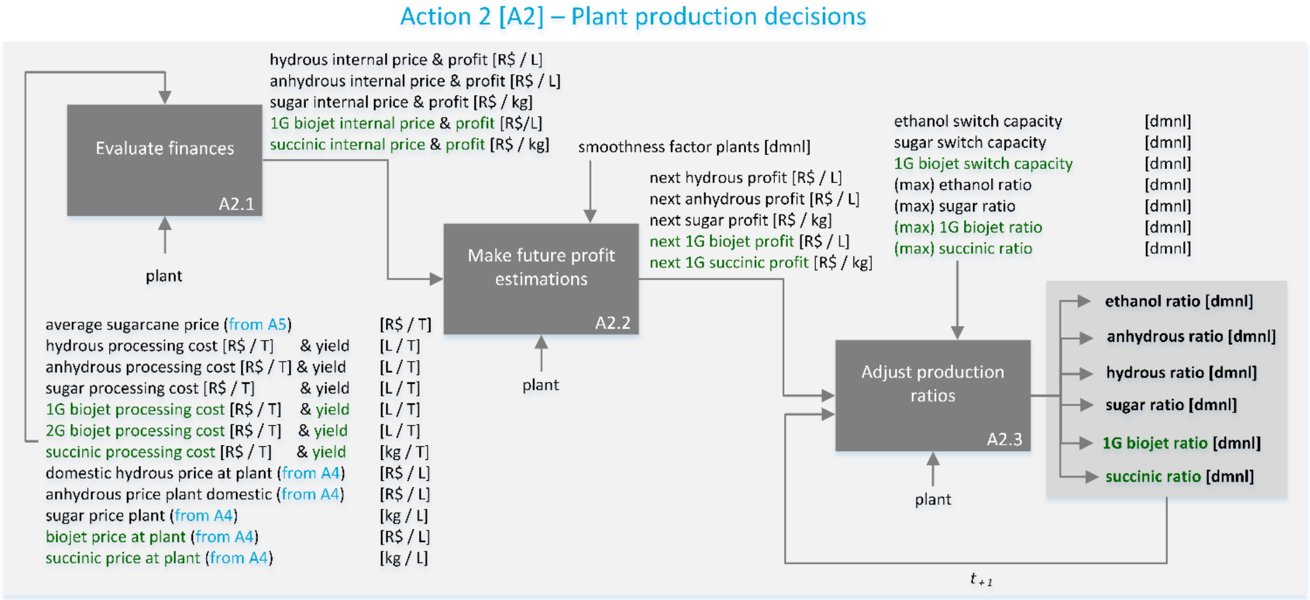


Figure 21: IDEF0 process steps in action 2 [A2] - plant production decisions

Subsequently, single exponential smoothing is used to calculate the `next product profit`. However, in this thesis an adjustment to the exponential smoothing mechanism was made. Namely, in the exponential smoothing equation (A2.2), the most recent profit data has the largest influence on the estimated `next product profit`. Armbrust (2014) chose to use the most recent daily profit of the processing plant for this estimation. However, the profit estimations are made only once per month. Therefore, in this thesis it is argued that the average profits over one month should be used as data input in the exponential smoothing function.

Finally, the production ratios are adjusted with the magnitude of the switch capacity for the product in favor of the product with the highest `next product profit` through A2.3.

Action 2 [A2] – Plant production decisions

START

Evaluate finances A2.1

Agent: Plant

Actions:

Determine profits of each product sales last day:

```
set profit for each product [R$ / L or kg] = product revenue [R$ / L or kg] - internal price of product [R$ / L or kg]
```

Make future profit estimations A2.2

Agent: Plant

Actions:

Future profit estimations are made through exponential smoothing:

```
set next profit of each product [R$ / L or kg] =
smoothness factor plants [dmnl] * product profit [R$ / L or kg] +
(1 – smoothness factor plants [dmnl]) * old next product profit [R$ / L or kg]
```

Adjust production ratios A2.3

Agent: Plant

Actions:

Production quantities are adjusted according to the estimated future profits:

```
IF plant type = 1 or plant type = 2
IF ELSE next hydrous profit > next anhydrous profit
        [
          THEN: set hydrous ratio [dmnl] = hydrous ratio [dmnl] + ethanol switch capacity [dmnl]
          (the max possible hydrous ratio = 1 and the min possible hydrous ratio = 0)
        ]
        [
          ELSE: set anhydrous ratio [dmnl] anhydrous ratio [dmnl] + ethanol switch capacity [dmnl]
          (the max possible anhydrous ratio =1 and the min possible hydrous ratio = 0)
        ]
IF plant type = 2
IF ELSE next sugar profit [R$ / kg] > (next hydrous profit [R$ / L] * hydrous ratio [dmnl] + next anhydrous profit [R$ / L] * anhydrous ratio [dmnl]

        [
          THEN: set sugar ratio [dmnl] = sugar ratio [dmnl] + sugar switch capacity [dmnl]
          (the max possible sugar ratio = 0.6)
          set ethanol ratio [dmnl] = 1 – sugar ratio [dmnl]
        ]
        [
          ELSE: set sugar ratio [dmnl] = sugar ratio [dmnl] – sugar swtich capacity [dmnl]
          (the min possible sugar ratio = 0.4)
          set ethanol ratio [dmnl] = 1 – sugar ratio [dmnl]
        ]
```

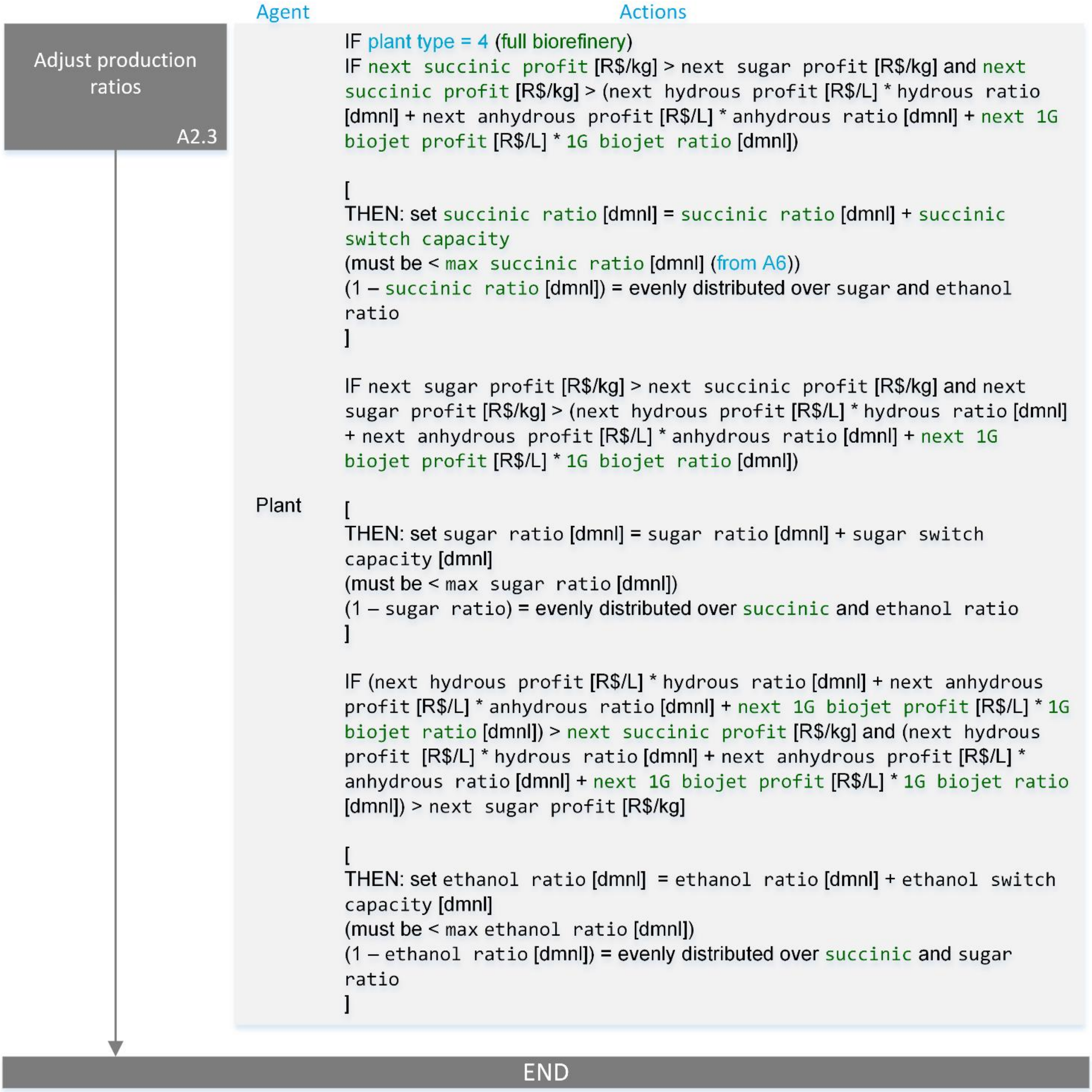
Adjust production ratios

A2.3

Agent: Plant

Actions:

```
IF plant type = 3 (partial biorefinery) or plant type = 4 (full biorefinery)
IF next hydrous profit [R$/L] > next anhydrous profit [R$/L] and next hydrous profit [R$/L] > next 1G biojet profit [R$/L]

[
THEN: set hydrous ratio [dmnl] = hydrous ratio [dmnl] + ethanol switch capacity [dmnl]
(max hydrous ratio = 1 and min hydrous ratio = 0)
]

IF next anhydrous profit [R$/L] > next hydrous profit [R$/L] and next anhydrous profit [R$/L] > next 1G biojet profit [R$/L]

[
THEN: set anhydrous ratio [dmnl] = anhydrous ratio [dmnl] + ethanol switch capacity [dmnl]
(max anhydrous ratio = 1 and min anhydrous ratio = 0)
]

IF next 1G biojet profit [R$/L] > next anhydrous profit [R$/L] and next 1G biojet profit [R$/L] > next hydrous profit [R$/L]
(must be < than max biojet ratio [dmnl] (from A6))

IF plant type = 3 (partial biorefinery)
IFELSE next succinic profit [R$/kg] > (next hydrous profit [R$/L] * hydrous ratio [dmnl] + next anhydrous profit [R$/L] * anhydrous ratio [dmnl] + next 1G biojet profit [R$/L] * 1G biojet ratio [dmnl])

[
THEN: set succinic ratio [dmnl] = succinic ratio [dmnl] + succinic switch capacity [dmnl]

]

[
THEN: set succinic ratio [dmnl] = succinic ratio [dmnl] – succinic switch capacity [dmnl]
(must be < max succinic ratio [dmnl] (from A6))
]
```



```
IF plant type = 4 (full biorefinery)
IF next succinic profit [R$/kg] > next sugar profit [R$/kg] and next succinic profit [R$/kg] > (next hydrous profit [R$/L] * hydrous ratio [dmnl] + next anhydrous profit [R$/L] * anhydrous ratio [dmnl] + next 1G biojet profit [R$/L] * 1G biojet ratio [dmnl])

[
THEN: set succinic ratio [dmnl] = succinic ratio [dmnl] + succinic switch capacity
(must be < max succinic ratio [dmnl] (from A6))
(1 – succinic ratio [dmnl]) = evenly distributed over sugar and ethanol ratio
]

IF next sugar profit [R$/kg] > next succinic profit [R$/kg] and next sugar profit [R$/kg] > (next hydrous profit [R$/L] * hydrous ratio [dmnl] + next anhydrous profit [R$/L] * anhydrous ratio [dmnl] + next 1G biojet profit [R$/L] * 1G biojet ratio [dmnl])

[
THEN: set sugar ratio [dmnl] = sugar ratio [dmnl] + sugar switch capacity [dmnl]
(must be < max sugar ratio [dmnl])
(1 – sugar ratio) = evenly distributed over succinic and ethanol ratio
]

IF (next hydrous profit [R$/L] * hydrous ratio [dmnl] + next anhydrous profit [R$/L] * anhydrous ratio [dmnl] + next 1G biojet profit [R$/L] * 1G biojet ratio [dmnl]) > next succinic profit [R$/kg] and (next hydrous profit [R$/L] * hydrous ratio [dmnl] + next anhydrous profit [R$/L] * anhydrous ratio [dmnl] + next 1G biojet profit [R$/L] * 1G biojet ratio [dmnl]) > next sugar profit [R$/kg]

[
THEN: set ethanol ratio [dmnl] = ethanol ratio [dmnl] + ethanol switch capacity [dmnl]
(must be < max ethanol ratio [dmnl])
(1 – ethanol ratio [dmnl]) = evenly distributed over succinic and sugar ratio
]
```

Figure 22: Agent activities for action 2 [A2]: plant production decisions

Action 5 [A5]: Sugarcane pricing – interlinking market prices with feedstock cost

Given the previously mentioned goal to internalize sugarcane pricing into the biorefinery model, the CONSECANA-SP mechanism as presented in the previous chapter was largely adopted. The conceptualization of sugarcane pricing (action 5) in the biroefinery model is displayed in *Figure 23*. In the first step of this action (A5.1), the average selling prices of the products in one year are calculated. These are the average market selling prices that were determined in A4 (see APPENDIX I) and recorded in a list during a production year. Therefore, this step is executed by the system and not the processing plant. However, in the next step (A5.2), each processing plant calculates its unique `TRS price`, based on the logic that was identified in chapter (4). This means that the average selling price in [R$/l or kg] of each product is converted to [R$/kg TRS] and weighed by the production volume of that particular product. The final step after calculation of the `TRS price` is to determine the `average sugarcane price` that the plant pays in a season (A5.3). This price does not only depend on the TRS price, because each plant has a unique mix of (1) contracted sugarcane supplied by suppliers and (2) sugarcane grown on leased land. Thus, it also depends on the plant's `production costs of sugarcane` as well as the land lease it needs to pay to the landowner (`landowner lease share`). In conclusion, A5 is expected to allow for insights into the real-world interlinkage that exists between market selling prices of the products and sugarcane prices.

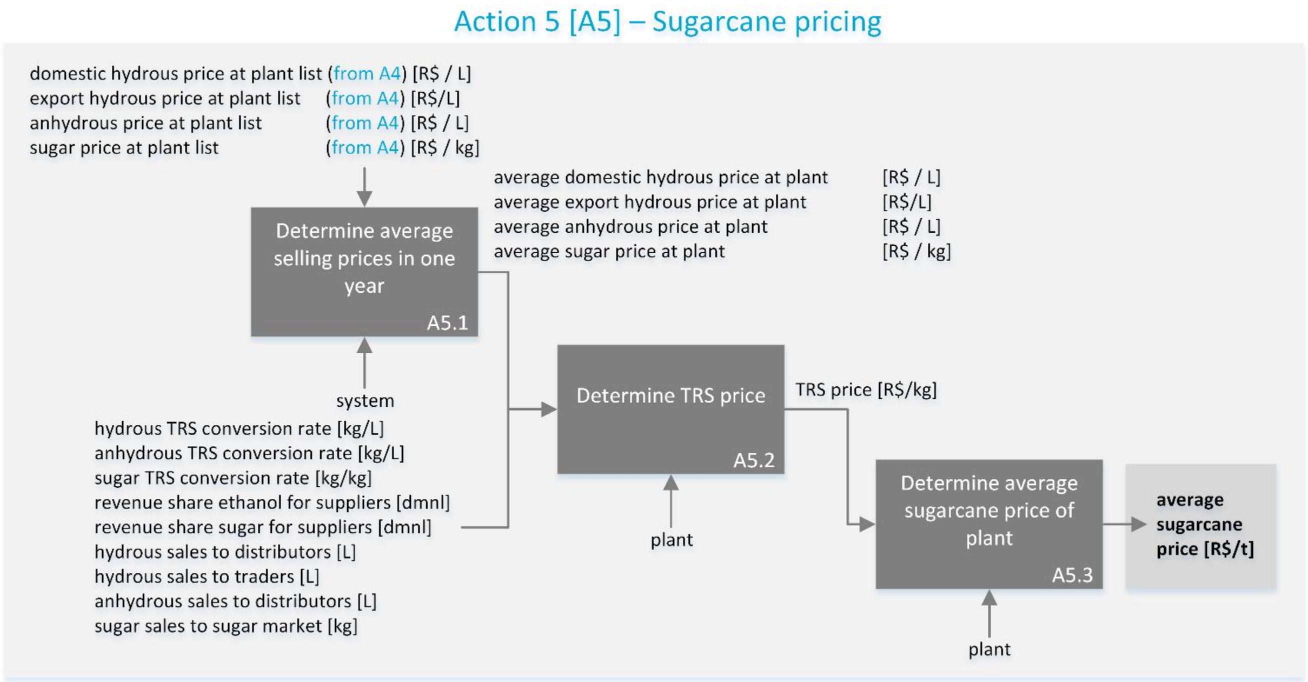


Figure 23: IDEF0 process steps in action 5 [A5] – sugarcane pricing

Action 5 [A5] – Sugarcane pricing

START

Determine average selling prices in one production year
A5.1

Agent: System

Actions:

Determine average selling prices for each product in one production year

```
set average export hydrous price at plant [R$/L] = mean of the export hydrous price at plant list [R$/L]

set average price of product at plant [R$/L or kg] = mean of product price at plant list [R$/L or kg]
```

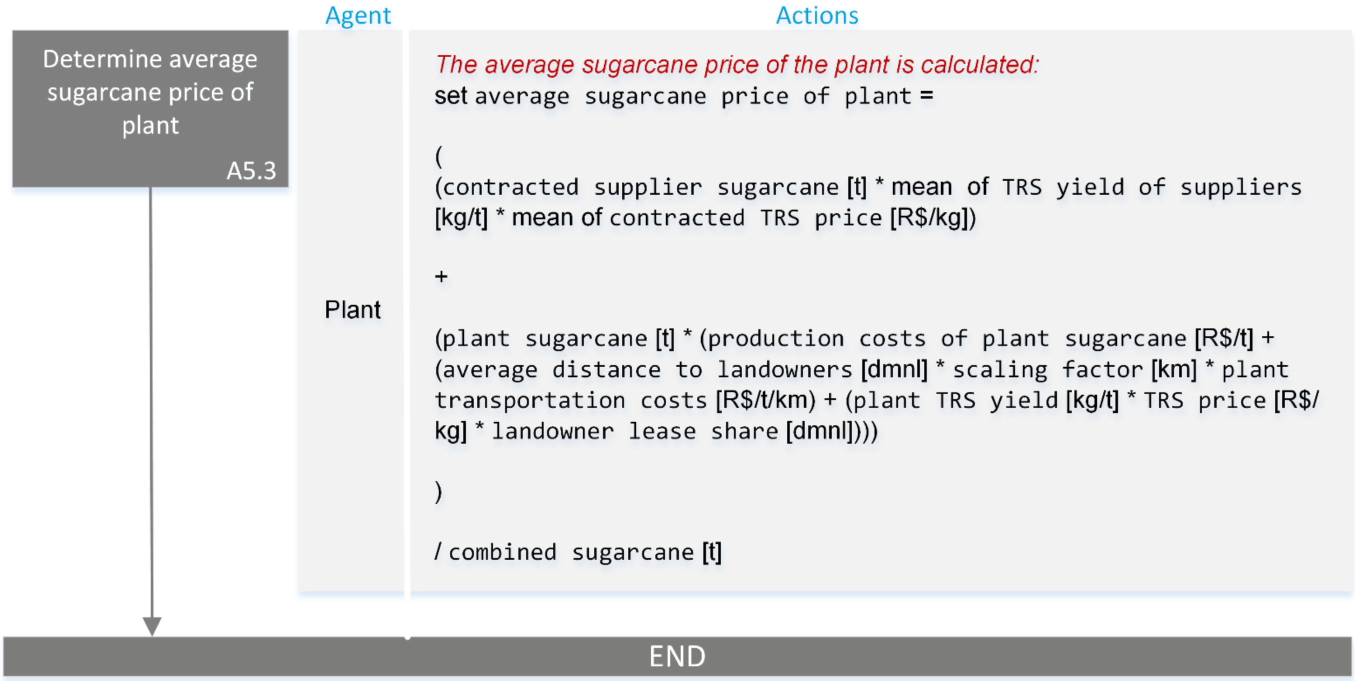
Determine TRS price
A5.2

Agent: Plant

Actions:

The unique TRS price for the plant is calculated:

```
IF plant type = 1

[
 set TRS price =
 (
   (((
 ((average domestic price of hydrous at plant [R$/L] / hydrous trs conversion rate [kg/L]) * hydrous sales to distributors [L])
 +
 ((average domestic price of anhydrous at plant [R$/L] / anhydrous trs conversion rate [kg/L]) * anhydrous sales to distributors [L])
 +
 ((average export price of hydrous at plant [R$/L] / hydrous trs conversion rate [kg/L]) * hydrous sales to traders [L]))

 / total ethanol sales [L]) * revenue share ethanol for suppliers [dmnl])
  )
 ]

IF plant type = 2

[
 set TRS price =
 (
   (((
 ((average domestic price of hydrous at plant [R$/L] / hydrous trs conversion rate [kg/L]) * hydrous sales to distributors [L])
 +
 ((average domestic price of anhydrous at plant [R$/L] / anhydrous trs conversion rate [kg/L]) * anhydrous sales to distributors [L])

 +
   ((average export price of hydrous at plant [R$/L] / hydrous trs conversion rate [kg/L]) * hydrous sales to traders [L])) / total ethanol sales [L]) * revenue share ethanol for suppliers [dmnl]) * total ethanol sales [L]
 +

   (((((average price of sugar at plant [R$/kg] / sugar trs conversion rate [kg/kg]) * sugar sales to sugarmarket [kg]) / total sugar sales [kg])) * revenue share sugar for suppliers [dmnl]) * total sugar sales [kg]

  ) / total sales [dmnl]

 ]
```



The average sugarcane price of the plant is calculated:
set average sugarcane price of plant =

(
(contracted supplier sugarcane [t] * mean of TRS yield of suppliers [kg/t] * mean of contracted TRS price [R$/kg])

+

(plant sugarcane [t] * (production costs of plant sugarcane [R$/t] + (average distance to landowners [dmnl] * scaling factor [km] * plant transportation costs [R$/t/km) + (plant TRS yield [kg/t] * TRS price [R$/kg] * landowner lease share [dmnl])))

)

/ combined sugarcane [t]

Figure 24: Agent activities for action 5 [A5]: sugarcane pricing

Action 6 [A6]: Biorefinery investments

As aforementioned, a conceptualization was developed of how processing plants may evaluate and make biorefinery investments **(**A6**)** (*Figure 26* and *Figure 27*). This action is conceptualized such that a processing plant's investment decision depends on two main factors: the perceived risk and expected return from the investment. This approach was adopted from (Wüstenhagen & Menichetti, 2012) (see *Figure 25*). Wüstenhagen and Menichetti (2012) argue that cognitive aspects play a central role in renewable investment decisions. In line of this reasoning, the conceptualized investment decision takes into account both perceived risks as well as expected returns. The final investment decision of the processing plant depends on a Net Present Value calculation (NPV), in which the perceived risk of the investment is incorporated.

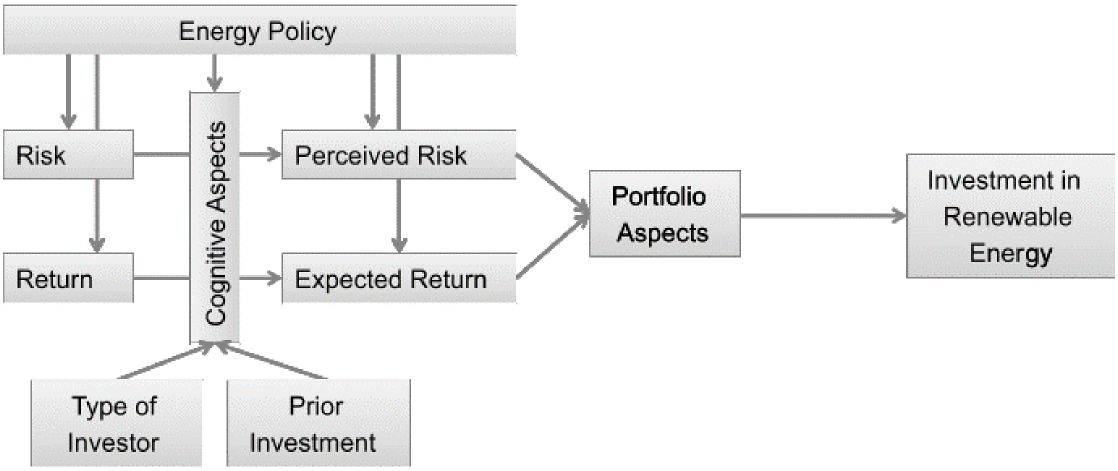


Figure 25: A model of renewable energy investments (adopted from (Wüstenhagen & Menichetti, 2012)

The use of NPV has both advantages and disadvantages. The main advantage is its simplicity and ability to boil down an investment decision to the net expected profits that could be made, while incorporating future risks. On the other hand, the discount rate used in NPV calculations is critical for the profitability of the investment decision. A more detailed elaboration of the uncertainties associated with the use of NPV is provided in section **(**6.5.2**)**.

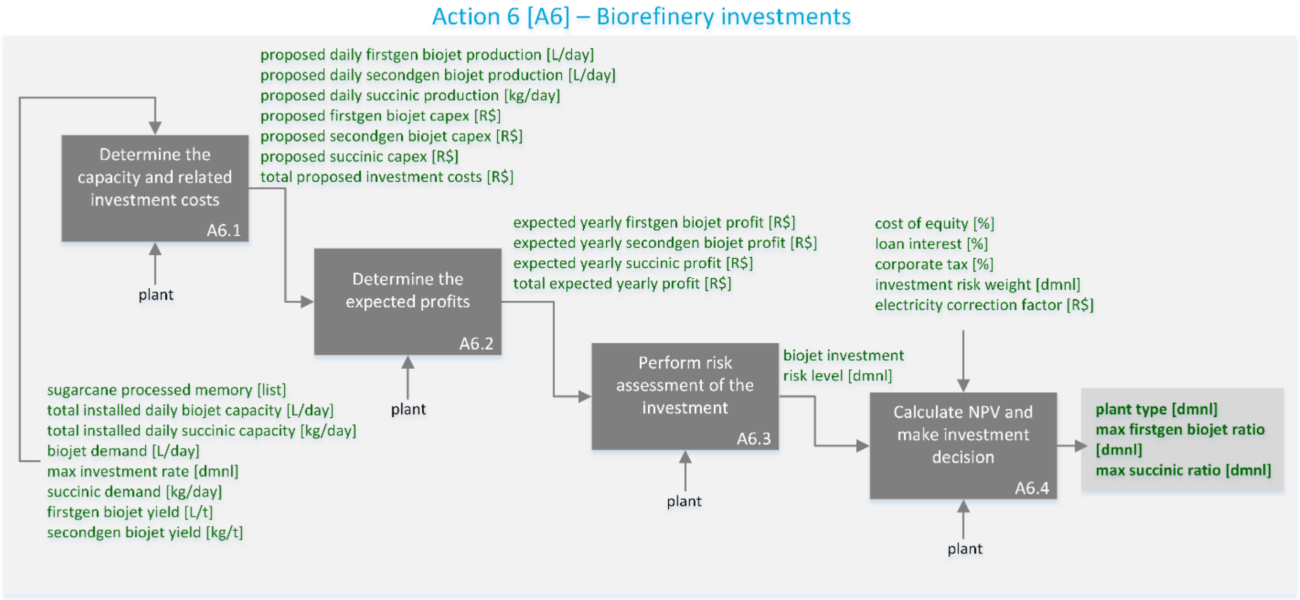


Figure 26: IDEF0 process steps in action 6 [A6] – Biorefinery investments

Several steps are to be carried out before the investment NPV is determined in (A6.4). First, each processing plants needs to decide in how much production capacity for 1G biojet fuel, 2G biojet fuel and biosuccinic acid it considers to invest (A6.1). This is determined through a logistic function, which expresses the market saturation of each particular product (the degree to which the demand for that particular product is fulfilled by the total installed production capacity for that product). The logic here is that plants – when the demand for the product remains constant –, would consider more production capacity when the market saturation is low and vice versa. This results in three proposed production capacities: the `proposed daily 1G biojet production`, the `proposed daily 2G biojet production` and the `proposed daily succinic acid production`. Furthermore, the investment costs that correspond to each of these proposed capacities are determined. This is done by using the CAPEX data available through the HIP project, which allows to calculate the specific investment costs for each capacity, by using the base capacity and CAPEX scaling factor. Thus, investment costs are adaptive to the capacity that is considered in the investment.

Once the investment costs are calculated, the expected profits are calculated in (A6.2). The expected profits for each product depend on the proposed capacity, the actual market selling price of that product (this is the average market selling price of the historical runtime of the model) and the production costs of that product. In this calculation, the processing plant takes into account that the average sugarcane price it pays might increase after converting to a biorefinery.

The final step before the NPV's are calculated, is to perform a risk assessment of the investment (A6.3). This was conceptualized in line with the well-known market diffusion curve, which is represented by the same logistic curve as was used for the proposed capacity. In the case of assessing the investment risk, the risk level is estimated to be highest when the market saturation for that product is lowest and vice versa. Finally, the NPV for both the biojet fuel investment as well as for the biosuccinic acid investment is determined (A6.4). This was done through a somewhat similar approach as applied by (de Vries, Chappin, & Richstein, 2013; Richstein, Chappin, & de Vries, 2014). However, there are two major differences with the application of de Vries and colleagues. First, it is assumed that processing plants have sufficient capital to fund the required equity themselves. This was done, because no data could be found about the financial states of existing processing plants. Furthermore, internalizing the acquaintance of capital by processing plants would deviate substantially from the research scope. Second, whereas de Vries and colleagues use a fixed discount rate in the NPV calculation, in this thesis a partially variable discount rate was chosen. This was done to simulate how NPV calculations would change in correspondence to perceived risk of processing plant for each production technology (that was determined in (A6.3). Once the NPV's for both biojet fuel and biosuccinic acid are calculated, a final investment decision is made for each product, based on whether the NPV is positive or negative.

Action [A6]– Biorefinery investments

START

Determine the capacity and related investment costs

A6.1

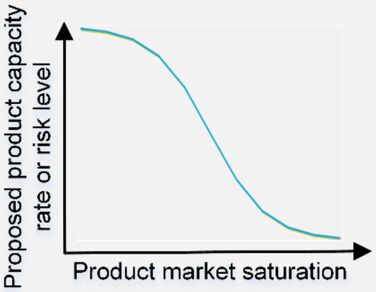
Agent

Actions

Plant

The proposed production capacity and corresponding capex for 1G biojet and succinic are determined:
product = 1G biojet or succinic

```
set product market saturation [dmnl] = total installed daily product capacity [L or kg/day] / product demand [L or kg/day]

set daily sugarcane processing capacity [t/day] = sugarcane processed memory [t] / length of harvest season [days]

set proposed product capacity rate [dmnl] = corresponding capacity on the market saturation logistic function
(proposed product capacity rate cannot be higher than the max acceptable product capacity rate)
```



```
set proposed daily product capacity [t/day] = proposed product capacity rate [dmnl] * daily sugarcane processing capacity [t/day]

set proposed daily product production [L or kg/day] = proposed daily product capacity [t/day] * product yield [L/t]

IF 2G biojet = TRUE
[
THEN:
set proposed secondgen biojet capacity [t/day] = bagasse extraction yield [t/day] * daily sugarcane processing capacity [t/day]

set proposed daily 2G biojet production [L/day] = proposed 2G biojet capacity [t/day] * 2G biojet yield [L/t]
]

set total proposed daily biojet production [L/day] = proposed daily 1G biojet production [L/day] + proposed daily 2G biojet production [L/day]

product = 1G biojet, 2G biojet or succinic
set proposed product capex [R$] = base product capex [R$] * (proposed product capacity [t/day] / base product capacity [t/day]) ^ product scaling factor [dmnl]
```

Calculate NPV and make investment decision

A6.4

Agent

Actions

Plant

The NPV for the biojet and succinic investment are determined:

set product WACC [dmnl] =

$$\left(\frac{\text{required equity}}{\text{total value}} * \frac{\text{cost of equity}}{100}\right) + \left(\frac{\text{required debt}}{\text{total value}} * \frac{\text{cost of debt}}{100}\right) * \left(\frac{\text{1-corporate tax}}{100}\right)$$

set discount rate [dmnl] =

$$\text{product WACC [dmnl]} + \frac{\text{product investment risk level * investment risk weight}}{100}$$

$$\text{set product NPV [} \mid \text{- proposed product capex} + \sum_{t=1}^{T} \frac{\text{expected yearly product profit}}{(1 + \text{discount rate})^{t}}$$

```
IF biojet NPV and succinic NPV > 0 → Invest in both products
[THEN:
    IF plant type = 1 [THEN: set plant type 3]
    IF plant type = 2 [THEN: set plant type 4]
    set max 1G biojet ratio [dmnl] = proposed 1G biojet ratio [dmnl]
    set max succinic ratio [dmnl] = proposed succinic ratio [dmnl]
    set processing cost of hydrous, anhydrous, sugar + electricity
    correction factor [R$/t]
]

IF biojet NPV > 0 and succinic NPV < 0 → Only invest in biojet
[THEN:
    IF plant type = 1 [THEN: set plant type 3]
    IF plant type = 2 [THEN: set plant type 4]
    set max 1G biojet ratio [dmnl] = proposed 1G biojet ratio [dmnl]
    set processing cost of hydrous, anhydrous, sugar + electricity
    correction factor [R$/t]
]

IF biojet NPV < 0 and succinic NPV > 0 → Only invest in succinic
[THEN:
    IF plant type = 1 [THEN: set plant type 3]
    IF plant type = 2 [THEN: set plant type 4]
    set max succinic ratio [dmnl] = proposed succinic ratio [dmnl]
]
```

END

The expected profits corresponding to the proposed production capacities are determined:

```
set adjusted TRS price [R$/kg] = TRS price [R$/kg] + counter offer deduction [dmnl] * TRS price [R$/kg]

IFELSE variable lease contracts = TRUE

[
THEN: then TRS price for lease contracts [R$/kg] = adjusted TRS price [R$/kg]
set adjusted average sugarcane price [R$/t] = calculated through A5.3
]

[
THEN: then TRS price for lease contracts [R$/kg] = TRS price
set adjusted average sugarcane price [R$/t] = calculated through A5.3
]

set adjusted internal price of product [R$/L or kg]= calculated through A4.1 by using adjusted average sugarcane price

set expected yearly product profit [R$/year] = (mean (product price at plant list) – adjusted internal price of product [R$/L or kg]) * length of harvest season [days]

set total expected yearly profit = ∑ product profit for each product [R$/year]
```

The risk level for biojet and succinic investments are determined:

```
set product investment risk level [dmnl] = corresponding risk level on the market saturation logistic function
```

Figure 27: Agent activities for action 6 [A6]: biorefinery investments

Action 8 [A8]: International hydrous ethanol trade

The final action elaborated in this chapter is for international hydrous ethanol trade **(**A8**)** **(***Figure 28* and *Figure 29*). From *Figure 28* it can be seen that **(**A8**)** consists of three different steps, of which the final outcomes are the `export shipment quantity` and the `import shipment quantity`. This actions starts by determining the `hydrous import price at the trader` as well as the `hydrous export price at the trader`. These prices are influenced by multiple factors: the distance of the trader to the processing plants (for logistic costs), the logistic costs between the trader and the foreign market (foreign logistics), the exchange rate between R$ and $, the foreign hydrous price at the port (in $), as well as the import and export tax in Brazil. Through the process in **(**A8.1**)**, the `prices at the trader` are determined.

Subsequently, the export price for which the processing plant could sell (if it chooses to do so) a part of its hydrous ethanol production to the trader is determined **(**A8.2**)**. Finally, the trader determines the import quantity that it sells to the distributors as well as the export quantity that it would like to buy from the processing plants **(**A8.3**)**. These import and export quantities are not constants. In fact, they are dynamically adjusted by the trader, based on the price different between the import and export price at the trader and the domestic selling price of hydrous ethanol. This was done to be able to simulate how import and exports could change when the foreign hydrous price at the port is changed in scenario analysis. Nevertheless, the magnitude of imports and exports was determined by the "normal import quantity" and the "normal export quantity", which are the historical average daily quantities observed in São Paulo state. As aforementioned, a normal distribution was used to simulate the seasonality of production by processing plants. This is particularly important for the inclusion of international hydrous trade, because this seasonality in the real-world sugarcane market and its relation to market selling prices often relates to import and export flows. Namely, after the harvest season finished, fuel stocks typically deplete, which relates to higher fuel prices and increasing imports and vice versa.

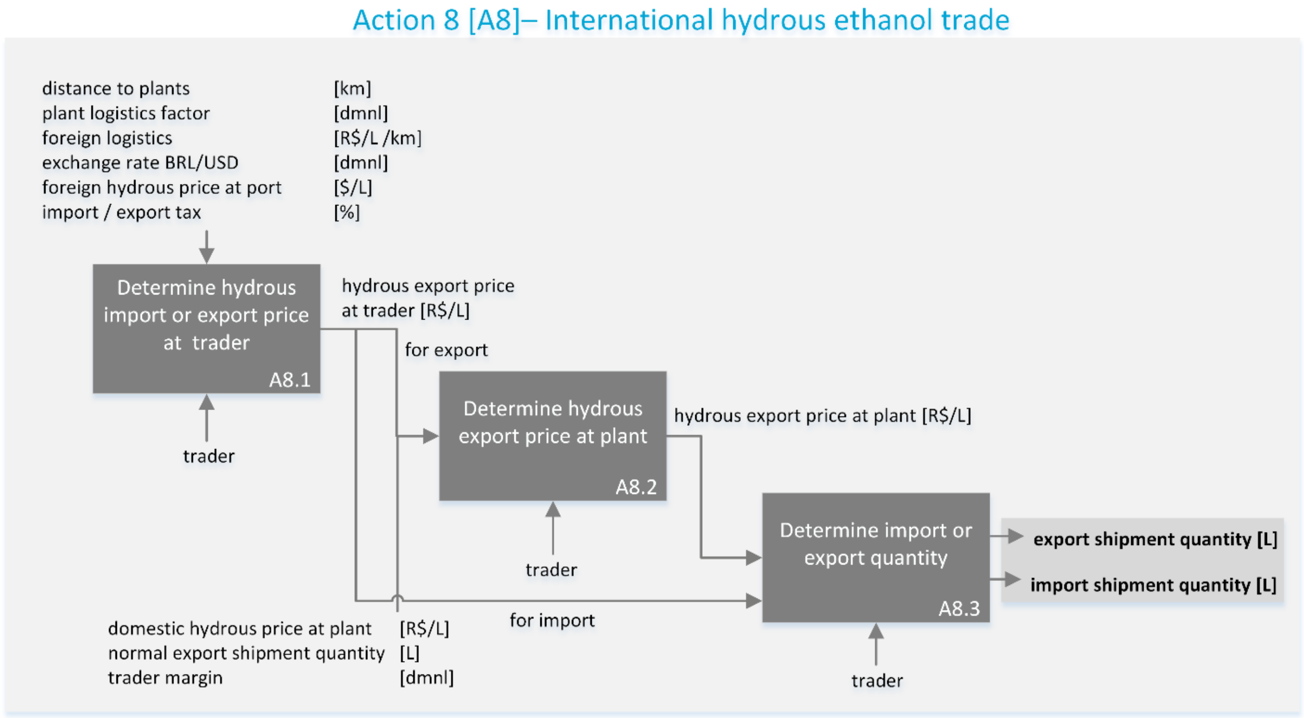
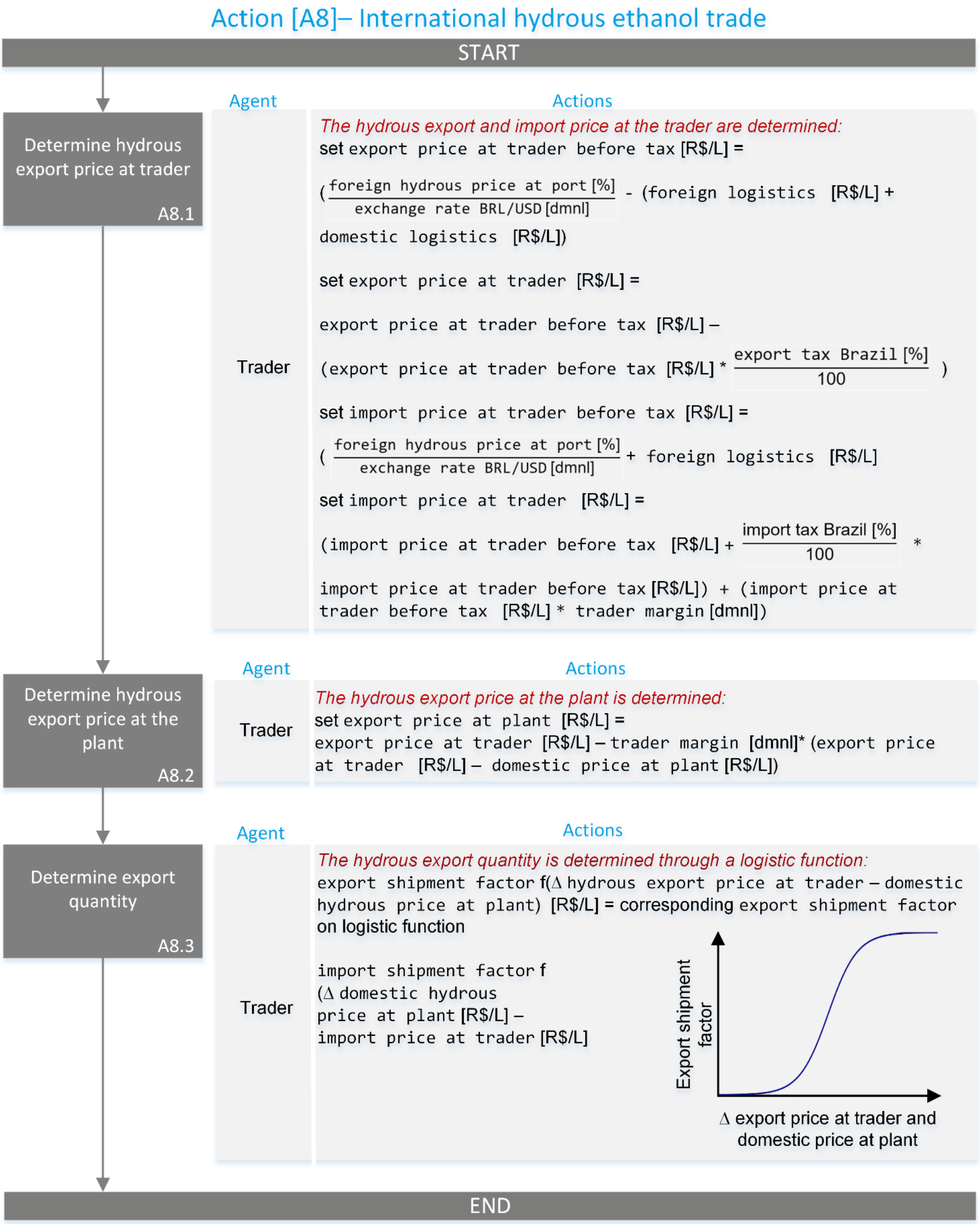


Figure 28: IDEF0 process description for action 8 [A8]: international hydrous ethanol trade



The hydrous export and import price at the trader are determined:

set export price at trader before tax [R\$/L] =

($\frac{\text{foreign hydrous price at port [\%]}}{\text{exchange rate BRL/USD [dmnl]}}$ - (foreign logistics [R\$/L] + domestic logistics [R\$/L])

set export price at trader [R\$/L] =

export price at trader before tax [R\$/L] –

(export price at trader before tax [R\$/L] * $\frac{\text{export tax Brazil [\%]}}{100}$)

set import price at trader before tax [R\$/L] =

($\frac{\text{foreign hydrous price at port [\%]}}{\text{exchange rate BRL/USD [dmnl]}}$ + foreign logistics [R\$/L]

set import price at trader [R\$/L] =

(import price at trader before tax [R\$/L] + $\frac{\text{import tax Brazil [\%]}}{100}$ *

import price at trader before tax [R\$/L]) + (import price at trader before tax [R\$/L] * trader margin [dmnl])

The hydrous export price at the plant is determined:

set export price at plant [R\$/L] =
export price at trader [R\$/L] – trader margin [dmnl]* (export price at trader [R\$/L] – domestic price at plant [R\$/L])

The hydrous export quantity is determined through a logistic function:

export shipment factor f(Δ hydrous export price at trader – domestic hydrous price at plant) [R\$/L] = corresponding export shipment factor on logistic function

import shipment factor f
(Δ domestic hydrous
price at plant [R\$/L] –
import price at trader [R\$/L]

Figure 29: Agent activities for action 8 [A8]: international hydrous trade

6

BIOREFINERY MODEL IMPLEMENTATION

- FROM CONCEPTS TO CODE

This chapter address different aspects of the implementation of the previously conceptualized biorefinery model. This is done in several sections. First, NetLogo specific implementation matters are discussed in section (6.1). Then the gathering of input data for the simulation model (6.2) as well as the key outcomes that were measured (6.3) are presented. Furthermore, section (6.4) elaborates on the verification and validation of the biorefinery model that was implemented. Then, the influence of the model's assumptions on the key outcomes of interested is assessed in (6.5). Provided this context, the base model results that were found in the scenario of no biorefinery market are presented and interpreted in section (6.6).

6.1 NetLogo implementation

The final conceptualization of the biorefinery model presented in the previous chapter was implemented into a simulation model in the NetLogo modelling environment (NetLogo, 2016). This section presents the basic concepts of NetLogo and how they were applied for the Biorefinery model. This is done by addressing four different aspects of the implementation: the model elements, spatial distribution, procedures and the model narrative.

6.1.1 Implementing the model elements

The coding process started with the definition of the model elements to be used in the model, based on the initial conceptualization. These elements include: (1) agent breeds, (2) links and (3) global variables. Ten different turtle "breeds" were included in the NetLogo code; one breed for each agent presented in the UML in the previous chapter. A breed is best described as a class to which a certain turtle (agent) belongs. Therefore, an agent is just an instance of an agent breed. In accordance with the conceptualization, not all agents were modelled with the same level of detail. In fact, landowners, the foreign market and biosuccinic market do not have any decision-logic. However, they do have a few states and it is convenient to model them for visualization purposes. For a detailed description of the states that each agent has, one is referred to APPENDIX II. In addition to agent-specific states, global variables were also included. These are variables that exist at the global level, and can thus be called by any turtle or link. The process of defining which variables should be agent states and which should be global variables, is an iterative process in which the modeler needed to clearly define whether a variable had to be agent specific or not. The global variables can exist internally in the simulation model, but can also be external variables. In contrast with agent states, global variables can be changed for experimentation purposes.

6.1.2 Spatial distribution in “the NetLogo World”

The NetLogo modelling environment allows for the interactive visualization of model elements in the so-called “world”. *Figure 30* shows a snapshot of the NetLogo world after setup (for a description of the meaning and color of elements, see APPENDIX II). As one can see, a map of São Paulo state was used as a visual reference for the allocation of agents. Whereas the NetLogo world view is convenient for the model user to get real-time insights into what happens during a simulation, its numeric dimensions are also important for the model to work properly. Spatial distribution of model elements (in the quantitative sense) was found to be only particularly important for the sugarcane procurement subsystem. This is due to the fact that the distance between suppliers, processing plants and landowners is of significant importance for the transportation costs of sugarcane. Therefore, the size of the NetLogo world was set such that the distance between these agents could sufficiently reflect the real-world catching radius of 40 kilometers. It was found that a world size of 20 x 20 patches can meet this goal. To convert the dimensionless NetLogo distances to km, a scaling factor of 1 patch equals 10 kilometers was used. However, this only implies that the catching radiuses of processing plants equal real-world scale. Other distances in the model do not relate to the real-world scale.

Figure 30: Spatial distribution of elements in the NetLogo World

6.1.3 Procedures

The actions that were defined in the previous chapter were formalized into so-called “procedures” in the NetLogo code. Procedures can be executed by both turtles and the system. Procedures that are executed by the system are not agent specific procedures, but they can still call agents while executing the procedure. *Table 13* summarizes all procedures that were implemented in the NetLogo code. As one can see from the table, the model includes a many procedures. Despite the fact that the size of the model requires many procedures, this was also partially done on purpose. Namely, the author found it more convenient to track down errors and to keep procedures structured and agent specific.

Furthermore, it is hoped that this will also increase the user friendliness for any potential future user that would like to adapt or simulate the model.

Table 13: Overview of procedures included in the NetLogo code

Procedures	Executed by	Other agents involved	Description
P1: Setup	System	All	Should be activated before the go procedure is activated to assign (initial) values to global variables and agent states.
P2: Supplier produce sugarcane	Supplier	N/A	To simulate annual sugarcane growing by suppliers.
P3: Negotiate supplier sugarcane contracts	System	Plants and suppliers	Similar to *action 1*
P4: Plant produce sugarcane	Plant	N/A	To simulate annual sugarcane growing by plants on leased land.
P5: Plant produce products	Plant	N/A	Similar to *action 3*
P6: Driver fuel demand	Driver	N/A	Similar to *action 9*
P7: Trader export	Trader	N/A	Similar to *action 8*
P8: Plant sell products	Plant	Plants, traders and distributors	Similar to *action 4*
P9: Trader import	Trader	N/A	Similar to *action 8*
P11: Distributor distribute fuels	Distributor	N/A	Similar to *A7.1, A7.2* and *A7.4*
P12: Plant finance	Plant	N/A	Similar to *A2.1, A2.2* and *A5.3*
P13: System consecana season evaluation	System	N/A	Similar to *A5.1*
P14: Plant TRS price calculation	Plant	N/A	Similar to *A5.2*

P15: Plant market reaction	Plant	N/A	Similar to *A2.3*
P16: Driver switch fuel	Driver	N/A	Similar to *A10*
P17: Distributor margin adjustment	Distributor	N/A	Similar to *A7.3*
P18: Plant biorefinery investment	Plant	N/A	Similar to *A6*
P19: Total system information	System	All	Use to record experiment outcomes in each tick, as well as to update global variables.

6.1.4 Building a simulation storyline - the model narrative

The final aspect of the NetLogo implementation discussed here is the simulation storyline. As seen before, the model consists of many different procedures. The coordination of when each procedure should be executed is crucial for the simulation model to work properly. Therefore, a model narrative was developed that describes in which sequence and frequency all procedures should be carried out in a simulation run. This model narrative is presented in *Figure 31* by means of a UML sequence diagram. For each procedure it is indicated whether it is activated each tick or with a certain frequency. One tick in the model was defined equal as one day. This was necessary for the simulation code to properly synchronize with the model elements adopted from (Armbrust, 2014), who also defined one tick as one day. The total length of each simulation run (the timeframe) was set at 5500 ticks, which about equals 15 years. This is the same timeframe as applied in the HIP project (BE-Basic Foundation, 2016).

Time aspects	**Description**
Time definition of “tick”	1 tick = 1 day
Timeframe (run length)	15 years = 5475 ticks

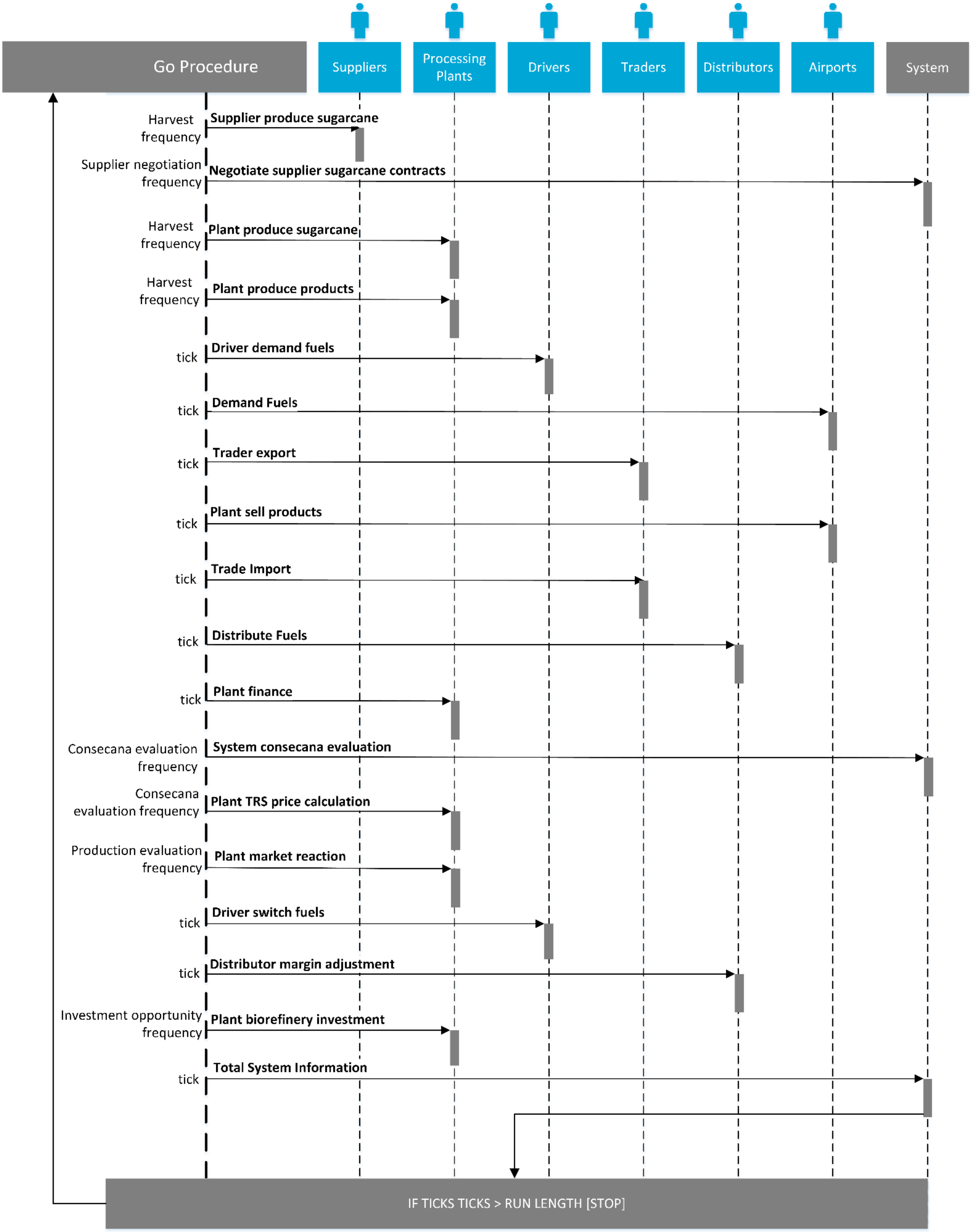


Figure 31: The GO Procedure depicted in an UML sequence diagram

6.2 Simulation input data sourcing

In the sourcing of the input data that was used for the NetLogo code, a distinction can be made between variables with sources and variables with assumed values. APPENDIX II presents an overview of all the variables that were included in the mode and the exact sources used. For variables with real data, a multitude of different types of sources were used, such as research reports, journal articles and websites. Furthermore, some variables were also validated through expert validation.

As was seen in the previous chapter, the model also makes use of numerous "soft variables", unknown variables as well as logistic functions. For the `supplier risk premium rates`, `landowner risk premium rates` as well as `processing plant risk profiles`, assumptions were made for their values. Because these assumptions come along with uncertainty, substantial attention was paid to investigate to which assumed variables the model is sensitive. The variables to which the model was found to be very sensitive were calibrated if needed. The logistic functions used for the international hydrous ethanol trade procedure were calibrated with real-world import and export data for the state of São Paulo.

6.3 Model data output and treatment

Table 14 provides an overview of the model outputs for which data was collected while executing the policy exploration simulations. This data was then processed into a wide variety of graphs with R statistics. For an overview of the complete R statistics script that was used, one is referred to APPENDIX V.

Table 14: Model key outputs and supporting outputs

Output	Unit	Description
		Key outputs
Biojet fuel demand satisfaction	[%]	The degree to which the total biojet fuel demand is satisfied by production.
Biosuccinic demand satisfaction	[%]	The degree to which the total biosuccinic demand is satisfied by production.
		Supporting outputs
Average sugarcane price paid by plants	[R$/t]	The average of all average sugarcane prices paid by plants.
Average sugarcane price paid by biorefineries	[R$/t]	The average of all average sugarcane prices paid by biorefineries (with plant type = 3 or plant type = 4).

Total hydrous ratio	[dmnl]	Expresses the average percentage of sugarcane that is used by plants for the production of hydrous ethanol.
Total anhydrous ratio	[dmnl]	Expresses the average percentage of sugarcane that is used by plants for the production of anhydrous ethanol.
Total sugar ratio	[dmnl]	Expresses the average percentage of sugarcane that is used by plants for the production of sugar.
Total 1G biojet fuel ratio	[dmnl]	Expresses the average percentage of sugarcane that is used by plants for the production of 1G biojet fuel.
Total biosuccinic acid ratio	[dmnl]	Expresses the average percentage of sugarcane that is used by plants for the production of biosuccinic acid.
1G biojet fuel production	[l/day]	The sum of 1G biojet fuel production of all plants.
2G biojet fuel production	[l/day]	The sum of 2G biojet fuel production of all plants.
Biosuccinic acid production	[kg/day]	The sum of biosuccinic acid production of all plants.
Biojet fuel price	[R$/l]	The average price of biojet fuel at the airport.
Biosuccinic acid price	[R$/kg]	The price of biosuccinic acid paid by the biosuccinic acid market.

6.4 Verification and Validation

6.4.1 Model verification

After implementation of the conceptualization in NetLogo, the Biorefinery simulation model was extensively verified to check whether the model worked as conceptualized. Particular attention was paid to properly synchronize the newly conceptualized elements of the biorefinery model with the elements that were adopted from the biojet model by (Armbrust, 2014).

Verification of the model elements by (Armbrust, 2014)

There were three major issues found in the source code of the model elements conceptualized by (Armbrust, 2014). First, a summation mistake was found in the ethanol distribution from processing plants to distributor agents. It was discovered that each distributor sets the amount of supplied hydrous ethanol and anhydrous ethanol equal to the total production of all plants combined. As a result, the total amount of hydrous and anhydrous ethanol supplied to each distributor was far too high. For instance, in the case of six distributors in the model, each distributor received 6 times more hydrous and anhydrous ethanol than it actually should. This mistake was resolved by dividing the total supply to each distributor by the number of distributors in the system, so that each distributor receives an equal share of supply.

Second, another mistake in the code was found in the individual fuel consumption of car drivers. Namely, the total GEEL demand (gasoline equivalent liters) of each driver was set equal to the GEEL demand of the whole car driver market. Given the fact that there are 50 car drivers in the model (with a medium market size), total fuel consumption was 50 times higher than the actual consumption for the car driver market. This mistake was also resolved by setting the GEEL demand of each car driver equal to the total GEEL demand of the car driver market divided by the number of car driver agents in the system.

Finally, a mistake was found in the production decision mechanism that plants use to adjust the production ratios for each product. As (Armbrust, 2014) indicated, the sugar and ethanol ratio can only vary between 0.4 and 0.6. However, it was found that there is no protection in the code to keep the production ratios within this limit. Therefore, the model could erroneously switch entirely to sugar or ethanol. After correction of this mistake, production quantities were found to be more stable, as plants were not able to alter their production ratios too much.

Verification of biorefinery model elements

The first subsystem that was implemented is the sugarcane procurement. Attention was paid to the correctness of the creation of production clusters around each processing plant. Initially it was found that suppliers as well as landowners were located outside the production clusters of processing plants. As a result, production quantities were low, even though the total sugarcane production was of similar magnitude than the real world value. From this insight, a mechanism was developed through which suppliers and landowners are always positioned within the catching radius of at least one plant.

After the issue of spatial distribution was resolved, particular attention was paid to the supplier contracts negotiation procedure. To check the correctness of his procedure, several actions were carried out. First, multiple single-agent verification tests were carried out in which the behavior of a single supplier agent were analyzed. Through these tests it could be checked whether the supplier actually made a contract for the highest offer, instead of a lower one.

Furthermore, it was challenging to make the TRS price calculation mechanism working properly. This was due to the fact that it was hard to identify whether the initially abnormal TRS prices were a calculation mistake or due to erroneous price levels in the model. TRS prices are based on all market selling prices in the model, and erroneous prices would thus result in an unreasonable TRS price.

Finally, the biorefinery investing procedure was verified. Through single-agent verification, it could be assessed whether processing plants responded to changing market prices for biojet fuel and biosuccinic acid.

6.4.2 Model validation

The Biorefinery model was validated in various ways. The main form of validation that was used is literature validation. Model behavior was compared with behaviors described in literature (please see APPENDIX III). Also, the magnitude of model outputs were checked for their reasonability, compared with historical data. However, not all model elements could be validated through literature validation, as some elements (such as the biorefinery investing procedure or the airport pricing fuel mechanism) do not yet exist in the real world. Therefore, expert consultation was carried out for some of the model's elements through two conversations with Marcelo Pierossi. Marcelo Pierossi is an agricultural consultant in the Brazilian sugarcane industry. For a transcript of the conversations held with Mr. Pierossi, please see APPENDIX III. For in-depth validation of the model elements developed in the biojet model, one is referred to (Armbrust, 2014). After validation, confidence was gained that the Biorefinery model can sufficiently explain the macroscopic behavior of interest for the research objective.

6.5 Sensitivity analysis and Uncertainty meta-analysis

6.5.1 Sensitivity analysis and calibration

Sensitivity analysis was performed for a large set of variables in the model. This was done for two types of variables: assumed “soft variables” and variables with a real-world value. For the soft variables, such as the supplier’s risk premium rate or the processing plant’s investment risk weight, sensitivity analysis was done to gain insight into how the key outcomes of the model might change, when their values are changed within a range of 10% of the base value. If found sensitive, these variables were calibrated. For the variables with a source, sensitivity analysis was performed to gain preliminary insights into the external variables to which the model is sensitive. It was found that the model is particularly sensitive to the global sugar price as well as the gasoline price. The average sugarcane price is very numerically sensitive to changes in the global sugar price; when the global sugar price is high, the average sugarcane price is also high.

With regard to the gasoline price, it was seen that an increase of the gasoline price leads to an increase of both the hydrous ethanol price as well as the gasohol price. This is in line with the observations made by various authors (e.g. (Ferraz Dias de Moraes & Zilberman, 2014; Serra et al., 2011; USDA, 2015a)). Thus the general price levels for all fuels increase when gasoline prices increase. Both the global sugar price and the gasoline price will be considered for scenario analysis in the next chapter.

For all sensitivity analyses, 30 simulation runs of 5500 ticks each were carried out for each parameter setting. These were then processed into graphs with R statistics. For a complete overview of all the parameters for which sensitivity analyses were carried out, one is referred to APPENDIX III.

As previously described, there are a total of four logistic functions used in the model. The export and import logistic functions were used as an approximation of how exports and imports may increase as a function of the price difference between the foreign and domestic hydrous ethanol price. These logistic functions were manually calibrated. This means, different settings for these logistic functions were used in the NetLogo code, to see which settings would best resemble the real-world import and export quantities. The final logistic functions used in the model are also provided in APPENDIX III.

6.5.2 Meta-analysis– questioning key assumptions under uncertainty

The previously presented sensitivity analysis provided valuable insights into which assumed variable the model is sensitive. Although some numerical sensitivity was observed, no variables were found to which the model is behaviorally sensitive. This could falsely suggest that the models assumptions do not have an impact on the simulation results. In this section, it is investigated what might happen if the main assumptions in the model would be changed or would not be valid anymore. A meta-analysis was performed to reflect on the key assumptions and the effect they might have on the experiment results presented in the next chapter.

Sugarcane procurement

The first main assumption that was made in the sugarcane procurement subsystem, is that processing plants do not own agricultural land for sugarcane. Instead, all the sugarcane that they can produce by themselves is produced on land that is leased from a landowner. In reality, however, some plants also own land for sugarcane production. Yet, in the reviewed data, only a distinction is made between supplier sugarcane and sugarcane produced through vertical integration. Data on the amount of land that processing plants own was not found, also not after expert consultation with Marcelo Pierossi. In that light, it was decided that all sugarcane produced by processing plants is grown on leased land. Lack of rigidity of this assumption may however have several implications. First, the average sugarcane price of sugarcane that is produced through vertical integration could be lower when processing plants are able to produce this on owned land. Second, the average sugarcane price would probably also be less volatile to the selling prices of sugar and ethanol, as land lease rates are based on the CONSECANA-SP calculated TRS price.

The second main assumption concerns the increased risk perception when suppliers would supply to a biorefinery. It was hypothesized that the conversion of a conventional processing plant to a biorefinery may distort the existing institutionalized way of sugarcane supply transactions. The existing CONSECANA-SP mechanism does not include the alternative use of sugarcane into the TRS price. Therefore, it is unknown how the TRS price of a biorefinery could be calculated by using the existing mechanism. On the long term, the CONSECANA-SP mechanism would likely need adjustment to incorporate the selling prices of alternative products in the TRS price calculation. However, on the short term, such a large institution as CONSECANA-SP is not likely to adapt its mechanism in the case of only a small market share of biojet fuel and biosuccinic acid. Therefore, it was assumed that suppliers will ask a risk premium (which is different for each supplier) on top of the base TRS price. In case this assumption would not be valid, the average sugarcane price paid by biorefineries would not be higher than the price paid by conventional plants. That could on its turn lead to more biorefinery investments.

Sugarcane processing

Two main assumptions for processing plants in the sugarcane processing system are discussed here.

The first assumption concerns the absence of economies of scale in the production mechanism of processing plants. For the Biorefinery model, it was assumed that plants do not make use of economies of scale: production costs are not reduced with increased production of a particular product. As mentioned before, economies of scale effects were omitted from the model scope as these would add a level of detail that is not deemed necessary to achieve the research objective. However, the absence of economies of scale could have several implications on the model outcomes. Namely, if the production technologies for sugar, ethanol, biosuccinic acid, 1G biojet fuel and 2G biojet fuel would have dynamic production costs, profits for one product might prove to be higher than the ones for another product,. This could then give rise to different production ratios for the amount of sugarcane used for that particular product.

The second assumption concerns the sugarcane crushing capacity of processing plants. As stated previously, the crushing capacity of plants are set equal to the amount of sugarcane that can be grown within its catching radius. Therefore, the crushing capacity will never be a limitation for the amount of sugarcane that can be procured by the plant. It was also stated that all plants in the model should collectively have sufficient capacity to process the total amount of sugarcane in the system. Another factor is that the implementation of the conceptualized interactions between suppliers and processing plants proved to be further complicated when crushing capacity would be a decision-factor in the procurement of sugarcane. This is due to the overlapping catching radiuses of processing plants. Invalidity of this assumption would cause processing plants to have a limitation on the amount of sugarcane that they can buy from suppliers or grow themselves. This would then lead to lower production quantities and a lower biojet fuel and biosuccinic acid capacity to invest in. This could however be compensated by the increased sugarcane crushing capacity of other processing plants, if one would assume that still all produced sugarcane should be used.

Biorefinery investing

For biorefinery investing, two key assumptions were made. First, it was assumed that processing plants base their final investment decision on a NPV calculation. The use of NPV calculations has several well-known limitations, which also apply to the conceptualized investing procedure. First, the expected profits are based on the historical market selling prices of biojet fuel and biosuccinic acid. This means that the product selling price is equal to the average of the historical daily selling prices known to the processing plant. In case these selling prices would change in the future, the processing plant would have wrongly calculated the profits. Furthermore, the discount rate of future cash flows has significant influence on the outcomes of the NPV calculation. In particular when each processing plant would use the same interest rate that is too high or too low, this could have great influence on the emerging biojet fuel and biosuccinic acid production. An attempt was made to partially resolve this by assigning heterogeneous risk attitudes to processing plants, so that they assess investment opportunities differently. Nevertheless, the discount rate is also based on the loan interest rate, which is equal for all processing plants.

Second, it is assumed that processing plants always have sufficient capital (30% of the investment is paid through equity (the firm’s on capital) and 70% through loans) to invest in biojet fuel and biosuccinic acid production capacity, regardless of their financial performance. Although it was considered to use a plant’s profits to determine its available capital, this was found to be too unreliable, as little is known about the financial management of processing plants. Naturally, this assumption could have major implications if not valid. Processing plants would base their investment decision not only on the NPV, but also on the amount of equity they can acquire to finance the investment. This could lead to lower biorefinery investments. In particular if one considers that processing plants in the Brazilian sugarcane industry have been in financial struggle in the past when ethanol and sugar prices are low.

6.6 Biorefinery base model results – no biorefinery market

Provided the aforementioned implementation in the NetLogo code and the model’s limitations, the base model results are presented in this section. These are the results from a scenario setting in which all base values were used, and the biorefinery market as well as foreign trade were deactivated. The graphs show the average of 30 simulation runs. As can be seen from *Figure 32*, both the hydrous ethanol consumer price and the gasohol consumer price fluctuate over the model run time. Price changes in hydrous ethanol are more dynamic than gasohol prices. This is partially due to the fact that gasohol prices only consist of 27% (the blending mandate) of anhydrous ethanol. Furthermore, both prices are rather stable within its bandwidth, indicating that the general behavior of the system is quite stable over time.

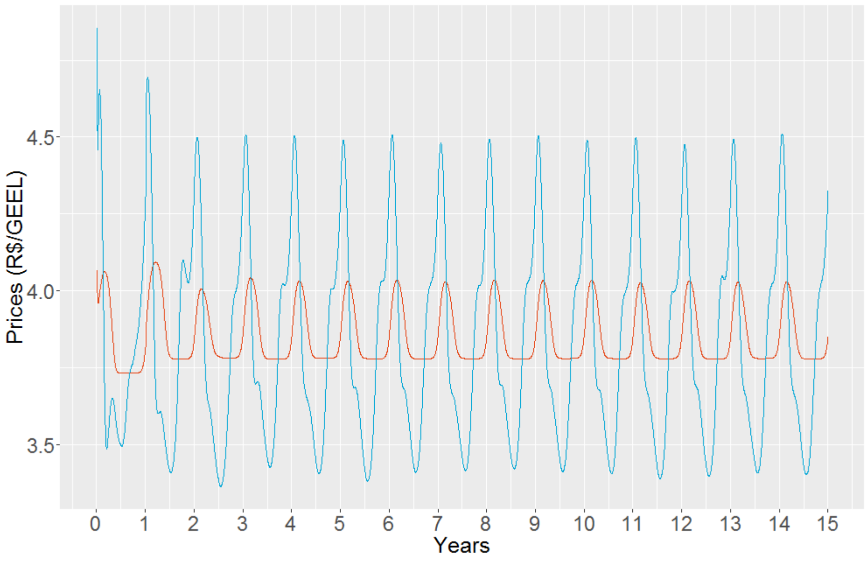


Figure 32: Biorefinery base model results without foreign trade – consumer fuel prices
🟦 hydrous ethanol consumer price [R$/GEEL] 🟧 gasohol consumer price [R$/GEEL]

Figure 34 shows the dynamics in production ratios of processing plants. As can be seen from the figure, the ratio of sugarcane used for hydrous ethanol, anhydrous ethanol and sugar fluctuates over the model run time. This is because processing plants change the production ratios in response to the profitability of hydrous and anhydrous ethanol respectively (as the sugar price is fixed). Nevertheless, these fluctuations are stable over the model run time, as there are no changes in external variables (such as the sugar price and the foreign hydrous ethanol price). The trend of fluctuations is expected to change through the experiments that will be presented in the next chapter.

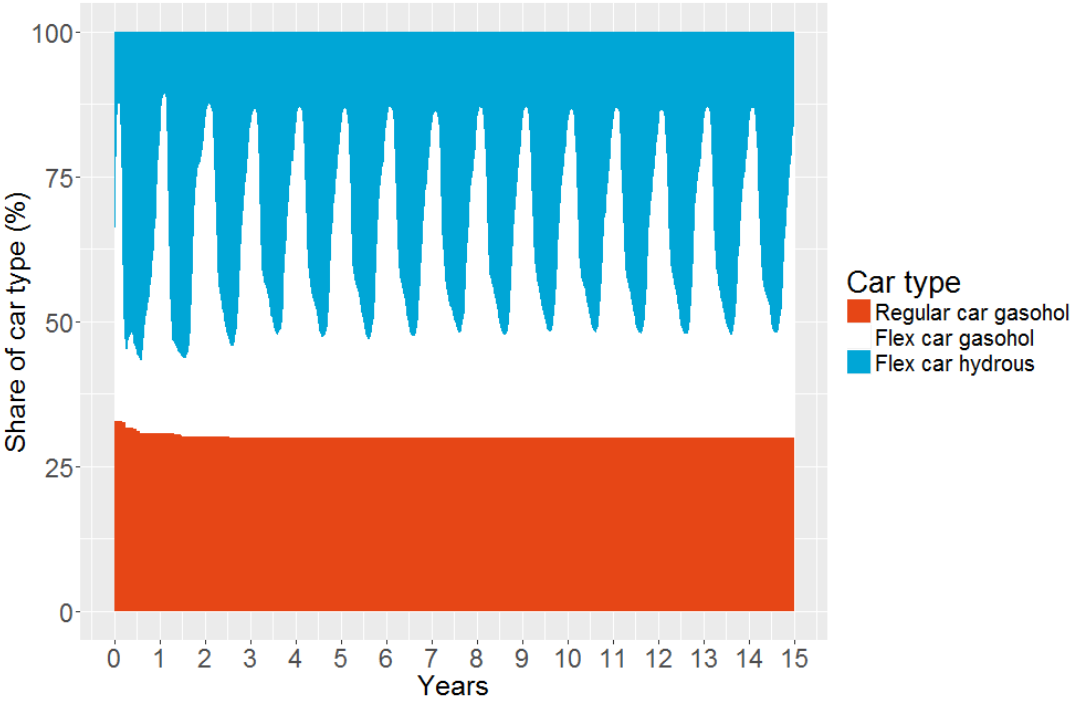


Figure 33: Biorefinery base model results without foreign trade – share of car type

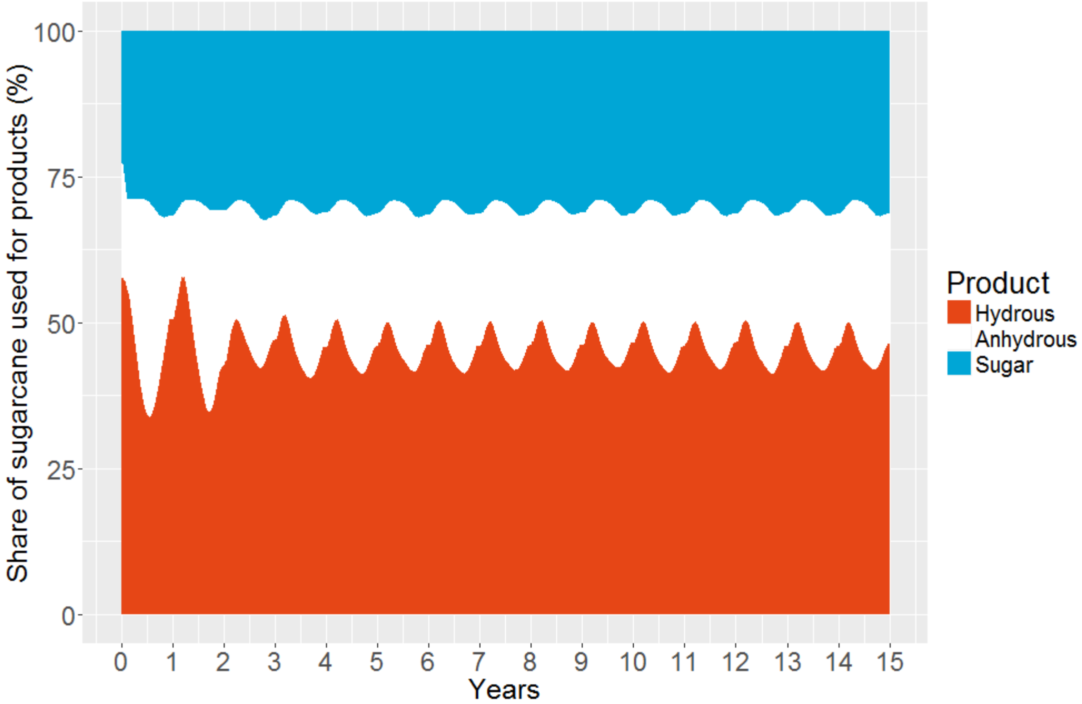


Figure 34: Biorefinery base model results without foreign trade – production decisions

Finally, *Figure 35* shows the behavior of the average sugarcane price of processing plants. As can be seen from the figure, the average sugarcane price shows a large initial increase, but stays rather stable over the rest of the model run time. This implies that the system shows stabilizing behavior for the average sugarcane price towards an equilibrium state. This is also in line with the conceptualization of the CONSECANA-SP mechanism, according to which sugarcane prices change with changes in the global sugar price, foreign hydrous ethanol price and domestic ethanol prices. Since these were kept constant in the baseline scenario, no significant variations in the average sugarcane price can be observed. The small fluctuations observed are due to the seasonal adjustment of the TRS price through the CONSECANA-SP mechanism.

Furthermore, through the initial increase that is observed after the first year, the initial average sugarcane price (which is based on the start TRS price), is corrected by the system for the market selling prices that occur in the first harvest season. This type of correcting behavior was observed for any start TRS price explored in the sensitivity analysis. When external variables are changed or the biorefinery market is activated, the average sugarcane price is expected to show more unstable behavior. If market prices for all products remain somewhat constant, the average sugarcane price will also show a stable behavior.

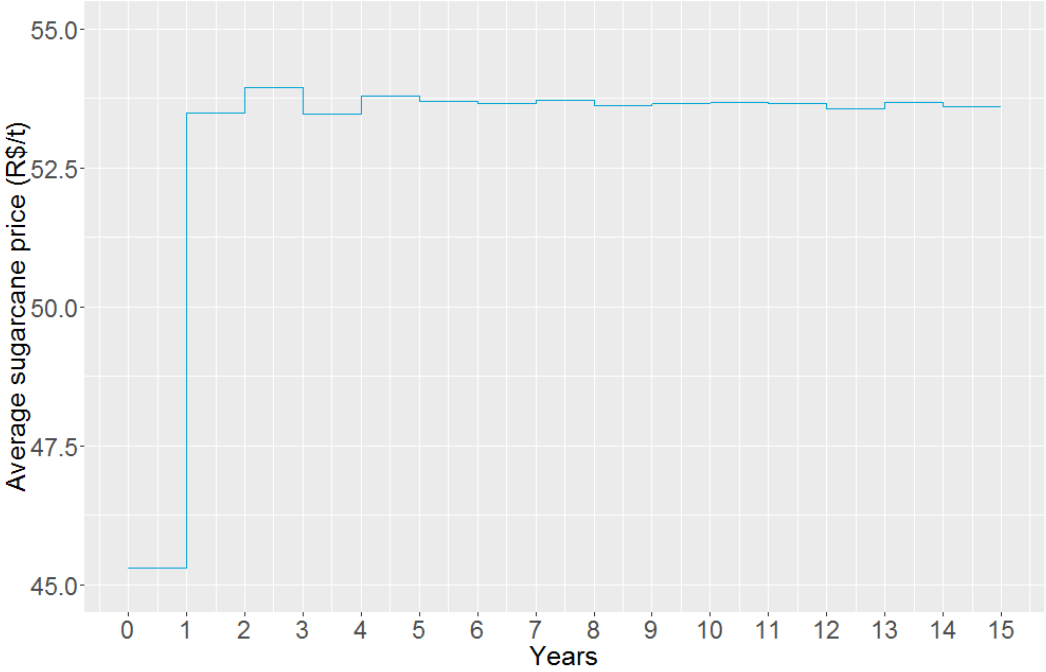


Figure 35: Biorefinery base model results without foreign trade – average sugarcane price

6.7 Conclusions

In chapter 5 and 6, the biorefinery model was conceptualized and implemented into a working NetLogo simulation model through a series of stages. Subsequently, base model simulations were executed, of which the results were presented in the previous section. From these results, several observations were made. First, it was seen that processing plants alter the quantity of sugarcane used for each product through the strategic decisions that were modelled, which also relates to car drivers' fuel consumption dynamics. Second, seasonal adjustment (although very small in constant external market conditions) of average sugarcane prices was seen. Furthermore, car drivers' consumption behavior is reflected in the observed dynamics of fuel prices. Provided these preliminary insights, the next chapter presents the design and results of a multitude of experiments that were performed. Through these experiments, the influence of policies and external variables (such as the global sugar price and the foreign hydrous ethanol price) on the emergence of biojet fuel and biosuccinic acid production was explored.

7

POLICY EXPLORATION:
THE BIOREFINERY MODEL IN ACTION

In this chapter, the previously implemented biorefinery model is used for policy exploration. First, section **(**7.1**)** presents the design of the three experiment sets (22 experiments in total) that were performed. The results of these experiments are then presented and analyzed by use of statistical and visual analysis in section **(**7.2**)**. Finally, in the last section insights are combined and their implications for policy development are elaborated on **(**7.3**)**.

7.1 Design of experiments

Through experimentation, a combination of one or more policies and external variables (a scenario) can be evaluated on its influence on the key outcomes of interest. *Figure 36* shows the experimental logic of the biorefinery model and all policies and external variables that can be experimented with.

Yet, not all possible scenarios are included in the analysis. Besides the fact that the number of scenarios are just too many to perform within the time constraint of this thesis, not all are relevant for answering the main research question. Therefore, a set of experiments was developed that was found sufficient to answer the main research question. Nevertheless, future researchers are encouraged to explore other scenarios as well, as will be discussed in chapter **(**8**)**.

In line with the main research question, the objective of the experiments performed in this chapter is to recommend a set of policies to increase demand satisfaction for biojet fuel and biosuccinic acid. The effectiveness of these policies is to be assessed under different scenarios of national and international competition between the sugar and ethanol market. Furthermore, a call was made to assess how the introduction of 2G biojet fuel technology could affect biojet fuel demand satisfaction.

Given these requirements, a set of 22 experiments was developed, which are categorized under three main experiment sets. These were found sufficient to answer the main research question. In line with the conceptualization and the research scope, the universal logic applicable to each experiment is: given an external biojet fuel and biosuccinic acid demand and related acceptable prices, to what extend can demand be satisfied? The values used for demand and prices are presented in *Table 15*.

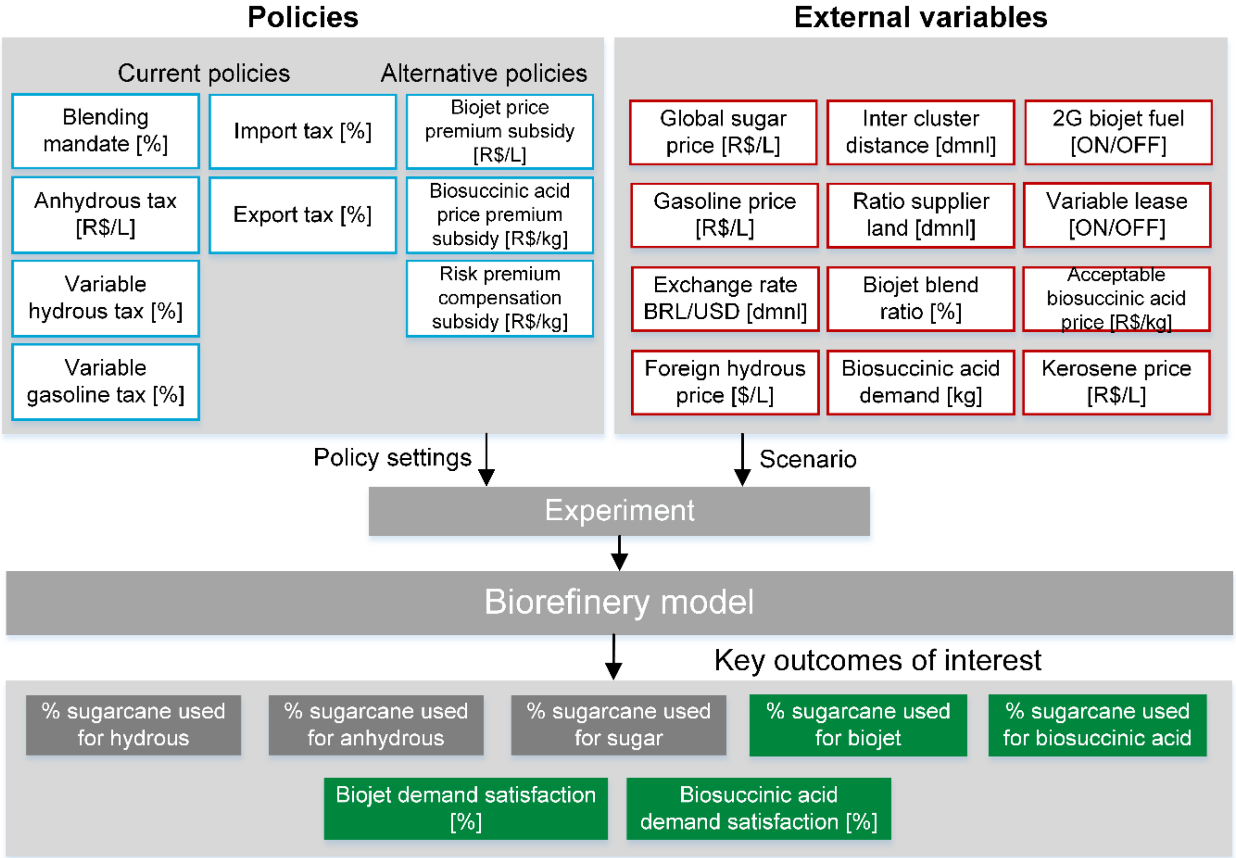


Figure 36: Experimental logic of the biorefinery model

Table 15: Price and demand settings used in all experiments

Variable	Value
Acceptable biojet fuel price	1.65 [R$/l] (50% higher than the kerosene price of 1.1)
Acceptable biosuccinic acid price	1.2 [R$/kg]
Daily biojet fuel demand	6980271 [l/day]
Daily biosuccinic acid	561644 [kg/day]

The first experiment set – "biorefinery baseline without international hydrous ethanol trade", serves as a baseline reference for the other experiments. In this experiment set, all external variables and policy settings were left in their baseline value. This allowed to gain insights into how biojet fuel and biosuccinic acid demand satisfaction might emerge when the existing policies (the formal institutions) and external variables remain constant. This experiment set consists of two parts: A and B. In part A, only 1G biojet fuel technology is activated, whereas in part B both 1G and 2G biojet fuel technology are activated. This might reveal how 2G bagasse-to-biojet fuel technology could change demand satisfaction to the 1G biojet fuel only case in part A. The results of the first experiment set are presented in (7.2.1).

Table 16: Design of experiment set 1

	Scenarios						Policy settings			
	1G	2G	External variables	Min	Max	Incr	Policy	Min	Max	Incr
A	ON	OFF	all in baseline value	N/A	N/A	N/A	baseline: current policy values			
B	ON	ON	all in baseline value	N/A	N/A	N/A	baseline: current policy values			

In the second experiment set – “abolishment of ethanol support”, the abolishment of current ethanol support policies was explored. As aforementioned, the aviation industry and chemical industry have pledged for a more ‘level playing field’; a sugarcane market in which incentives for the production of biojet fuel and biosuccinic acid are more competitive (IATA, 2013). This implies that current ethanol support policies are claimed to be a hindering factor for biojet fuel and biosuccinic acid demand satisfaction. In that light, the influence of three ethanol supporting policies was explored in experiment set 2: the blending mandate, variable hydrous ethanol tax and variable gasoline tax. This might provide insights into how biojet fuel and biosuccinic acid production would increase when a level playing field is created. The scenario spaces for each policy setting are presented in *Figure 36*. Furthermore, in line with the main research question, competition with the sugar market and road transport market was included in this experiment set. This was done through altering the global sugar price variable and the foreign hydrous ethanol price. In order to explore different combinations of the global sugar price and the foreign hydrous ethanol price, the experiment set consists of different experiments which have different settings for these prices: 2A, 2B, 2C, 2D, 2E, 2F, 2G, 2H and 2I. The results of the second experiment set are presented in section **(**7.2.2**)**.

Table 17: Design of experiment set 2

	Scenarios						Policy settings			
	1G	2G	External variables	Min	Max	Unit	Policy	Min	Max	Incr
A	ON	OFF	global sugar price foreign hydrous price	2.5 [high] 0.2 [low]		[R$/kg] [$/l]	Blending mandate	0, 15, 27		
B	ON	OFF	global sugar price foreign hydrous price	2.5 [high] 1.2 [high]		[R$/kg] [$/l]	Variable hydrous tax	12, 20, 30		
C	ON	OFF	global sugar price foreign hydrous price	0.5 [low] 0.2 [low]		[R$/kg] [$/l]	Variable gasoline tax	0		
D	ON	OFF	global sugar price foreign hydrous price	0.5 [low] 1.2 [high]		[R$/kg] [$/l]				
E	ON	OFF	global sugar price foreign hydrous price	1.24 [base] 0.2 [low]		[R$/kg] [$/l]				
F	ON	OFF	global sugar price foreign hydrous price	1.24 [base] 1.2 [high]		[R$/kg] [$/l]				
G	ON	OFF	global sugar price foreign hydrous price	2.5 [high] 0.66 [base]		[R$/kg] [$/l]				
G	ON	OFF	global sugar price foreign hydrous price	2.5 [high] 0.66 [base]		[R$/kg] [$/l]				
G	ON	OFF	global sugar price foreign hydrous price	2.5 [high] 0.66 [base]		[R$/kg] [$/l]				

Finally, the performance of three alternative policies is evaluated in the third experiment set. These policies are: (1) the biojet fuel price premium subsidy, (2) the biosuccinic acid price premium subsidy and (3) the risk premium compensation subsidy. A detailed explanation of these policies is provided in section **(**7.2.3**)**. Each policy's effectiveness was evaluated under three scenarios of global sugar price and foreign hydrous ethanol price, which corresponds to nine different experiments: 3A, 3B, 3C, 3D, 3E, 3F, 3G, 3H and 3I. Additionally, two experiments were added in which a combination of the price premium subsidy and risk premium compensation subsidy was evaluated under the base scenario of global sugar price and foreign hydrous ethanol price: 3J and 3K. The results of experiment set three are presented in section **(**7.2.3**)**.

Table 18: Design of experiment set 3

	Scenarios						Policy settings			
	1G	2G	External variables	Min	Max	Unit	Policy	Min	Max	Incr
A	ON	OFF	global sugar price foreign hydrous price	1.24 [base] 0.66 [base]		[R$/kg] [$/l]	biojet fuel price premium subsidy	0.5	3	0.5
B	ON	OFF	global sugar price foreign hydrous price	0.5 [low] 0.2 [low]		[R$/kg] [$/l]	biojet fuel price premium subsidy	0.5	3	0.5
C	ON	OFF	global sugar price foreign hydrous price	2.5 [low] 1.2 [low]		[R$/kg] [$/l]	biojet fuel price premium subsidy	0.5	3	0.5
D	ON	OFF	global sugar price foreign hydrous price	1.24 [base] 0.66 [base]		[R$/kg] [$/l]	biosuccinic acid price premium subsidy	0.5	3	0.5
E	ON	OFF	global sugar price foreign hydrous price	0.5 [low] 0.2 [low]		[R$/kg] [$/l]	biosuccinic acid price premium subsidy	0.5	3	0.5
F	ON	OFF	global sugar price foreign hydrous price	2.5 [low] 1.2 [low]		[R$/kg] [$/l]	biosuccinic acid price premium subsidy	0.5	3	0.5
G	ON	OFF	global sugar price foreign hydrous price	1.24 [base] 0.66 [base]		[R$/kg] [$/l]	risk premium compensation subsidy	0.5	3	0.5
H	ON	OFF	global sugar price foreign hydrous price	0.5 [low] 0.2 [low]		[R$/kg] [$/l]	risk premium compensation subsidy	0.5	3	0.5
I	ON	OFF	global sugar price foreign hydrous price	2.5 [low] 1.2 [low]		[R$/kg] [$/l]	risk premium compensation subsidy	0.5	3	0.5
J	ON	OFF	global sugar price foreign hydrous price	1.24 [base] 0.66 [base]		[R$/kg] [$/l]	biojet fuel price premium subsidy risk premium compensation subsidy	1 0.1	2 0.5	0.5 0.2
K	ON	OFF	global sugar price foreign hydrous price	1.24 [base] 0.66 [base]		[R$/kg] [$/l]	biosuccinic acid price premium subsidy risk premium compensation subsidy	0.1 0.1	0.3 0.5	0.1 0.2

7.2 Results of experiments

This section presents the results of the aforementioned experiments that were performed. Results are presented through a series of different types of graphs: boxplots, lines and stacked graphs. The purpose of these graphs, as well as guidance for interpreting them is provided in *Figure 37*.

Furthermore, in experiment set 3, statistical analysis was performed for the insights on which final recommendations are based. Each unique parameter setting within each experiment was repeated 30 times, to accommodate for statistical analysis based on the central limit theorem. Although a larger sample may further increase the reliability of these analysis, a compromise had to be made between increased reliability and a manageable simulation time. For further details about the statistical methods used and SPSS outputs, one is referred to APPENDIX V.

Support for reading the graphs in this section

- **Boxplot graphs**
  - Used to visualize the variability of the variable of interest.
  - Each boxplot has a width of 1 year.
  - The body of the boxplot indicates the lower and upper 25% quartile.
  - The lower and upper vertical black lines (whiskers) indicate the variability of values outside the lower and upper quartiles. Dots outside the whiskers indicate outlier values.
  - The horizontal black line in within each boxplot indicates the median value.
- **Line graphs**
  - Simple line graphs are used to visualize intra-season dynamics that cannot be captured by boxplots.
- **Stacked graphs**
  - Are used to express what portion each value contributes to the sum of all variables (100%).
  - Each colored area represents a variable, and the size of the are represents its value.
- **Grid graphs**
  - Are used to visualize results of experiments in which multiple variables and settings are explored. These graphs aim to facilitate comparison of results of multiple settings.
  - *2 axes grid*: to compare results of multiple experiments with no policy scenarios.
  - *3 axes grid*: to compare results of multiple experiments with one policy variable. In this case, only the upper axis represents policy settings.
  - *4 axes grid*: to compare results of multiple experiments with two policy variables. In this case, both the upper and right axes represent the policy settings.

Figure 37: Support for reading the graphs in this section

7.2.1 Experiment set 1: Biorefinery baseline results without foreign trade

Experiment 1A: 1G biojet fuel technology only scenario

For the baseline scenario, it was found that demand satisfaction for both biojet fuel and biosuccinic acid is zero, when only 1G biojet fuel technology is activated. Partial explanation for the lack of demand satisfaction may be found in the higher average sugarcane prices that biorefineries pay compared to conventional plants, as can be seen from *Figure 38*. Furthermore, the boxplots indicate that the average sugarcane price paid by biorefineries also has more variance than for conventional plants.

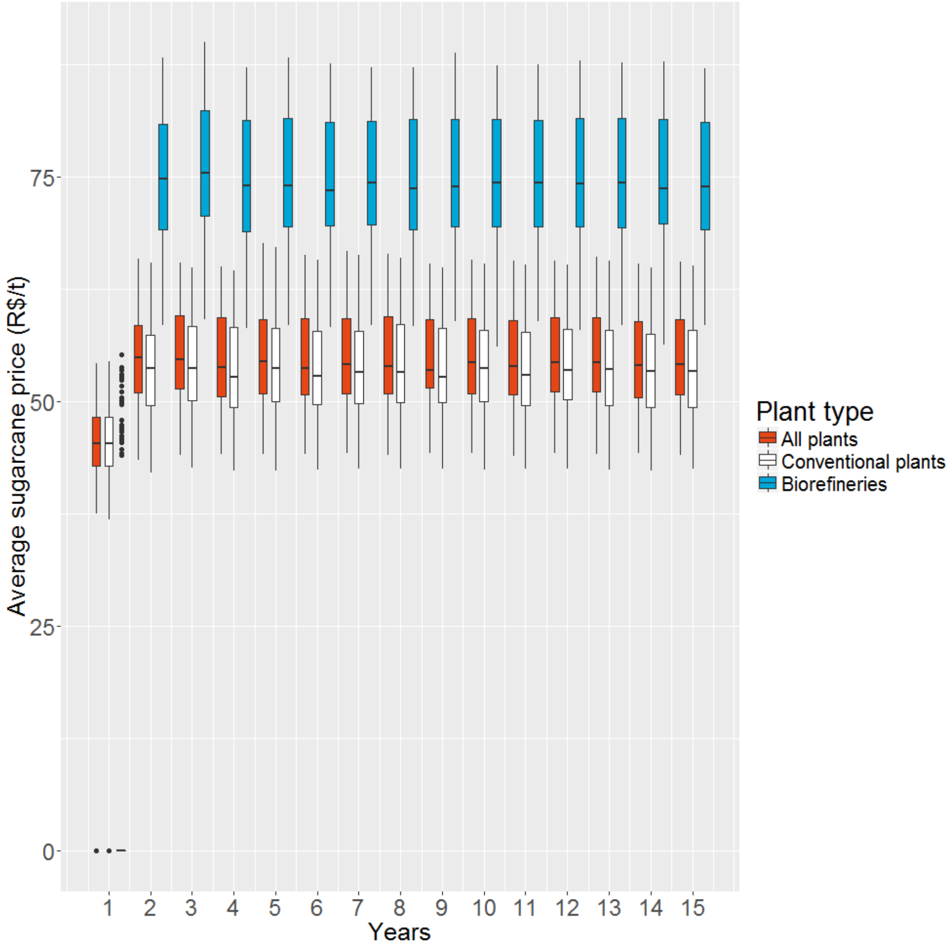


Figure 38: Experiment 1A – average sugarcane price

Experiment 1B: 1G and 2G biojet fuel technology scenario

The aforementioned results for biojet fuel are very different when 2G biojet fuel technology is activated. As can be seen from *Figure 39*, biojet fuel demand satisfaction is nearly fully met when 2G biojet fuel is activated. In this case, 1G biojet fuel production is still zero, and all demand satisfaction results from 2G biojet fuel production (*Figure 40*). The cyclical changes in 2G biojet production that can be seen from the figure are due to the seasonality of sugarcane supply as mentioned earlier in this thesis.

Furthermore, one can see that although the average sugarcane price of biorefineries is higher than for conventional processing plants (as was also the case in the 1G biojet only scenario), biojet demand can still be met. This is due to the fact that the average sugarcane price does not influence the decision to invest in or produce 2G biojet, nor does it influence its production costs. As described in chapter (5), the investment decision for 2G biojet fuel depends on the CAPEX, OPEX and estimated profits.

Bagasse is used for the production of 2G biojet. As was seen from the conceptualized pricing mechanism, the average sugarcane price is only influenced by the TRS price. Naturally, 2G biojet technology does not have an effect on the production of biosuccinic acid, and thus, the demand satisfaction for biosuccinic acid remains at zero.

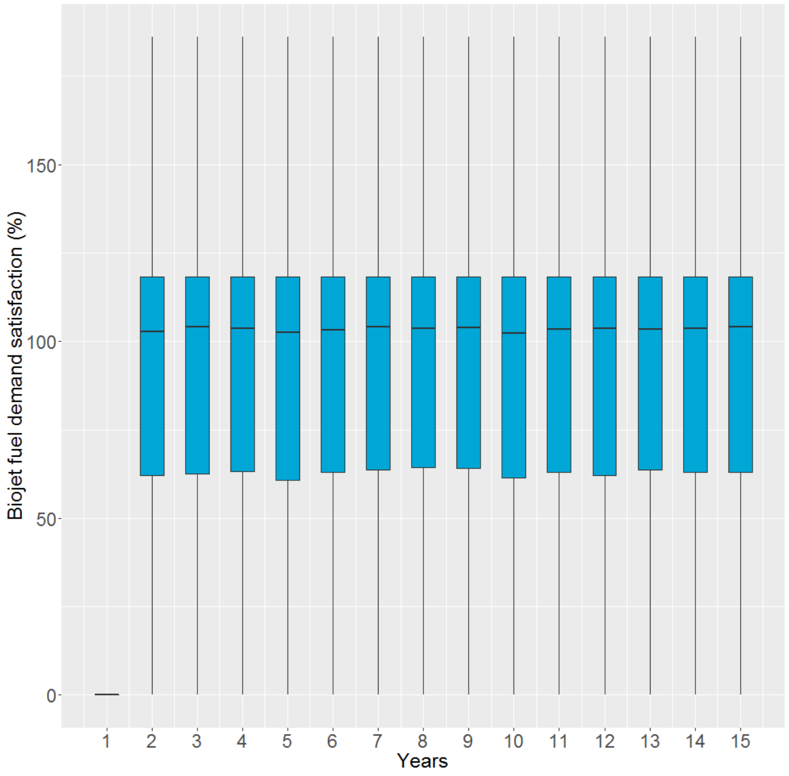


Figure 39: Experiment 1B – biojet fuel demand satisfaction

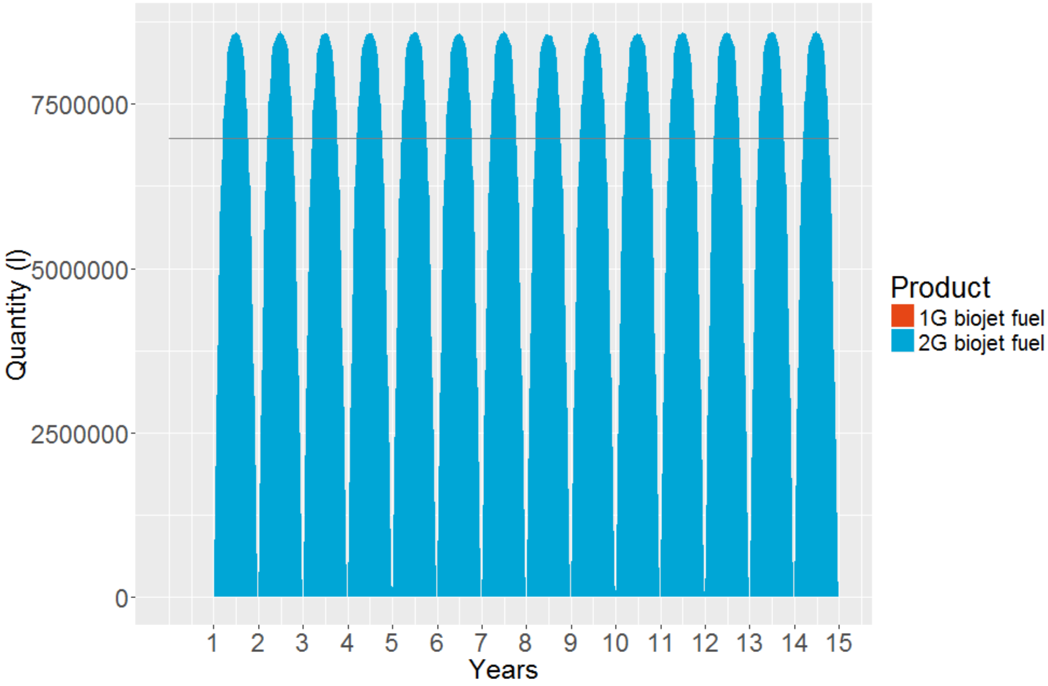


Figure 40: Experiment 1B – biojet fuel production

7.2.2 Experiment set 2: Abolishment of government ethanol support

As aforementioned, the second experiment set consists of nine experiments that have a unique setting of the global sugar price and foreign hydrous ethanol price. For reader comfort, *Table 19* provides a structured overview of the price settings used in each experiment.

Table 19: Settings for sugar and foreign hydrous ethanol price for experiment set 2

Global sugar price [R$/kg]				
High	**Base**	**Low**		
Experiment 2A	Experiment 2E	Experiment 2C	**Low**	Foreign hydrous ethanol price [$/l]
Experiment 2G	Experiment 2I	Experiment 2H	**Base**	
Experiment 2B	Experiment 2F	Experiment 2D	**High**	

Biojet fuel demand satisfaction was found to be zero in all nine experiments that were performed. This implies that under all explored combinations of global sugar price settings, foreign hydrous ethanol price settings, variable hydrous tax settings and blending mandate settings, biojet demand satisfaction cannot be achieved for a biojet fuel price of 1.65 R$/l. Even in the case of highest ethanol discouragement (variable hydrous tax = 30% and the blending mandate = 0%), no demand satisfaction is observed.

A partial explanation for this might be found in the high average sugarcane price paid by biorefineries compared to conventional plants. *Figure 41*, shows the sugarcane price paid by biorefineries and conventional plants for the scenario of highest ethanol discouragement.

- As can be seen from the figure, the average sugarcane price paid by biorefineries often tends to be higher than for conventional plants.
- Furthermore, one can see that that the price for biorefineries generally shows far more variance than for conventional plants. This variance results from the negotiations between biorefineries and suppliers, in which the heterogeneity of risk profiles of both agents can give rise to a wide envelope of different average sugarcane prices.
- Another factor in the lack of biojet fuel demand satisfaction may be that the acceptable biojet fuel price of 1.65 R$/l (50% higher than the fossil fuel kerosene price) is just too low for biojet fuel production to be profitable, in particular if one considers that the production costs of biojet fuel are largely determined by the average sugarcane price. These observations suggest two directions for the development of alternative policies. First, a policy could be developed that stimulates reduction of the average sugarcane price paid by biorefineries. Second, policy solutions may be found in subsidizing the biojet fuel price, in order to stimulate biojet fuel

production. In that light, alternative policies are explored in experiment set 3 that might be able to stimulate the emergence of biojet fuel demand satisfaction.

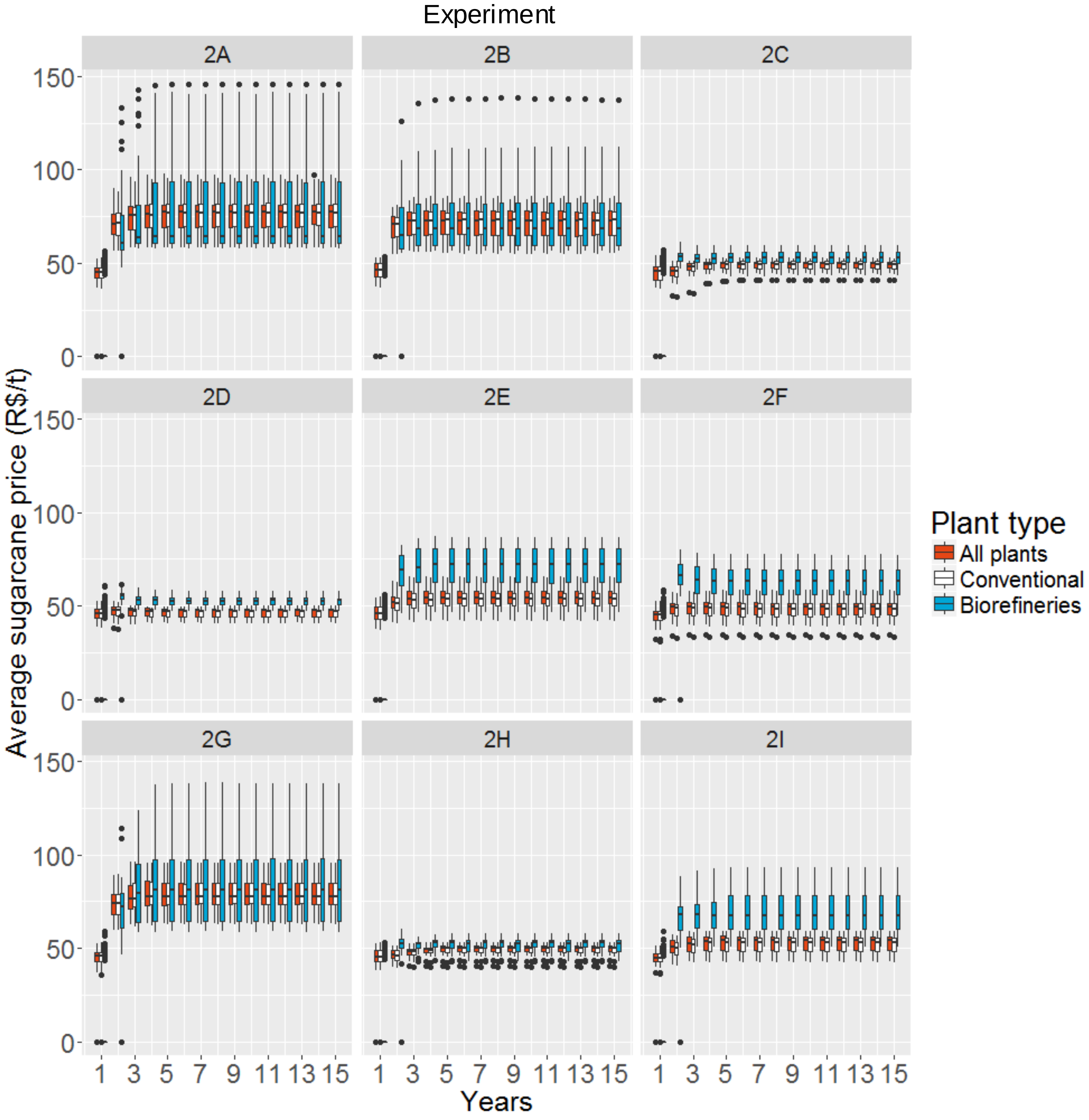


Figure 41: Experiment set 2 – average sugarcane price with highest domestic ethanol discouragement (blending mandate = 0 and variable hydrous tax = 30%)

Figure 42 show the demand satisfaction for biosuccinic acid that was observed for each experiment. Whereas no demand satisfaction was observed for biojet fuel, there is demand satisfaction for biosuccinic acid. Several observations can be made from *Figure 42*.

- First, biosuccinic acid demand satisfaction is highest in experiment C (both a low global sugar price and foreign hydrous ethanol price), when ethanol discouragement is highest (variable hydrous tax = 30% and the blending mandate = 0%). The second highest biosuccinic demand satisfaction is observed for experiment E, in which the global sugar price is low and the foreign hydrous ethanol price is at its base value.

- Second, for the scenario in which ethanol discouragement is highest, biosuccinic demand satisfaction is lowest in experiment A, B and G. In all these three experiments, the global sugar price is, which suggests that the global sugar price has a high influence on the emergence of biosuccinic acid production.

- Thirdly, the results indicate that an increase in foreign hydrous ethanol price, corresponds to lower biosuccinic acid demand satisfaction, and vice versa. Yet, as expected exports (when the foreign hydrous ethanol price is high) have a higher impact than ethanol imports (when the foreign hydrous ethanol price is low). This is due to the fact that traders have more export capacity than import capacity, in line with the observed real-world behavior.

- Finally, presents the observed production ratios of processing plants for the scenario of highest ethanol discouragement. Since a relatively very small amount of sugarcane is used for biosuccinic acid production, the observed visual production ratio for biosuccinic acid is negligible.

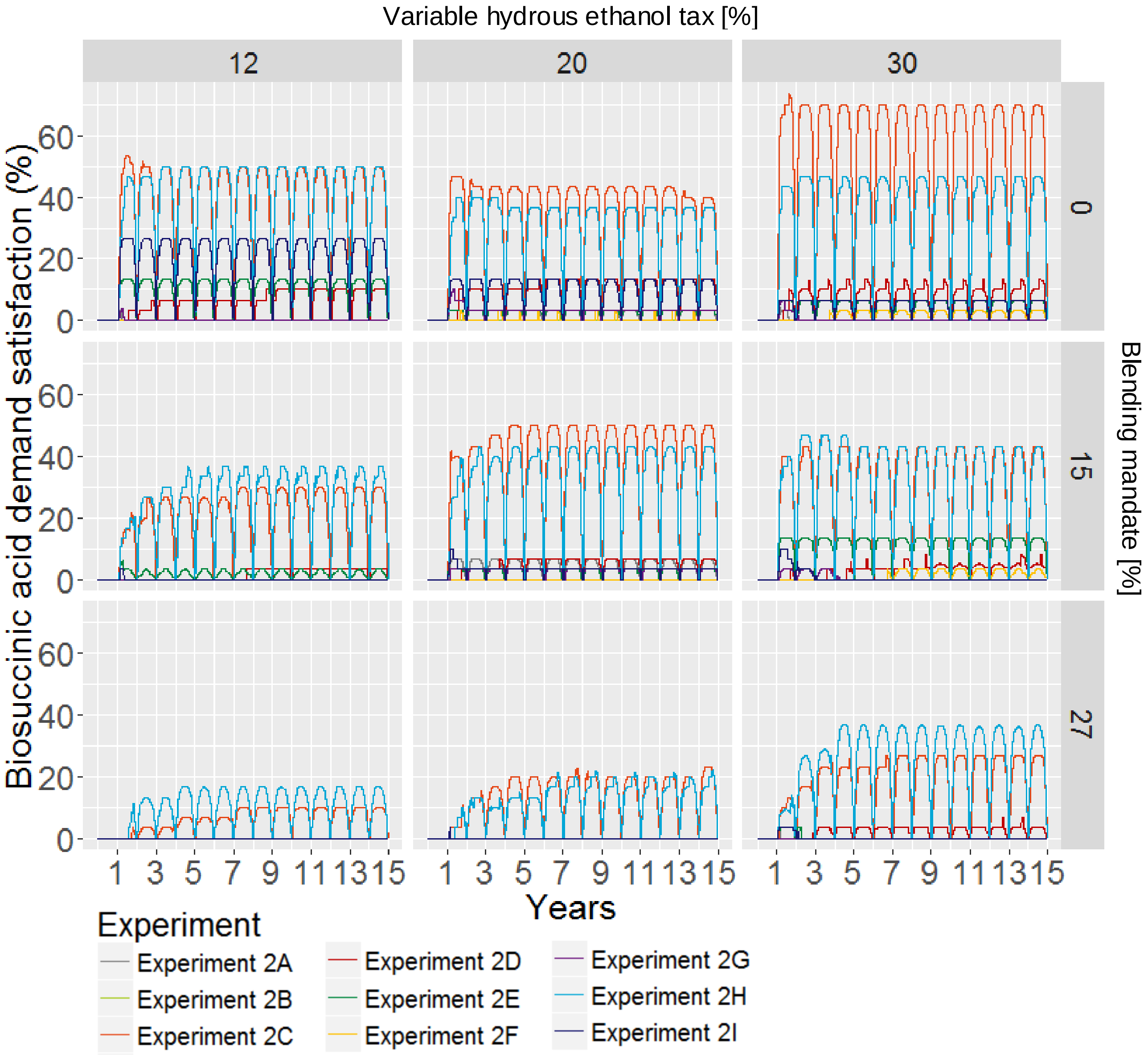


Figure 42: Experiment set 2 – biosuccinic acid demand satisfaction

Furthermore, from *Figure 43* it can be seen that flex processing plants adjust their production ratios (the quantity of sugarcane used for each product), but the sugar ratio is never higher than the ethanol ratio. This is due to two main reasons.

- First, the presented data is for all processing plants combined, which also includes ethanol-only plants. Therefore, the anhydrous and hydrous ethanol ratio combined are likely to be always higher than the sugar ratio.

- Second, changes in the sugar and ethanol ratio depend on the global sugar price and foreign hydrous ethanol price. When the global sugar price is high (experiment 2A, 2B and 2G), the sugar ratio is relatively high, whereas the sugar ratio is relatively low when the foreign hydrous ethanol price is high.

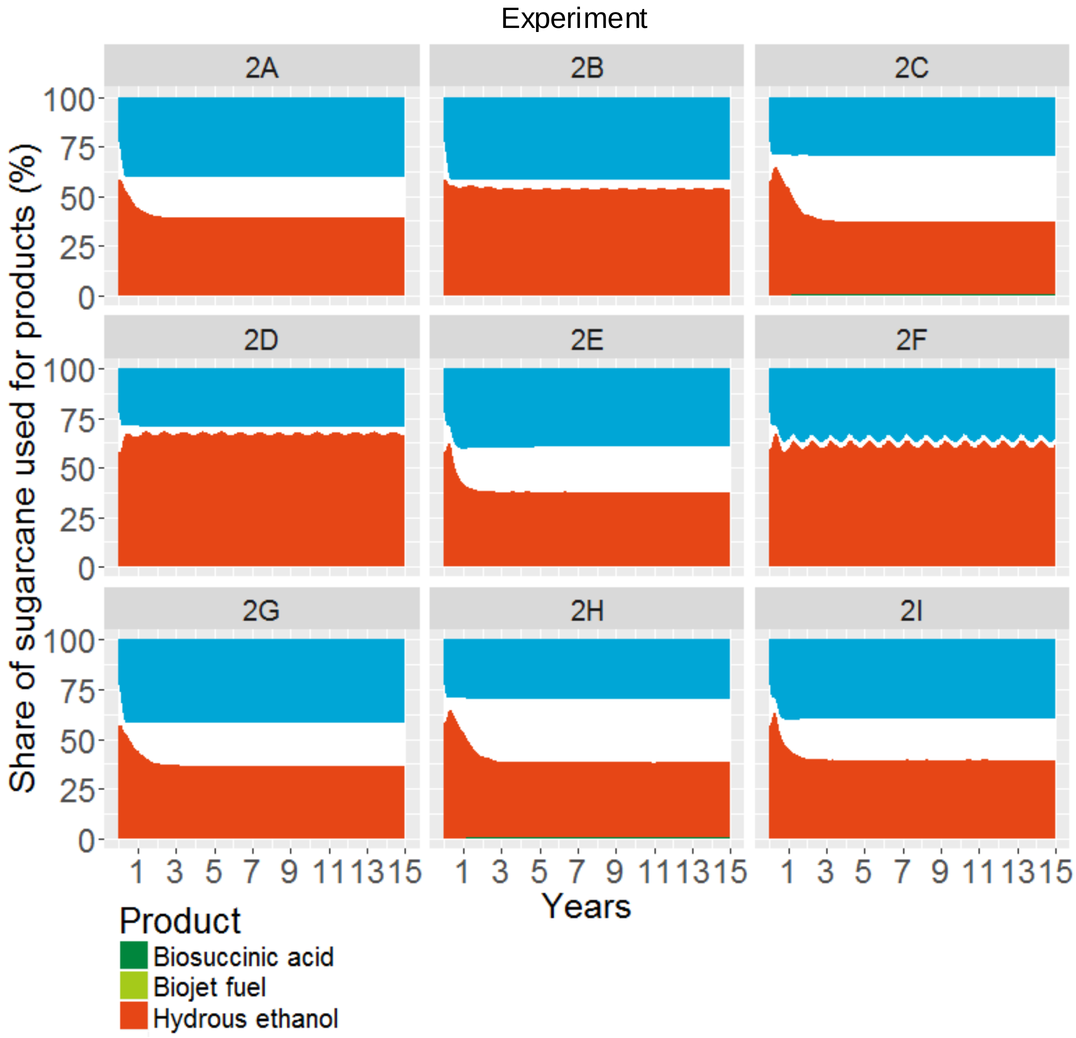


Figure 43: Experiment set 2 – production ratios with highest domestic ethanol consumption discouragement (blending mandate = 0 and variable hydrous tax = 30%)

In conclusion, increasing abolishment of ethanol support tends to correspond to higher demand satisfaction levels for all experiments. Furthermore, competition with the sugar and foreign hydrous ethanol market has a large impact on the observed biosuccinic acid demand satisfaction.

7.2.3 Experiment set 3: exploration of alternative policies

The previous analysis of experiment set 2 has shown that even in the scenario of highest ethanol discouragement, no biojet fuel demand satisfaction is observed. Furthermore, two factors were mentioned that could be attributing factors in lacking demand satisfaction: a high average sugarcane for biorefineries and a too low biojet price. In that light, two alternative policies are proposed and evaluated: a biojet price premium subsidy and a risk premium compensation subsidy. The former attempts to increase the biojet price paid to biorefineries (a demand side policy) and the latter attempts to reduce the average sugarcane price for biorefineries (a supply side policy).

Both policies are of the market conduct regulation type, as they attempt to influence agents' decision, instead of the market structure. The biojet price premium subsidy is merely an increase of the biojet price that is paid to biorefineries, which targets to increase the profitability of biojet fuel production. Therefore, the biojet price paid by airports remains the same. On the supply side, the risk premium compensation subsidy targets to decrease the contracted TRS price of supply contracts between biorefineries and suppliers. By doing so, the average sugarcane price for a specific biorefinery could be decreased. Yet, this depends on the mix of sugarcane supply of each individual biorefinery. Namely, the average sugarcane price paid for sugarcane produced by the biorefinery itself is not reduced by this policy, as it was assumed that landowner lease contracts remain constant over the model runtime (see chapter 5).

Although demand satisfaction was observed for biosuccinic acid, the demand was not fully satisfied in any of the scenarios. Therefore, a similar price subsidy policy as for biojet fuel was explored: biosuccinic acid price premium subsidy. Furthermore, the risk premium compensation subsidy was also explored for biosuccinic acid.

Experiment set 3 was designed to explore how the proposed alternative policies can increase biojet fuel and biosuccinic acid demand satisfaction under different scenarios of the global sugar price and the foreign hydrous ethanol price. The first nine experiments: 3A until 3I explore the effectiveness of each policy separately. In attempt to reduce the number of scenarios to be evaluated, three scenarios were selected based on the previous insights gained through experiment set 2: the most favorable scenario, the base scenario and the least favorable scenario (*Table 20*). Through this selection, it was ought possible to sufficiently explore how policy effectiveness could be influenced by the global sugar price and foreign hydrous ethanol price. Furthermore, through experiment 3J and 3K, the combination of price premium subsidies and the risk premium compensation subsidy was evaluated. Finally, for all experiments in the third experiment set the policy costs were recorded and analyzed. This allowed to compare the cost-benefit performance of each policy.

Table 20: Settings for sugar and foreign hydrous ethanol price for experiment set 3 🟩 most favorable scenario ⬜ base scenario 🟧 least favorable scenario

Global sugar price [R$/kg]				
High	Base	Low		
N/A	N/A	Experiment 3B Experiment 3E Experiment 3H	Low	Foreign hydrous ethanol price [$/l]
N/A	Experiment 3A Experiment 3D Experiment 3G	N/A	Base	
Experiment 3C Experiment 3F Experiment 3I	N/A	N/A	High	

Biojet fuel price premium subsidy

Figure 44 shows the biojet fuel demand satisfaction that was observed for experiment 3A, 3B and 3C, for six different levels of the biojet price premium subsidy. A series of observations can be made from the graph.

- First, in line with expectations, the effectiveness of the policy tends to be lower when the global sugar price and the foreign hydrous ethanol price are highest (3C), and highest when the global sugar price and the foreign hydrous ethanol price are lowest (3A). This also reflects in the production ratios of plants (the graph can be found in APPENDIX V). This is confirmed by the findings that were made through statistical analysis, of which the results are shown in *Table 21*. The subsidy levels shown in this table are the levels for which highest demand satisfaction was observed (no significant difference in demand satisfaction is observed when they are further increased). The average biojet fuel demand satisfaction is the average satisfaction over the entire length of a run.

Table 21: Outcomes of statistical analysis for experiment 3A, 3B and 3C (for more details about the statistical analysis, please see APPENDIX V)

Experiment	Most effective biojet price premium subsidy level	Average biojet fuel demand satisfaction
3A	2.5 R$/l	54.5%
3B	2 R$/l	51.0%
3C	2 R$/l	33.8%

- Second, the results in *Table 21* show that full biojet demand satisfaction is never achieved. Even when the biojet price paid to biorefineries is at a level of 4.65 R$/l (3 R$/l subsidy and 1.65 R$/l airport price), not enough biojet is produced. One of the reasons for this could be that the most risk averse processing plants will never invest in biojet fuel production capacity. Furthermore, the seasonality of sugarcane supply plays an important role in the observed demand satisfaction. Since each boxplot represents a whole year, biojet demand satisfaction can never be achieved on a yearly basis, because of the low production quantities in the tales of the harvest season. This means, biojet demand satisfaction might be (almost) completely satisfied during production peaks, not on an average yearly basis.

- Finally, the biojet price premium subsidy seems an effective measure to increase biojet fuel demand satisfaction. But, full demand satisfaction is never achieved. Furthermore, the policy's effectiveness significantly decreases when there is strong competition with the sugar and foreign hydrous ethanol market (experiment 3F). Finally, in the base scenario, a price premium subsidy of 2.5 R$/l seems sufficient to increase biojet demand satisfaction up to the maximum possible level the system allows. Yet, this reflects in a biojet price paid to biorefineries of 4.15 R$/l, which is well above the acceptable price paid by airports of 1.65 R$/l.

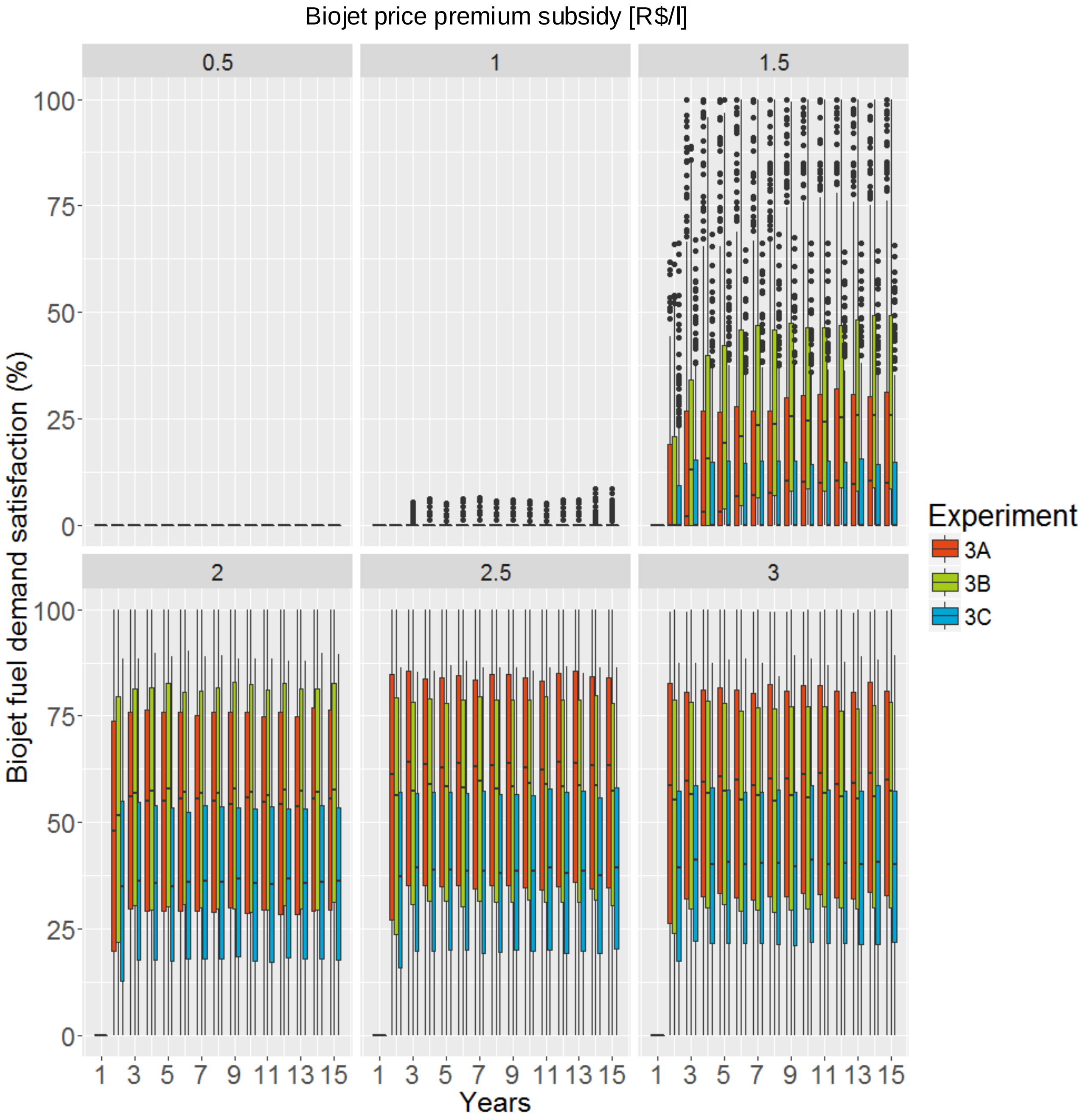


Figure 44: Experiment 3A, 3B and 3C – biojet demand satisfaction when biojet price premium subsidy policy is activated

Biosuccinic acid price premium subsidy

Figure 45 shows the biosuccinic acid demand satisfaction when the price premium for biosuccinic acid is activated. Furthermore, *Table 22* presents the findings of statistical analysis. Several insights can be gained from these results.

Table 22: Outcomes of statistical analysis for experiment 3D, 3E and 3F (for more details about the statistical analysis, please see APPENDIX V)

Experiment	Most effective biosuccinic acid price premium subsidy level	Average biosuccinic acid demand satisfaction
3D	1 R$/kg	77.8 %
3E	0.5 R$/kg	68.1 %
3F	1.5 R$/kg	38.4 %

- First, in line with expectations, the effectiveness of the biosuccinic acid price premium subsidy is relatively higher than was the case with the biojet fuel price premium subsidy. As can be seen from the table, an average biosuccinic acid demand satisfaction of nearly 80% is achieved in the base scenario, with a subsidy level of 1 R$/kg. Still, this corresponds to a very small production ratio (the graph can be found in APPENDIX V). In contrast, when competition with sugar and ethanol exports is high (3F), a subsidy level of 1.5 R$/kg is needed to achieve only half of this demand satisfaction.

- Second, the boxplots indicate a different level of variance for each experiment. Experiment 3D shows the least variance, indicating the highest policy robustness of the biosuccinic acid price premium subsidy. In contrast, for experiment 3F, very large variance is observed. For instance, for a subsidy level of 2 R$/kg, demand satisfaction moves between nearly zero and nearly one hundred, with a median around 45%. This indicates low policy robustness in this case. Partial explanation for this may be found in the increased competition with sugar and ethanol exports.

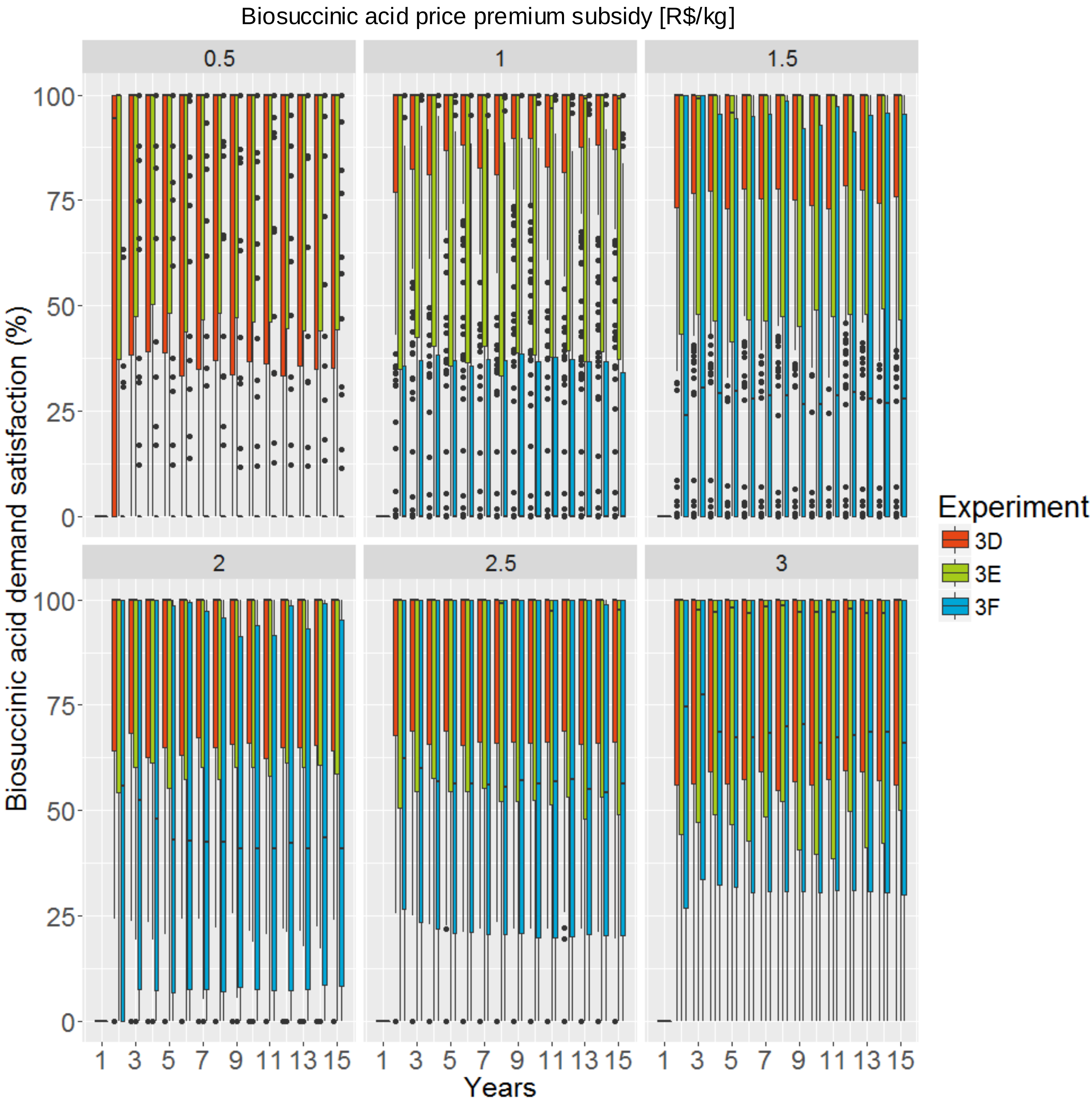


Figure 45: Experiment 3D, 3E and 3F – biosuccinic acid demand satisfaction when biosuccinic acid price premium subsidy policy is activated

Risk premium compensation subsidy

No biojet nor biosuccinic acid demand satisfaction was observed for any level of the risk premium compensation subsidy for experiment 3G, 3H and 3I. This suggests that merely reducing the average sugarcane price paid by biorefineries is not sufficient to increase demand satisfaction. Therefore, experiment 3J and 3K presented in the next two sections explore the effectiveness of combining the risk premium compensation subsidy with price premium subsidies.

Combining the biojet price premium and risk compensation subsidy

In experiment 3J, a combination of the biojet price premium and risk compensation subsidy was explored. This was only done for the base scenario of the global sugar price and foreign hydrous ethanol price. The results of this experiment are shown in *Figure 46* and the results of statistical analysis are shown in *Table 23*. If one compares experiment 3J with 3A (where only the price premium subsidy was activated and with a base sugar and foreign hydrous ethanol price), several observations can be made.

Table 23: Outcomes of statistical analysis for experiment 3J (for more details about the statistical analysis, please see APPENDIX V)

Experiment	Most effective subsidy levels	Average biojet fuel demand satisfaction
3J	biojet price premium subsidy: 2 R$/l risk premium compensation subsidy: 0.1 R$/kg TRS	52.5 %
3A vs. 3J	no significant difference	

- First, the boxplots suggest that addition of the risk premium leads to a higher biojet demand satisfaction only in some instances. Yet, the difference in biojet demand satisfaction was not found to be statistically significant in any of the cases compared with experiment 3A. In fact, statistical analysis showed that at a biojet price premium subsidy of 1.5 R$/l, the average biojet demand is significantly lower when the risk premium compensation subsidy is increased. Thus, in this range of combinations, the policy appears to be counter effective.

- Furthermore, when the price premium subsidy is 2.0 R$/l, an increase of the risk premium subsidy has no significant effect on demand satisfaction. Combining a biojet fuel price premium of 2 R$/l and a risk premium compensation subsidy of 0.1 R$/kg TRS was found to have the highest average biojet fuel demand satisfaction of 52.5%. In line with the previous observations about the seasonality of production, full demand satisfaction is never achieved.

- In conclusion, the results indicate that combining both policies does not have any significant effect on biojet fuel demand satisfaction. In some instances, it even has a counter effective working. Partial explanation for this may be found in the fact that the overall average sugarcane price of the biorefinery is decreased, but this sugarcane can still be used for any product. Thus, not only the production costs of biojet fuel are decreased, but also for all other competing products (sugar, ethanol and biosuccinic acid). This could then lead plants to decide to prefer producing these products instead of biojet fuel. Therefore, more refined policy development is recommended to ensure that the low priced sugarcane would specifically be used for biojet production and biosuccinic acid production.

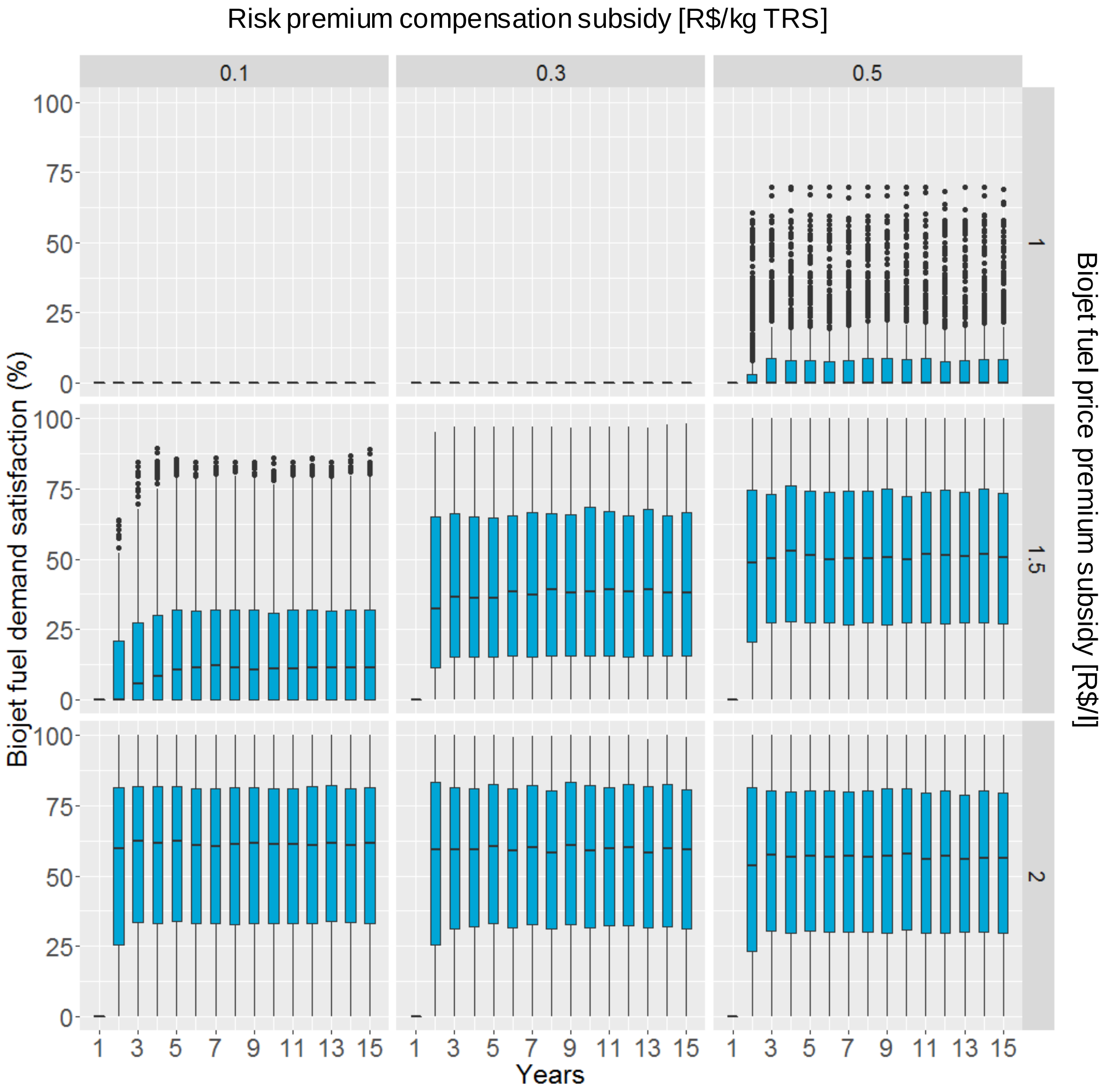


Figure 46: Experiment 3J – biojet demand satisfaction when both biojet price premium subsidy and risk premium compensation subsidy are activated

Combining the biosuccinic acid price premium and risk compensation subsidy

Similar as for the previous experiment, the price premium and risk compensation subsidy were evaluated for biosuccinic acid. The results of experiment 3K are shown in *Figure 47* and the results of statistical analysis are shown in *Table 24*. A series of observations can be made from these results.

Table 24: Outcomes of statistical analysis for experiment 3K (for more details about the statistical analysis, please see APPENDIX V)

Experiment	Most effective subsidy levels	Average biosuccinic acid demand satisfaction
3K	Biosuccinic acid price premium subsidy: 0.5 R$/kg risk premium compensation subsidy: 0.1 R$/kg TRS	72.8 %
3D vs. 3K	no significant difference	

- Although the boxplots in *Figure 47* might suggest otherwise, the combination of the biosuccinic acid price premium subsidy and the risk premium compensation subsidy shows no significantly different biosuccinic acid demand satisfaction, compared with experiment 3D.

- Furthermore, at a biosuccinic acid price premium level of 0.3 R$/l counterintuitive behavior is observed. Namely, the biosuccinic acid demand satisfaction seems to decrease when the risk premium compensation subsidy is increased. This indicates that in this case, the risk premium compensation subsidy is counter effective. The difference in demand satisfaction observed for a compensation subsidy of 0.1 R$/kg TRS or 0.5 1 R$/kg TRS is however not statistically significant. Thus, there is no difference in demand satisfaction for both subsidy levels.

- At the most effective subsidy levels mentioned in *Table 24*, an average biosuccinic acid demand satisfaction of 72.8% is observed. A similar “ceiling” was observed in the previous experiment of biojet fuel. Partial explanation might be found in the fact that the overall average sugarcane price of biorefineries is lowered through the risk premium compensation subsidy.

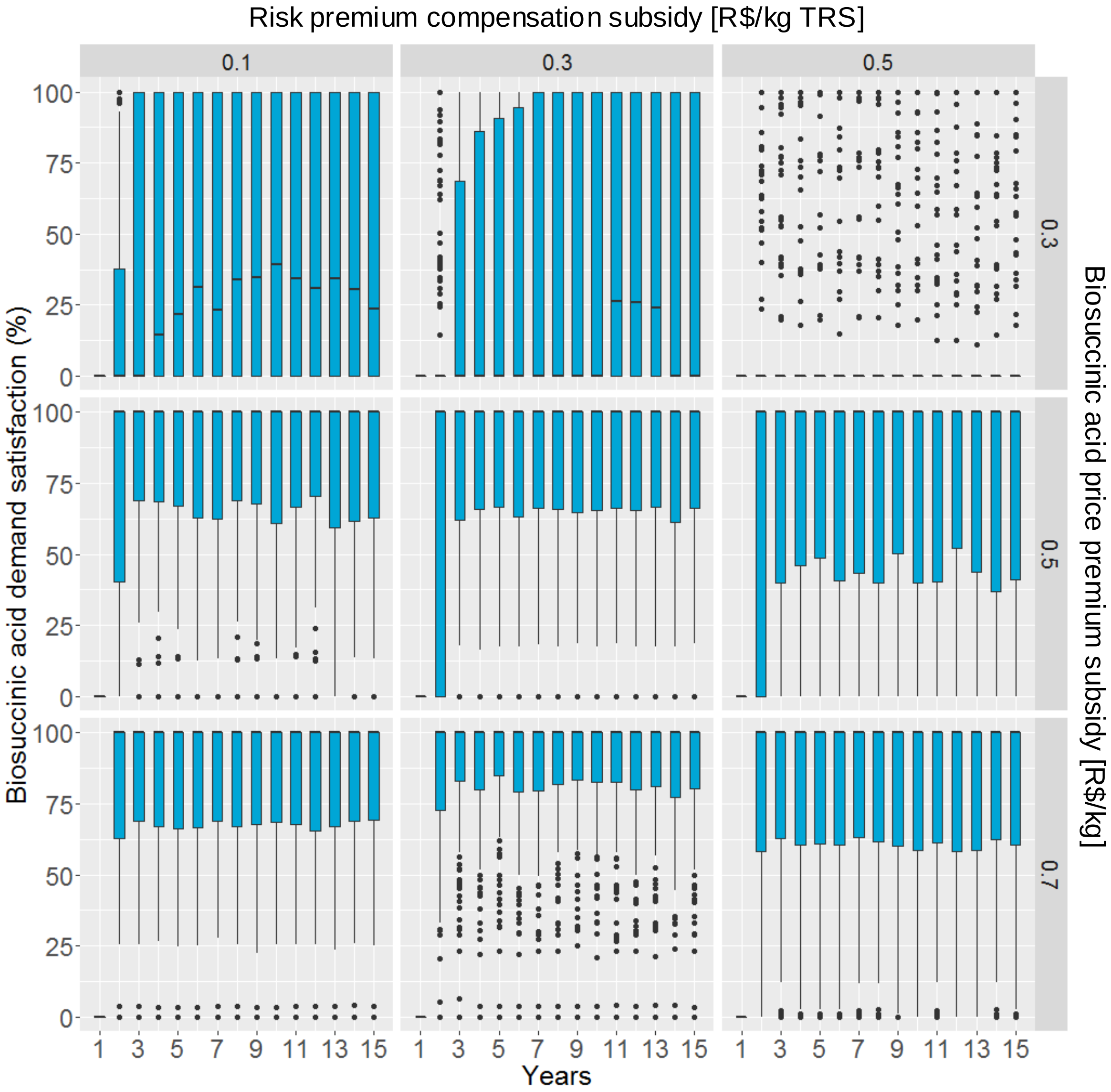


Figure 47: Experiment 3K – biosuccinic acid demand satisfaction when both biosuccinic acid price premium subsidy and risk premium compensation subsidy are activated

Costs-effectiveness comparison of policies

For all policy experiments, the daily policy expenditures were also recorded to compare cost-effectiveness of the different policies. Since the risk premium compensation was found to have no effect on demand satisfaction at any setting, it is not considered for comparison. *Table 25* shows the comparisons tested through statistical analysis. These results indicate that for both biojet fuel (3A) and biosuccinic acid (3D), the price premium-only policy has significantly lower daily policy costs than the combined policies. In line with the previous insights, it can thus be concluded that the risk premium compensation subsidy is not cost-effective at all; it does not have any significant effect on demand satisfaction for either product, while it does significantly increase the daily policy costs.

Table 25: Daily policy costs and outcomes of statistical analysis (for more details about the statistical analysis, please see APPENDIX V)

Experiment	Policy costs
3A	Average daily policy costs: 9.511.227 R$
3J	Average daily policy costs: 10.729.266 RS
3A vs. 3J	The average daily policy costs for 3A are lower than for 3J
3D	Average daily policy costs: 436.877 R$
3K	Average daily policy costs: 1.145.929 R$
3D vs. 3K	The average daily policy costs for 3D are lower than for 3K

7.3 Insights: implications for policy development

The proceeding analysis revealed some noteworthy insights into the competitive nature of the Brazilian sugarcane market, and its implications for the emergence of biojet fuel and biosuccinic acid production through the HIP biorefinery concept. Yet, what do these insights mean for policy development? What aspects should be taken into account in the design of effective policies that could promote biojet fuel and biosuccinic acid production?

First, existing ethanol support policies certainly put ethanol at a competitive advantage compared to biojet fuel and biosuccinic acid. It was seen that demand satisfaction increases when ethanol support is lowered and a more level playing field is created. However, for biojet fuel, even when all ethanol support is abolished, no demand satisfaction was observed. Furthermore, the results for biosuccinic acid indicate that, although abolishment of ethanol support seems to promote biosuccinic acid production (and probably also biojet fuel, if the selling price would be higher), merely abolishment is not enough to achieve the target demand satisfaction. This suggests that biojet fuel and biosuccinic acid production needs to be actively supported through government policies.

Demand side policies (a price premium subsidy for biojet fuel and biosuccinic acid) were found to be very effective to increase demand satisfaction for both products. Yet, at the highest effective premium subsidy level of 2.5 R$/l, biojet fuel demand satisfaction is no higher than 54.5%. For biosuccinic acid, a price premium of 1 R$/l corresponds to a demand satisfaction of 77.8%. For both products, no significant increases in demand satisfaction could be achieved for higher subsidy levels. In that light, also a supply side policy was developed.

The supply side policy that was explored – the risk premium compensation subsidy – aimed to reduce the average sugarcane price paid by biorefineries. Although the sugarcane price was very responsive to this subsidy, this did not reflect in any significant increase of demand satisfaction for both products. When combined with the price premium subsidy, it even proved counter effective in some cases. Therefore, it was concluded that the risk premium compensation subsidy, either as a single policy or combined, is not effective to increase demand satisfaction for both products. A likely reason for this policy's ineffectiveness is the fact that the lower-priced sugarcane can still be processed into all different products, based on the production decisions of a biorefinery. This means that the production costs for all products are lowered, and thus the net effect of the policy on demand satisfaction is insignificant. Therefore, more refined policy development is needed to ensure that the lower-priced sugarcane would specifically be used for biojet production and biosuccinic acid production.

Furthermore, it was seen that the observed demand satisfaction is significantly influenced by competition with the sugar and foreign hydrous ethanol market. Such competition can influence policy effectiveness and should be taken into account in further policy development.

The introduction of 2G bagasse-to-biojet proved very effective; biojet fuel demand satisfaction was nearly entirely fulfilled. Therefore, this technology could present a significant opportunity. Yet, several barriers might present themselves. First, as indicated by Mr. Pierossi, there is increasing discontent among farmers with the fact that processing plants do not have to remunerate for bagasse under the CONSECANA-SP mechanism, while they generate valuable bioelectricity with this bagasse. Furthermore, processing plants would have to procure sugarcane residues, in order to generate bioelectricity to power the plant, if bagasse is to be used for biojet fuel production. This might involve additional costs. Furthermore, if 2G bagasse-to-ethanol technology finds commercialization, competition for bagasse might arise as well.

Finally, the seasonality of sugarcane production and processing should be addressed in policy development. If it is desirable to maintain a constant blending rate for biojet fuel throughout the year, investments in sufficient storage capacity for biojet fuel are required. In particular to reduce the volatility of the biojet fuel price. Supply shortages due to seasonality effects were also observed in the ethanol market in the past, before they were resolved through various government regulations.

III

Conclusions, Recommendations, Limitations & Reflection

8

CONCLUSIONS, RECOMMENDATIONS & LIMITATIONS

8.1 Conclusions

The research presented in this thesis was aimed at the exploration of policies that might effectively stimulate biojet fuel and biosuccinic acid production through the HIP biorefinery concept, within the context of national and international competition with the sugar and ethanol market.

This objective was operationalized in the following main research question:

Main research question

> "What set of policies can be recommended to increase the production of biojet fuel and biosuccinic acid, within the context of national and international competition between the road transport and sugar market?"

In attempt to answer this question, a blended research framework of institutional economics and complex adaptive systems theory was used to develop an agent-based modelling and simulation model: the biorefinery model. Through an iterative process, this simulation model was then used to explore how current policies might hinder biojet fuel and biosuccinic acid production, as well as to explore the possible effectiveness of alternative policies under different scenarios of national and international competition with the sugar and ethanol market.

In this section, an answer to the main research question is gradually formulated by answering the sub-questions in a sequential order. Please note that all conclusions drawn in this section should be considered within the research limitations presented in section **(**8.3**)** and the model's scope and assumptions presented in chapter **(**5**)**.

Actors' behaviors and interactions give rise to a dynamic sugarcane market

1. *What actors in the sugarcane market of São Paulo state are involved in the emergence of biojet fuel and biosuccinic acid production, and what rules adequately characterize the interactions between these actors?*

The following key actors were identified: processing plants, sugarcane suppliers, landowners, fuel distributors, car drivers, and traders.

Processing plants are the central player in the emergence of biojet fuel and biosuccinic acid production. Through decisions at the strategic institutional level, most plants can alter how much sugarcane is used for each product, as well as decide to invest in biojet fuel and/or biosuccinic acid production capacity. These behaviors have shown to create substantial dynamics in the emergence of biojet fuel and biosuccinic acid production in the biorefinery model.

Suppliers are important in sugarcane procurement. It was seen that suppliers can have a significant impact on sugarcane supply for processing plants, since they can choose to whom to supply to on a yearly basis. Furthermore, the unique TRS price for each processing plant, which is calculated through CONSECANA-SP, is central in supply decisions. The interactions between processing plants and suppliers can largely influence the average sugarcane price that is paid by biorefineries.

Car drivers' consumption behavior stimulates production dynamics. In line with the conceptualization developed by Armbrust (2014), car drivers' fuel switching behavior gives rise to dynamics in price levels for hydrous and anhydrous ethanol (through fuel distributors), and accordingly production ratios (through processing plants). This unique fuel "flexing" characteristic of the Brazilian sugarcane market should be considered in the design of effective policies.

The influence of international trade

2. *What influence does international trade of sugar and ethanol has on the emergence of biojet fuel and biosuccinic acid production?*

This research has indicated that international trade of sugar and ethanol might have high influence on the emergence of biojet fuel and biosuccinic acid production. For both products, lower demand satisfaction was seen at times of high competition with the sugar market and ethanol exports, whereas high demand satisfaction was seen at times of low competition with the sugar market, and ethanol imports. Therefore, the nexus between the domestic and foreign markets should be an integral part in the development of effective policies. In particular in the context of increasing adoption of bioethanol promoting policies worldwide.

Potential for 2G bagasse-to-biojet production technology

3. *What is the effect of the introduction of the 2G bagasse-to-biojet fuel production technology on the production quantity of biojet fuel?*

Exploration of the 2G bagasse-to-biojet technology showed positive results for biojet fuel demand satisfaction. Even if ethanol support policies remain in their status-quo, nearly full biojet fuel demand satisfaction was observed, at the acceptable biojet fuel price of 1.65 R$/l. Furthermore, 2G biojet fuel production emerged, while the average sugarcane price paid by biorefineries was around 35% higher than for conventional processing plants. 2G biojet fuel production decisions were found to be not sensitive to the average sugarcane price, as this price does not include the value of bagasse. Therefore, 2G bagasse-to-biojet fuel could present a significant opportunity to increase biojet fuel production, as for now it is not affected by CONSECANA-SP sugarcane pricing.

Current government policies as a barrier for commercialization of biojet fuel and biosuccinic acid

4. *What effect do current policies of the government of Brazil have on the emergence of biojet fuel and biosuccinic acid production?*

The multi-scenario experimental analysis performed in chapter 7 has shown that current government ethanol-support policies hinder commercialization of biojet fuel and biosuccinic acid production. For biosuccinic acid, higher demand satisfaction was observed when ethanol support was decreased. Nevertheless, the results for biojet fuel indicated that abolishment of ethanol-support policies (and thus the creation of a level playing field) alone might not be sufficient to stimulate biojet fuel production at the acceptable biojet fuel price of 1.65 R$/l. Furthermore, the effectiveness of ethanol discouragement was found to be largely affected by competition with the sugar market and foreign hydrous ethanol market. That is, even though domestic ethanol consumption is discouraged, and thus more sugarcane could be available for biojet fuel and biosuccinic acid production, sugar and ethanol production might be increased instead of biojet fuel and biosuccinic acid production, at times when demand for sugar and international hydrous ethanol trade is high.

Exploration of alternative policies to increase biojet fuel and biosuccinic acid production

5. *What set of policies can be recommended to increase the production of biojet fuel up to 50% of the jet fuel demand in São Paulo state in the period 2015 until 2030?*

Two different alternative policies were developed and explored in this research: a biojet price premium and a risk premium compensation subsidy. The former is a demand-side policy that attempts to increase biojet fuel production by artificially increasing the biojet fuel price paid to biorefineries. The latter is a supply-side policy that attempts to decrease the average sugarcane price paid by biorefineries. For the base scenario (with a medium sugar price and foreign hydrous ethanol price), statistical analysis showed that a price premium level of 2.5 R$/l is most effective, which corresponds to an average biojet fuel demand satisfaction of 54.5%. However, even in the most favorable scenario (international competition is low), demand satisfaction did not reach higher than 51% (with a subsidy level of 2 R$/l). Furthermore, in line with the previous insights about the influence of international trade, the policy's effectiveness significantly decreases at times of high international trade (the most effective subsidy level is then 2 R$/l, which corresponds to an average demand satisfaction of 33.8%).

In attempt to increase demand satisfaction, the risk premium compensation subsidy was explored. This exploration suggested that this policy is not effective at all, also when combined with the price premium subsidy. As described in chapter 7, partial explanation for the policy's ineffectiveness, may be found in the fact that the lower-priced sugarcane can still be processed into all products, and thus the relative effect on production costs is negligible. Therefore, in-depth research is needed to develop supply-side policies that specifically target the reduction of sugarcane costs for biojet fuel production, in the context of CONSECANA-SP.

In conclusion, no policies were found that are able to meet the demand target as described in the above research question. Yet, the biojet price premium shows most promising results to increase biojet fuel production. Combined with the insights gained from sub-question 4, it can be recommended that a combination of decreasing ethanol support and subsidizing the biojet fuel price paid to biorefineries may be effective to meet the demand target.

6. *What set of policies can be recommended to increase the production of biosuccinic acid up to 50% of the estimated world demand in the period of 2015 until 2030?*

For biosuccinic acid, the same two types of policies were explored as for biojet fuel, and the insights gained were of similar nature than for biojet fuel. The biosuccinic acid price premium subsidy was found to be effective in increasing biosuccinic acid demand satisfaction, in contrast with the risk premium compensation subsidy, which had no significant effect at all. Statistical analysis showed that the most effective price premium level is 1 R$/l, which corresponds to a demand satisfaction of 77.8%. This corresponds to a biosuccinic acid price of 1.2 R$/kg. Full average demand satisfaction is never achieved, which is likely due to the seasonality of sugarcane supply and processing. Similar to biojet fuel, policy effectiveness is largely influenced by competition with the sugar market and international hydrous ethanol trade. In case of high competition, a subsidy level of 1.5 R$/kg responds to a demand satisfaction of only 38.4%.

8.2 Recommendations

Following the above conclusions, a series of recommendations can be made to the aviation and chemical industry, as well as for to the government of Brazil.

Recommendations to the aviation and chemical industry

v. The aviation industry is advised to **reconsider the production of 1G biojet fuel from sugarcane feedstock on its commercial feasibility**, as the research conducted in this thesis suggests poor potential for this production technology. Only with strong government subsidizing, 1G biojet fuel production may be increased in the dynamic context of competition with the sugar and ethanol market. Furthermore, institutional aspects of sugarcane procurement cannot be omitted from any feasibility study concerning the commercialization of 1G biojet fuel. Instead, they should be an integral part of it, with the privately constructed CONSECANA-SP sugarcane pricing institution as focal point of attention.

vi. Furthermore, the aviation industry is recommended to conduct further research into the **commercial potential of 2G bagasse-to-biojet fuel**, as this research indicated there might be large potential for this production technology. Particular attention should be paid to the risk of future adoption of bagasse in sugarcane prices, and an economic assessment of procuring sugarcane residues to replace currently generated bagasse-based bioelectricity.

vii. For the chemical industry, there **might be potential to use sugarcane for commercial production of biosuccinic acid**. However, if the target of 50% of the estimated world demand is to be met, government intervention through a price premium subsidy may be needed.

viii. Both industries should take notice of the **very dynamic nature of the sugarcane market**. That is, car drivers' consumption decisions and (inter) national competition between the sugar and ethanol market, are likely to be an unstable context for either 1G biojet fuel or biosuccinic acid to be commercialized. Furthermore, if one considers that the car driver market in Brazil has been growing rapidly, and gasoline shortages are expected in the near future (as mentioned by Mr. Pierossi), intensified competition for sugarcane feedstock might be expected.

Recommendations to the government of Brazil

iii. If the government of Brazil would take a **standpoint of discouraging biojet fuel and biosuccinic acid production**, it might be most effective to maintain its current ethanol support combined with an increase of import taxes on hydrous ethanol. As long as domestic price levels of ethanol and sugar remain high, no significant commercialization of biojet fuel and biosuccinic acid production could be expected.

iv. On the other hand, if the government of Brazil would take a **standpoint of stimulating biojet fuel and biosuccinic acid production**, for instance in the context of rising use of electric vehicles, price premium subsidies combined with ethanol discouragement may be an effective policy.

8.3 Limitations and Future Research

The following main limitations were identified and may be addressed in future research.

i. As models are abstractions of reality, modelling comes along with a multitude of scoping decisions and assumptions. For a full overview of the biorefinery model's scope, assumptions, and their limitations, one is referred to chapter **(**5**)**.

ii. In the biorefinery model, key focus is on the emergence of biojet fuel and biosuccinic acid production. In order to facilitate this, biojet fuel demand and biosuccinic acid demand were made constant and exogenous. This means, it was assumed that the airports and the biosuccinic acid market will demand a constant daily quantity of biojet fuel and biosuccinic acid, respectively, as long as the price of biojet fuel and biosuccinic acid equal the exogenous acceptable prices for these products. Thus, the question of interest was: how can biojet fuel and biosuccinic acid demand satisfaction be increased, under a fixed demand and price? The implication of this approach is that there is no feedback between biojet fuel/biosuccinic acid supply and demand that reflects in price changes for these products. Within the scope of the research, this was deemed not necessary. Nevertheless, in future research agent behavior could be incorporated for the airports and biosuccinic acid market, if one intends to gain insights into the interrelation between supply and demand. This could address questions such as: how does the consumption of airports and the biosuccinic acid market change in relation to the product price and supply?

iii. The CONSECANA-SP sugarcane pricing institution played a central role in the conceptualization of sugarcane procurement dynamics. In the biorefinery model, CONSECANA-SP was conceptualized in order to gain insights into the implications of CONSECANA-SP for the emergence of biojet fuel and biosuccinic acid production. It was concluded that CONSECANA-SP could present a significant barrier for this emergence. However, as this study was of exploratory nature, it was not studied how the CONSECANA-SP system could be adjusted to accommodate for the inclusion of biorefineries in the average sugarcane price calculation. Furthermore, the growing concerns by farmers about lacking remuneration for bagasse as indicated by Mr. Pierossi, were not studied. The effects of including bagasse in the sugarcane price are expected to be large, and therefore further research is needed. Future researchers are encouraged to study the process through which the CONSECANA-SP institution could be changed or reformed. Theory on institutional change and reform might accommodate this.

iv. Within the time constraints and scope of the research presented in this thesis, a specific selection of experiments was made that was sufficient to answer the main research question. However, in the development of the biorefinery model, a multitude of unexplored external variables were added for future experimentation. For instance, a switch was included in the model that allows to simulate how variable lease contracts between landowners and processing plants might affect the average sugarcane price paid by biorefineries. Furthermore, through adjusting the inter production cluster distance between processing plants, the market density can be adjusted, which allows to explore how sugarcane prices could be affected by the degree of competition among processing plants. *Table 26* presents the external variables that may be included in future research.

Table 26: Recommended external variables for experiments in future research

External variable	Purpose
kerosene price (carbon tax)	A price increase of petroleum-derived kerosene (e.g. through a carbon tax) would increase the acceptable price of biojet fuel, and thus the profitability of biojet fuel production.
pure gasoline price	The pure gasoline price has the potential to influence car drivers' fuel consumption decisions. At times when the pure gasoline price is high, car drivers typically divert to ethanol consumption. Gasoline prices could also be increased through a carbon tax.
inter cluster distance	To explore the effect of market density on the average sugarcane price paid by biorefineries. There might be more potential for biorefineries in low-market density areas.
variable lease contracts	To explore the impact of variable lease contracts on the average sugarcane price paid by biorefineries. If contracts would be based on a "floating" yearly calculated TRS price, different outcomes may arise.
ratio of land for suppliers	To explore the effect of vertical integration on the average sugarcane price. Through this variable, the distribution of total land between suppliers and landowners can be altered.
exchange rate BRL/USD	Through adjusting the exchange rate, one can explore the impact of currency fluctuations on international hydrous ethanol trade.

v. Finally, the geographical and regional aspects of São Paulo state were not included in the biorefinery model. Although an approximation for geographical aspects of sugarcane procurement was made through transportation distances and the inter cluster distance, no other aspects were included. Naturally, micro-scale social structures as well as characteristics of agricultural lands (e.g. location, slope, and accessibility) might be important features, depending on the research objective. For a more detailed analysis of the sugarcane market in São Paulo state, the use of Graphical Information Systems (GIS) and interviews with locals is recommended.

9

RESEARCH EVALUATION & PERSONAL REFLECTION

“Success consists of going from failure to failure without loss of enthusiasm”

- Winston Churchill

In this chapter, the author takes a step back from the research to reflect. Reflection is done in two parts. In the first part, the research is evaluated on the used methodology. In the second part, the author provides a personal reflection on the experience of conducting the research.

The Destination: the research in perspective

Evaluation of applied theories

In this thesis, a blended application of complex adaptive systems theory and new institutional economics was used to construct a conceptual model for analysis, which served as the scientific research perspective to analyze the sugarcane market of São Paulo. Then, the agent based modelling paradigm was used to develop a simulation model that allowed for policy exploration. The use of this methodology presented various challenges and opportunities.

First, the inclusion of institutional economics theory was found very useful to identify and analyze the different types of institutions in the complex adaptive systems perspective. For instance, at the governance level the concept of transaction uncertainty and transaction costs economics allowed to enhance the researcher’s understanding of why the CONSECANA-SP sugarcane pricing mechanism was developed between suppliers and processing plants and what implications it could have for the emergence of biojet fuel and biosuccinic acid production. Furthermore, it provided a useful framework to structure the different types of sugarcane procurement that were observed. In particular the three attributes of transactions (asset specificity, frequency and uncertainty) provided guidance in identifying and analyzing institutions, in particular for sugarcane procurement. Finally, the Williamson four-layer model (Williamson, 1998) provided a useful distinction between institutions and to define which levels were modelled endogenously or exogenously. The concept of transaction costs aligns with the concept of bounded rationality and actor heterogeneity applied in the complex adaptive systems perspective.

Although the institutional perspective defined in chapter 3 was found useful to identify and analyze institutions (as presented in chapter 4), it provided less assistance in the actual conceptualization of the agent based biorefinery model (as presented in chapter 5). That is, the conceptualization of institutions into pseudo-code is primarily a process in which the modeler interprets the institutions and constructs a conceptualization that he or she thinks sufficiently represents the identified institutions. The use of the MAIA method developed by (Ghorbani, 2013) may be a useful method to structure this process.

Evaluation of the application of ABM

With regard to the modelling method, agent-based modelling provided useful within the research scope of analyzing how biojet fuel and biosuccinic acid production may be increased by influencing individual agents' behaviors and interactions. Furthermore, agent-based modelling was the recommended method in the thesis project description. Yet, for semi-agents (such as the sugar market) that do not have an internal decision logic and heterogonous characteristics, there is no clear advantage of using ABM. For these agents, a CGE approach that uses price elasticities may be a better approach if one would intend to model supply and demand effects.

Taking this further, an interesting question is whether a similar answer to the research question could have been found if a CGE approach was used to model the sugarcane market of São Paulo state. In this hypothetical case, a model would have been developed that is based on the principle of finding a general equilibrium in which all market prices and quantities are in equilibrium. Such a model would carry key assumptions of CGE, such as: perfect competition between agents, homogenous and constant agent preferences, and homogeneous production costs for processing plants. But, foremost, a limited amount of institutions could be incorporated in the model. Therefore, no insights could be gained into how institutions, in particular at the governance level and the strategic level present barriers as well as opportunities for the emergence of biojet fuel and biojet production.

For all but the sugarcane procurement sub-system, the perfect competition assumption would present significantly different outcomes. As analyzed and conceptualized in this research, strong competition can exist between suppliers and processing plants (in dense geographical areas). In case perfect competition would be assumed, factors such as risk profiles and transportation distance could not be taken into account. Furthermore, it would be assumed that the supply and demand of sugarcane would be in equilibrium and are not limited by geography. Yet, these factors are important in a plant's investment decisions for biojet fuel and biosuccinic acid, as well as their production quantities (through the average sugarcane price). In fact, production technologies are usually constant in CGE models. In that light, a CGE approach may not sufficiently capture the emergence of biojet fuel and biosuccinic acid production, and through which policies and external variables this emergence may emerge.

Heterogeneous agent preferences are a key aspect of ABM. In the biorefinery model, various agent preferences were included, such as risk attitudes, fuel preferences, and car drivers' inclination to switch fuels. In contrast, such preferences are generally assumed constant in CGE models, and agents' only behavior is profit maximizing. The CGE approach may therefore present more predictable and lower variance results. Furthermore, plants in the biorefinery model all have unique production costs for each product (to represent heterogeneity), whereas these would all be assumed homogenous in a CGE model. Assumed homogeneity is likely an oversimplified representation of production, which would not allow to capture why processing plants behave differently in terms of investing and production.

In conclusion, for the analysis and simulation of the emergence of biojet fuel and biosuccinic acid production, a CGE approach would likely give different outcomes. If the analysis would focus on equilibrium analysis of an already established biojet fuel and biosuccinic acid, a CGE model may give more similar outcomes.

Finally, several remarks can be made about the software that was used for model implementation and data analysis. First, the NetLogo software used for implementation of the conceptualization into a simulation model, presented several opportunities and challenges. NetLogo is a user-friendly and straightforward software, and its modelling language fits well with the ABM theory. For instance, it allows fast and structured construction of ABM models with a clear separation of agents, states, procedures and external variables. Yet, as the size of the model increases, it becomes increasingly hard to verify and debug the model. Since NetLogo does not support a built-in debugging tool, verification is a very time consuming process that requires a structured and customized approach of the modeler. This is something to be taken into account by modelers when using NetLogo.

The Journey: a personal reflection on the research process

Months ago, I embarked on this research endeavor, driven by a strong interest to learn the ABM modelling environment and a passion for aviation and sustainability. Yet, back then I was unaware of the challenges and experiences that were waiting for me. Upon finalizing, this section is dedicated to elaborating on my personal experiences of my first acquaintance with independent academic research as well as to provide advices for future students conducting their master thesis with modelling. Therefore, this section is written in first person.

The Beginning: Research Orientation & Literature Research

From the early beginning of the project, I followed a strategy of striving for “full spectrum knowledge” about the research problem. I believed that the more knowledge I would gain about the topic, the better I could define the research scope. Also, I was driven by personal interest in the subject from time to time, instead of being necessarily efficient. Furthermore, even though it has been clear from the start of the project that the research would be based on (Armbrust, 2014) (as described in the project details), I was cautious to simply adopt the biojet model and see how I could extend it to be used within my research scope. I believed that simply adopting the model would narrow my personal research vision on the problem, and I would not be able to nurture my own development process as a researcher.

Yet, looking back this approach has had both advantages and drawbacks. The extensive literature review proved to be a valuable asset in the analysis of the sugarcane system and conceptualization of the biorefinery model, as I had a clear view of the elements I omitted from the model scope. On the other hand, it cost a lot of time to read, analyze and gain insights from each literature source. Therefore, I am not sure whether my insights from the literature research would have been less sufficient to achieve the research objective when I would have read less sources. Processing so many sources made me experience the research as slightly chaotic during this research stage. Furthermore, I think that for some insights in this stage, I unconsciously “re-walked” previous trains of thoughts made by Armbrust (2014).

Building the ABM: Conceptualization & Formalization

From the research orientation and literature research, I gradually proceeded with conceptualization and formalization of the biorefinery model. In this stage, the extensive literature review was very useful to conceptualize the model, and in particular to gain better understanding of the implications of my scoping decisions. This stage reconfirmed to me that one of the hardest parts of modelling is to define and justify the model’s boundaries and to know when you should let go of elements. I supported these decisions by researching a lot on the boundary elements, in order to make a well-balanced decision on whether and how to model it. Yet, sometimes the realization that an element had to be left out of the model only came after I modelled it. This made the conceptualization and formalization a time consuming process. My general feeling in this research stage was that I was sometimes “taken hostage” by my thrive to develop the model with high scrutiny. Looking back, I think I might have done better not trying to make the conceptualization perfect, before implementing in NetLogo. I would advise people to start modelling in NetLogo as soon as possible, by building an initially very simple model and gradually expanding it. Even with a simple model, important initial insights can be gained which can then enrich further development of the conceptualization. This is especially advisable when one has no prior experience in NetLogo, as this approach will also allow you to better synchronize the conceptualization with the actual capabilities of NetLogo.

Figure 48 depicts a simplification of the modelling cycle through which I developed the biorefinery model. Through iterations in the modelling cycle, the biorefinery model was gradually constructed up to the level that it could generate enough generative sufficiency to grow the emergent behavior of interest. One of the major challenges for a modeler is to know when you should “leave the modelling cycle”. That is, one can be caught up in too many iterations of the modelling cycle; more than is necessary to grow the emerging behavior of interest. In my case, I think I made more iterations than necessary, which endangered my time available for experimentation. Therefore, I advise future modelers to plan pauses in advance, at which you take a step back and look what amount of generative sufficiency the model has at that point. Still, I discovered the experimentation results were not correct after I left the modelling cycle, and I had to go back to correct the NetLogo implementation. Naturally, one should not recklessly start modelling in NetLogo straight away, but I believe a lot of insights can be generated by making full iterations through the modelling cycle as early as possible in the research project. This also allows you to explore the unknown areas of expertise, before it is actually needed to be used. Nevertheless, modelling is a very time consuming process and there is no easy answer on how the process can be speeded up.

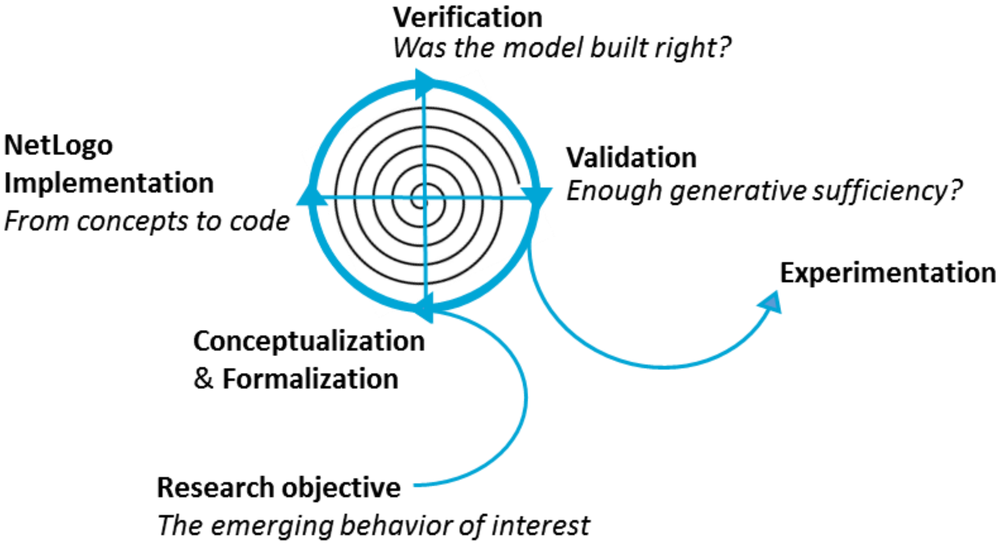


Figure 48: Reflection on the evolutionary/incremental modelling cycle

From concepts to code (and back): NetLogo Implementation

In an iterative process with conceptualization and formalization, I implemented the model into a simulation model in the NetLogo software. It is this part of the project where I encountered most delay. Due to the fact I did not have previous experience in using NetLogo, I followed a blended approach in which I was learning to use the software while simultaneously applying it. I experienced that NetLogo is an easy-to-understand software, also if you do not have previous experience in using “code language”.

Yet, whereas individual procedures can be rather simple, it is the whole collective web of intertwined simple procedures that can quickly make the model complicated. This is particular challenging for the verification of the model, as the traceability of relations can be very hard. Because NetLogo does not have built-in tools for debugging, this was a very time consuming process. For instance, in case an abnormal value was observed at the system level, I had to trace down all related procedure elements that have an influence on this variable in order to find the mistake.

Furthermore, the use of elements of the biojet model by (Armbrust, 2014) came along with two main challenges. First, it was challenging to synchronize the adopted model elements with new model elements. This concerns matters such as different naming of variables, timing of procedure activation and “coding style”. Each modeler develops his or her own coding style within the boundaries of the modelling environment, and this is no different for NetLogo. It can thus be very time consuming to understand another modeler’s source code. Through this experience, I have attempted to make the NetLogo user friendly for future researchers. Second, I discovered a multitude of mistakes in the NetLogo source code of (Armbrust, 2014). These were major mistakes that significantly changed the behavior of his model. Therefore, I had to thoroughly verify the biojet model elements. This also made me realize that my NetLogo code could have unnoticed mistakes. In knowledge that my results could be used in future research, I did the model verification with high scrutiny. This made that in this research state I was overwhelmed that I had to spend more time than anticipated. I also learned from this that it can be challenging to estimate the required time for a methodology you have not applied before.

Model Use: Policy experimentation

After I gained confidence that the biorefinery model had enough generative sufficiency, I used it for policy exploration. During this research stage, I encountered various challenges. First, I had to learn how to use R statistics for data visualization of the NetLogo csv file outputs, as I did not use this software before. Although a pre-developed R script was available, I had to significantly extend and adjust it to fit my purposes, which required more time than anticipated. Once the R script and the experimental design were ready, I started with executing the experiments in NetLogo. This requires tremendous CPU power (it is practically running at 100% load during the entire experiment), and therefore it is very time consuming when experiments have to be repeated. Unfortunately, during analysis of the initial experimentation results, I discovered counterintuitive results. Namely, the average sugarcane price paid by biorefineries was lower than could be expected in line with the conceptualization. After correcting the model code, the model performed well in the experiments.

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APPENDICES

LIST OF APPENDICES

APPENDIX I: IN DEPTH CONCEPTUALIZATION

Action	Belongs to	Description
[A1]: supplier contract negotiations	Plants and suppliers	Used to simulate annual sugarcane supply contract negotiations between plants and suppliers.
[A2]: production decisions	Plants	Used to simulate how plants change the amount of sugarcane used for each product in response to changes in market prices.
[A3]: sugarcane processing	Plants	Used to simulate sugarcane processing into products, taking into account the plant's production yields and decisions.
[A4]: selling products	Plants	Used to simulate sales between plants and distributors and between plants and traders, depending on the selling prices.
[A5]: sugarcane pricing	Plants	Used to simulate the pricing of sugarcane, taking into account the CONSECANA-SP system for the calculation of the TRS price, as well as the sugarcane mix (supplier or landowner).
[A6]: biorefinery investments	Plants	Used to simulate how plants could assess and decide on biorefinery investments.
[A7]: road fuels distribution & pricing	Distributors	Used to simulate the distribution and blending of fuels, as well as variations in market prices in response to supply and demand dynamics.
[A8]: international hydrous trade	Traders	Used to simulate imports and exports of hydrous ethanol, as a result of changes in foreign and domestic prices, import and export taxes and the currency exchange rate.
[A9]: fuel demand see {Armbrust, 2014 #198}	Car drivers	Used to simulate the real fuel demand of car drivers, depending on their car driver type and daily GEEL demand.
[A10]: switch fuels see {Armbrust, 2014 #198}	Car drivers	Used to simulate the dynamics in car driver fuel consumption, as a result of changes in market prices and personal characteristics such as fuel preference.

Action 3 [A3]: Sugarcane processing

The processing plants process the sugarcane into the products, depending on the `plant type`, `processing yields`, `production ratios` and the amount of `daily sugarcane`. *Figure 49* presents the IDEF0 process diagram of the sugarcane processing action. As can be seen from this figure, first the available amount of `daily sugarcane` is determined before the products are produced (A3.1). In the biojet model, sugarcane supply was assumed to be constant and equally distributed over each day (Armbrust, 2014). However, this assumption does not hold for the biorefinery model, as sugarcane is a seasonal crop and in reality harvest quantities approach a bell shaped distribution over a harvest season. Analysis of historical trading patterns showed that import and export peaks seem to correlate to this seasonality. That is, when domestic production is high traders tend to export, and when domestic production is high, traders tend to import (assuming all other variables constant). To approximate such dynamics, the sugarcane supply in a harvest season was assumed to follow a normal distribution.

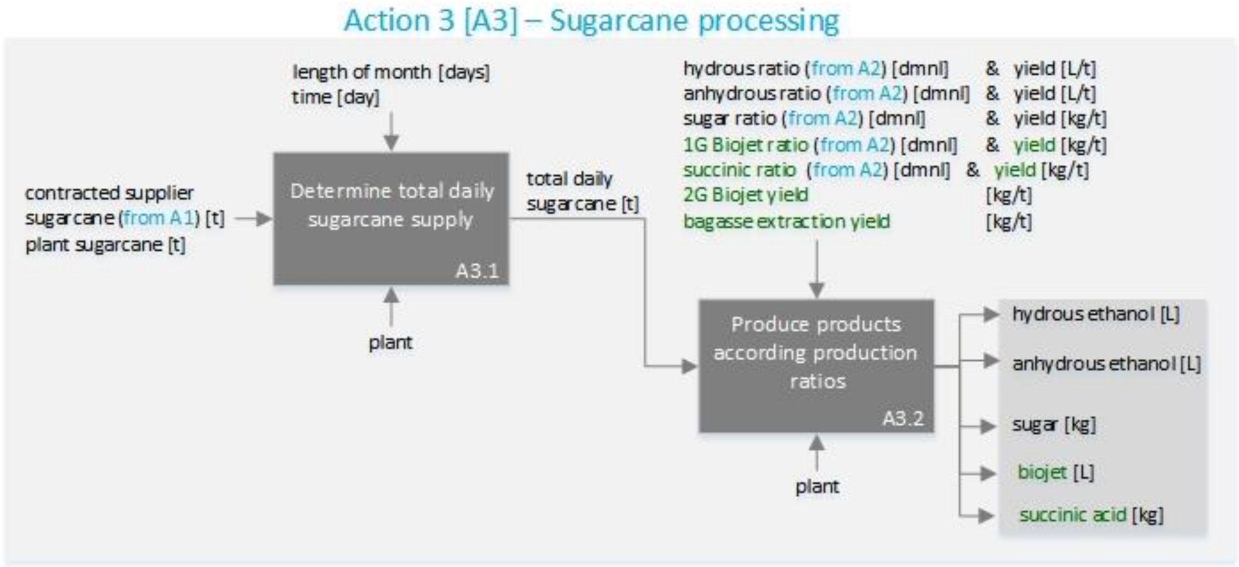
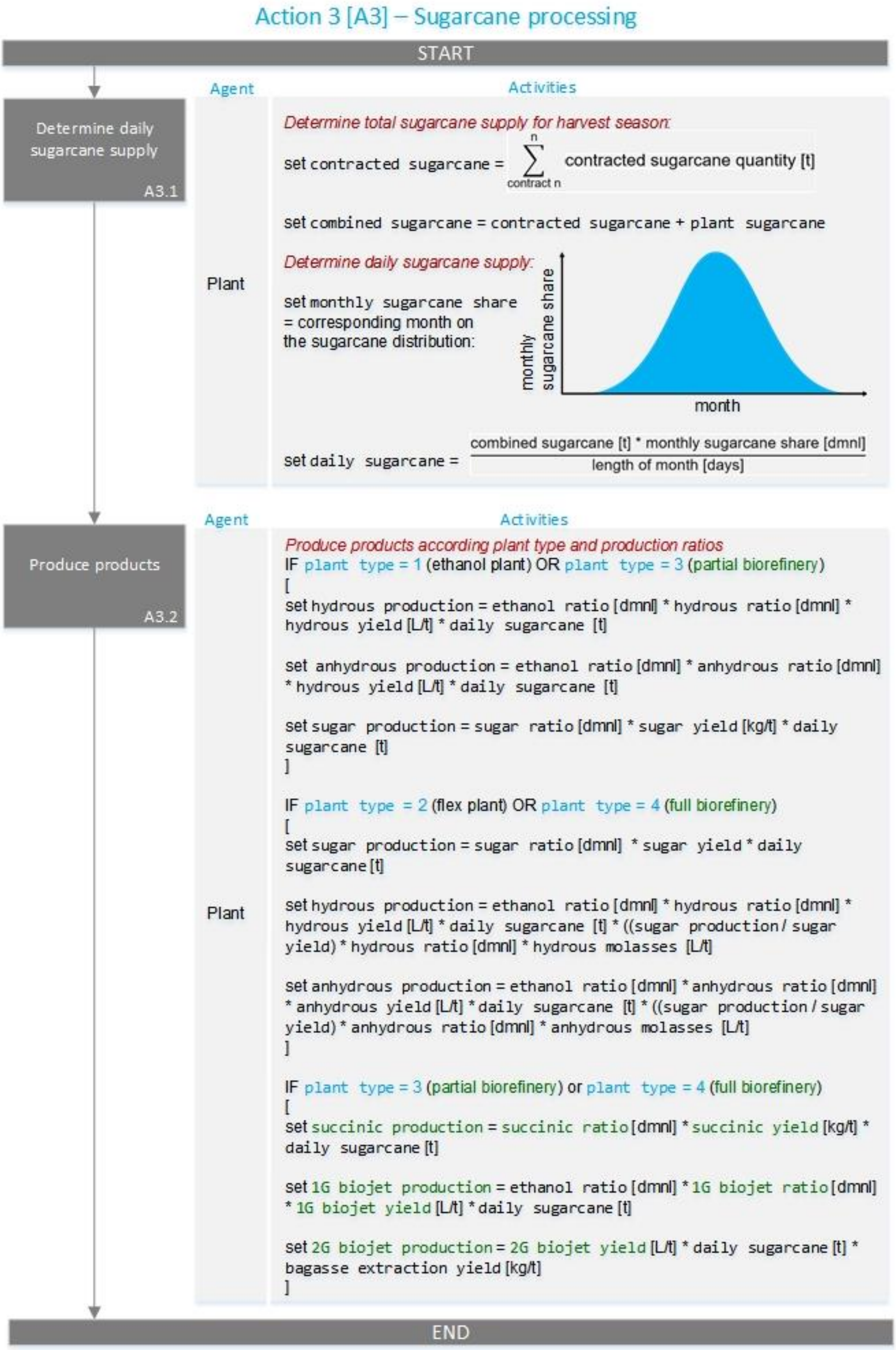


Figure 49: IDEF0 process description for action 3 [A3]: sugarcane processing

Once the quantity of `daily available sugarcane` is calculated, the sugarcane is processed into products, based on the `production ratios` (A2.1). These production ratios express the ratio (between 0 and 1) of sugarcane that is processed into a certain product category. For instance, when the `sugar ratio` is 0.4, 40% of the `daily available sugarcane` will be processed into sugar. Subsequently, the quantity of sugarcane allocated for each product category, is then processed into that specific product, depending on the `yields` of the processing plant (which are unique for every plant). The production ratios are determined through action 2. These ratios express the ratio (between 0 and 1) of sugarcane used for a certain product category.



```
Determine total sugarcane supply for harvest season:
set contracted sugarcane = $\sum_{contract\ n}^{n}$ contracted sugarcane quantity [t]
set combined sugarcane = contracted sugarcane + plant sugarcane
Determine daily sugarcane supply:
set monthly sugarcane share = corresponding month on the sugarcane distribution:
set daily sugarcane = $\frac{\text{combined sugarcane [t] * monthly sugarcane share [dmnl]}}{\text{length of month [days]}}$
```

```
Produce products according plant type and production ratios
IF plant type = 1 (ethanol plant) OR plant type = 3 (partial biorefinery)
[
    set hydrous production = ethanol ratio [dmnl] * hydrous ratio [dmnl] * hydrous yield [L/t] * daily sugarcane [t]
    set anhydrous production = ethanol ratio [dmnl] * anhydrous ratio [dmnl] * hydrous yield [L/t] * daily sugarcane [t]
    set sugar production = sugar ratio [dmnl] * sugar yield [kg/t] * daily sugarcane [t]
]
IF plant type = 2 (flex plant) OR plant type = 4 (full biorefinery)
[
    set sugar production = sugar ratio [dmnl] * sugar yield * daily sugarcane [t]
    set hydrous production = ethanol ratio [dmnl] * hydrous ratio [dmnl] * hydrous yield [L/t] * daily sugarcane [t] * ((sugar production / sugar yield) * hydrous ratio [dmnl] * hydrous molasses [L/t]
    set anhydrous production = ethanol ratio [dmnl] * anhydrous ratio [dmnl] * anhydrous yield [L/t] * daily sugarcane [t] * ((sugar production / sugar yield) * anhydrous ratio [dmnl] * anhydrous molasses [L/t]
]
IF plant type = 3 (partial biorefinery) or plant type = 4 (full biorefinery)
[
    set succinic production = succinic ratio [dmnl] * succinic yield [kg/t] * daily sugarcane [t]
    set 1G biojet production = ethanol ratio [dmnl] * 1G biojet ratio [dmnl] * 1G biojet yield [L/t] * daily sugarcane [t]
    set 2G biojet production = 2G biojet yield [L/t] * daily sugarcane [t] * bagasse extraction yield [kg/t]
]
```

Figure 50: Agent activities for action 3 [A3]: sugarcane processing

Action 4 [A4]: Selling products

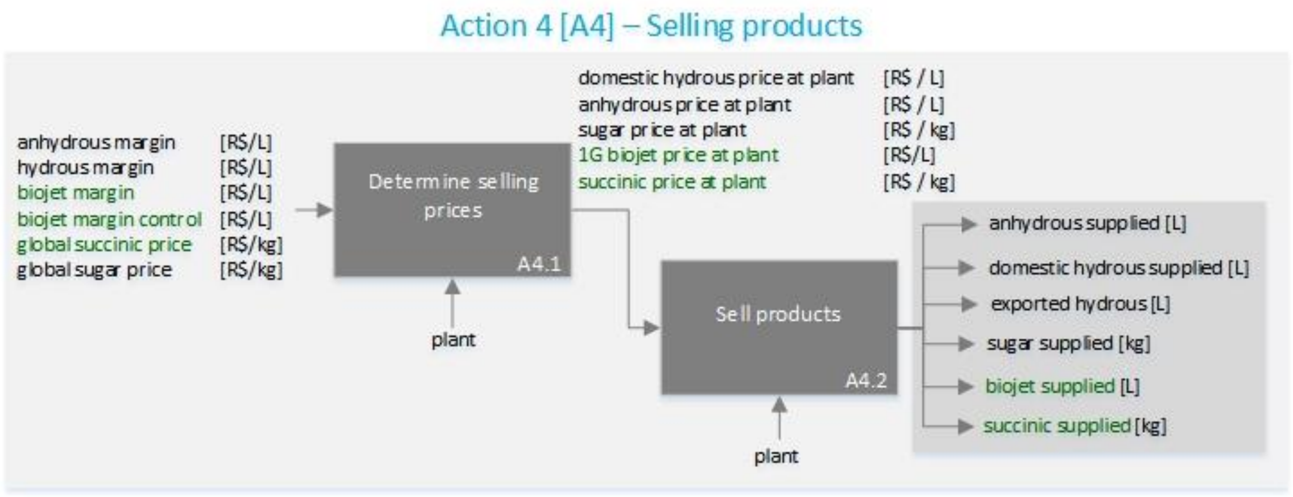


Figure 51: IDEF0 process description for action 4 [A4]: selling products

Action 7 [A7]: Road fuels distribution and pricing

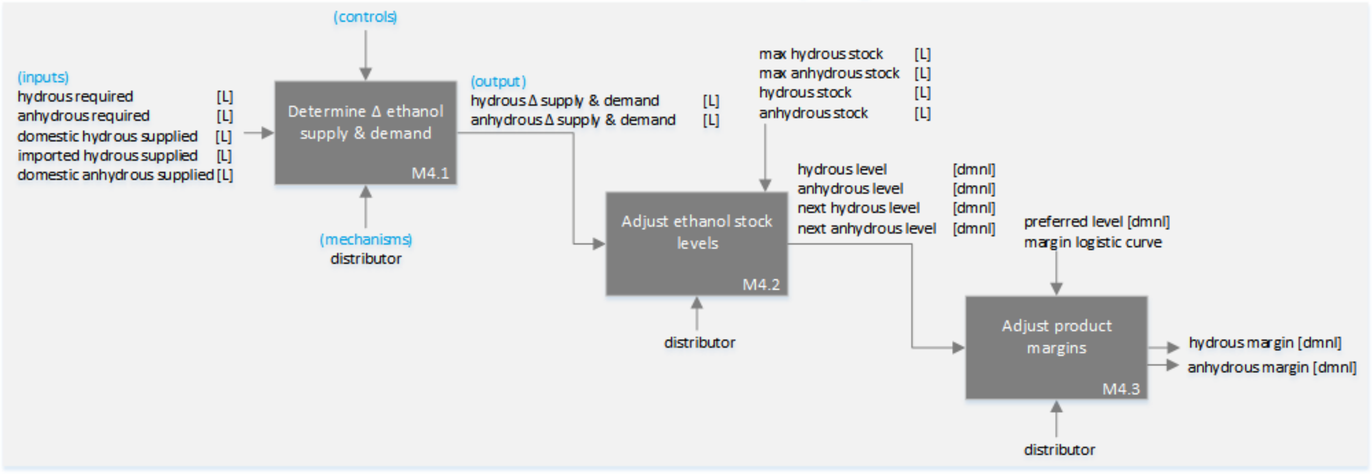
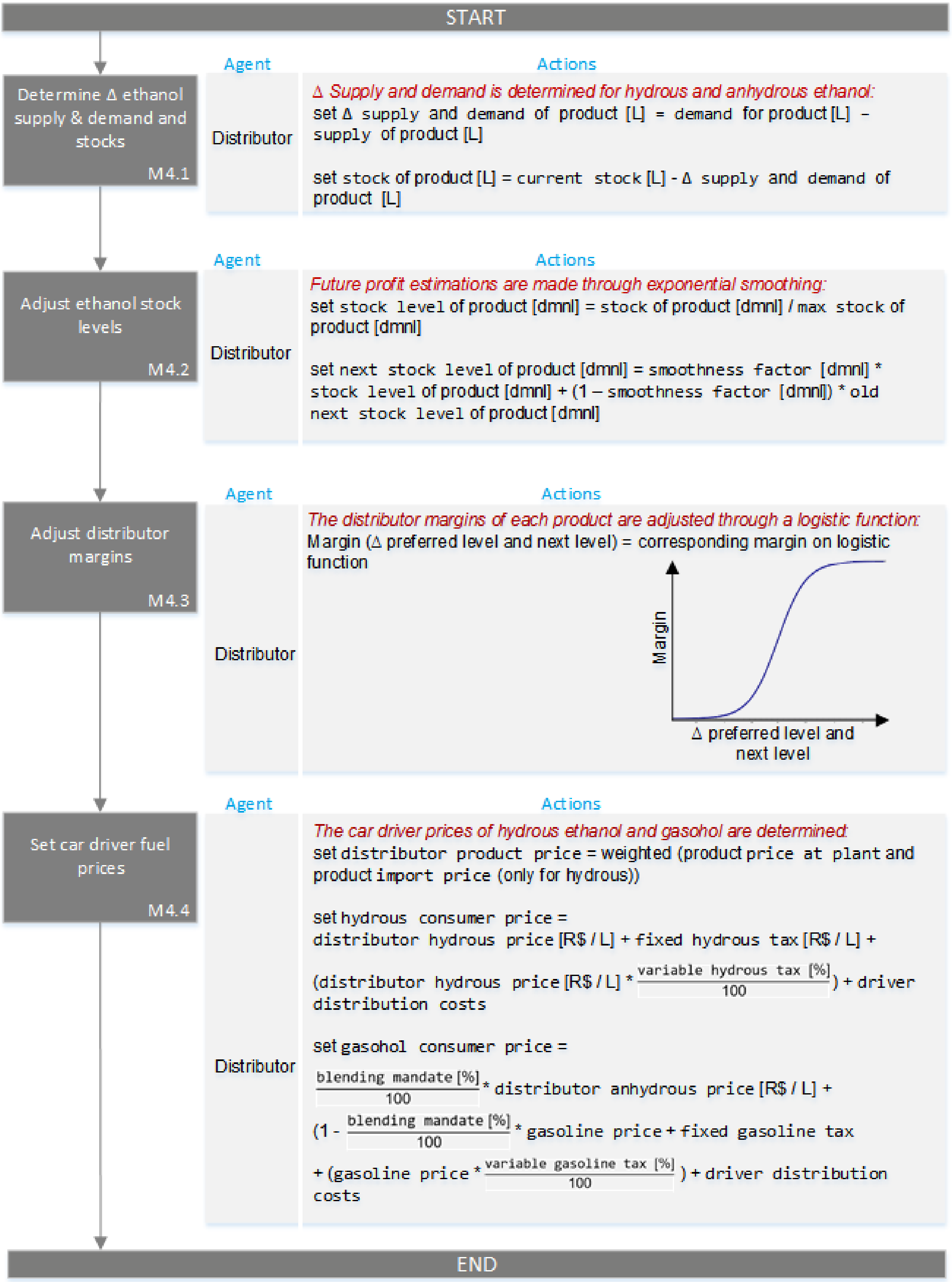


Figure 52: IDEF0 process description for action 7 [A7]: road fuels distribution and pricing



Δ Supply and demand is determined for hydrous and anhydrous ethanol:

set Δ supply and demand of product [L] = demand for product [L] – supply of product [L]

set stock of product [L] = current stock [L] - Δ supply and demand of product [L]

Future profit estimations are made through exponential smoothing:

set stock level of product [dmnl] = stock of product [dmnl] / max stock of product [dmnl]

set next stock level of product [dmnl] = smoothness factor [dmnl] * stock level of product [dmnl] + (1 – smoothness factor [dmnl]) * old next stock level of product [dmnl]

The distributor margins of each product are adjusted through a logistic function:

Margin (Δ preferred level and next level) = corresponding margin on logistic function

The car driver prices of hydrous ethanol and gasohol are determined:

set distributor product price = weighted (product price at plant and product import price (only for hydrous))

set hydrous consumer price =
distributor hydrous price [R$ / L] + fixed hydrous tax [R$ / L] +
(distributor hydrous price [R$ / L] * $\frac{\text{variable hydrous tax [\%]}}{100}$) + driver distribution costs

set gasohol consumer price =
$\frac{\text{blending mandate [\%]}}{100}$ * distributor anhydrous price [R$ / L] +
(1 - $\frac{\text{blending mandate [\%]}}{100}$ * gasoline price + fixed gasoline tax
+ (gasoline price * $\frac{\text{variable gasoline tax [\%]}}{100}$) + driver distribution costs

Figure 53: Agent activities for action 7 [A7]: road fuels distribution and pricing

APPENDIX II: NETLOGO IMPLEMENTATION

Glossary of all variables in the NetLogo model

Agent	Description
Processing plant	white = plant type 1, red = plant type 2, orange = plant type 3, green = plant type 4
Supplier	white farmer symbol
Landowner	green person symbol
Distributor	multicolor hexagon shape
Car driver	red = regular gasohol, yellow = FFV gasohol driver, blue = FFV hydrous driver
Trader	money symbol
Airports	airport symbol
Biosuccinic acid market	circle
Sugar market	circle
Foreign market	flag

PROCESSING PLANT STATES						
Variable	Is a	Type	Base value	Value range	Unit	Sources
STATES WITH INPUT DATA						
Plant type	Processing plant state	Integer	1, 2, 3 or 4	1 – 4	[dmnl]	Assumption
Plant risk attitude	Processing plant state	Integer	1 + random 3	1 – 3	[dmnl]	Assumption
Counter offer deduction	Processing plant state	Real	If plant risk attitude = 1, deduction = 0.5 If plant risk attitude = 2, deduction = 0.75 If plant risk attitude = 3, deduction = 0.1	0.1 – 0.75	[dmnl]	Assumption
Investment risk weight	Processing plant state	Integer	If plant risk attitude = 1, risk weight = 13 If plant risk attitude = 2, risk weight = 8 If plant risk attitude = 3, risk weight = 3	3 – 13	[dmnl]	Assumption
Production start date	Processing plant state	Integer	random 30	0 - 29	[day]	Assumption
Plant base sugarcane yield	Processing plant state	Real	81 ± random (10%)	N/A	[t/ha]	(Crago et al., 2010)
Bagasse extraction yield	Processing plant state	Real	0.28	N/A	[t wet bagasse/t]	(BE-Basic Foundation, 2016; Kaup, 2015)
Plant TRS yield	Processing plant state	Floating point	140 ± random (2%)	N/A	[kg/t]	Assumed slightly higher than mentioned in (UNICA, 2016) 2014/2015 harvest report

Operating costs plant sugarcane	Processing plant state	Floating point	2387 ± random (10%) (actually for 3rd party suppliers)	N/A	[R$/ha]	(Kaup, 2015)
Sugar yield	Processing plant state	Floating point	133 ± random (10%)	N/A	[kg/t]	(H. de Gorter et al., 2013)
Hydrous yield	Processing plant state	Floating point	75.03 ± random (10%)	N/A	[l/t]	(H. de Gorter et al., 2013)
Anhydrous yield	Processing plant state	Floating point	71.74 ± random (10%)	N/A	[l/t]	(H. de Gorter et al., 2013)
Hydrous molasses	Processing plant state	Floating point	2.69 ± random (10%)	N/A	[l/t]	(H. de Gorter et al., 2013)
Anhydrous molasses	Processing plant state	Floating point	6.56 ± random (10%)	N/A	[l / t]	(H. de Gorter et al., 2013)
First generation biojet yield	Processing plant state	Floating point	0.701 – 0.949 ± random (10%) * anhydrous yield	N/A	[l/t]	(BE-Basic Foundation, 2016)
Second generation biojet yield	Processing plant state	Floating point	93.6 – 125.4 ± random (10%)	N/A	[l/t wet bagasse]	(BE-Basic Foundation, 2016)
Succinic yield	Processing plant state	Floating point	104.6 – 141.5 ± random (10%)	N/A	[kg/t]	(BE-Basic Foundation, 2016)
Sugar processing cost	Processing plant state	Floating point	IF second generation = false [94 ± random (10%)] IF second generation = true and plant type = 3 or 4 [94 ± random (10%) + electricity correction factor]	N/A	[R$/t]	(H. de Gorter et al., 2013)
Hydrous processing cost	Processing plant state	Floating point	IF second generation = false [26.77 ± random (10%) + electricity correction factor] IF second generation = true and plant type = 3 or 4 [26.77 ± random (10%) + electricity correction factor]	N/A	[R$/t]	(H. de Gorter et al., 2013)
Anhydrous processing cost	Processing plant state	Floating point	IF second generation = false [52 ± random (10%)] IF second generation = true and plant type = 3 or 4 [52 ± random (10%) + electricity correction factor]	N/A	[R$/t]	(H. de Gorter et al., 2013)

First generation processing cost	Processing plant state	Floating point	0.179 – 0.241 ± random (10%) + (anhydrous_processing_cost / anhydrous_yield) * firstgen_biojet_yield	N/A	[R$/t]	(BE-Basic Foundation, 2016)
Second generation processing cost	Processing plant state	Floating point	0.07 – 0.099 ± random (10%)	N/A	[R$/t wet bagasse]	(BE-Basic Foundation, 2016)
Succinic processing cost	Processing plant state	Floating point	89.7 – 117.9 ± random (10%)	N/A	[R$/t]	(BE-Basic Foundation, 2016)
Plant transportation costs	Processing plant state	Floating point	0.085 ± random (10%)	N/A	[R$/t/km]	(BE-Basic Foundation, 2016)
INTERNALLY CALCULATED STATES						
See the NetLogo source code. Available upon request with the author or thesis supervisors.						

SUPPLIER STATES						
Variable	Is a	Type	Value	Value range	Unit	Sources
STATES WITH INPUT DATA						
Supplier TRS yield	Supplier state	Floating point	137 ± random (10%)	N/A	[kg/t]	(UNICA, 2016) 2014/2015 harvest report
Supplier base yield	Supplier state	Floating point	75 ± random (10%)	N/A	[t/ha]	(Crago et al., 2010)
INTERNALLY CALCULATED STATES						
See the NetLogo source code. Available upon request with the author or thesis supervisors.						

DRIVER STATES					
Variable	Is a	Type	Value	Unit	Sources
STATES WITH INPUT DATA					
Driver type	Driver state	Integer	1 + random (3) (gives 1, 2 or 3)	[dmnl]	N/A
Preference	Driver state	Floating point	If driver type = 1, preference = 1.5 If driver type = 2, preference = random-float 0.5 + 1 If driver type = 3, preference = random-float 0.5 + 0.5	[dmnl]	(Armbrust, 2014)
Switch inclination	Driver state	Floating point	If driver type = 1, switch inclination = random-float 0.3 + 0.5 If driver type = 2, switch inclination = random-float 1.75 + 0.25 If driver type = 3, switch inclination = random-float 1.75 + 0.25	[dmnl]	(Armbrust, 2014)
Fuel evaluation frequency	Driver state	Floating point	If driver type = 1, fuel evaluation frequency = 30 If driver type = 2, fuel evaluation frequency = integer ((1 / switch inclination) * 20) If driver type = 3, fuel evaluation frequency = integer ((1 / switch inclination) * 20)	[dmnl]	(Armbrust, 2014)
Driver distribution costs factor	Driver state	Integer	30	[%]	(Armbrust, 2014)
INTERNALLY CALCULATED STATES					
See the NetLogo source code. Available upon request with the author or thesis supervisors.					

SUGAR MARKET STATES					
Variable	Is a	Type	Value	Unit	Sources
STATES WITH INPUT DATA					
Sugar price	Sugar market state	Floating point	Global sugar price	[R$/kg]	(USDA, 2016)
INTERNALLY CALCULATED STATES					
See the NetLogo source code. Available upon request with the author or thesis supervisors.					

AIRPORT STATES					
Variable	Is a	Type	Value	Unit	Sources
STATES WITH INPUT DATA					
Daily KEEL demand	Airport state	Real	KEEL demand Sao Paulo: 3714547000 KEEL demand Rio de Janeiro: 1381051000	[l]	2020 scenario (BE-Basic Foundation, 2016)
Biojet transportation costs	Airport state	Floating point	0.0315 for Sao Paulo 0.0894 for Rio de Janeiro	[R$/l]	(BE-Basic Foundation, 2016)
INTERNALLY CALCULATED STATES					
See the NetLogo source code. Available upon request with the author or thesis supervisors.					

GLOBAL VARIABLES					
Variable	Is a	Type	Value	Unit	Sources
SYSTEM VARIABLES					
SYSTEM VARIABLES WITH INPUT DATA					
Total available land for sugarcane	Global variable	Integer	5000000	[ha]	UNICA
CONSECANA VARIABLES					
CONSECANA VARIABLES WITH INPUT DATA					
Sugar TRS conversion rate	Global variable	Real	1.0474 conversion from kg sugar to kg trs. (the average value of brown and white sugar)	[dmnl]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
Hydrous TRS conversion rate	Global variable	Real	1.6913 conversion from hydrous liters (true liters, not GEEL) to KG trs	[dmnl]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
Anhydrous TRS conversion rate	Global variable	Real	1.7651 conversion from anhydrous liters (true liters, not GEEL) to KG trs	[dmnl]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
Sugar revenue share for plants	Global variable	Real	0.405	[dmnl]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
Sugar revenue share for suppliers	Global state	Real	0.595	[dmnl]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
Ethanol revenue share for plants	Global state	Real	0.379	[dmnl]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
Ethanol revenue share for suppliers	Global state	Real	0.621	[dmnl]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
INTERNALLY CALCULATED CONSECANA VARIABLES					

TIMING VARIABLES					
TIMING VARIABLES WITH INPUT DATA					
Run start date	Global state	Integer	0	[days]	N/A
Length of harvest season	Global state	Integer	330; normal distribution assumption	[days]	(BNDES & CGEE, 2008; Ferraz Dias de Moraes & Zilberman, 2014)
Length of year	Global state	Integer	365	[days]	N/A
Tick interval	Global state	Integer	1	[days]	N/A
Supplier negotiation frequency	Global state	Integer	365	[days]	assumption
Consecana evaluation frequency	Global state	Integer	364	[days]	(CONSECANA-PARANÁ, 2012; CONSECANA-SP, 2006)
Length of month	Global state	Integer	30	[days]	N/A
Production evaluation frequency	Global state	Integer	30	[days]	(Armbrust, 2014)
Investment opportunity frequency	Global state	Integer	363	[days]	N/A
Harvest frequency	Global state	Integer	365	[days]	(BNDES & CGEE, 2008; Ferraz Dias de Moraes & Zilberman, 2014)
SUPPLIER GLOBALS					
GLOBAL SUPPLIER VARIABLES WITH INPUT DATA					

Supplier transportation costs	Global state	Real	0.085 ;assumed equal for processing plants	[R$/t/km]	(BE-Basic Foundation, 2016)
PROCESSING PLANT GLOBALS					
GLOBAL PROCESSING PLANT VARIABLES WITH INPUT DATA					
Start TRS price	Global state	Real	0.47	[R$/kg]	(USDA, 2015a)
Min sugar ratio	Global state	Real	0.4	[dmnl]	(Ferraz Dias de Moraes & Zilberman, 2014; McKay et al., 2015)
Max sugar ratio	Global state	Real	0.6	[dmnl]	(Ferraz Dias de Moraes & Zilberman, 2014; McKay et al., 2015)
Min ethanol ratio	Global state	Real	0.4	[dmnl]	(Ferraz Dias de Moraes & Zilberman, 2014; McKay et al., 2015)
Max ethanol ratio	Global state	Real	0.6	[dmnl]	(Ferraz Dias de Moraes & Zilberman, 2014; McKay et al., 2015)
Sugarcane distribution list	Global state	List	[(0.03), (0.06), (0.08), (0.11), (0.14), (0.16), (0.14), (0.11), (0.08), (0.06), (0.03)]	[dmnl]	Assumption
Month (1 to 11) sugarcane distribution	Global state	Real	item on sugarcane distribution list	[dmnl]	Assumption
Switch capacity	Global state	Real	0.1	[dmnl]	{UNICA, 2016 #166} 2014/2015 harvest report used as approximation
Corporate tax	Global state	Integer	35	[%]	(BE-Basic Foundation, 2016)
Loan interest	Global state	Integer	12	[%]	(BE-Basic Foundation, 2016)

Smoothness factor for plants	Global state	Real	0.25	[dmnl]	(Armbrust, 2014)
First generation biojet scaling factor	Global state	Real	0.65	[dmnl]	(BE-Basic Foundation, 2016)
Second generation biojet scaling factor	Global state	Real	0.65	[dmnl]	(BE-Basic Foundation, 2016)
Succinic scaling factor	Global state	Real	0.7	[dmnl]	(BE-Basic Foundation, 2016)
Electricity correction factor	Global state	Real	6.3 (average profits made from electricity sales per ton of sugarcane)	[R$]	Calculated based on {de Gorter, 2013 #2}
Catching radius	Global state	Integer	4 (* scaling factor)	[dmnl]	{Ferraz Dias de Moraes, 2014 #219}
Max investment rate	Global state	Real	0.2	[dmnl]	Assumption
INTERNALLY CALCULATED GLOBAL PROCESSING PLANT VARIABLES					
GLOBAL CAR DRIVER VARIABLES					
GLOBAL CAR DRIVER VARIABLES WITH INPUT DATA					
Total daily GEEL demand	Global state	Integer	17836556264	[GEEL/day]	(UNICA, 2016)
Gasoline energy density	Global state	Integer	100 ;energy density in relation to other fuels products; gasoline taken per definition as 100	[dmnl]	(Armbrust, 2014)
Hydrous energy density	Global state	Integer	67 ;hydrous energy density is 2/3 of gasoline	[dmnl]	(Armbrust, 2014)
Anhydrous energy density	Global state	Integer	67 ;anhydrous density is 2/3 of gasoline	[dmnl]	(Armbrust, 2014)

Driver logistics factor	Global state	Integer	30	[%]	Armbrust
%-price-switch	Global state	Integer	10	[dmnl]	Armbrust
GLOBAL DISTRIBUTOR VARIABLES					
GLOBAL DISTRIBUTOR VARIABLES WITH INPUT DATA					
Plant logistics factor	Global state	Integer	40	[%]	(Armbrust, 2014)
Smoothness factor for distributors	Global state	Real	0.25	[dmnl]	(Armbrust, 2014)
Preferred level	Global state	Real	0.5	[dmnl]	(Armbrust, 2014)
Start level	Global state	Real	0.5	[dmnl]	(Armbrust, 2014)
Storage capacity	Global state	Integer	20	[days]	Assumption
GLOBAL TRADER VARIABLES					
GLOBAL TRADER VARIABLES WITH INPUT DATA					
Foreign logistics	Global state	Real	0.13 [price to transport from Sao Paulo port to US. Philadelphia port: 7416 miles]	[R$/l]	(Crago et al., 2010)
Trader margin	Global state	Integer	10	[%]	Assumption
Normal export shipment quantity	Trader state	Floating point	5425110; Average daily export quantity in Sao Paulo between 2012 – 2015 (multiplied by 2 in the model)	[l/day]	(UNICA, 2016)

Normal import shipment quantity	Trader state	Floating point	103604; Internal variable Average daily import quantity in Sao Paulo between 2012 – 2015 (multiplied by 2 in the model)	[l/day]	(UNICA, 2016)
GLOBAL AIRPORT VARIABLES					
GLOBAL AIRPORT VARIABLES WITH INPUT DATA					
Total KEEL demand	Global state	Integer	Internal variable	[KEEL/day]	N/A
KEEL demand Sao Paulo	Global state	Real	3714547000; 2020 scenario	[KEEL/day]	HIP & flightpath to aviation
KEEL demand Rio de Janeiro	Global state	Real	1381051000; 2020 scenario	[KEEL/day]	HIP & flightpath to aviation

POLICIES					
Variable	Is a	Type	Value	Unit	Sources
Blending mandate	Policy	Real	27	[%]	[in 2015] (USDA, 2015a)
Anhydrous tax	Policy	Real	0.05	[R$/l]	(USDA, 2015a)
Variable hydrous tax	Policy	Real	12	[%]	(USDA, 2015a)
Fixed hydrous tax	Policy	Real	0	[R$/l]	(USDA, 2015a)
Variable gasoline tax	Policy	Real	25	[%]	(USDA, 2015a)
Fixed gasoline tax	Policy	Real	0.48	[R$/l]	(USDA, 2015a)
Hydrous export tax	Policy	Real	20	[%]	(Elobeid & Tokgoz, 2008)
Hydrous import tax	Policy	Real	11.75	[%]	(Elobeid & Tokgoz, 2008)

EXTERNAL VARIABLES					
Variable	Is a	Type	Value	Unit	Sources
Global sugar price	External variable	Real	1.24	[R$/kg]	(average for 2010 to 2015) (USDA, 2016)
Domestic gasoline price	External variable	Real	1.6	[R$/l]	(average for 2013 to 2014) (ANP, 2015)
Exchange rate BRL/USD	External variable	Real	0.43	[dmnl]	(average between 2010 and 2015) (X-RATES, 2016)
Foreign hydrous price	External variable	Real	0.66	[$/l]	(NY harbor price) {OPIS, 2016 #299}
Inter cluster distance	External variable	Real	2	[dmnl]	By default to simulate competition. Assumption
Ratio supplier land sugarcane	External variable	Real	0.4	[dmnl]	{Ferraz Dias de Moraes, 2014 #219}
Landowner lease share	External variable	Real	0.25	[%]	Assumption
Kerosene price	External variable	Real	1.1	[R$/l]	{aeroportos, 2016 #298}
Biojet blend ratio	External variable	Real	50	[%]	HIP

APPENDIX III: VALIDATION OF THE BIOREFINERY MODEL

Transcript of expert consultation with Marcelo Pierossi

MEETING 1

About Marcelo Pierossi:

Marcelo Pierossi is a Sao Paulo based agricultural consultant in the Brazilian sugarcane industry with more than 20 years. He is founder and owner of AgroPerforma: an agricultural consultancy company founded in 2014. Before that, he was employed at the Center of Sugarcane Technology and the Copersugar Technological Center.

Points discussed:

- The Brazilian sugarcane industry produces around 30 billion liters of ethanol per year and 100% of the cars produced in Brazil are FFV's. Only imported cars and most trucks/pickups are not FFV's.

- For FFV drivers it is more profitable to drive ethanol when its price is around 70% of the price of Gasoline C (because of the lower mileage that can be achieved with ethanol). Because of the seasonality of sugarcane production, ethanol prices during the season are different than ethanol prices in off season. There is small sugarcane, sugar and ethanol production in the tales of the season: it looks like a normal distribution. Therefore, ethanol prices are strongly correlated with seasonality.

- The center south area is responsible for about 90% of the sugarcane production in Brazil, and the Northern part for about 10%.cane / ethanol price has a strong correlation with the seasonality

- The CEPEA provides data for current and historical selling prices of anhydrous and hydrous ethanol at the plant. These are the prices plants get paid by the distributors, and are thus without taxes and freight. These are probably the same prices as used for CONSECANA.

- I explained Mr. Pierossi my hypothesis that it could be challenging for the production of biojet fuel and biosuccinic acid to evolve if sugar and ethanol are still relatively more profitable. Mr. Pierossi answered that the structure of the Brazilian sugarcane market as it is today is working very well. There is no shortage of ethanol, but in the next years, problems could be faced, because less pure gasoline might be available. This is due to the fact that Brazil is not investing in oil refinery capacity nowadays. Therefore, the Brazilian government indicated that within 5 years, there could be a shortage in pure gasoline. This would have to be compensated by increased ethanol production. However, if sugarcane production would not be increased and would also be used for other products (biojet fuel and biosuccinic acid in this case), then this could be a problem. The amount of land used for sugarcane can still be increased, but not really in the state of Sao Paulo. Sao Paulo is very saturated already. Most expansion is possible in other states, such as Matto Grosso do Sul, Goiás and Minas Gerais. But, in particular in Goiás there is also some competition with other crops.

- I explained Mr. Pierossi that in the Biorefinery model I attempted to simulate how suppliers interact with processing plants and how processing plants also grow sugarcane themselves through vertical integration. Mr. Pierossi mentioned that all sugarcane transactions in Sao Paulo state are fully regulated by CONSECANA-SP. He knows that in some areas there is strong competition between plants for sugarcane, because in such areas there is less sugarcane available than the plants are able to crush. In such a situation, the suppliers have a strong bargaining position and can earn more than the CONSECANA-SP based price. Plants will then make higher bids to suppliers than the CONSECANA-SP based price. Also, the costs of leasing land depend on the market situation. Mr. Pierossi explains that there are three main types of sugarcane procurement in Brazil: (1) vertical production on owned land; (2) vertical production on leased land and (3) independent suppliers produce sugarcane and deliver to the sugar mill. For the second type, landowners are paid according the CONSECANA-SP based sugarcane price. The lease rate also partially depends on the characteristics of the land (such as fertility, slope etc.). For the third type, the suppliers pay the transportation costs and are paid for their sugarcane according to the CONSECANA-SP based TRS price of the plant. An overall remark is that sugarcane growing is very expensive, due to the expensive equipment and need for trained staff. Furthermore, he mentioned that the sugarcane procurement is very complex and not much is known about how frequent each procurement type is used.

- I explained Mr. Pierossi my hypothesis about how CONSECANA-SP could be a barrier for biorefineries. Since the sugarcane price is based on the market prices of sugar and ethanol, it might be too expensive for the production of biojet fuel and biosuccinic acid. Another barrier would be that a biorefinery could disturb existing relations between suppliers and processing plants, because a biorefinery cannot use CONSECANA-SP anymore. Therefore, the biorefinery would probably have to pay a higher price for sugarcane, because there is more uncertainty for the supplier. Mr. Pierossi answered to this that suppliers are likely to just keep selling their sugarcane to conventional processing plants, as long as that is most profitable. Sugarcane is the best sugar-based feedstock. He questions why sugarcane would be used for the production of biojet fuel and biosuccinic acid, if there would be competition with ethanol and sugar. Furthermore, he mentions: if a supplier used to deliver sugarcane to a processing plant for several years or even decades, and used to get paid based on CONSECANA-SP, why would he then supply to a new partner? He would need more money, because of the increased uncertainty/risk.

- Mr. Pierossi mentions that another very important issue nowadays is the fact that bagasse is used by processing plants to produce bioelectricity of which a part is sold to the electricity grid. However, suppliers only get paid for the sugar juice content of the sugarcane, and not for bagasse (the fibers). Thus, some suppliers say that bioelectricity profits could not be made without the sugarcane he supplies. There is no regulation about that in the CONSECANA-SP model yet. He explains there is a movement going by suppliers to get this changed. However, as a traditional institution, CONSECANA-SP is adopting very slow; not at the speed the suppliers want. This is also because there are three players in determining the CONSECANA-SP regulation: ORPLANA (the sugarcane growers association), UNICA (the sugarcane processing plants association) and the state of Sao Paulo. Possible changes that would have to be made to the CONSECANA-SP system in case of biorefineries entering the market, could face similar challenges. The players will not easily change the CONSECANA-SP regulations, as long as biorefineries only represent a small part of the market. In Mr. Pierossi's opinion, no changes should be made to the COSECANA-SP model if there is only a small market share of biorefineries. Another problem is lacking interest of processing plants to produce other products than they are used to.

MEETING 2

- What is the distribution (in percentages) of the three common contract structures in São Paulo state (1. Land owned and operated by mills, 2. Land leased and operated by mills, 3. Independent farmers supply to mills)?

  About 30 to 50% of sugarcane is supplied by suppliers.

- Do you know in what regions in São Paulo state there is much competition between sugar mills for sugarcane from independent farmers (where the crushing capacity is more than the available sugarcane)?

  Competition exists in the areas where traditional processing plants exist. These plants have a long history and there is a high density of processing plants and there is less sugarcane than can be processed by all the processing plants together. There is less competition in the new expansion areas west of Sao Paulo state.

- In those areas with many sugar mills, is there also much competition for land to lease? I read that land lease rates for sugar mills have increased significantly over the last 10 years due to competition. Is that correct?

  Yes, land lease costs in the sugarcane industry rose about 150% in the last 10 years (article; magazine)

- If independent farmers have multiple sugar mills close by, can they choose another sugar mill to supply to every year? In other words, do the supply contracts have a duration of one harvest season?

  Yes, they can. What also sometimes happens is that processing plants are acquired by other processing plants and then closed. As a result, the processing plant can get more sugarcane. An example is San Martino mill which bought Santa Cruz mill in 2007. Sugarcane is the most important asset for processing plants. The more sugarcane is processed, the higher the industrial yields can be.

- What is the most common way of exporting hydrous ethanol; by sugar mills or trading companies?

  This is often done by trading companies, such as Copersugar or Cargill. Only some large “milling groups” like Raizen arrange exports themselves. Individual mills are not able to arrange exports themselves.

- How often can “flex mills” (mills producing both ethanol and sugar) change their production quantities? In other words, how often do they evaluate how much sugarcane juice they will use for sugar production and ethanol production?

  Most mills are flex mills. Typically the production range is between 45% to 55%, depending on the market prices of sugar and ethanol. Mills are very flexible to change these production ratios. However, the market does not change so quickly; it is not common for market prices to change daily. Usually one product is preferred during the entire length of a season. This is also because of long term sales contracts made in advance.

- Why are there still some ethanol-only plants in Sao Paulo?

  When all your crushing capacity is satisfied, you also start to produce sugar. Earlier is difficult, because more investments are required to run both an ethanol and a sugar production line. Plants usually start with only ethanol production technology and then invest in sugar production technology when the amount of sugarcane supplied is increased. This has to do with the growth cycle of sugarcane.

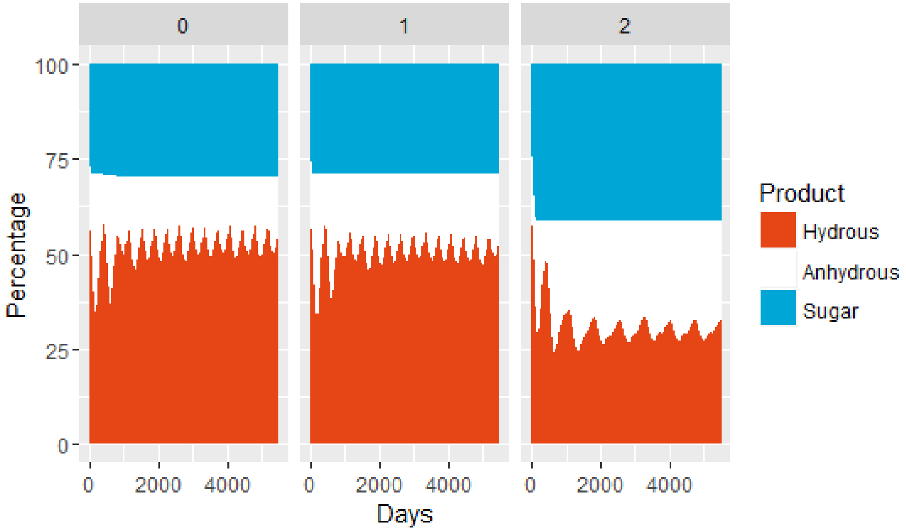
- What is the estimated average, min and max crushing capacity of sugar mills in São Paulo state?

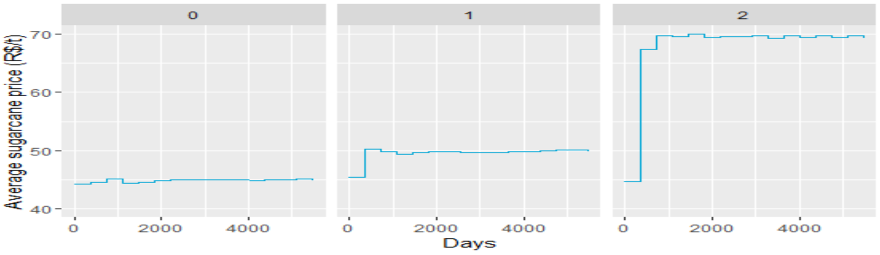
  No answer.

Desk validation

Validation point:

The production of sugar should increase/decrease when the global sugar price is increased/decreased and all other variables remain constant.



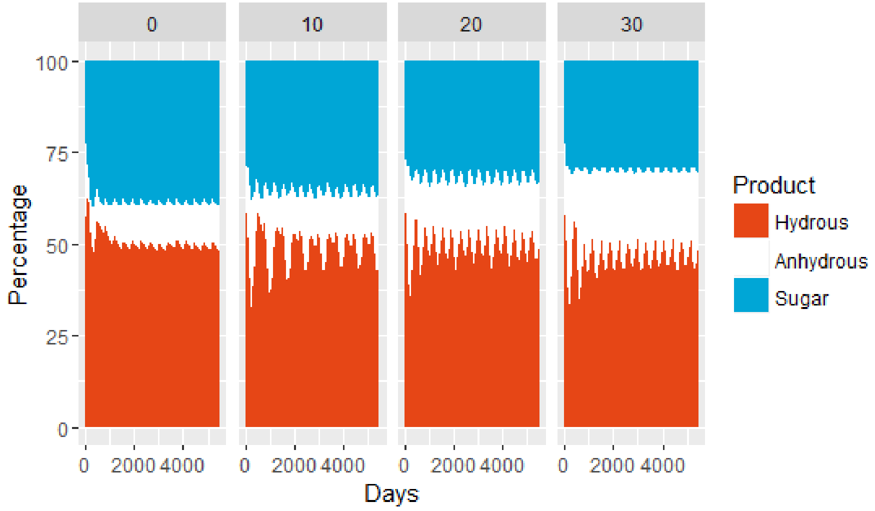


Insights:

As can be seen from the above figures, sugar production is indeed increased when the global sugar price is increased. However, sugar production is not decreased then the global sugar price is decreased. This is due to the fact that the sugar production started in its minimal production rate of 0.4. Furthermore, one can see that the average sugarcane price is increases significantly when sugar production is high.

Validation point:

Anhydrous ethanol production should increase/decrease when the blending mandate is increased/decreased and all other variables are constant.

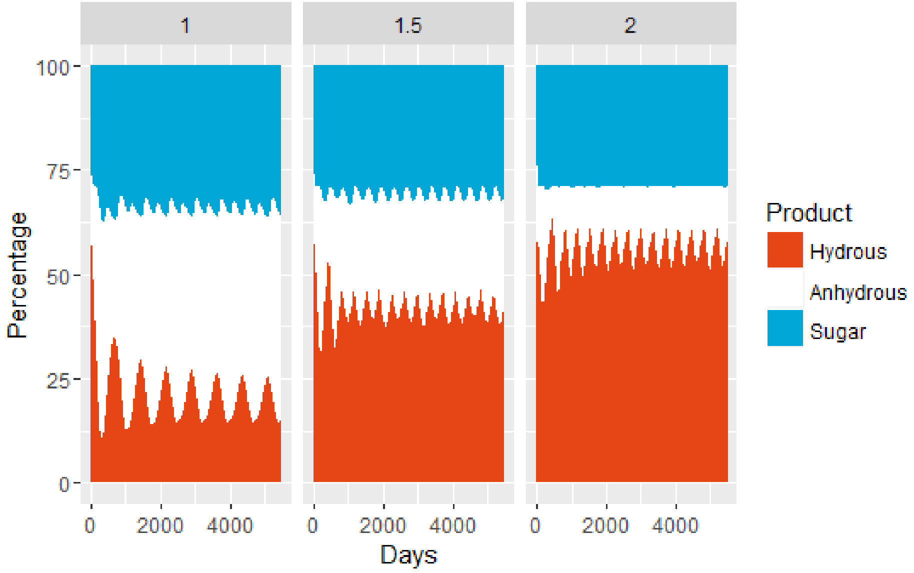


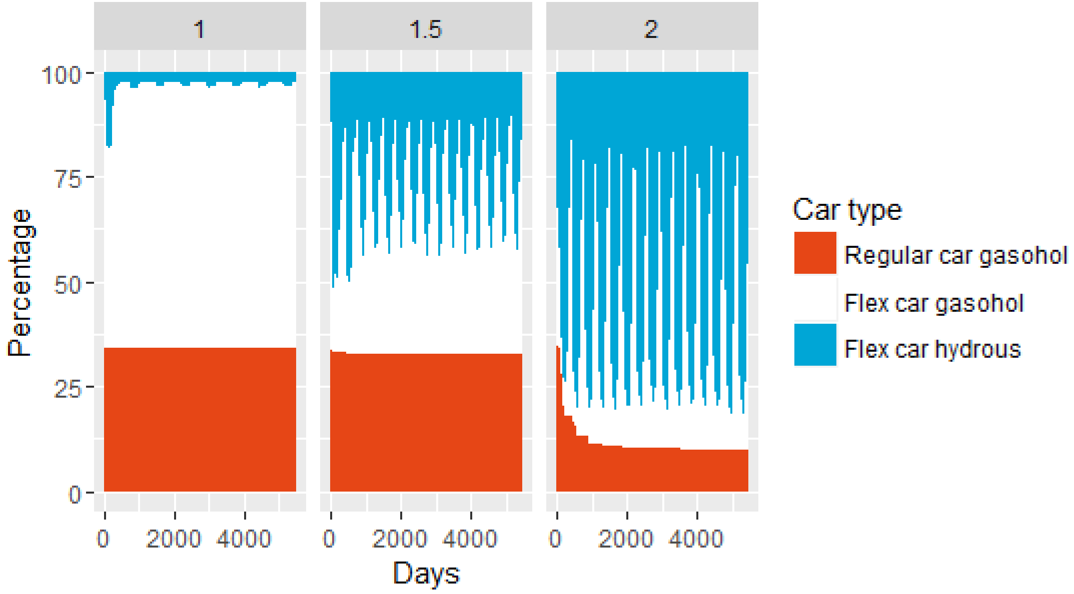
Insights:

As can be seen from the above figures, anhydrous production is increased when the blending mandate is increased. Therefore, hydrous production is decreased. On the other hand, hydrous production is high when anhydrous production is low due to the low blending mandate.

Validation point:

Hydrous ethanol consumption should increase/decrease when the gasoline price is increased/decreased and all other variables are constant.





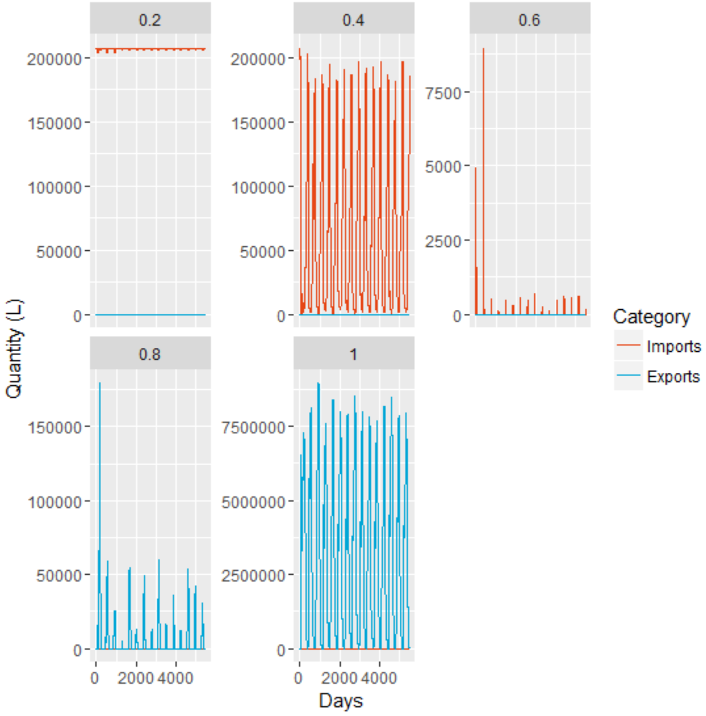
Insights:

As can be seen from the above figures, hydrous ethanol production is maximized when the gasoline price is low. This is due to the fact that anhydrous production decreases. On the other hand, hydrous ethanol production and consumption decreases when the gasoline price is decreased.

Validation point:

Hydrous ethanol imports should increase/decrease when the foreign hydrous ethanol price is decreased/increased and all other variables are constant.

Hydrous ethanol exports should increase/decrease when the foreign hydrous ethanol price is increased/increased and all other variables are constant.

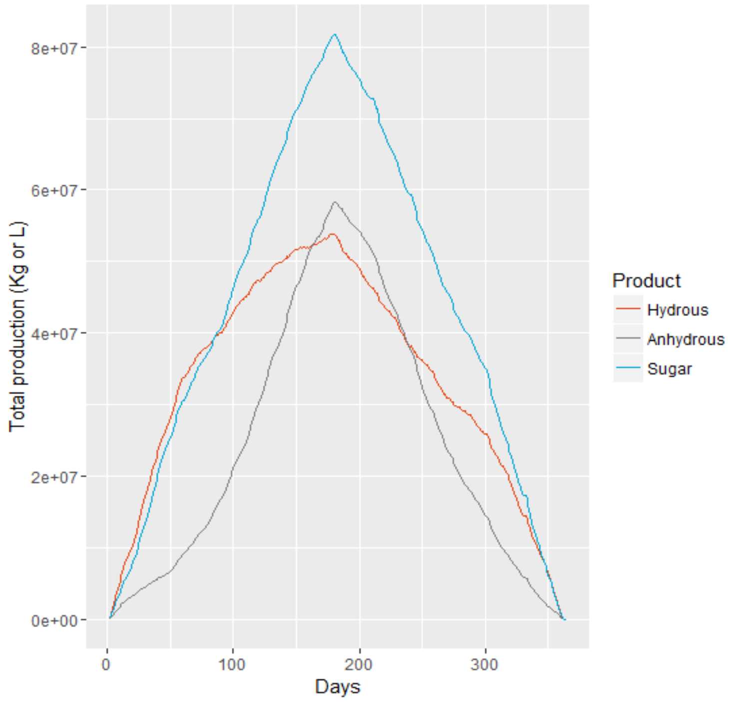


Insights:

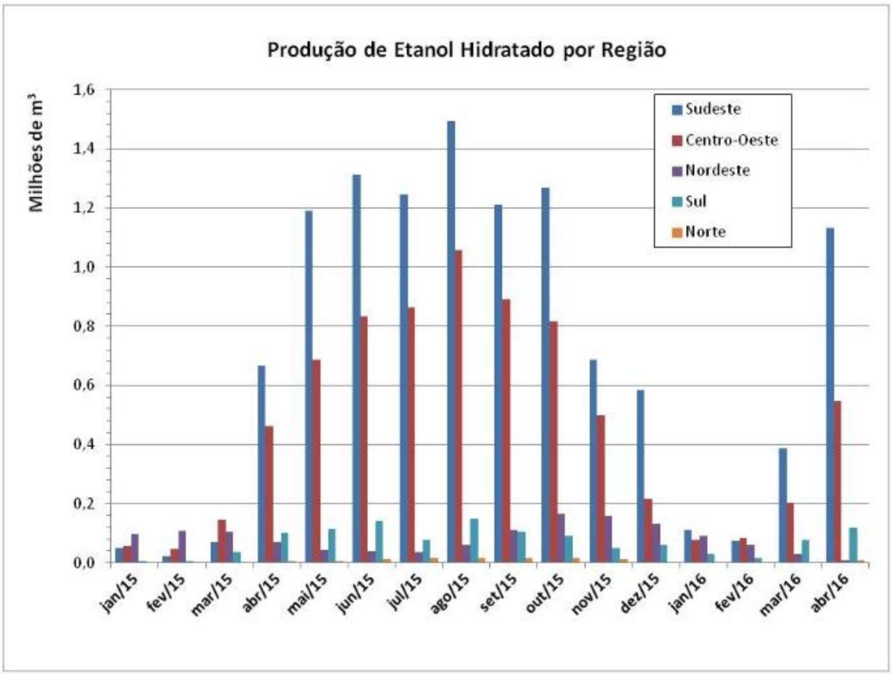
As can be seen from the above figure, ethanol imports and exports are very responsive to changes in the foreign hydrous ethanol price. When the foreign hydrous ethanol price is high, exports are high as well. On the other hand, imports increase when the foreign hydrous ethanol price is decreased.

Validation point:

Production quantities should have a bell-shaped like behavior of the length of each harvest season.



10. PRODUÇÃO DE ETANOL HIDRATADO POR REGIÃO (Período: jan/2015 até abr/2016).

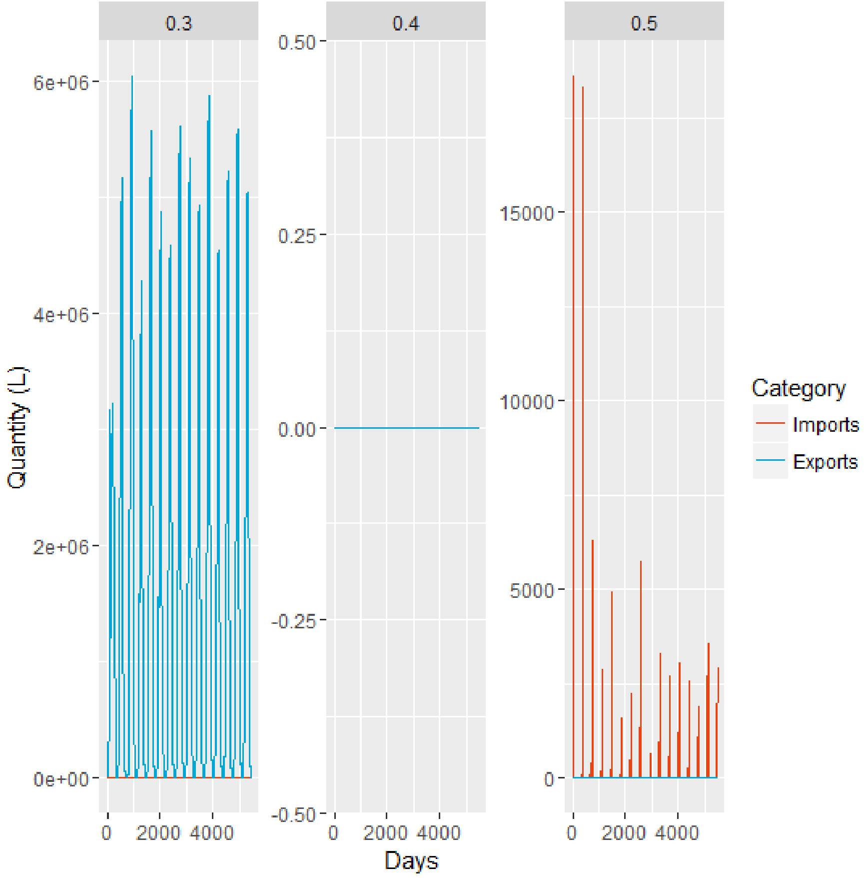


Insights:

As can be seen from the above figure, the production quantities of the different products behave like a normal distribution-like shape. The lower figure shows the production quantities of hydrous ethanol in the São Paulo area in red. As one can see, the distribution of production over the harvest season shows a similar behavior as is observed in the real-world case.

Validation point:

When keeping the foreign hydrous ethanol price constant, ethanol exports should increase when the exchange rate is low (the Brazilian real gets worth more compared to the US dollar), whereas ethanol exports should have the opposite behavior.

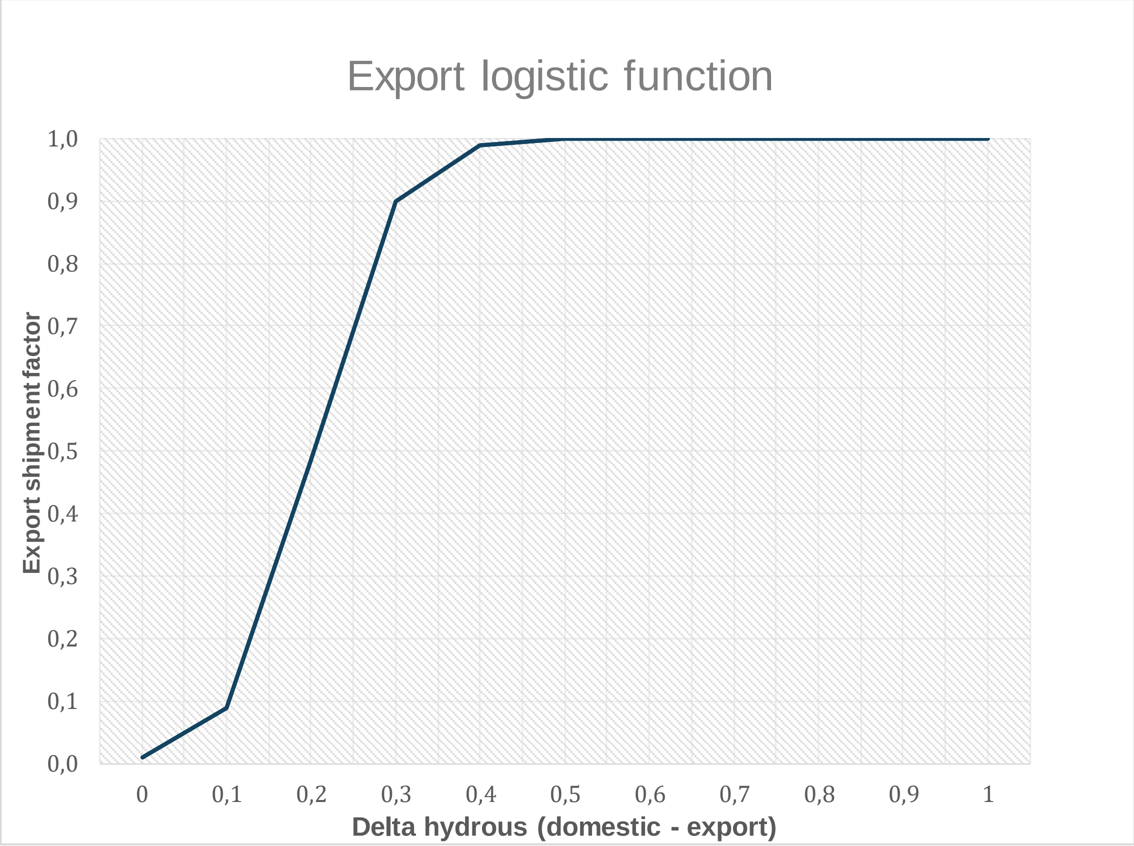


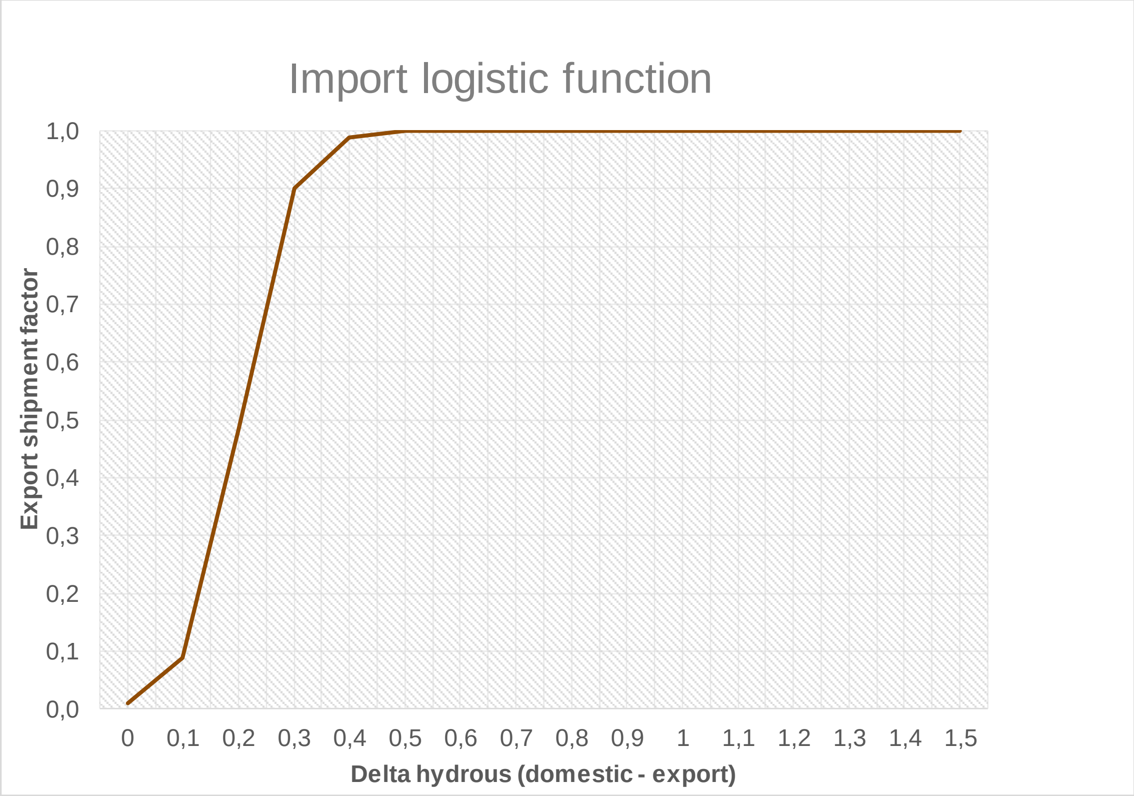
Insights:

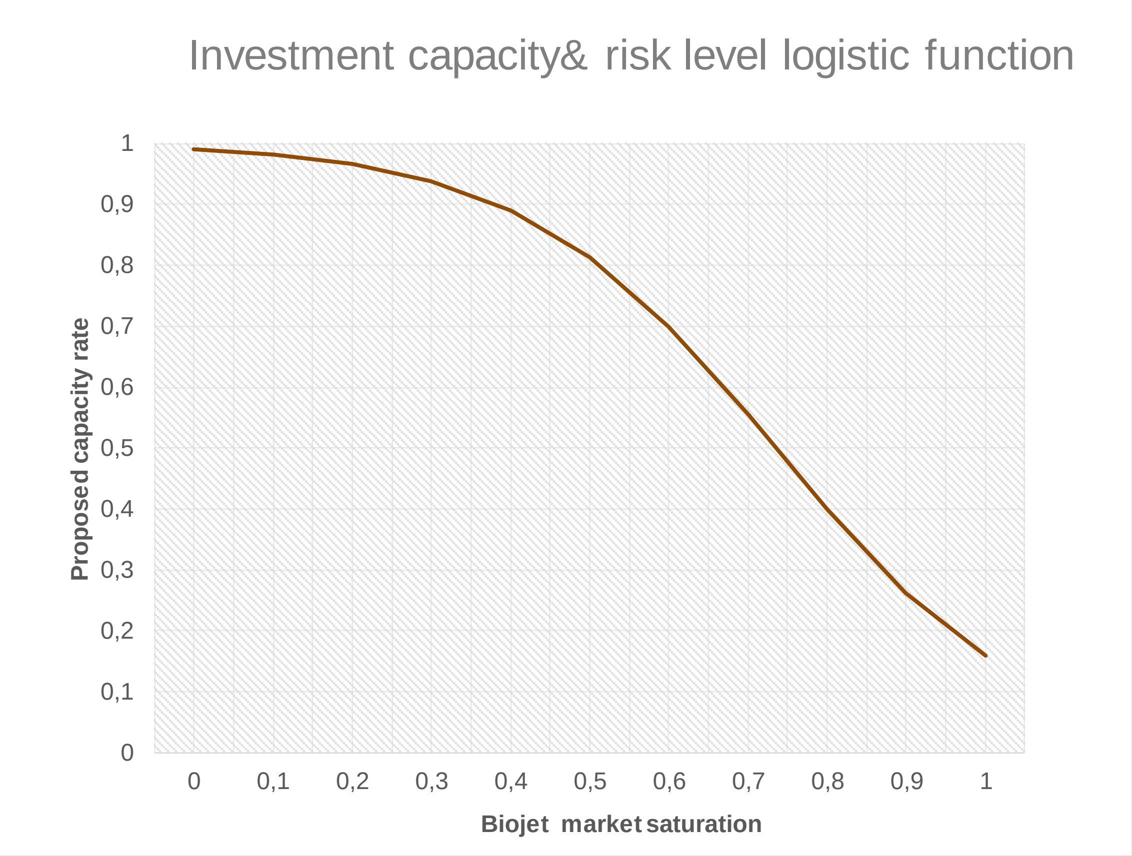
As shown in the figure above, ethanol imports and exports indeed change when the exchange rate is adjusted. This is a behavior that is often seen in the real-world case as well and can have significant influence on the hydrous ethanol imports and exports.

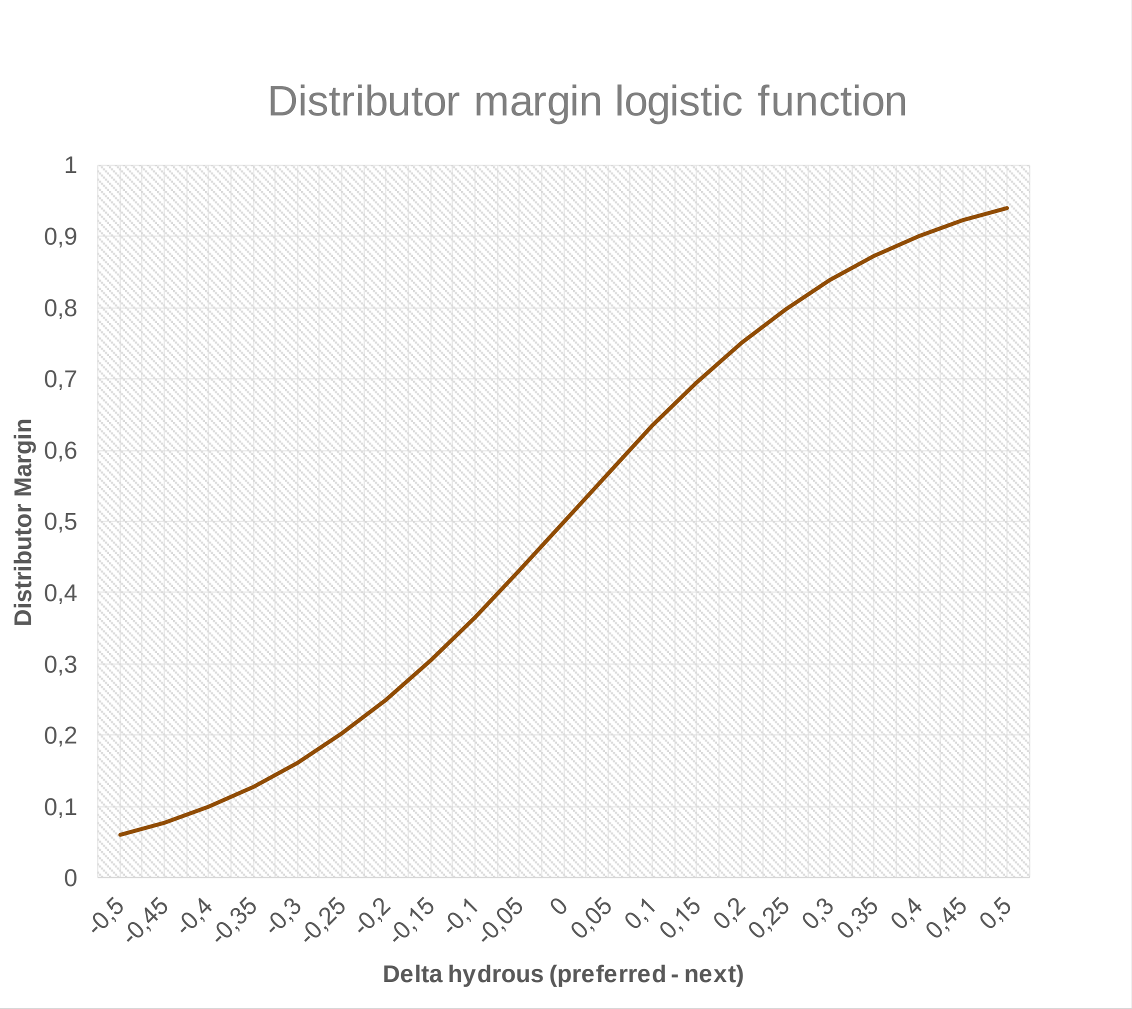
APPENDIX IV: SENSITIVITY ANALYSIS AND CALIBRATION

Logistic functions






Investment capacity& risk level logistic function
Proposed capacity rate
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
Biojet market saturation


Distributor margin logistic function
Distributor Margin
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,5
-0,45
-0,4
-0,35
-0,3
-0,25
-0,2
-0,15
-0,1
-0,05
0
0,05
0,1
0,15
0,2
0,25
0,3
0,35
0,4
0,45
0,5
Delta hydrous (preferred - next)

Biorefinery base model sensitivity analysis and calibration

Biorefinery base model sensitivity analysis without international hydrous trade

Table 27: Sensitivity analysis settings and results for the biorefinery base model without foreign trade

Variable	Min (-10%)	Base	Max (+10%)	Numerically sensitive?	Behaviorally sensitive?	Calibrated value
catching radius	3.6	4	4.4	no	no	N/A
start TRS price	0.423	0.47	0.517	yes, the average sugarcane price	no	unchanged; data source used
total available land	4500000	5000000	5500000	no	no	N/A
smoothness factor plants	0.25	0.5	0.75	yes, the average sugarcane price	no	N/A
smoothness factor distributor	0.25	0.5	0.75	no	no	N/A
switch capacity	0.09	0.1	0.11	no	no	N/A
global sugar price	1.35	1.5	1.65	yes, the average sugarcane price and production ratios	no	unchanged; subject for scenario analysis
gasoline price	1.62	1.8	1.98	yes, the GEEL hydrous and gasohol price and	no	unchanged; subject for scenario analysis

				production ratios		
ratio total supplier land	0.36	0.4	0.44	no	no	N/A

Table 28: Parameters used for biorefinery base model sensitivity analysis with international hydrous trade

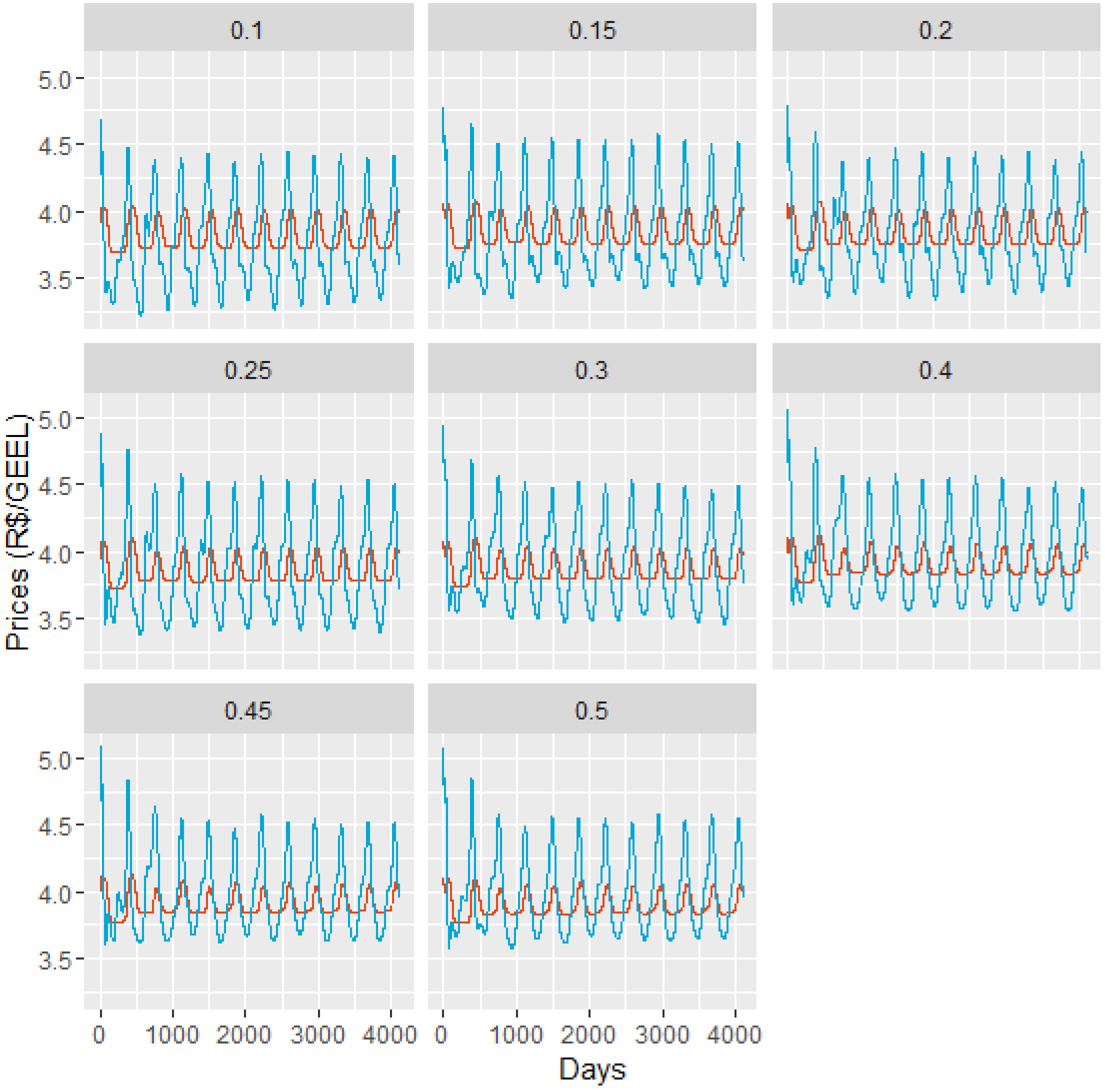
Variable	Min (-10%)	Base	Max (+10%)	Numerically sensitive?	Behaviorally sensitive?	Calibrated value
Normal import quantity	93243,6	103604	113964,4	no	no	N/A
Normal export quantity	4882599	5425110	5967621	yes	no	N/A

Table 29: Parameters used for biorefinery model sensitivity analysis without international hydrous trade

Variable	Min (-10%)	Base	Max (+10%)	Numerically sensitive?	Behaviorally sensitive?	Calibrated value
Inter cluster distance	1.8	2	2.2	yes	no	unchanged; subject for scenario analysis
Max investment rate	0.18	0.2	0.22	yes, the biosuccinic acid demand satisfaction and average sugarcane price	no	N/A
Biojet blend ratio	45	50	55	yes, the biosuccinic acid demand satisfaction	no	unchanged; subject for scenario analysis

Biosuccinic acid demand	1010959	1123288	1235617	yes, the 2G biojet demand satisfaction	no	N/A
Electricity correction factor	5.67	6.3	6.93	yes, the 1G biojet production	no	N/A
Supplier risk premium rate sensitivity	-0.1	0	0.1	yes, the biosuccinic acid demand satisfaction	no	N/A
Landowner risk premium risk premium rate sensitivity	-0.1	0	0.1	yes, the biosuccinic acid demand satisfaction and sugarcane price paid by biorefineries and	no	N/A
Investment risk weight sensitivity	-0.1	0	0.1	yes, the average sugarcane price	no	N/A
Counter offer deduction	-0.1	0	0.1	yes, the succinic demand satisfaction and the average sugarcane price	no	N/A

Sensitivity analysis for the landowner lease share



Biorefinery base model sensitivity analysis with international trade

Table 30: Parameters used for biorefinery base model sensitivity analysis with international hydrous trade

Variable	Min (-10%)	Base	Max (+10%)	Sensitive?	Calibrated value
Foreign hydrous price	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2			yes	unchanged; subject for scenario analysis
Normal import quantity	93243,6	103604	113964,4	yes	unchanged
Normal export quantity	4882599	5425110	5967621	yes	unchanged

APPENDIX V: COMPLEMENT FOR DATA TREATMENT AND VISUALIZATION

Complement of results presented in chapter 7

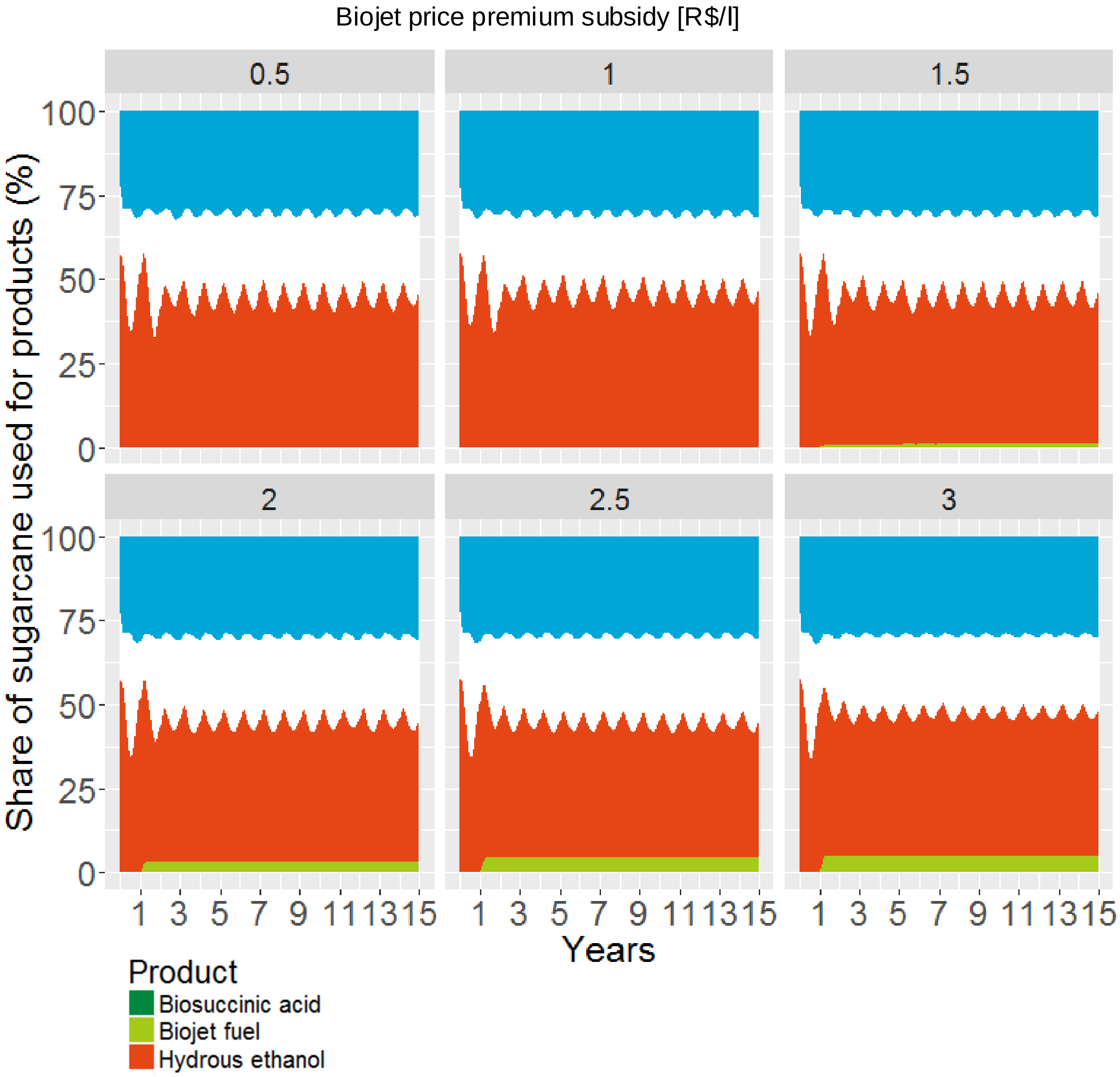


Figure 54: Experiment 3A – percentage of sugarcane used for each product when biojet price premium subsidy policy is activated

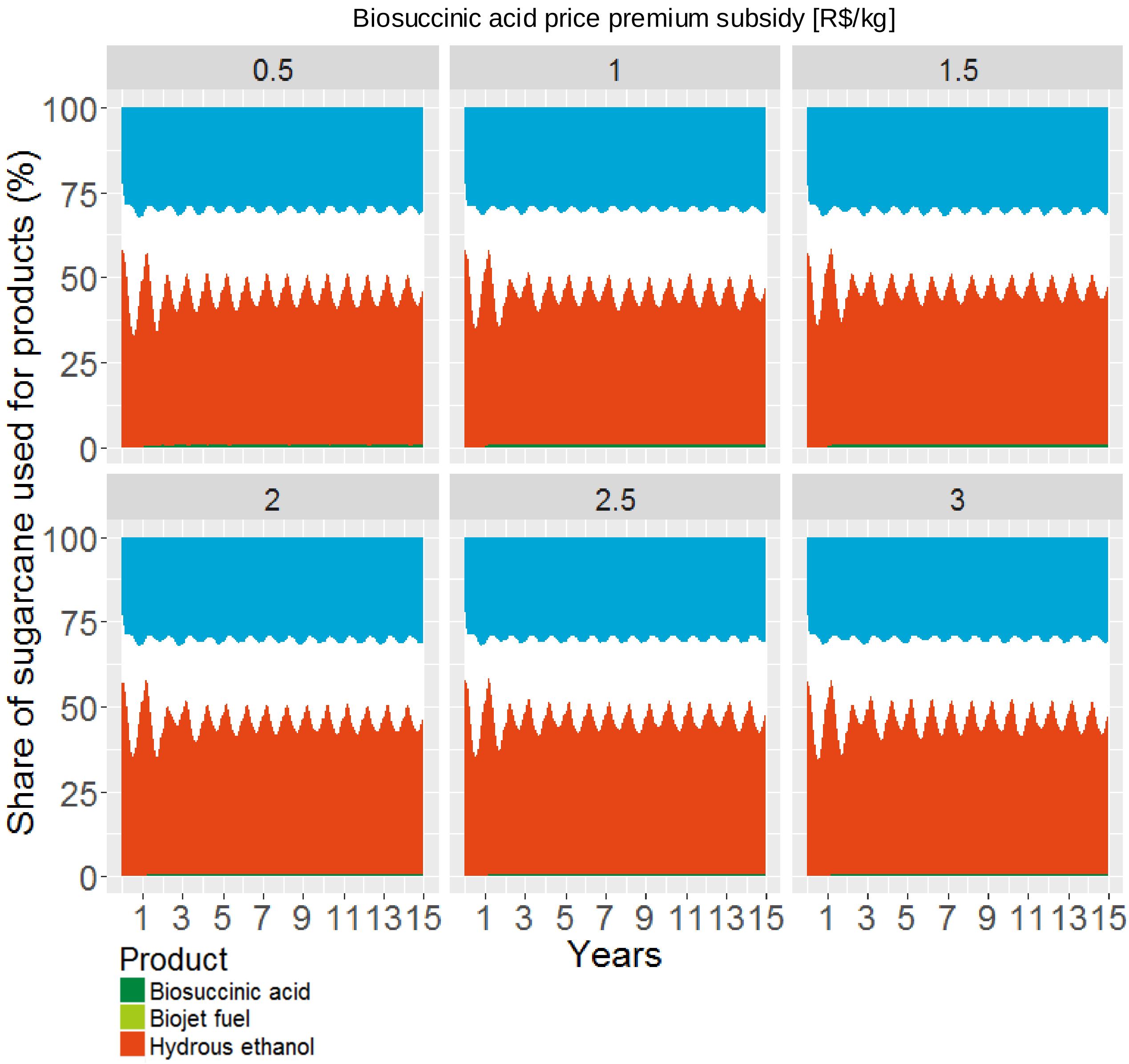


Figure 55: Experiment 3D – percentage of sugarcane used for each product when biosuccinic acid price premium subsidy policy is activated

R statistics script

The R statistics script that was used for visualization of the NetLogo experimentation results is too long to display here. The source code is is available upon request with the author or thesis supervisors.

Statistical analysis with SPSS

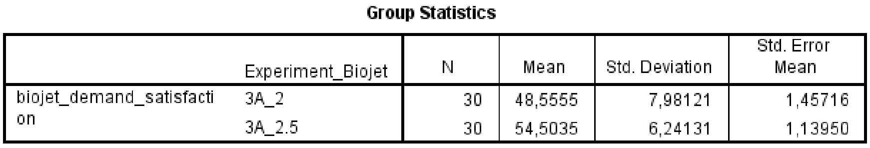
This appendix presents the results of the statistical tests that were performed, and the process through which this was done. First, the results of the three different scenarios for each policy experiment were used to identify the policy setting that relates to the highest demand satisfaction for biojet fuel and biosuccinic acid. The goal here, was to analyze at the policy values for which a further increase would not lead to significantly more demand satisfaction. Then, the best results from different policies were compared. The SPSS statistical software was used for carrying out the statistical analyses. As the experiments were run for 30 repetitions, the central limit theorem was used to choose the proper statistical tests. Four statistical tests were used for comparing the means of the different results. Before being applied, the conditions for their use were checked and verified:

- **Student T-test for differences in averages**: used to compare the averages of a desired variable for two different conditions.
- **ANOVA**: used to compare the averages of groups of more than two settings. When the conditions of ANOVA were not fulfilled (differences in variance between groups), the non-parametric test of **Kruskal-Wallis** was applied.
- **Student T test for a known average**: used to compare the results of the best setting with the desired results of 100% demand satisfaction.

1. Biojet fuel demand satisfaction: comparison

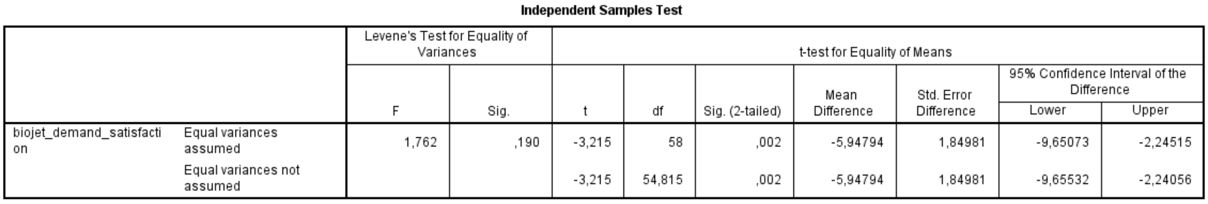
1.1 Experiment 3A: changes in biojet fuel subsidy (0.5-1-1.5-2-2.5-3)

- 3A_ 2 - 3.A_2.5



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3A_2	30	48,5555	7,98121	1,45716
	3A_2.5	30	54,5035	6,24131	1,13950

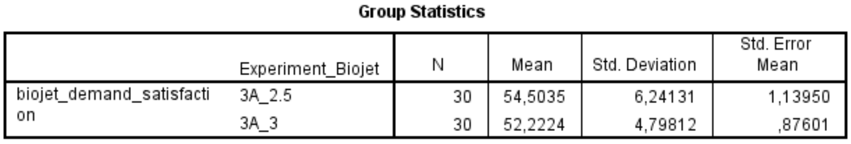


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	1,762	,190	-3,215	58	,002	-5,94794	1,84981	-9,65073	-2,24515
	Equal variances not assumed			-3,215	54,815	,002	-5,94794	1,84981	-9,65532	-2,24056

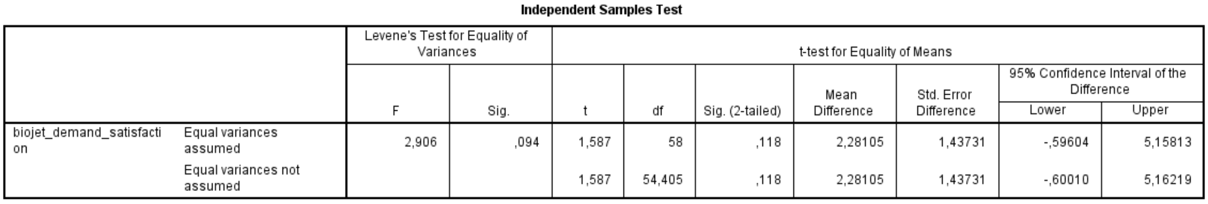
Result: H0 is rejected, the average of 3A_2 is lower than the average of 3A_2.5.

- 3A_2.5 - 3A_3



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3A_2.5	30	54,5035	6,24131	1,13950
	3A_3	30	52,2224	4,79812	,87601

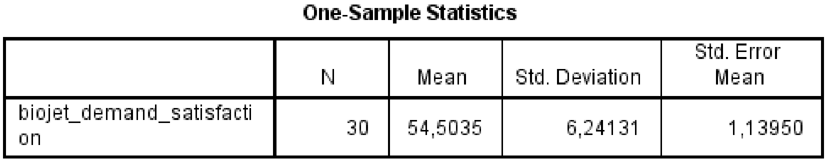


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	2,906	,094	1,587	58	,118	2,28105	1,43731	-,59604	5,15813
	Equal variances not assumed			1,587	54,405	,118	2,28105	1,43731	-,60010	5,16219

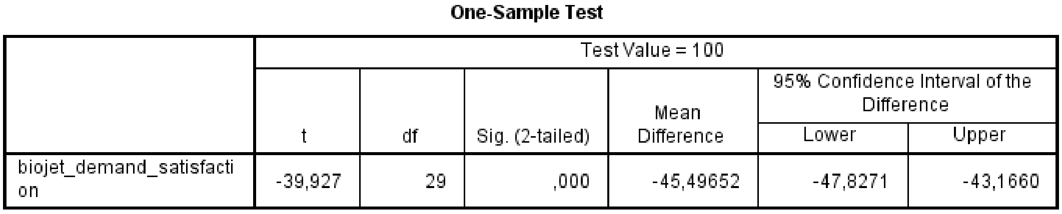
Result: H0 is accepted, averages are equal.

- 3A_2.5 - 100%



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	30	54,5035	6,24131	1,13950



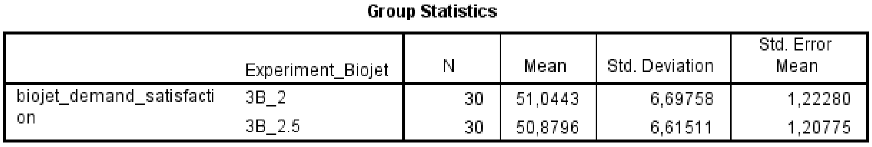
One-Sample Test

	Test Value = 100					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
biojet_demand_satisfaction	-39,927	29	,000	-45,49652	-47,8271	-43,1660

Result: H0 is rejected, the average of 3A_2.5 is lower than 100%.

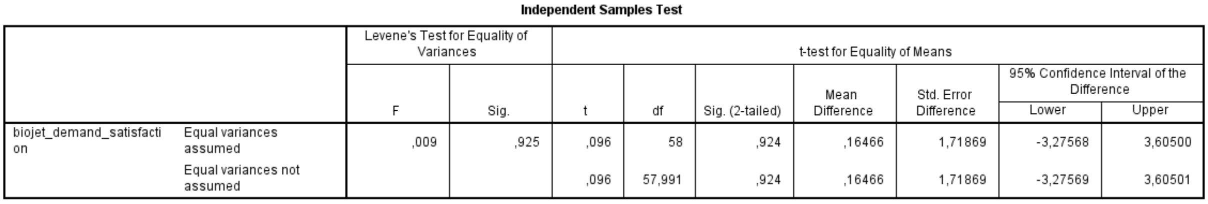
1.2 Experiment 3B: changes in biojet fuel subsidy (0.5-1-1.5-2-2.5-3)

- 3B_2 - 3B_2.5



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3B_2	30	51,0443	6,69758	1,22280
	3B_2.5	30	50,8796	6,61511	1,20775

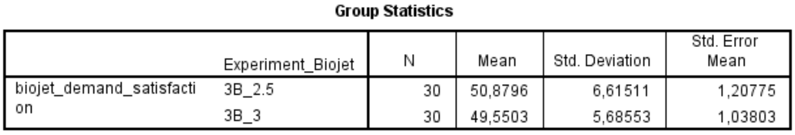


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	,009	,925	,096	58	,924	,16466	1,71869	-3,27568	3,60500
	Equal variances not assumed			,096	57,991	,924	,16466	1,71869	-3,27569	3,60501

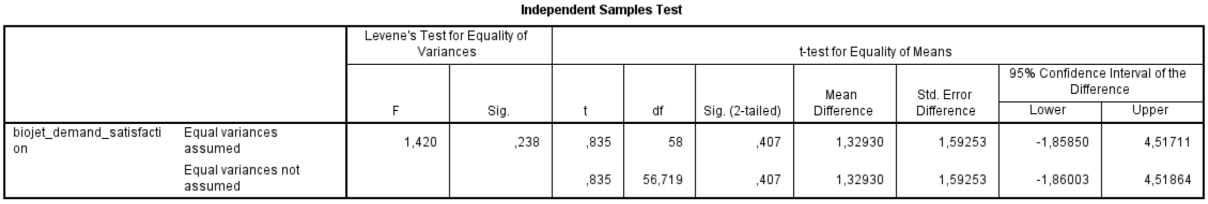
Result: H0 is accepted, averages are equal.

- 3B_2.5 - 3B_3



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3B_2.5	30	50,8796	6,61511	1,20775
	3B_3	30	49,5503	5,68553	1,03803

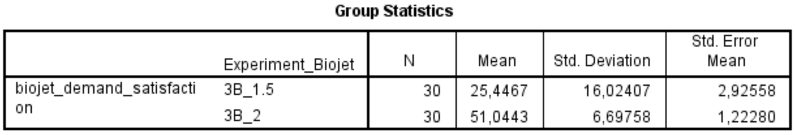


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	1,420	,238	,835	58	,407	1,32930	1,59253	-1,85850	4,51711
	Equal variances not assumed			,835	56,719	,407	1,32930	1,59253	-1,86003	4,51864

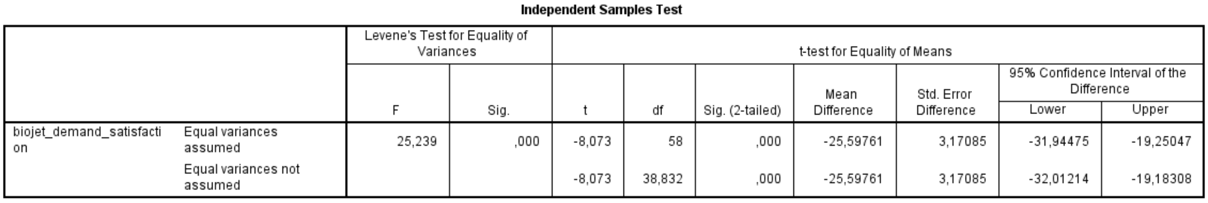
Result: H0 is accepted, averages are equal.

- 3B_1.5 - 3B_2



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3B_1.5	30	25,4467	16,02407	2,92558
	3B_2	30	51,0443	6,69758	1,22280

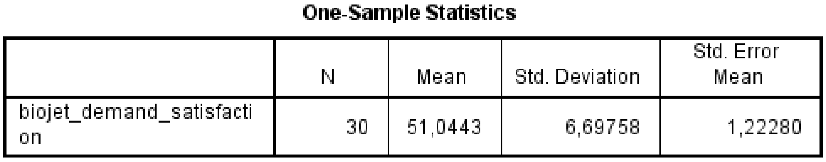


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	25,239	,000	-8,073	58	,000	-25,59761	3,17085	-31,94475	-19,25047
	Equal variances not assumed			-8,073	38,832	,000	-25,59761	3,17085	-32,01214	-19,18308

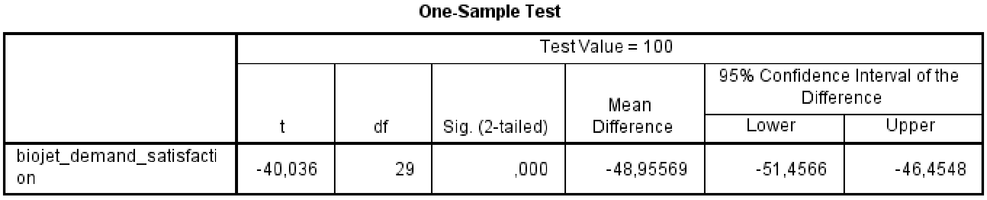
Result: H0 is rejected, the average of 3B_1.5 is lower than the average of 3B_2.

- 3B_2 - 100%



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	30	51,0443	6,69758	1,22280



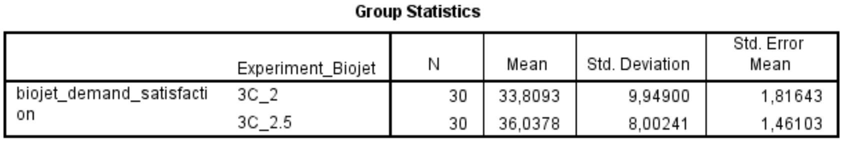
One-Sample Test

	Test Value = 100					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
biojet_demand_satisfaction	-40,036	29	,000	-48,95569	-51,4566	-46,4548

Result: H0 is rejected, the average of 3B_2 is lower than 100%.

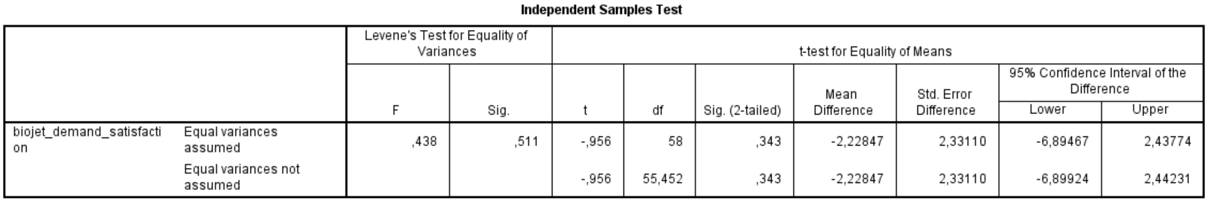
1.3 Experiment 3C: changes in biojet fuel subsidy (0.5-1-1.5-2-2.5-3)

- 3C_2 - 3C_2.5



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3C_2	30	33,8093	9,94900	1,81643
	3C_2.5	30	36,0378	8,00241	1,46103

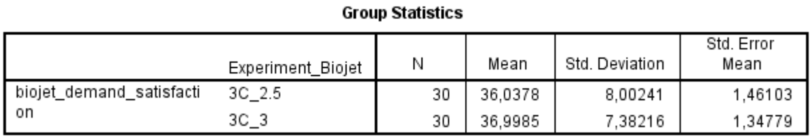


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	,438	,511	-,956	58	,343	-2,22847	2,33110	-6,89467	2,43774
	Equal variances not assumed			-,956	55,452	,343	-2,22847	2,33110	-6,89924	2,44231

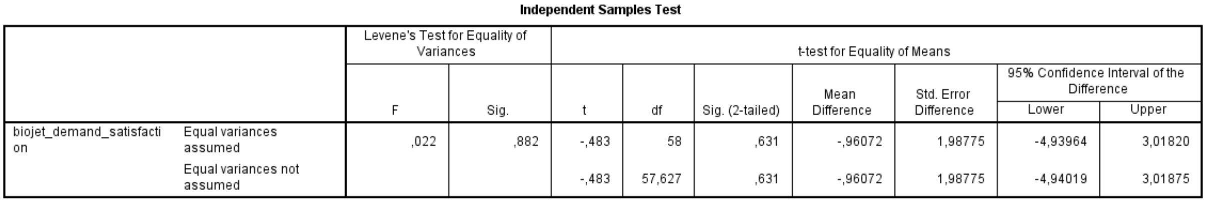
Result: H0 is accepted, averages are equal.

- 3C_2.5 - 3C_3



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3C_2.5	30	36,0378	8,00241	1,46103
	3C_3	30	36,9985	7,38216	1,34779

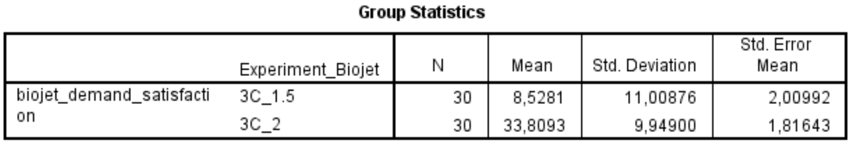


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	,022	,882	-,483	58	,631	-,96072	1,98775	-4,93964	3,01820
	Equal variances not assumed			-,483	57,627	,631	-,96072	1,98775	-4,94019	3,01875

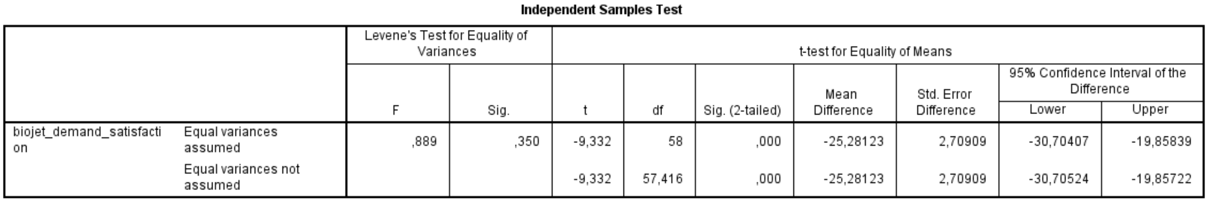
Result: H0 is accepted, averages are equal.

- 3C_1.5 - 3C_2



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3C_1.5	30	8,5281	11,00876	2,00992
	3C_2	30	33,8093	9,94900	1,81643

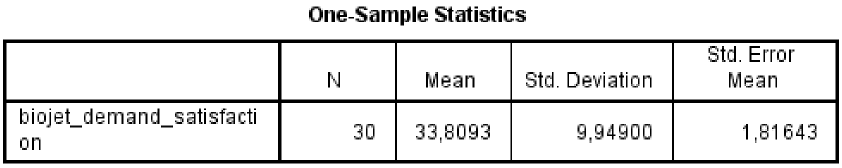


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	,889	,350	-9,332	58	,000	-25,28123	2,70909	-30,70407	-19,85839
	Equal variances not assumed			-9,332	57,416	,000	-25,28123	2,70909	-30,70524	-19,85722

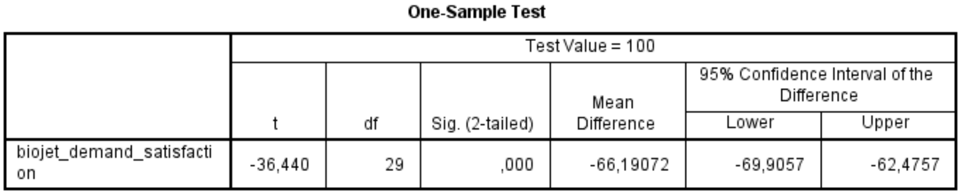
Result: H0 is rejected, the average of 3C_1.5 is lower than the average of 3C_2.

- 3C_2 - 100%



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	30	33,8093	9,94900	1,81643



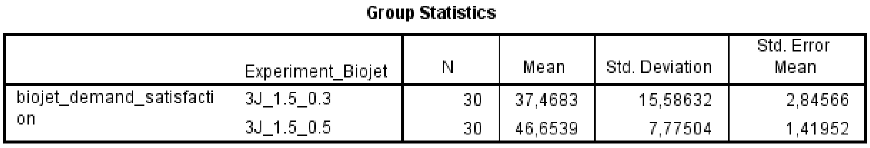
One-Sample Test

	Test Value = 100					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
biojet_demand_satisfaction	-36,440	29	,000	-66,19072	-69,9057	-62,4757

Result: H0 is rejected, the average of 3C_2 is lower than 100%.

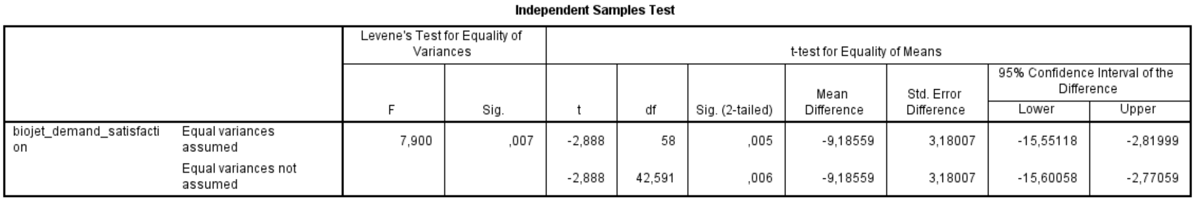
1.4 Experiment 3J: changes in biojet fuel subsidy (1-1.5-2) and risk premium compensation (0.1-0.3-0.5)

- 3J_1.5_0.3 - 3J_1.5_0.5



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3J_1.5_0.3	30	37,4683	15,58632	2,84566
	3J_1.5_0.5	30	46,6539	7,77504	1,41952

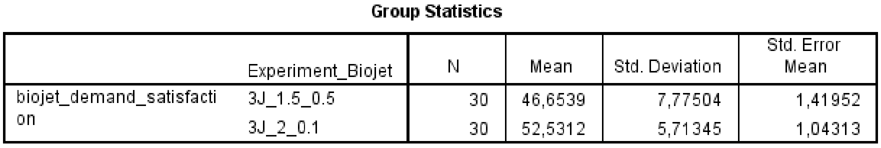


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	7,900	,007	-2,888	58	,005	-9,18559	3,18007	-15,55118	-2,81999
	Equal variances not assumed			-2,888	42,591	,006	-9,18559	3,18007	-15,60058	-2,77059

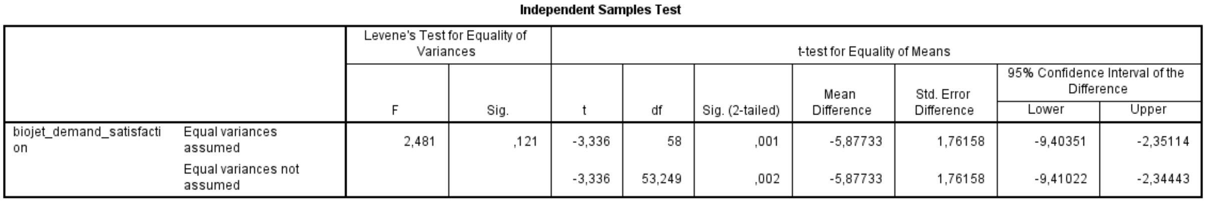
Result: H0 is rejected, the average of 3J_1.5_0.3 is lower than the average of 3J_1.5_0.5.

- 3J_1.5_0.5 - 3J_2_0.1



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3J_1.5_0.5	30	46,6539	7,77504	1,41952
	3J_2_0.1	30	52,5312	5,71345	1,04313

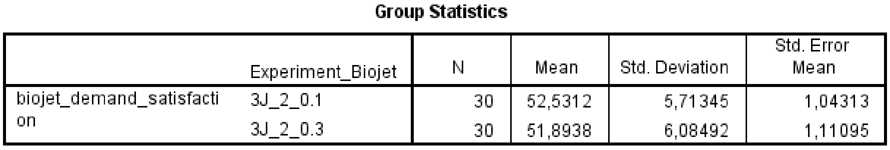


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	2,481	,121	-3,336	58	,001	-5,87733	1,76158	-9,40351	-2,35114
	Equal variances not assumed			-3,336	53,249	,002	-5,87733	1,76158	-9,41022	-2,34443

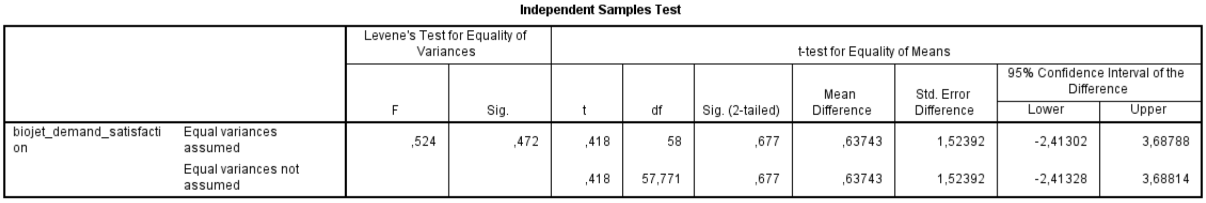
Result: H0 is rejected, the average of 3J_1.5_0.5 is lower than the average of 3J_2_0.1.

- 3J_2_0.1 - 3J_2_0.3



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3J_2_0.1	30	52,5312	5,71345	1,04313
	3J_2_0.3	30	51,8938	6,08492	1,11095

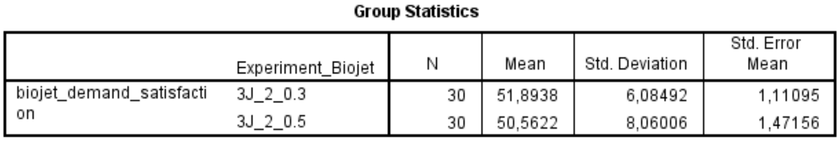


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	,524	,472	,418	58	,677	,63743	1,52392	-2,41302	3,68788
	Equal variances not assumed			,418	57,771	,677	,63743	1,52392	-2,41328	3,68814

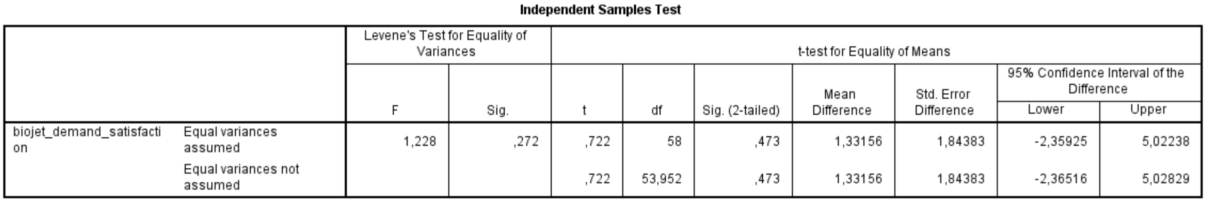
Result: H0 is accepted, averages are equal.

- 3J_2_0.1 - 3J_2_0.5



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3J_2_0.3	30	51,8938	6,08492	1,11095
	3J_2_0.5	30	50,5622	8,06006	1,47156

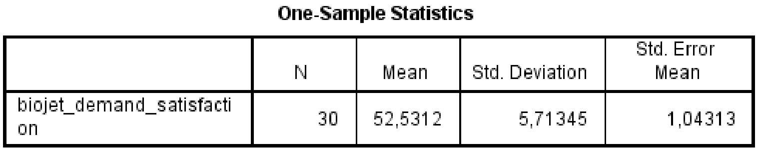


Independent Samples Test

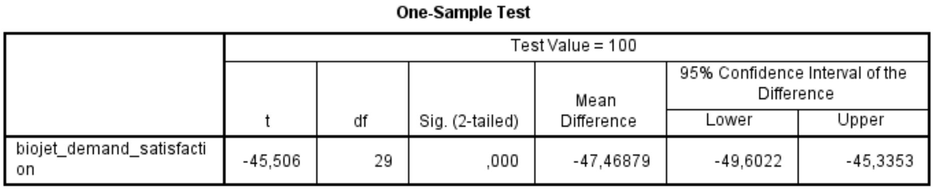
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	1,228	,272	,722	58	,473	1,33156	1,84383	-2,35925	5,02238
	Equal variances not assumed			,722	53,952	,473	1,33156	1,84383	-2,36516	5,02829

Result: H0 is accepted, averages are equal.

- 3J_2_0.1 - 100%


One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	30	52,5312	5,71345	1,04313


One-Sample Test

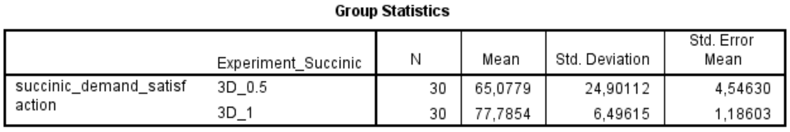
	Test Value = 100					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
biojet_demand_satisfaction	-45,506	29	,000	-47,46879	-49,6022	-45,3353

Result: H0 is rejected, the average of 3J_2_0.1 is lower than 100%.

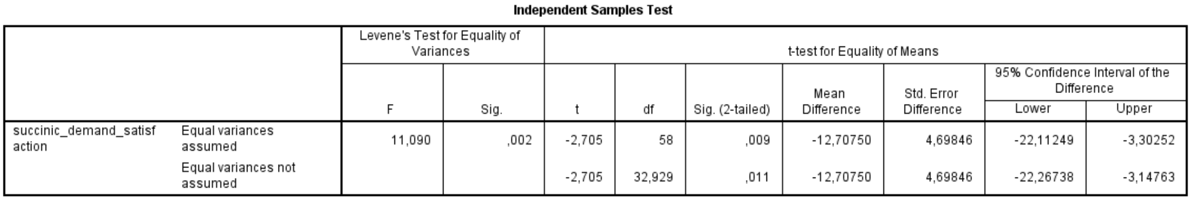
2. Biosuccinic acid demand satisfaction: comparison

2.1 Experiment 3D: changes in biosuccinic acid subsidy (0.5-1-1.5-2-2.5-3)

- 3D_0.5 - 3D_1


Group Statistics

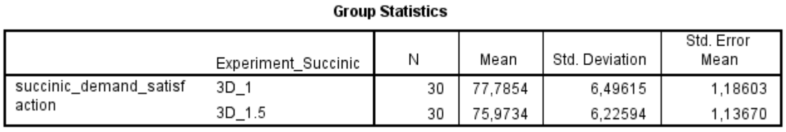
	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3D_0.5	30	65,0779	24,90112	4,54630
	3D_1	30	77,7854	6,49615	1,18603


Independent Samples Test

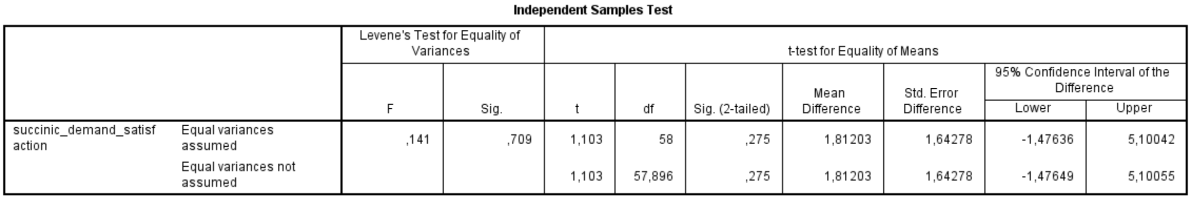
		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	11,090	,002	-2,705	58	,009	-12,70750	4,69846	-22,11249	-3,30252
	Equal variances not assumed			-2,705	32,929	,011	-12,70750	4,69846	-22,26738	-3,14763

Result: H0 is rejected, the average of 3D_0.5 is lower than the average of 3D_1.

- 3D_1 - 3D_1.5


Group Statistics

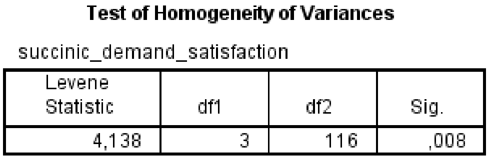
	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3D_1	30	77,7854	6,49615	1,18603
	3D_1.5	30	75,9734	6,22594	1,13670


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	,141	,709	1,103	58	,275	1,81203	1,64278	-1,47636	5,10042
	Equal variances not assumed			1,103	57,896	,275	1,81203	1,64278	-1,47649	5,10055

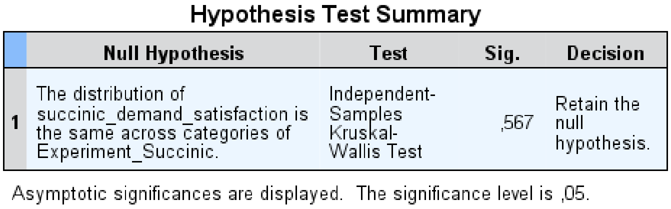
Result: H0 is accepted, averages are equal.

- 3D: Group comparison (3D_1.5, 3D_2, 3D_2.5 and 3D_3)


Test of Homogeneity of Variances

succinic_demand_satisfaction

Levene Statistic	df1	df2	Sig.
4,138	3	116	,008



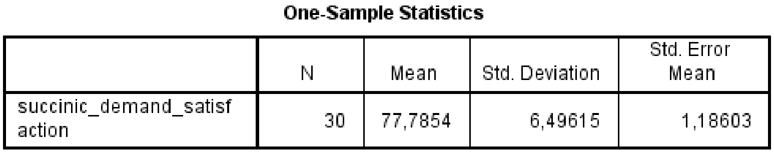
Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of succinic_demand_satisfaction is the same across categories of Experiment_Succinic.	Independent-Samples Kruskal-Wallis Test	,567	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is ,05.

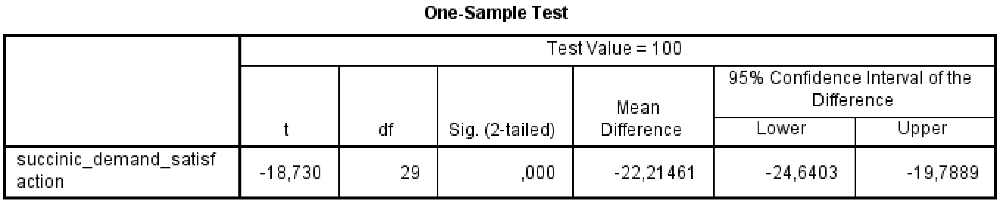
Result: H0 is accepted, averages are equal.

- 3D_1 - 100%



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	30	77,7854	6,49615	1,18603



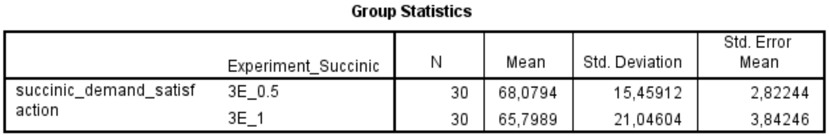
One-Sample Test

	Test Value = 100					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
succinic_demand_satisfaction	-18,730	29	,000	-22,21461	-24,6403	-19,7889

Result: H0 is rejected, the average of 3D_1 is lower than 100%.

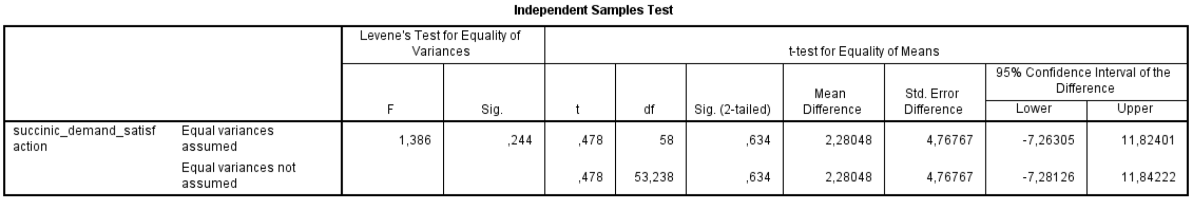
2.2 Experiment 3E: changes in biosuccinic acid subsidy (0.5-1-1.5-2-2.5-3)

- 3E_0.5 - 3E_1



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3E_0.5	30	68,0794	15,45912	2,82244
	3E_1	30	65,7989	21,04604	3,84246

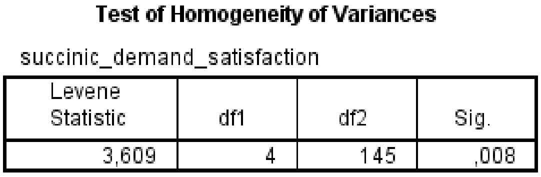


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	1,386	,244	,478	58	,634	2,28048	4,76767	-7,26305	11,82401
	Equal variances not assumed			,478	53,238	,634	2,28048	4,76767	-7,28126	11,84222

Result: H0 is accepted, averages are equal.

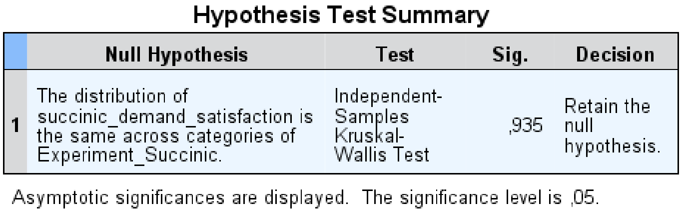
- 3E: Group comparison (3E_1, 3E_1.5, 3E_2, 3E_2.5 and 3E_3)



Test of Homogeneity of Variances

succinic_demand_satisfaction

Levene Statistic	df1	df2	Sig.
3,609	4	145	,008



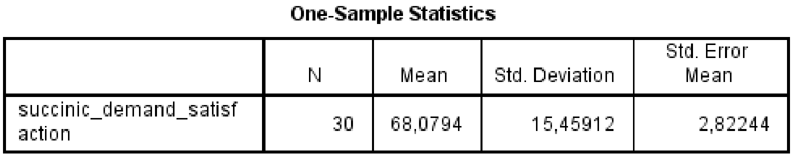
Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of succinic_demand_satisfaction is the same across categories of Experiment_Succinic.	Independent-Samples Kruskal-Wallis Test	,935	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is ,05.

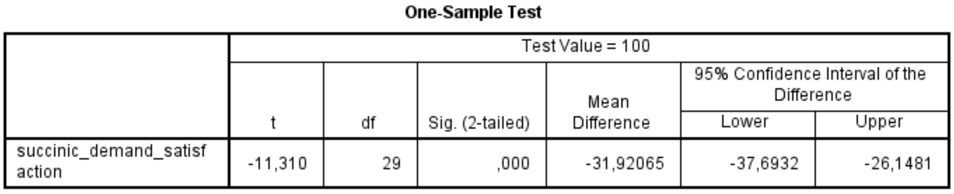
Result: H0 is accepted, averages are equal.

- 3E_0.5 - 100%



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	30	68,0794	15,45912	2,82244



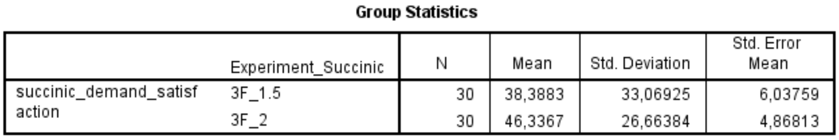
One-Sample Test

	Test Value = 100					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
succinic_demand_satisfaction	-11,310	29	,000	-31,92065	-37,6932	-26,1481

Result: H0 is rejected, the average of 3E_0.5 is lower than 100%.

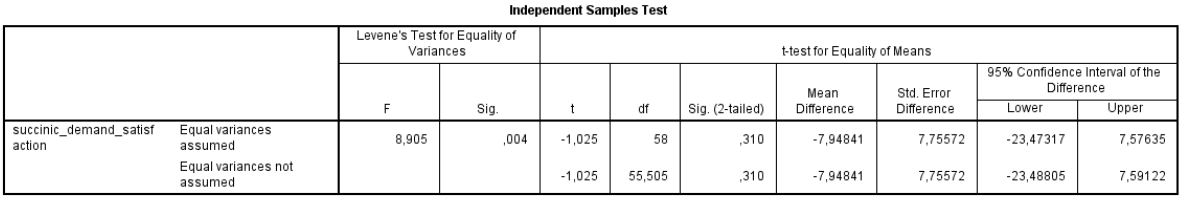
2.3 Experiment 3F: changes in biosuccinic acid subsidy (0.5-1-1.5-2-2.5-3)

- 3F_1.5 - 3F_2



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3F_1.5	30	38,3883	33,06925	6,03759
	3F_2	30	46,3367	26,66384	4,86813

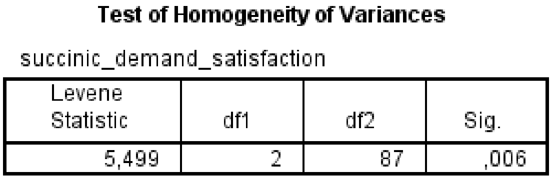


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	8,905	,004	-1,025	58	,310	-7,94841	7,75572	-23,47317	7,57635
	Equal variances not assumed			-1,025	55,505	,310	-7,94841	7,75572	-23,48805	7,59122

Result: H0 is accepted, averages are equal.

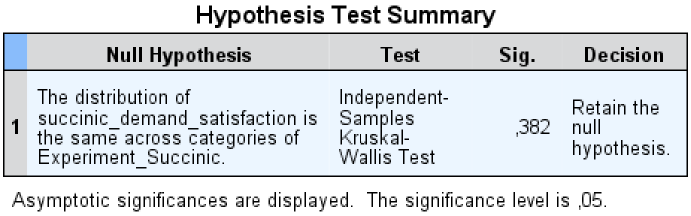
- 3F:ANOVA 2-3



Test of Homogeneity of Variances

succinic_demand_satisfaction

Levene Statistic	df1	df2	Sig.
5,499	2	87	,006



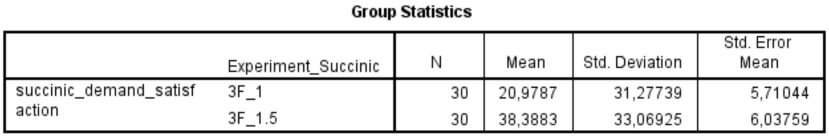
Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of succinic_demand_satisfaction is the same across categories of Experiment_Succinic.	Independent-Samples Kruskal-Wallis Test	,382	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is ,05.

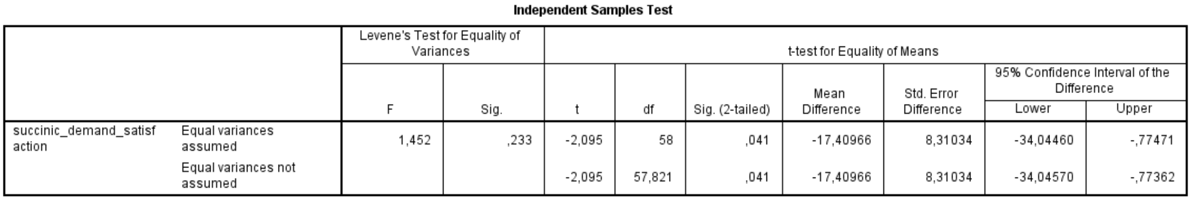
Result: H0 is accepted, averages are equal.

- 3F_1 - 3F_1.5



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3F_1	30	20,9787	31,27739	5,71044
	3F_1.5	30	38,3883	33,06925	6,03759

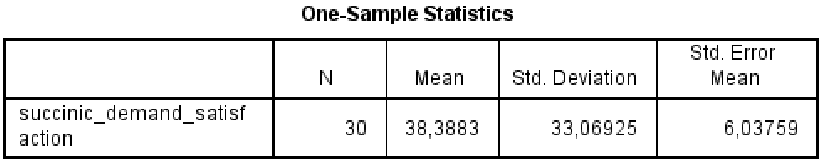


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	1,452	,233	-2,095	58	,041	-17,40966	8,31034	-34,04460	-,77471
	Equal variances not assumed			-2,095	57,821	,041	-17,40966	8,31034	-34,04570	-,77362

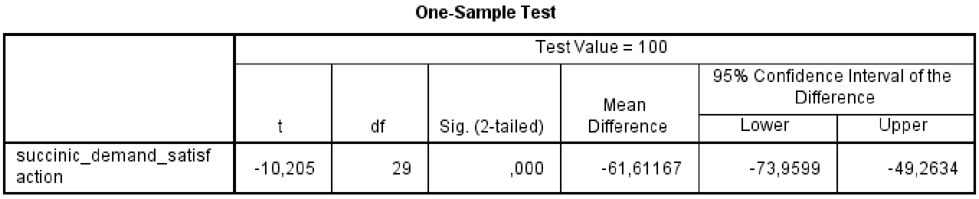
Result: H0 is rejected, the average of 3F_1 is lower than the average of 3F_1.5.

- 3F_1.5 - 100%



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	30	38,3883	33,06925	6,03759



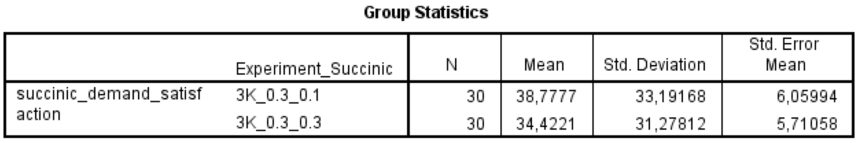
One-Sample Test

	Test Value = 100					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
succinic_demand_satisfaction	-10,205	29	,000	-61,61167	-73,9599	-49,2634

Result: H0 is rejected, the average of 3F_1.5 is lower than 100%.

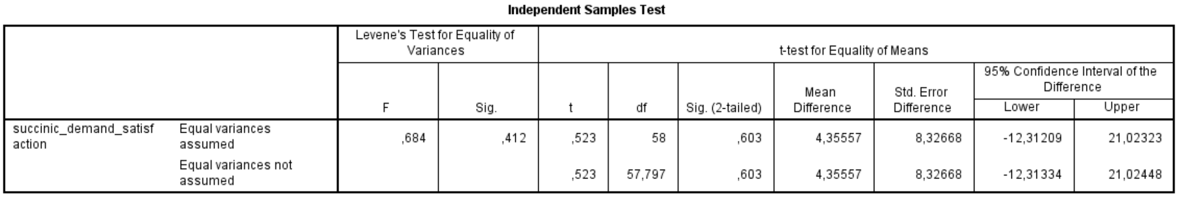
2.4 Experiment 3K: changes in biosuccinic acid subsidy (0.3-0.5-0.7) and risk premium compensation (0.1-0.3-0.5)

- 3K_0.3_0.1 - 3K_0.3_0.3



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3K_0.3_0.1	30	38,7777	33,19168	6,05994
	3K_0.3_0.3	30	34,4221	31,27812	5,71058

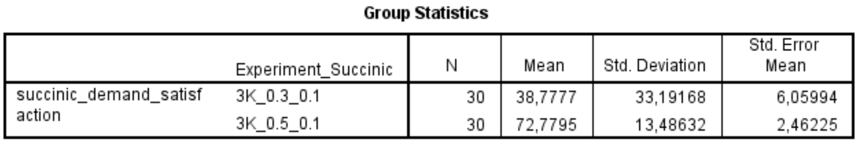


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	,684	,412	,523	58	,603	4,35557	8,32668	-12,31209	21,02323
	Equal variances not assumed			,523	57,797	,603	4,35557	8,32668	-12,31334	21,02448

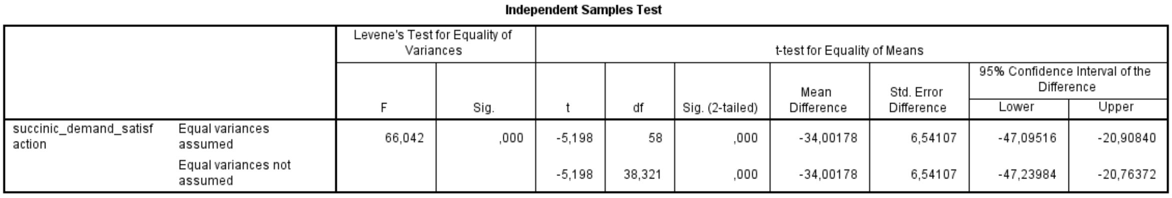
Result: H0 is accepted, averages are equal.

- 3K_0.3_0.1 - 3K_0.5_0.1



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3K_0.3_0.1	30	38,7777	33,19168	6,05994
	3K_0.5_0.1	30	72,7795	13,48632	2,46225

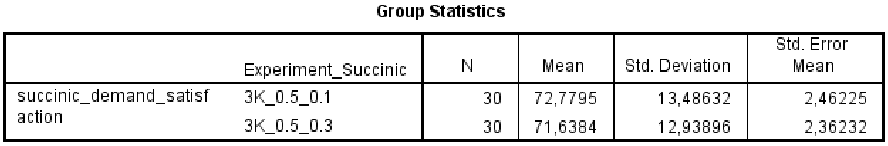


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	66,042	,000	-5,198	58	,000	-34,00178	6,54107	-47,09516	-20,90840
	Equal variances not assumed			-5,198	38,321	,000	-34,00178	6,54107	-47,23984	-20,76372

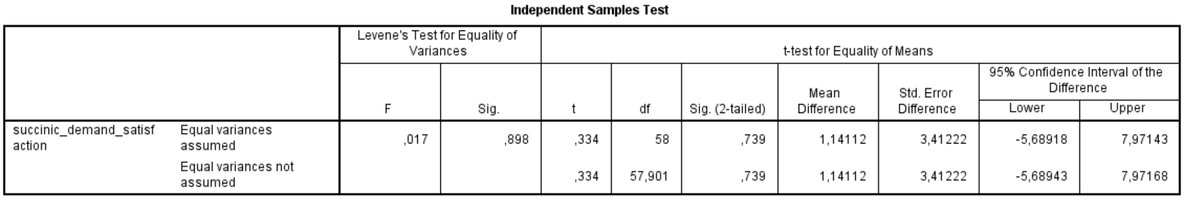
Result: H0 is rejected, the average of 3K_0.3_0.1 is lower than the average of 3K_0.5_0.1.

- 3K_0.5_0.1 - 3K_0.5_0.3



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3K_0.5_0.1	30	72,7795	13,48632	2,46225
	3K_0.5_0.3	30	71,6384	12,93896	2,36232

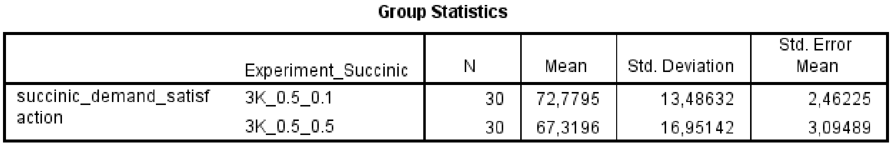


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	,017	,898	,334	58	,739	1,14112	3,41222	-5,68918	7,97143
	Equal variances not assumed			,334	57,901	,739	1,14112	3,41222	-5,68943	7,97168

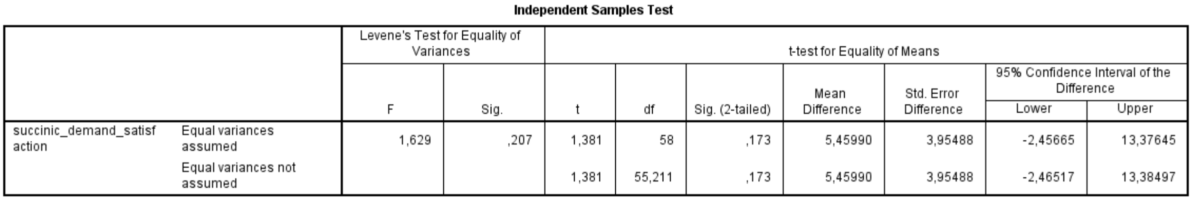
Result: H0 is accepted, averages are equal.

- 3K_0.5_0.1 - 3K_0.5_0.5



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3K_0.5_0.1	30	72,7795	13,48632	2,46225
	3K_0.5_0.5	30	67,3196	16,95142	3,09489

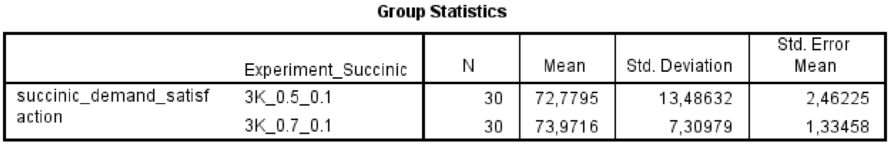


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	1,629	,207	1,381	58	,173	5,45990	3,95488	-2,45665	13,37645
	Equal variances not assumed			1,381	55,211	,173	5,45990	3,95488	-2,46517	13,38497

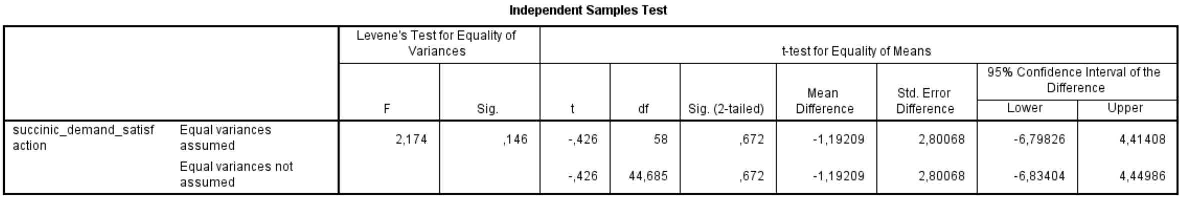
Result: H0 is accepted, averages are equal.

- 3K_0.5_0.1 - 3K_0.7_0.1



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3K_0.5_0.1	30	72,7795	13,48632	2,46225
	3K_0.7_0.1	30	73,9716	7,30979	1,33458

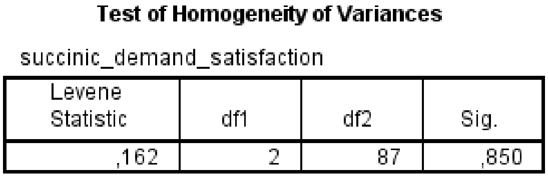


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	2,174	,146	-,426	58	,672	-1,19209	2,80068	-6,79826	4,41408
	Equal variances not assumed			-,426	44,685	,672	-1,19209	2,80068	-6,83404	4,44986

Result: H0 is accepted, averages are equal.

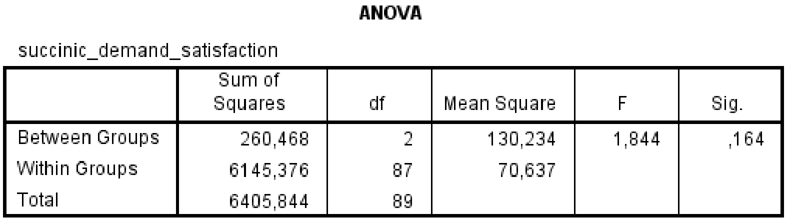
- 3K: Group comparison (3K_0.7_0.1, 3K_0.7_0.3 and 3K_0.7_0.5)



Test of Homogeneity of Variances

succinic_demand_satisfaction

Levene Statistic	df1	df2	Sig.
,162	2	87	,850



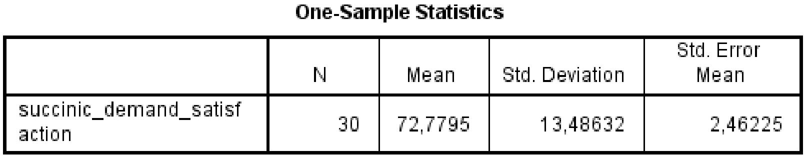
ANOVA

succinic_demand_satisfaction

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	260,468	2	130,234	1,844	,164
Within Groups	6145,376	87	70,637		
Total	6405,844	89			

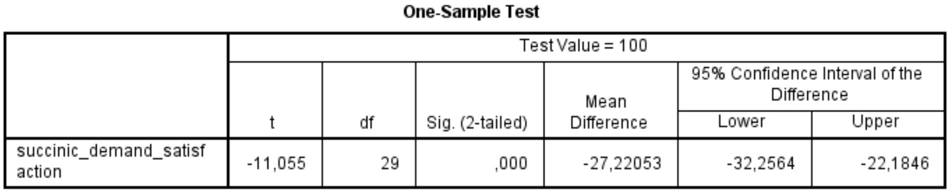
Result: H0 is accepted, averages are equal.

- 3K_0.5_0.1 - 100%



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	30	72,7795	13,48632	2,46225



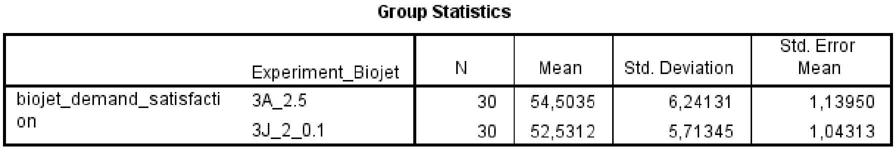
One-Sample Test

	Test Value = 100					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
succinic_demand_satisfaction	-11,055	29	,000	-27,22053	-32,2564	-22,1846

Result: H0 is rejected, the average of 3K_0.5_0.1 is lower than 100%.

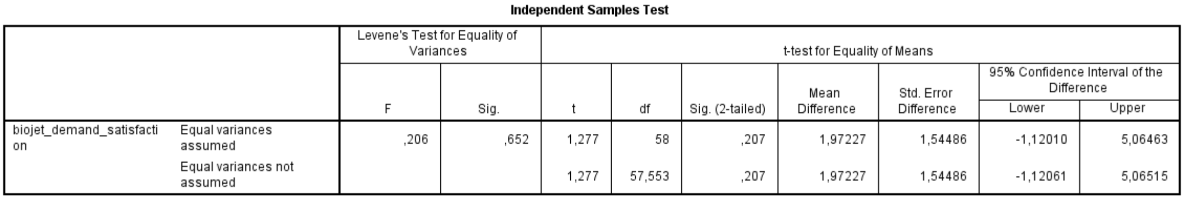
3. Policy comparison biojet fuel (base)

3.1 Demand comparison: Experiments 3A_2.5 and 3J_2_0.1



Group Statistics

	Experiment_Biojet	N	Mean	Std. Deviation	Std. Error Mean
biojet_demand_satisfaction	3A_2.5	30	54,5035	6,24131	1,13950
	3J_2_0.1	30	52,5312	5,71345	1,04313



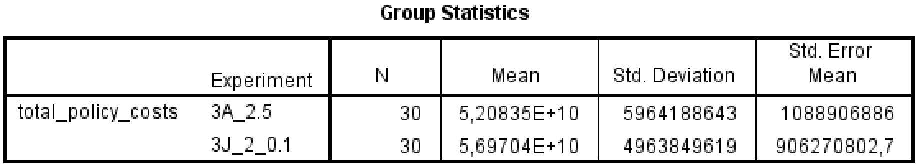
Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
biojet_demand_satisfaction	Equal variances assumed	,206	,652	1,277	58	,207	1,97227	1,54486	-1,12010	5,06463
	Equal variances not assumed			1,277	57,553	,207	1,97227	1,54486	-1,12061	5,06515

Result: H0 is accepted, averages are equal.

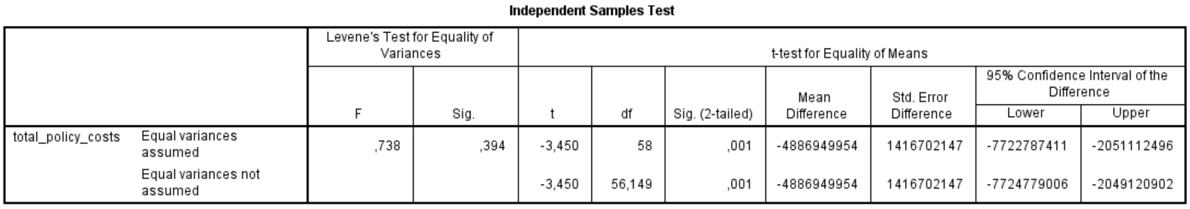
3.2 Cost comparison: Experiments 3A_2.5 and 3J_2_0.1

- Total policy costs over the 15 years run period



Group Statistics

	Experiment	N	Mean	Std. Deviation	Std. Error Mean
total_policy_costs	3A_2.5	30	5,20835E+10	5964188643	1088906886
	3J_2_0.1	30	5,69704E+10	4963849619	906270802,7

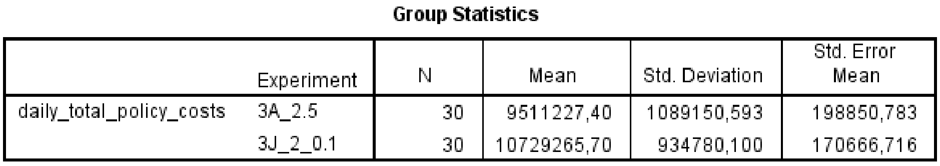


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
total_policy_costs	Equal variances assumed	,738	,394	-3,450	58	,001	-4886949954	1416702147	-7722787411	-2051112496
	Equal variances not assumed			-3,450	56,149	,001	-4886949954	1416702147	-7724779006	-2049120902

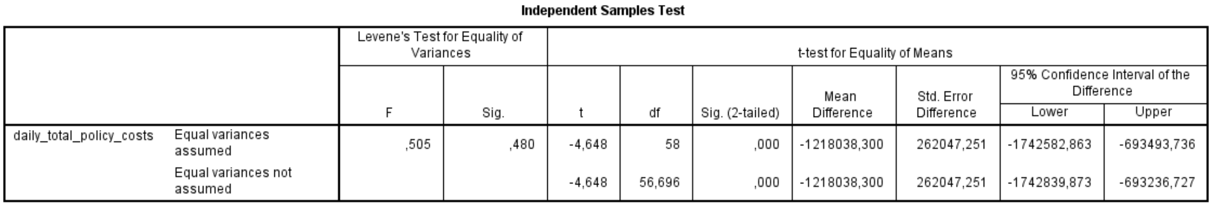
Result: H0 is rejected, averages are different. The average of 3A_2.5 is lower than the average of 3J_2_0.1.

- Average of daily policy costs over the entire run period



Group Statistics

	Experiment	N	Mean	Std. Deviation	Std. Error Mean
daily_total_policy_costs	3A_2.5	30	9511227,40	1089150,593	198850,783
	3J_2_0.1	30	10729265,70	934780,100	170666,716



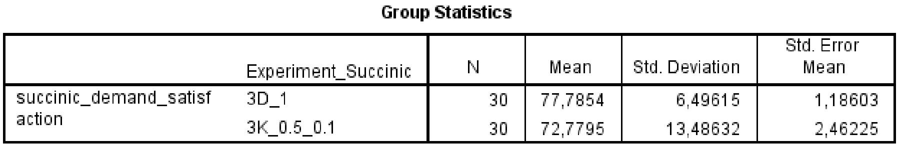
Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
daily_total_policy_costs	Equal variances assumed	,505	,480	-4,648	58	,000	-1218038,300	262047,251	-1742582,863	-693493,736
	Equal variances not assumed			-4,648	56,696	,000	-1218038,300	262047,251	-1742839,873	-693236,727

Result: H0 is rejected, averages are different. The average of 3A_2.5 is lower than the average of 3J_2_0.1.

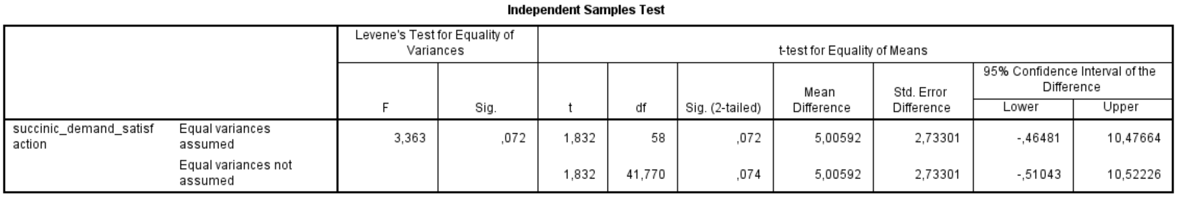
4. Policy comparison biosuccinic acid (base)

4.1 Demand comparison: Experiments 3D_1 and 3K_0.5_0.1



Group Statistics

	Experiment_Succinic	N	Mean	Std. Deviation	Std. Error Mean
succinic_demand_satisfaction	3D_1	30	77,7854	6,49615	1,18603
	3K_0.5_0.1	30	72,7795	13,48632	2,46225



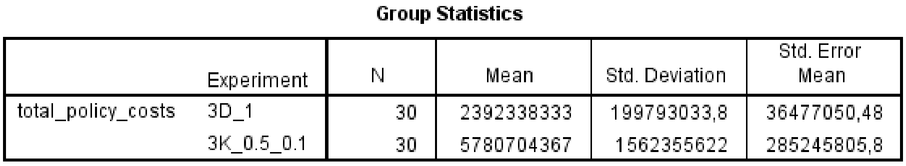
Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
succinic_demand_satisfaction	Equal variances assumed	3,363	,072	1,832	58	,072	5,00592	2,73301	-,46481	10,47664
	Equal variances not assumed			1,832	41,770	,074	5,00592	2,73301	-,51043	10,52226

Result: H0 is accepted, averages are equal.

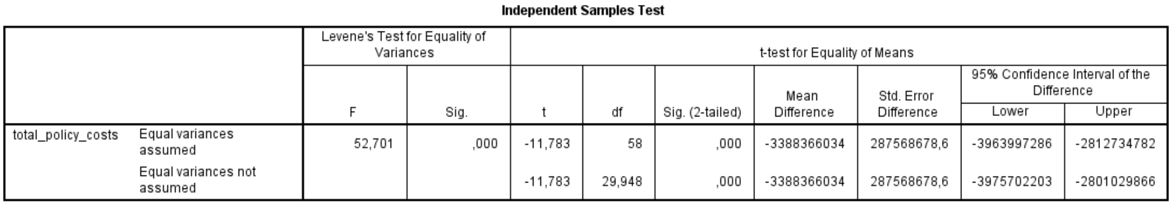
4.2 Cost comparison: Experiments 3D_1 and 3K_0.5_0.1

- Total policy costs over the 15 years run period



Group Statistics

	Experiment	N	Mean	Std. Deviation	Std. Error Mean
total_policy_costs	3D_1	30	2392338333	199793033,8	36477050,48
	3K_0.5_0.1	30	5780704367	1562355622	285245805,8

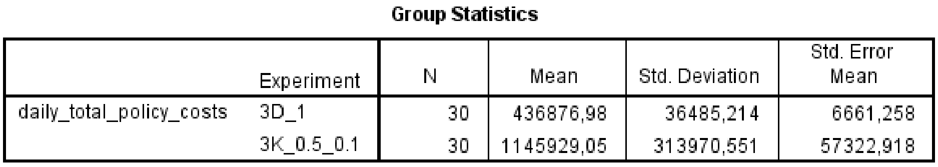


Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
total_policy_costs	Equal variances assumed	52,701	,000	-11,783	58	,000	-3388366034	287568678,6	-3963997286	-2812734782
	Equal variances not assumed			-11,783	29,948	,000	-3388366034	287568678,6	-3975702203	-2801029866

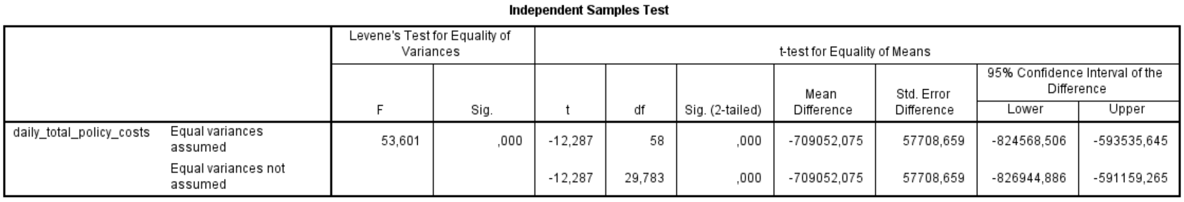
Result: H0 is rejected, averages are different. The average of 3D_1 is lower than the average of 3K_0.5_0.1.

- Average of daily policy costs over the entire run period



Group Statistics

	Experiment	N	Mean	Std. Deviation	Std. Error Mean
daily_total_policy_costs	3D_1	30	436876,98	36485,214	6661,258
	3K_0.5_0.1	30	1145929,05	313970,551	57322,918



Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
daily_total_policy_costs	Equal variances assumed	53,601	,000	-12,287	58	,000	-709052,075	57708,659	-824568,506	-593535,645
	Equal variances not assumed			-12,287	29,783	,000	-709052,075	57708,659	-826944,886	-591159,265

Result: H0 is rejected, averages are different. The average of 3D_1 is lower than the average of 3K_0.5_0.1.