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Allocation of biomass from production sites to bioenergy plants in Flanders

The role of multimodal transportation networks

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Abstract

To reduce human dependency on limited fossil fuel and to mitigate climate change, increasing attention is attributed to the development of the bioenergy sector. Besides, the development of the bioenergy sector also favours social and economic objectives by among others creating jobs and increasing farmers' incomes. Although a variety of policy initiatives from global, national and local levels are launched to promote the development of the bioenergy sector, a sustainable development is hampered by high logistics costs, particularly related to the handling and transportation of biomass to the conversion facility. Therefore, increasing research attention must go to the optimisation of the biomass-for-bioenergy supply chain. This master thesis research frames in the doctoral research "Spatio-temporal location-allocation modelling for the energetic valorisation of low input high diversity (LIHiD) biomass", which comprises an intelligent use of a complete biomass supply network to maximise the energy output, to maximise the economic profit and/or to minimise the total greenhouse gas emissions of the chain.

This master thesis intends to answer three research questions (related to the three research objectives). First, the research investigates how to build a consistent multimodal transportation network based on different unimodal transportation networks considering restrictions and attributes related to energy consumption, costs and CO_2-emissions required during the allocation of biomass to the conversion facilities. Secondly, the research explores whether and how the developed multimodal transportation network can be used to optimise the allocation of biomass to the conversion facilities considering single and multiple objectives. Finally, a sensitivity analysis is performed to study how the allocation of biomass to the conversion facilities changes by varying the definition of the multimodal transportation network or the parameters of the location-allocation analysis. To perform this sensitivity analysis, relevant data are collected for Flanders (case study area) from existing datasets and literature research, and are processed by ArcGIS software as well as MATLAB software.

As a result, a multimodal transportation network in Flanders is successfully built based on three unimodal transportation networks (road network, railway network and navigable waterway network). The key attributes (energy consumption, costs and CO_2-emissions) calculated from collected data and the restrictions (drive direction and vehicle type) realized by Visual Basic scripts are also attached. The developed multimodal transportation network is the basis for location-allocation analysis performed in ArcGIS software in which the allocation of biomass from the biomass production sites to the conversion facilities is optimised considering single (primarily for minimum energy consumption) and multiple criteria (i.e., minimise a combination value of energy consumption, cost and CO_2-emissions). Based on the sensitivity analysis using the created multimodal transportation network of Flanders, it is concluded that in all scenarios road transport is the major transportation mode. When transshipment costs are not considered, minimal energy is consumed for transport. However, when transshipment costs are incorporated, rail and waterway transport are not longer included in the result. Therefore, scenarios are analysed for a derived network in which the transportation segment lengths have been artificially magnified. Analysis of these scenarios indicates that the contribution of waterway transportation is gradually increasing with the scale factor but nevertheless remains low while the contribution of railway transportation remains limited to 2%. Furthermore, scenario analysis shows that the energy consumption, CO_2-emissions, time use and total cost are not proportional to the distance travelled since the share of the three transportation modes is important. From scenarios using a network scaled with factor 10 for distance and assuming that the available capacity of the conversion plants ranges from 100% to 1.5% it is concluded that the lower the available capacity, the more energy must be consumed to allocate the biomass to the conversion plants. Furthermore, the multimodal network always leads to the lowest amount of energy consumed in comparison with a unimodal road network or with bimodal networks (road-rail or road-water). Finally the scenario analysis indicates that when three criteria are optimised simultaneously rather than the single energy consumption, energy consumption for transport approaches very close to the minimal value and is lower than in case CO_2-emissions or costs would be minimised.

Table of contents

List of figures

List of tables

List of abbreviations

DSS	Decision Support System
ER	Entity Relation
EU	European Union
EU-ETS	European Emission Trading Scheme
GBEP	Global Bioenergy Partnership
GCW	Gross Combination Weights
GIS	Geographic Information System
GIS-T	Geographic Information System for Transportation
GHG	Greenhouse Gas
H	Highway
HR	Highway +Railway
HRW	Highway + Railway + Waterway
HW	Highway + Waterway
LA	Location-Allocation
LIHiD	Low Input High Diversity
NREAPs	National Renewable Energy Action Plans
OD	Origin-Destination
OPP_HA	Grassland Area
PROD_MIN	Minimum Productivity
PROD_AVG	Average Productivity
PROD_MAX	Maximum Productivity
RES-E	Renewable Energy Source in Electricity
RES-H&C	Renewable Energy Source in Heating and Cooling
RES-T	Renewable Energy Source in Transport
TEU	Twenty feet Equivalent Unit
VT	Vehicle Type

1 Introduction

1.1 *Problem statement*

In order to reduce human dependence on limited fossil fuels and to mitigate climate change, a switch to a fully renewable energy system with no or low associated greenhouse gas (GHG) emissions will be required (Cornelissen, Koper, & Deng, 2012). Bioenergy is assumed to be a decisive component of the renewable energy market (Cornelissen et al., 2012; IPCC, 2011; Kraemer & Schlegel, 2007) if smartly designed and applied under favourable conditions (Gold & Seuring, 2011). It also can bring about extra income for farmers (EPA et al., 2009; Zhao et al., 2012) and create extra jobs (GBEP, 2007). Simultaneously, a range of relevant policy initiatives with ambitious targets (e.g., Kyoto Protocol with Clean Development Mechanism and 20-20-20 goals of European Union), further promotes the development of the bioenergy sector owing to its competitive advantages over other renewable sources (e.g., wind and solar). For example, biomass is a very versatile resource that can serve electricity production, heating and transportation, and can be stored and released when needed (Kraemer & Schlegel, 2007; Rentizelas, Tolis, & Tatsiopoulos, 2009). However, the development of a sustainable, efficient and effective bioenergy supply chain is hampered by high logistics costs and complexity (Iakovou et al., 2010), caused by e.g., spatial distribution, low bulk density, high moisture content and seasonal and cyclic availability of biomass (Rentizelas et al., 2009). Because of the spatially distributed nature of biomass and the low possibility of local conversion to bioenergy, handling and transportation of biomass is always needed and accounts for a significant part of this supply chain (Panichelli & Gnansounou, 2008). Besides, it reduces the potential profits of the whole supply chain instead of adding value, and thus the transportation is often regarded as a potentially expensive and challenging aspect of the logistics system considered by many bioenergy stakeholders and logistics system managers (Veal, 2010). To ensure sustainability in terms of economy, environment and energy security in a long term, the biomass-for-bioenergy supply chain should be optimised, particularly the transportation part.

This master thesis frames in the doctoral research “Spatio-temporal location-allocation modelling for the energetic valorisation of low input high diversity (LIHiD) biomass” in which a decision support system (DSS) is developed to optimise the strategic design of biomass supply networks in terms of energy efficiency, economic profit and/or greenhouse gas emissions taking into account all operations occurring in the biomass supply chain. Strategic design encompasses long term decisions including size, location and technology of facilities (storage, pre-treatment or conversion plants) and the allocation of biomass to facilities. Since logistics issues complicate the development of a sustainable, efficient and effective biomass-for-bioenergy supply chain, the intelligent use of a complete transportation network is important. To approach reality, a multimodal transportation network must be considered in which different types of transport (road, railway and navigable waterway) are integrated between which the biomass can be exchanged. Developing a multimodal transportation network considering restrictions and attributes related to energy consumption, costs and CO_2-emissions and analysing the influence of the defined transportation network to the allocation of biomass to the conversion facilities contribute to the understanding of the influence of transportation of biomass in the allocation of biomass to conversion facilities.

1.2 *Research objectives*

There are three general objectives of this master thesis. The first objective is to find out how to build a consistent multimodal transportation network based on different unimodal transportation networks and considering restrictions and attributes related to energy consumption, costs and CO_2-emissions during the delivery of biomass to the conversion facilities. The second objective is to explore whether and how this multimodal transportation network can be used in Flanders to optimise the allocation of biomass to conversion facilities in the biomass-for-bioenergy supply chain considering single (primarily for energy consumption) and multiple objectives (i.e., minimise a combination value of energy consumption, costs and CO_2-emissions). The third objective is to assess the sensitivity of the allocation of biomass to the conversion facilities to the definition of the multimodal transportation network or the definition of the location-allocation procedure. As a result, a relatively comprehensive understanding about the role of multimodal transportation network in biomass-for-bioenergy supply chain including relevant challenges is expected.

2 Literature review

2.1 *What is bioenergy?*

Bioenergy refers to the renewable energy produced from biomass consisting of organic material (e.g., wood and energy crops) and waste materials (e.g., wood waste and manure) (EPA, 2009). Traditional bioenergy such as fuelwood and charcoal only delivering heat (GBEP, 2007), is often characterized by inefficiency, wasting and negative environmental impacts (Johnson, 2012). Furthermore, it is gradually replaced by modern bioenergy especially in industrialized countries, produced from industrial wood residues, energy plantation, etc. (Frank, 2007). Compared with the traditional one, modern bioenergy is produced in a more efficient way and is available in all energy carriers (e.g., heat, electricity and fuel) (Johnson, 2012).

According to reports and journal articles published in recent years (GBEP, 2007; Jang, Gläser, Liu, & Dong, 2010; Yang et al., 2013), the contribution of bioenergy is approximately 50 EJy^{-1}, which accounts for around 10% of the primary global energy supply, and for about 80% of the renewable energy produced. But according to the research by Parikka (2004), the total sustainable worldwide biomass energy potential is about 100 EJy^{-1}. This implicates that in most areas of the world, recent biomass use is distinctly below the available potential, except Asia. However, to what extent that bioenergy can contribute to the primary energy consumption also largely depends on the quantities of potential energy farming (Hoogwijk et al., 2003).

Different researches estimate the bioenergy potential in 2050. However, the numbers are diverse because of different considerations and methodologies. According to the scenario developed by Fischer and Schrattenholzer (2001), the proportion of bioenergy supply in total global primary energy will increase to 15% by 2050, and simultaneously it will consist 95% of the renewable energy system (Cornelissen et al., 2012). The recent research carried out by Jang et al. (2010) assumed bioenergy production in 2050 to be 0-1500 EJy^{-1}. The pessimistic scenario (0 EJy^{-1}) occurs in the case of high population growth, high food demand, and low yielding of agricultural production. An opposite condition serves the optimistic scenario (1500 EJy^{-1}).

Bioenergy, as one of the renewable energy sources, also competes with others such as wind and solar. Compared with those whose availability are intermittent, bioenergy can be a baseload renewable energy source if its feedstock supply is stable (EPA et al., 2009) by well-organized storage. Also, it can reduce land degradation through planting of perennial bioenergy feedstock, increase the energy accessibility in rural areas and facilitate the rural development (GBEP, 2007). Another benefit of bioenergy compared with other renewable energy sources is its flexibility, which means it can serve electricity, heating and transport (Kraemer & Schlegel, 2007).

However, some challenges do still exist. One of the key challenges is the sustainability of bioenergy, which should be judged from the whole production chain and take all environmental, social and economic aspects into account (GBEP, 2007). In short term, loss of biodiversity, deforestation, decreasing food security, violation of land property rights, additional pressure on land and on valuable ecosystem (e.g., rainforest), are examples of negative environmental and social effects which may be generated by bioenergy production (Jang et al., 2010; Kaditi, 2009). Fortunately, these issues primarily originate from the first generation bioenergy. The second or third or even fourth generation bioenergy avoid these negative effects, promise more opportunities. The distinctness among them is briefly discussed in the following section.

2.2 *Bioenergy policy framework*

2.2.1 Global situation

Besides rising energy price (especially oil price), policy initiatives are key drivers of bioenergy growth (GBEP, 2007; Junginger et al., 2011). Although according to the report by Elisa, Kati, and Ambra (2009) that there are no international agreements specifically addressing bioenergy issues on multilateral level, some of internationally legally-binding environmental agreements are related to bioenergy and promote its deployment. United Nations Framework Convention on Climate Change (especially Kyoto Protocol with Clean Development Mechanism), and the Convention on Biodiversity and United Nations Convention on Combat Desertification are examples.

To support the deployment of biomass and bioenergy especially in developing countries, Global Bioenergy Partnership (GBEP) is built in 2005. Its mission is to support capacity building of national governments, international organizations and other partners to achieve the sustainable development of bioenergy (GBEP, 2011). The sustainability of bioenergy is measured by several ecological, social and economic indicators, like soil quality, water quality, biological diversity in landscape, change in income and jobs in bioenergy sector, productivity and gross value added, etc (UN-ENERGY, 2007).

According to Parikka (2004), the use of bioenergy approximates 75% in developing countries (mainly for heat production), and 25% is used in industrialized countries, mainly to achieve the emission targets. For developing countries, biomass is the first energy source (35% in total energy) (Hall, Rosillo-Calle, & De Groot, 1992). Simultaneously many developing countries with abundant natural resources and relatively lower costs of land and labour, can obtain benefits through trade with developed countries (Kaditi, 2009). Recently, the international trade of various bioenergy commodities (e.g., bioethanol, biodiesel and wood pellets) has grown rapidly (Junginger et al., 2011). Although this international market may help developing countries to gain additional income and increase the employments, whether their total social welfare is improved or not still should be investigated carefully, especially when rent-seeking behaviour occurs. The externalities of bioenergy production (e.g., social and environmental side effects) are not always taken into account into the final market price, which may lead to unsustainable development. In other words, the wealth gain in developed consuming regions is at the cost of the welfare in developing producing regions. Thus, to ensure the production of bioenergy in a sustainable way, international standards and certification systems for trade are significantly important (Kaditi, 2009). Unfortunately, according to the report by Kaditi in 2009, there is no specific forum to deal with biomass trade on international level. But, the international biomass conference and expo organized by BBI international do exist. In 2013, this conference will take place in April, in Minneapolis, USA (BBI international, 2013).

2.2.2 Situation in Europe

To show its commitment to tackle the climate change threat and to lead the world in demonstrating how greenhouse gas (GHG) emissions could be cut, the European Union (EU) decided in 2008 to reduce GHG emission (European Commission, 2010) by introducing the European Union (EU) Energy and Climate Package. This package includes three key objectives (known as 20-20-20 targets) to be met by the European member states by 2020: i.e. from 1990 levels, a 20% reduction in EU GHG emissions, a 20% improvement in the EU's energy efficiency and raising the share of EU energy consumption produced from renewable resources to 20% (European Commission, 2012a). Within the last target, an additional sub-target imposes a biofuel use of at least 10% in the transport sector (Schwaiger et al., 2012; Vandermeulen et al., 2011). These three targets are also interconnected and influence each other. For example, a reduction in energy consumption contributes to reach the renewable energy target and lowers GHG emissions (IEEP, 2010). To deliver these targets successfully, there are four measures deployed from the Energy and Climate Package. The first one is to redesign and improve the European Emission Trading Scheme (EU-ETS), focusing on the question of whether the EU-ETS is an appropriate vehicle for increasing the use of solid and liquid biofuel (Schwaiger et al., 2012). Correspondingly, some rules are changed such as the previous free allocation of allowances for GHG emissions will be progressively replaced by auctioning (European Commission, 2012a). Since around 60% of the EU's total emissions come from sectors outside the EU-ETS such as housing, agriculture, waste and transport (excluding aviation) (European Commission, 2012a), nation targets for non-EU ETS emissions is crucially regarded as the second measure. The third one refers to the national renewable energy targets. According to the examination of National Renewable Energy Action Plans (NREAPs), bioenergy (biomass, bioliquids and biofuels) accounts for almost 54.5% of the 2020 renewable target and its contribution to final energy consumption is expected to more than double from 5.4% in 2005 to almost 12% (124 Mtoe, 1 Mtoe= 41.868 PJ) in 2020 (IEEP, 2010). Following these ambitious targets, a new tendency of increasing the energy supply based on bioenergy has undoubtedly emerged and it has indeed happened in many EU members' countries such as Denmark, UK, Ireland, Netherlands, Germany, Austria, etc. Also, biomass as source of bioenergy is forecasted to contribute around two-thirds of the EU's primary renewable energy consumption in 2020 (Kautto et al., 2012). Thus, on national level, some countries (e.g. Austria and UK) not only have drawn up national biomass action plans to serve the national renewable energy action plans (Kautto et al., 2012), but also developed biomass certification systems for sustainable biomass trade (Kraemer & Schlegel, 2007). After all, the yields of biomass differ from one country to another due to different climate condition leading to different efficiency of photosynthesis. Normally, countries with a high ratio of hectares of agricultural land per capita have higher potential to produce biomass for energy. Besides, the energy production cost in EU also varies (Esteban & Carrasco, 2011), and it is likely that EU will import biomass because of lower production costs in the developing countries (Kraemer & Schlegel, 2007). Last element of the Energy and Climate Package is to create a legal framework for environmentally safe use of carbon capture and storage technologies (European Commission, 2012a). However, general results from European Semester in last year are not optimistic. Only 11 out of 27 member states are expected to reach their national targets with existing measures. The others will not reach their targets without significant extra efforts, among which Belgium (European Comission, 2012b).

Besides, although the development of bioenergy in EU provides many new opportunities such as rural development (Banse et al., 2011), climate change mitigation, energy security, increasing trade of forest raw materials (Mansikkasalo, 2012) as well as more advanced education and training related to bioenergy (Watkinson et al., 2012), some challenges still need to be overcome such as negative effects on environment (i.e. threaten biodiversity), and the conflict between bioenergy production and food security (FAO, 2012; van Dam et al., 2007). For example, the area of Danish non-food agricultural production boomed from 300 km^2 in 1995 to 1,500 km^2 in 2005 and this size will be doubled in 2025 (Holm Nielsen, Oleskowicz-Popiel, & Al Seadi, 2007). In general, bioenergy generation in EU must be carefully controlled to make sure the biomass, is efficiently used with low associated GHG emissions (IEEP, 2010).

2.2.3 Situation in Flanders, Belgium

Belgium is a federal state consisting of three regions: the Flemish region, the Walloon region and the Brussels-capital region. The evolution of the Belgian energy policy has been shaped by the country's general political evolution, leading to the transfer of wide competences from the states to the regions (Marchal & Ryckmans, 2006). Because of a federal state, each region in Belgium has the capacity to draw up own policies in specific domains (e.g., agriculture, road infrastructure, spatial planning and environment) within the framework of the federal level.

Yearly Belgian CO_2-emissions are around 150 Mtons, and the major part of these emissions are caused by Flanders because of its high number of industries (Van Stappen et al., 2003). Until 2002, no noticeable record of renewable energy planning existed. From then, the renewable energy source system was set up (Verbruggen, 2009), driven by the Kyoto Protocol, the EU Energy and Climate Package and the strong support delivered by the green certificate system. Especially, in the framework of Kyoto Protocol, Belgium should have achieved a reduction of 7.5% of GHG emission compared with its 1990 level in 2012. Besides, there are five green certificates mechanisms on-going in Belgium as instruments in the frame of GHG mitigation. Two of them are running in Flanders: one is Green Certificate related to produce green power and the other is Cogen Certificate focusing the primary energy saving (Van Stappen et al., 2003). The renewable energy market in Belgium is growing rapidly and the role of biomass gradually becomes significant.

Since 2005, biomass has been taking a growing share while coal is decreasing accordingly (Marchal & Ryckmans, 2006). In 2006, the proportion of dry biomass in the renewable sources of Flanders has reached 50% (Ryckmans, 2007). For heating, an inventory of Flanders in 2007 indicates the use of 9.4 PJ heat from biomass, and by 2020, more than 90% of a potential proactive renewable heat target (35 PJy^{-1}) come from biomass according to scenario calculation (IEA, 2009). But it should be mentioned that most of the bio-based energy for heating is produced from burning biomass in combination with fossil fuel. For example, the recent energy law in Flanders requires that fossil fuel should be blended with 4 vol.% of biofuels (Vandermeulen et al., 2011). The estimated annual biomass resources in Flanders within the framework of Belgium are displayed in table 1.

Table 1 Estimated annual available biomass resources in Flanders and Belgium (Marchal & Ryckmans, 2006)

Biomass type	**Flanders (ktoe)**	**Belgium (ktoe)**
Solid agricultural residue	n.d.	9
Manure	100	100-158
Forest residues	0	137
Wood industry by-products	283	327
Green wastes	66	84
Industrial organic residues	18	18
Total	**467**	**675-733**

According to NREAP, Belgium splits its overall 13% renewable energy target by 2020 into 20.9% renewable energy source in electricity (RES-E), 11.9% in RES-Heating and Cooling (RES-H&C) and 10.1% RES-Transport (RES-T) (EREC, 2011). Amongst the other renewable energy types, biomass and biogas occupy largely proportion as table 2 shows. But it should be noticed that the Belgian NREAP does not propose any burden sharing scheme of its overall 13% renewable energy target between regions and federal state, although such an agreement would be crucial for the implementation of the action plan (EREC, 2011). Besides, according to the latest projections, Belgium is listed as one of member states that are furthest from reaching the 2020 targets (European Comission, 2012b). Simultaneously, the 2010 version of the Climate Policy Tracker gives Belgium a rating of E (indicating low efficient implementation of policy and legislation towards to state's 2050 vision) and some recommendations on most urgent actions such as improving the efficiency of cars, putting a higher energy taxes or a CO_2 tax (ECOFYS, 2011). Also, a comprehensive national climate and energy strategy towards a zero carbon economy by 2050 is necessary.

Table 2 Projections for renewable sources for electricity production, heating and cooling, and transport in 2020 (EREC, 2011)

RES 2020 type	**RES-E 2020 (%)**	**RES-H&C (%)**	**RES 2020 type**	**RES-T (%)**
Biomass (solid, biowaste, bioliquid)	8.7	9.1	Bioethanol	1.0
Biogas	1.3	0.3	Biodiesel	8.0
Other renewable sources (e.g. wind and hydro)	10.9	2.5	Renewable electricity	1.1
Total RES	**20.9**	**11.9**	**Total RES**	**10.1**

2.3 ***Biomass-for-bioenergy supply chain***

2.3.1 Components

Biomass logistics is a general concept applied to analyse and manipulate the flow of materials from the production sites such as woody plantations, forests and grasslands, to the conversion facilities (Veal, 2010). It broadly involves six key operations, i.e. biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy (De Meyer et al., 2012). The complexity of the biomass supply chain is evidenced in figure 1. It covers many different operation sequences and loops. The rest products after conversion can be fed back into the supply process and mixing of different product types is frequently applied.

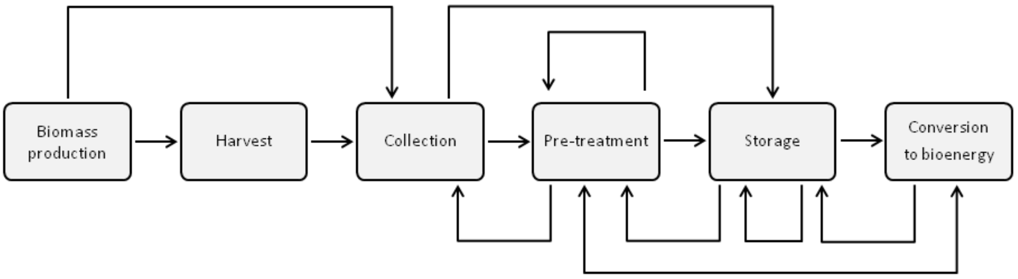


Figure 1 A flow chart represents the possible sequences of operations in the biomass supply chain (Block = operation, Arrow = possible transport link between operations) (De Meyer et al., 2012)

However, due to the general characteristics of biomass (i.e., low bulk density, low energy content and high moisture content), the integral biomass supply chain should be considered in order to maintain its competitive advantage relative to other energy resources. In the following paragraphs the different operations of the biomass supply chain are described focusing on the use of LIHiD biomass.

2.3.1.1 Biomass production

Biomass is a term for all living or recently living organic material derived from plants and animals (microorganisms) (Biomass Energy Centre, 2011). This definition includes all vegetation as well as organic waste, e.g. crop, crop waste, trees, wood waste and animal waste. Through photosynthesis, green plants convert radiant energy from the sun into chemical energy stored in the chemical bonds of organic matter, in the form of glucose or sugar. The chemical energy in plants is passed on to animals and people that eat them or released when these chemical bonds are broken by combustion, decomposition or digestion (McKendry, 2002a).

Due to its short reproduction cycle, biomass is a renewable resource used as an alternative renewable energy source. Also, the carbon dioxide, which is believed to be the major GHG to cause global climate change (Solomon et al., 2009), released from the energy production is utilized for biosynthesis during the growth of biomass. As a result, the net CO_2 release is small (Cheng, 2010; Holm Nielsen et al., 2007; Zhou et al., 2009). Producing the energy from biomass therefore could significantly reduce the CO_2 production which is mainly caused by fossil fuel burning previously, and simultaneously reduce the world’s dependence on fossil fuel (Suurs & Hekkert, 2009). But, the sustainable use of the biomass must always be a prior factor.

A variety of biomass resources exists including sugar crops (e.g. sugarcane, sugar beet and sweet sorghum), starch crops (e.g. corn, wheat, potato and sweet potato), agricultural residues (e.g. wheat straw, rice straw and manures), herbaceous biomass (e.g. switchgrass, miscanthus and coastal Bermuda grass), woody biomass and oilseeds (e.g. soybean, rapeseed, sunflower, oil palm and waste edible oil) (Wang & Keshwani, 2010). Some food-based crops such as sugar crops, starch crops and oilseeds, constitute the main feedstock of the first generation biofuel. Their products are biodiesel, corn ethanol and sugar alcohol, which are currently commercially available (Suurs & Hekkert, 2009). However, the conflict between the biomass production for energy and the biomass production for food emerged among scientists as well as in the whole society (e.g. increasing use of corn in the USA to produce ethanol resulted in a decrease of corn export and increase in corn price) (Gold & Seuring, 2011; Suurs & Hekkert, 2009; Yiqun, 2008). Therefore, the production of the second generation biofuels rises. These second generation biofuels are produced from lignocellulosic feedstock like non-food crops, cheap and abundant plant waste biomass such as forest residues, agricultural residues, grass and aquatic biomass, anticipated to significantly reduce the CO_2 production without competing with food (Suurs & Hekkert, 2009). Hydrotreating oil, bio-oil, lignocellulosic ethanol, butanol, etc. expected commercially viable by 2015 (Parker et al., 2010), are their end products. Moreover, the research on the third generation biofuels (e.g., algae and cyanobacteria) and the fourth generation biofules (e.g., biohydrogen and bioelectricity from photosynthetic mechanisms) is also being explored (Antizar-ladislao & Thrrion-Gomez, 2008).

Apart from the types of biomass mentioned above (i.e. monoculture crops on fertile soil e.g. corn, soybean and oilseed rape, and waste biomass e.g. waste wood and animal manures), another source of biomass is also available for the production of bioenergy, i.e. low input high diversity (LIHiD) biomass. This LIHiD biomass encompasses high diversity mixtures of plants growing with low inputs on non-agricultural land (Tilman et al., 2006). It includes habitats such as (half) natural grasslands, heath lands and meadows (often in nature reserves), multifunctional forests, small landscape elements (e.g. roadside) and urban green (e.g. parks and gardens) in which regular management with removal of residues is needed to maintain or increase the nature value or guarantee safety (Bervoets, 2008). According to the report by Tilman et al. (2006 & 2007), high diversity grasslands have higher bioenergy yields, greater CO_2 reduction and less agrichemical pollution per hectare compared with monoculture crops on fertile soils. Besides, because bioenergy production from LIHiD systems originates from non-agricultural land, no conflict exists with food production and simultaneously loss of biodiversity is avoided (Tilman et al., 2006). These benefits are also confirmed by other researchers' case studies (Weigelt et al., 2009; Zhou et al., 2009).

Generally, different biomass types possess different physical characteristics which mainly include biomass yield per year, moisture content, higher or lower heating value and energy yield. Table 3 summarises these characteristics of some biomass types. Among the rest, switchgrass and miscanthus are two plants of grasslands. It must be noticed that these data are only indicative and very depend on regional climate, soil, etc. (McKendry, 2002a). Also, these characteristics influence each other. For example, the moisture content of biomass is one of key factors for bulk density, which means high moisture content often causes a higher bulk density due to the high density of water (1000 kg/m^3) (Sultana & Kumar, 2011). Compaction of biomass also has impact on bulk density in order to achieve more efficient transportation and storage.

Table 3 Some attributes of different forms of biomass

Biomass type	**Crop yield (Mg/ha, dry)**	**Moisture (% H_2O)**	**Higher heating value (GJ/Mg, dry)**	**Energy yield (GJ/ha)**	**Source**
Sugar beet	11	76	17.4	190	Börjesson, (1996)
Potato	7.7	78	17.0	130	Börjesson, (1996)
Wheat	7 grain/ 7 straw (14 total)	16	12.3 (straw)	123	McKendry, (2002)

Biomass type	Crop yield (Mg/ha, dry)	Moisture (% H_2O)	Higher heating value (GJ/Mg, dry)	Energy yield (GJ/ha)	Source
Switchgrass	8	13-15	17.4	139	McKendry, (2002)
Miscanthus	12-30	11.5	18.5	222-555	McKendry, (2002)

2.3.1.2 Harvesting and collection

Harvesting and collection of biomass are considered as mechanical activities as well as thinning operations in the biomass supply chain (Gold & Seuring, 2011). During these processes, different machine systems are involved based on the management objectives, the specific biomass requirements for pre-treatment or conversion as well as weather conditions and available equipment.

Because a variety of harvesting and collection operations exist, this section intends to give some examples of the most applied equipment used to harvest and collect biomass. To begin the harvesting process, all grasses should be cut. Cutter bar or stickle bar mowers are typical shear force cutting devices for grass harvesting. It is primarily composed by knives and guards. And cutting occurs when the grass is pinned against a guard and the knife's blade severs the crop materials. Compared with other mowers (e.g., rotary mowers and flail mowers) leading to small grass clippings complicating the collection (Vlaams Department Leefmilieu, 2006), cutting of grass from a cutter bar mower is not so aggressive (Veal, 2010). But the limitation of capacity is a shortcoming of a cutter bar mower. Distinguished from the grass harvesting, specialized equipment is required to harvest woody biomass because of the increased sized of material and rugged conditions (Veal, 2010). A feller-buncher combined with chainsaw, harvester and forwarder are possible systems to harvest forest biomass, but their operation costs are relatively high (Veal, 2010).

After harvest (and possible pre-treatment), biomass needs to be collected and transported to a local storage point (usually at the roadside) or a central storage site from where transport vehicles move the biomass to other junctions in the biomass supply chain or to the conversion facility. A tractor with a trailer is the most general collection option to collect biomass (with or without combined pre-treatment operation) at a certain period after cut. The mow-load combination immediately collects the biomass during the cutting operation with or without simultaneous pre-treatment. Normally, the collection of woody biomass costs more among others because of size and equipment required.

The main challenge in this section is to develop a cost-effective and sustainable harvesting and collection since the current technologies are often costly, lead to significant amounts of soil compaction, and introduce dirt and rocks into the feedstock collected (U.S. Department of energy, 2004).

2.3.1.3 Pre-treatment

In order to improve the efficiency of storage, transport and conversion, there are three possible pre-treatment methods, namely, sizing, drying and densification, which are separately stated in the following paragraphs.

Sizing operation minimises the size of feedstock (e.g. size the wood to chips of 5-50 mm length) to achieve more convenient handling, increases the efficiency of the supply chain due to positive scale effects (Suurs, 2002), as well as to meet the particle size requirements of the storage and bioenergy facility (McKendry, 2002b). With different scales of operation, sizing is classified into local sizing (chipping or chopping) which is considered to be included in the cutting or collection operations, and central sizing (grinding or pulverisation) which is only performed at the central storage point or the bioenergy facility. Besides, the processing capacities depend on the type of chipper. For instance, the capacity of chipping installations for large scale (i.e. roll crusher, hammer mill and MP bolagen) is distinctly various from 1-10 Mgh^{-1} to 80 Mgh^{-1} (Suurs, 2002).

Drying is used as pre-treatment because of several reasons. First of all, drying is a solution to deal with the feedstock which is too wet for conversion to power or liquid fuel (e.g. woody biomass has a moisture content of typically about 50%) (Suurs, 2002). Secondly, drying reduces the risk of decomposition of wet biomass and avoids the accompanying effects such as health hazards (Suurs, 2002). Also, transport costs are affected by the weight of biomass rather than the volume. Therefore, the process of drying can be used to bring down the transport cost by reducing the weight of biomass. However, before drying operations can start, the biomass must meet the size requirements of the drier by for example sizing to chips before drying operation (Suurs, 2002). Principally, there are two approaches to dry the biomass: thermal drying and natural drying (Koppejan & Van Loo, 2012). And, the most common and simple way of natural drying is rotary drum dryer that biomass is dried by directly contact to hot air or flue gas when they are rotating in a drum (Suurs, 2002).

The process of densification is usually achieved through effectively removing any voids in the materials by applying a mechanical force to the biomass (Veal, 2010), resulting a higher bulk density. The main benefits from this procedure are twofold. Firstly, densification enhances the convenience and safety to handle and store (Sokhansanj & Turhollow, 2004) as well as to transport by reducing the risk of decomposition or self-ignition and increasing the energy content. Secondly, pellets can immediately substitute coal (Suurs, 2002).

2.3.1.4 Storage

Storage is not only necessary but also critical in the biomass supply chain, because many types of biomass are harvested at a specific time of the year but required at conversion facilities on a year-round basis (Rentizelas et al., 2009). Thus, seasonal availability induces the need for storage facilities.

The simplest way of storing biomass is to pile it. Considering biomass is a biological material influenced by microbial activities and susceptive to environmental conditions, the challenge is to minimise the degradation during storage. For the required biomass component (i.e., sugars, carbohydrates, or cellulose) to be maintained in a usable form, the moisture control during this process is significant (Veal, 2010). At the same time, a long-term storage of baled herbaceous biomass is inclined to indoor storage. And, its outdoor storage is only feasible for a short-term (Koppejan & Van Loo, 2012). Baled woody biomass can be stored outdoors due to their low tendency to biological degradation and moisture accumulation, while fine wood waste is preferably stored in closed silos to avoid dust emissions (Koppejan & Van Loo, 2012).

These storage facilities can be located in the farm/forest (i.e. local storage), an intermediate site between feedstock and conversion facility or at conversion facilities. Local storage is usually characterised by low cost, but includes many potential problems such as spores and fungus formation, and self-ignition (Rentizelas et al., 2009). Intermediate storage facilities will result in a relatively higher delivery cost, but it can reduce spoilage and deterioration of biomass compared to open on-farm storage (Carolan, Dale, & Joshi, 2007). Besides, the method of multi-biomass storage suggested by Rentizelas et al. (2009), may make the inflow of biomass throughout the year smoother and reduce total system cost as well as storage space required may be reduced.

2.3.1.5 Conversion

The process of conversion is depended upon many factors such as the type and the quantity of biomass, the desired form of energy i.e. end-use requirement, environmental standards, economic condition and project specific factors (McKendry, 2002c). Generally, there are two technologies that convert biomass to bioenergy: thermo-chemical and bio-chemical conversion. Their principal characteristics are summarized in table 4. Mechanical extraction is also used to produce oil from the seeds of various biomass crops (McKendry, 2002c). But this technology is not relevant in the context of LIHiD systems and thus it is not discussed.

Table 4 Principal characteristics of conversion types for biomass for bioenergy (Pongrácz, n.d.)

	Combustion	Gasification	Pyrolysis	Anaerobic digestion	Fermentation
Input materials (preferable)	Pellets, wood waste	Forest products, energy crops, biowaste	Forest products, energy crops, agricultural and urban organic waste	Biowaste, energy crops	Food crops and forest residues, energy crops, biowaste
Limiting factors	Moisture <50%	Moisture <50%	Moisture <45%	Total solids 4-40%	Homogenous input, nutrients, pH, moisture
Operating temperature	>800℃	650-1200℃	400-800℃	35℃ or 55℃	15-60℃
Oxygen requirements	Excess of oxygen	Partial oxidation	Absence of oxygen	Absence of oxygen	Depends on type of microbes involved
Main products	Heat	Syngas	Pyrolysis oils, biochar	Biogas	Alcohol
Applications End use	Electricity, heat production, liquid or gaseous fuels	Synthetic fuel production	Fuel for engines	Transportation, fuel, digestate as fertilizer or soil conditioner	Transportation, fuel, digestate as fertilizer or animal feed

2.3.1.5.1 Thermo-chemical conversion

Principally, there are three process options available for thermo-chemical conversion: i.e. combustion, gasification and pyrolysis. Their main characteristics are shown in table 4, and their brief descriptions are given.

Combustion (i.e. burning the biomass in air), is applied to convert the chemical energy stored in biomass into heat, mechanical power or electricity (McKendry, 2002c). The combustion process requires (dried) feedstock with moisture content lower than 50% (e.g., agricultural waste, wood and municipal solid waste) although it is possible to burn any type of biomass (Iakovou et al., 2010; McKendry, 2002c). The gasification of biomass at high temperature (e.g., 800-900℃), results in a high production of gaseous products and small quantities of char and ash (Demirbas, 2002). Compared with burning wood in a combustor, the energy released from gasification may be of more use, which could be used to fuel a gas engine rather than hot air (McKendry, 2002a). Pyrolysis, differs from gasification in that the products of interest are the char and liquids, which as a result of heating the biomass in the absence of air to around 500 ℃ (Demirbas, 2002; McKendry, 2002c). Also, it can produce predominantly bio-oil used in engines and turbines if flash pyrolysis is used with an efficiency of up to 80%. Except these three major processes, another approach called liquefaction also should be mentioned. It converts biomass into stable liquid hydrocarbon at low temperature and high hydrogen pressures. But considering it is a more complex and more expensive process than pyrolysis, there is low interest in it (McKendry, 2002c).

2.3.1.5.2 Bio-chemical conversion

Fermentation and anaerobic digestion are the two main processes for bio-chemical conversion (McKendry, 2002c). Fermentation is used commercially on a large scale to produce ethanol from sugar crops and starch crops, but is very limited for the conversion of lignocellulosic biomass such as wood and grasses (Iakovou et al., 2010; McKendry, 2002c). Anaerobic digestion is the conversion of organic matter (e.g., bio-waste and energy crops) directly to biogas by micro-organisms in the absence of oxygen (Pongrácz, n.d.). It is commercially proven technology and is widely used for treating organic wastes with high moisture content (i.e. 80-90% moisture) (Iakovou et al., 2010). According to the report published by ODE-Vlaanderen (2012), the biogas yield of grass is 180 Nm^3 Mg^{-1} and 1 Nm^3 biogas has a heating value of 23 MJ Nm^{-3}. The interesting thing is that, according to the report by SGC (2012), the grass per tonne produces 95 Nm^3 of biogas. Besides, fresh grass and roadside grass compared with natural grass also have different values (Herman Klein Teeselink, 2007). When biogas is converted from natural grasses, it is used in a combined heat and power to produce heat and electricity where more or less of 15% energy produced is lost (ODE-Vlaanderen, 2012).

2.3.2 Transportation of biomass

Transport, broadly speaking, is applied to overcome the space and enables the mobility of people and goods from one place to another (Rodrigue, 2013). It consumes the land and simultaneously supports the various relations among locations. In general, the modes of transportation mainly include airlift, shipping, railway and road. These different structured routes with different nodes (i.e. terminals, transit and transfer points) constitute the transportation networks. It can be defined in terms of its components such as routes, nodes and terminals, or depicted by a combination of different modes. A clear and straightforward definition of transportation system therefore largely depends on the specific perspectives, which can be viewed from the point of different infrastructure, the operators or users (Mahrous, 2012). Besides, the definitions also vary by the scale such as global, national, regional and local.

2.3.2.1 Transport types

Infrastructure consumes the land, and at the same time it is consumed by various vehicles such as bicycle, car and train. Considering the characteristics of biomass and the existing infrastructure in Flanders, truck, train and ship are chosen as typical biomass carriers (Forest Commission, 2012). However, each vehicle has its restrictions in comparison with others associated with different performances (e.g. cost, energy consumption or capacity). For example, trucks request the least infrastructure and they are served as the lowest cost transportation with relatively small quantities of biomass within relatively short distance. While the volume of transporting materials becomes larger, train and ship turn more competitive compared with trucks due to their larger capacity and lower average cost per kilometre. From energy consumption aspect, in one kilometre, the weight of energy consumption for a truck with diesel electric engine and one twenty feet equivalent unit (TEU) used for transmission is about 0.22 kg. However, when a truck is replaced by a ship under the same condition, the weight of energy consumption is 0.036 kg which is much lighter (IUVA, 2010). Also, the capacity of a ship is much larger than the capacity of a truck's. However, the existing infrastructure prevents some destinations from being reached by ship or train and enough biomass must be available to meet the capacity of the train or ship. Some characteristics of different transportation types are given in table 5. It should be mentioned that, in fact, these values are rather variable according to literature research. For example, the speed range of freight train transport can vary from 65 km h^{-1} to 250 km h^{-1} (Rui, 2006), and the average speed of trucks is largely limited by road property and infrastructure (Gold & Seuring, 2011). Simultaneously, there are not so many academic papers or reports indicating the value of one feature (e.g., energy consumption, costs or CO_2-emissions) involving truck, train and ship at the same time. To serve this research and avoid the noise caused by different ways of measurement, the values of energy consumption, costs and CO_2-emissions provided in table 5 are obtained following the rule that, the values of truck, train and ship for one attribute come from the most recent literature. Thus, Searcy, Flynn, Ghafoori, & Kumar (2007) for cost and Responsible Care, ECTA & Cefic (2011) for CO_2-emissions are referenced. Moreover, the values of energy consumption are estimated values of energy consumption for truck, train and ship in 2015 provided by Börjesson (1996), which is highly cited. General descriptions for each type (i.e. truck, train and ship) and corresponding restrictions are stated separately in the following paragraphs.

Table 5 General characteristics of transport modes (mainly for Belgium / Europe)

	Truck	**Train**	**Ship**	**Source**
Average speed (meter minute^{-1})	750 (very variable)	1666.7	250	OECD, (2007); Rui, (2006); Tele Atlas, (2003)
Energy consumption (MJ Mg^{-1} km^{-1})	1.3	0.63	0.17	Börjesson, (1996)
Variable cost based on distance (＄ Mg^{-1} km^{-1})	0.12	0.023	0.01	Searcy, Flynn, Ghafoori, & Kumar, (2007)
CO_2-emissions (g Mg^{-1} km^{-1})	62	22	31	Responsible Care, ECTA & Cefic, (2011)
Weight (Mg)	19 (two axles)	90.72	Class1: 300 Class2: 600 ⋮ ⋮ Class5: >2500	International transport forum, (2011a); Veal (2010); Milieurapport Vlaanderen, (2010)

2.3.2.1.1 Truck

The motor vehicles such as truck and trailer are often used to transport agricultural feedstock, especially in a relatively short distance (Veal, 2010). There are various types of trucks that can be applied for biomass transportation. The common examples are straight truck, semi-truck, day cab and sleeper cab. Their capacities to haul materials also differ as determined by weight and dimension. The weight mentioned is not only limited by the capacity of the vehicle itself, but is also limited by the (national) legal gross vehicle weight rating which means the maximum amount of weight a road vehicle can carry on public roads (Veal, 2010). For example, the allowed gross combination weights (GCW) in Sweden is 60 Mg with a 40 Mg load capacity permission, while in Europe, the GCW is 40 Mg with a load capacity permission of 25 Mg (Suurs, 2002). In Belgium, the maximum permission weights of trucks with two axles are 19 Mg (See table 5). Table 6 displays a dimension aspect of trucks in Belgium.

Table 6 Permissible maximum dimensions of trucks in Belgium. (International transport forum, 2011b)

Height	**Width**	**Length**		
		Lorry or Trailer	Road Train	Articulated Vehicle
4 m	2.55 m	12 m	18.75 m	16.50 m

Besides, the average speed and transfer time are of importance from logistic aspect due to their significant effects on energy consumption and operation costs. The main restrictions of truck transportation for biomass are speed limitation, e.g., trucks are restricted in speed to 50 km h^{-1} during morning rush hours (Tele Atlas North America, 2003). In Belgium, the speed limit on motorways is 120 km h^{-1}, and the main roads have a speed limit of between 70 km h^{-1} and 90 km h^{-1} (AngloINFO, 2013). Besides, volume capacity and physical accessibility determined by infrastructure service are also important.

2.3.2.1.2 Train

When conversion facilities are further away from collection areas, truck transportation loses its competitive advantage and the rail system becomes more preferable choice due to its larger load capacity per time with relative lower cost (Veal, 2010). As a result, railway plays an important role in long-distance travel. Moreover, biomass is allowed to be accumulated at local facilities until a sufficient volume is reached to dispatch a unit train in order to get a relatively high efficiency of delivery. Normally the capacity of one single railcar is 90.72 Mg (Veal, 2010).

The average speed of freight train is diverse in different countries according to different applications (Rui, 2006). The main restrictions for freight trains are accessibility as well as time schedule because of many freight trains operated following a fixed time table. Besides, the cost of freight trains is expected to decline 10% in the future compared with 2005 due to improved planning and logistical operation (Rich, 2009). At the same time, its share among three modes (i.e., truck, rail and waterway) is anticipated to increase from 20% in 2005 to 22% in 2020 and 23% in 2030, within EU27 (Rich, 2009).

2.3.2.1.3 Shipping

When much greater distance is required for transport, barges are considered due to their lower cost (See table 5) as well as their huge capacity for moving goods, e.g. the typical barge can carry the same weight of material as 15 railcars or approximately 1360 Mg (Veal, 2010). But, with long distance travel, some disadvantages such as lack of reliability, low speed and also change of biomass characteristics during transport are at stake.

Generally, there are two categories to transport biomass, i.e. bulk ships and container ships. Bulk ships transport unpackaged material e.g. grain and coal, while a container ship transport biomass in containers with a capacity expressed by TEU or 20ft equivalent unit that run on fairly regular schedule (Veal, 2010). Although, from the energy consumption or capacity aspect, transport by ship is the ideal choice, it is not always used in reality for biomass transport or considered in the research by other authors since one of the major advantages for bioenergy system is the reliance on locally available feedstock.

2.3.2.2 Multimodal transportation system

Bielli et al. (2006, p 1705) define a multimodal transportation system as *"the combination of all traveller modes and kinds of transportation systems operated through various information transportation systems"*. Considering the aspects from users and transport's objective, the concept proposed by Mahrous (2012) that treats multimodal transportation system as a set of available modes chosen by users with different combinations to meet their needs, is therefore preferred. The modes here represent the different ways of transport i.e. roads, railways and navigable bodies of water. They are all physically existing services and are consumed by different vehicles. And, these modes also have their respective weaknesses and strengths. To potentially cancel negatives and maximise their benefits, Mahrous (2012) argues that a combination of them is therefore often used.

The main components in each mode are network, routes, nodes and terminals (Mahrous, 2012). The network provides a framework for routes in a system, while a route is simply a line between two points (Mahrous, 2012). The nodes can be crossing points or transit points, while the terminals represent the ending points. Besides, the transfer points among different modes play a significant role because they allow the good or people to transfer from one mode to another. Different modes in one system are connected together through these switching points. So, even if two modes have routes coincidentally across at the same geographical locations, the transfer action cannot happen in this crossing point without transfer points. Besides, these transfer points are often associated with extra costs (e.g. extra energy consumption, time expense, CO_2-emissions or labour payment). The general indication for these values is shown in table7, and they will be used in this research. It should be noticed that the estimations for time and CO_2-emissions are based on implicit rather than explicit statements in literature, because there is not so much clear indications associated with transshipment cost. Besides, it must be pointed out that the transfer cost mentioned (Table 7) indicates the cost of loading and unloading of one mode, while the transfer points refer to transfer from one mode to another.

Table 7 Transfer costs for truck, train and ship

	Truck	**Train**	**Ship**	**Source**
Energy consumption (MJ Mg^{-1})	5	10	40	Suurs, (2002)
Time expense (minute Mg^{-1})	1.5	1.5	1.5	Suurs, (2002)
CO_2-emissions (g Mg^{-1})	72	72	72	CER Calculations, (no date)
Cost (Euro Mg^{-1})	2.49	4.05	2.4	Hoefnagels & Junginger, (2011)

2.4 *Modelling the biomass-for-bioenergy supply chain using GIS technology*

2.4.1 Modelling the multimodal transportation network

A Geographical Information System (GIS) is capable to capture, store, analyse, manipulate and display geographically referenced information (Ma, Scott, Degloria, & Lembo, 2005; Thill, 2000). Its specific application and adaptation, based on network data model, to research, plan and manage transportation is named Geographic Information System for Transportation (GIS-T) (Thill, 2000). GIS-T encompasses the study of flow and movement and lies at the core of transportation research.

There are three basic GIS-T primitives: points, nodes and link (Zhou, Lu, & Wang, 2000). A point refers to the identified points fixed and regarded as the traffic origins or destinations. A node is identified as a special point considering an intersection or route beginning and ending. A link indicates a traffic route between two nodes. A transportation network is modelled as a set of interconnected nodes and links, and simultaneously storing topological relationship of connectivity (Mandloi & Thill, 2010). Based on a network data model, GIS can accomplish simple as well as sophisticated network analysis such as Route Analysis, Closest Facilities Analysis, Vehicle Routing Problem, Origin-Destination Cost Matrix, Location-Allocation Analysis and many others.

The concept of multimodal transportation network as mentioned above is defined as a set of available modes chosen by users with different combinations to meet their needs. Thus, emphasis in representing a multimodal network and possible movements on it, is on the modelling of transfer points or those locations on the network where transfer from one mode to another can occur (Mandloi & Thill, 2010). In the biomass-for-bioenergy supply chain, these points may locate the places where transfer of biomass happens, such as a port or a railway station. The connectivity between two modes is established only at these transfer points and they also suggest some substantial impedance such as extra energy consumption, CO_2-emissions and economic cost caused by the transfer manipulation and labour needed (See table 7). Besides, when time consumption is considered, the value of this impedance is rather elastic due to the possibility of unpredictable waiting time.

Different ways for designing multimodal networks are stated by Bielli et al. (2006). Traditionally, the approach of modelling multimodal network is to build a sub-network of each mode in separately spatial data base, and integrate them based on defined connectivity among modes (Mandloi & Thill, 2010).

Furthermore, a wide and successful application of GIS in modelling multimodal transportation network (Arampatzis et al., 2004; Beuthe et al., 2002; Beuthe et al., 2001; Zhang et al., 2013) has proven its suitability and great contribution. For example, Arampatzis et al. (2004) sucessfully use a GIS-based multimodal transportation network to analyse and evaluate different transport policies presented; Beuthe et al. (2002) developed a GIS-based multimodal freight transport network to estimate some external costs caused by freight transport in Belgium.

2.4.2 Location – allocation optimisation

According to ReVelle & Eiselt (2005, p.1), the term "Location Analysis" as associated with modelling and solving the problems of locations, can best be defined as *"sitting facilities in some given space"*. It is generally characterized by four components: a given space, possible locations of facilities, existing locations of consumers and a metric of measuring distances or times between facilities and consumers (ReVelle & Eiselt, 2005). As Ranta (2005) mentioned that the typical problems of location analysis are rather complicated and data intensive, because the number of possible solutions is equal to the wanted number of locations multiplied by the number of alternative sites and sometimes different strategies for each location are also involved.

The term "Allocation Analysis" refers to the process through which a set of designated features is assigned to the locations without surpassing the capacity of locations (Eastman, Fulk, & Toledano, 1993; ESRI, 2013). It is often accompanied by additional decision criteria related to each locational alternative (Malczewski, 1999).

Location-Allocation (LA) analysis, typically involves these two interrelated analysis mentioned: location analysis and allocation analysis (Malczewski, 1999). It allows analysts to locate the facilities according to objectives on the one hand, and allocate the demands to them on the other hand. Thus, it is regarded as an important solver for the problems of integrated logistics optimisation (Zhang & Hu, 2006).

The Network Analyst extension of ArcGIS 10.0 software encompasses a location-allocation (LA) analysis-tool. For the allocation of P demand points to N facilities the rationale of the LA-tool is as follows:

- When a subset of candidate facilities n ($n \in N$) is required, the total possible combinations are equal to C_N^n. It means if 10 out of 50 conversion facilities need to be located, the number of possible solutions is more than one billion ($C_{100}^{10} = \frac{100!}{10!*90!}$). To avoid potentially huge examinations and solve problems in a relatively short time, a semi-randomised solution combined with the method of vertex substitution heuristic is applied here (ESRI, 2012); Firstly, an origin-destination matrix based on all demand points (=origins, P) to each facility (= destinations, N) with minimal cost (such as shortest distance or minimal energy consumption), is generated (allocation process). Through a semi-randomised selection, a current result of conversion facilities n is sited. And, its objective value is also calculated (e.g., the shortest-path or the minimal energy consumption);
- Then, two loops are implemented. The outer loop chooses each leaving conversion facility (in total is N-n) following a sequence and passes it to the inner loop. When inner loop receives this site, it uses this conversion facility

to replace each facility located in current results. After the completion of inner loop, the new results (in total is n) calculated from objective function are used to compare with the current solution. If the value comes from new results is lower than the current one, the examined facility will be swapped into the current solution (Densham & Rushton, 1991). If more than one value is lower than the current result, the lowest situation is considered. After finishing the outer loop (one iteration), if no substitution occurs, the current solution is the final outcome. However, if substitution is involved, the iteration is repeated. This iteration procedure is displayed in figure 2 as location process.

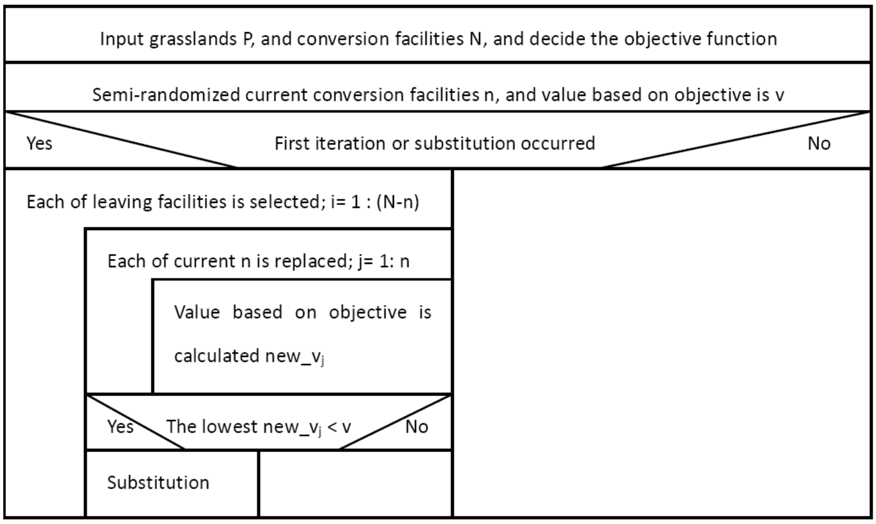


Figure 2 An N-S flow chat about the algorithm behind the LA analysis

Besides, according to Densham & Rushton (1991), the vertex substitution heuristic compared with other heuristics performs better and often finds the optimal solution after two iterations and within four iterations. However, it also must be admitted that the results are near-optimal rather than exact.

Furthermore, there are many precedents that treat location-allocation analysis as crucial part to solve problems in biomass for bioenergy supply chain. Möller (2003) uses LA for allocating forest wood chip resources to energy plants in Denmark with least-cost allocation. Ranta (2005) applies it to perform resource-side analysis for finding optimal power plant locations for utilizing logging residuals in Finland according to a least-cost manner. Shi et al. (2008) uses the MAXATTEND model (in LA) to evaluate the feasibility of setting up new power plants in Guangdong by defining the supply area of each candidate site based on transportation distance along roads. Sultana & Kumar (2012), based on location-allocation model, determine the optimal location of 13 plants to be built in the Province of Alberta through transport cost optimization. But, it is undeniable that other methods such as a linear programming are preferred by other researchers (Hongwattanakul & Phruksaphanrat, 2012) to accomplish the optimum allocation.

2.4.3 Advantages and challenges

The major benefit from using GIS to optimise the location and allocation of the biomass supply is that it allows users to explicitly and quantitatively account for variation of geographic factors that affect the whole biomass-for-bioenergy supply chain (Ranta, 2005). And, it provides a good platform for building multimodal network because of its great ability of data integration (Arampatzis et al., 2004). Besides, it enables to deal with spatial and non-spatial data. Some other potential advantages related to GIS are in the area of geographical visualisation, such as displaying simple statistical summaries and plotting of data in map format with location information, which is better than traditional reporting (Ranta, 2005).

Also, some drawbacks do exist. One of them is caused by data itself. As Yeh and Chow (1997) mention, the application of location-allocation analysis is very limited by the availability of data, especially at the district and street block level. Thus, the optimal locations identified may not be a practical solution as a result of lack of available data. For example, the facilities may locate unsuitable areas such as roads and seas. Simultaneously, the spatial scale for addressing the problem should be evaluated, which might lead to a risk of misinterpretation of mapped output (Ranta, 2005). Although GIS software provides good opportunities for solving various logistics problem, some other complementary software such as Matlab software or Microsoft .Net, are sometimes needed.

3 Materials and methods

3.1 *Study area*

3.1.1 Geography of Flanders

Flanders (total area 13,512 km^2) located in the northern part of Belgium, is adjacent to France, the Netherlands and the North Sea (Figure 3, the light grey part) (Maes & Van Dyck, 2001). It comprises the provinces of Antwerp, East Flanders, Limburg, Flemish Brabant and West Flanders (Figure 4). The political region of Flanders was created along with the Walloon Region and the Brussels-Capital Region during the federalization of Belgium between 1980s and 1990s (Encyclopedia Britannica, 2012). Although the Brussels-Capital Region lies within Flanders as an enclave, this region is excluded from the study area because it is administratively separated from Flanders. The main topography of Flanders is predominantly flat to undulating, and Flanders is maritime climate with significant precipitation in all seasons.

Figure 3 The location of study area (Flanders) named VLAANDEREN

Source from (Neutens et al., 2012)

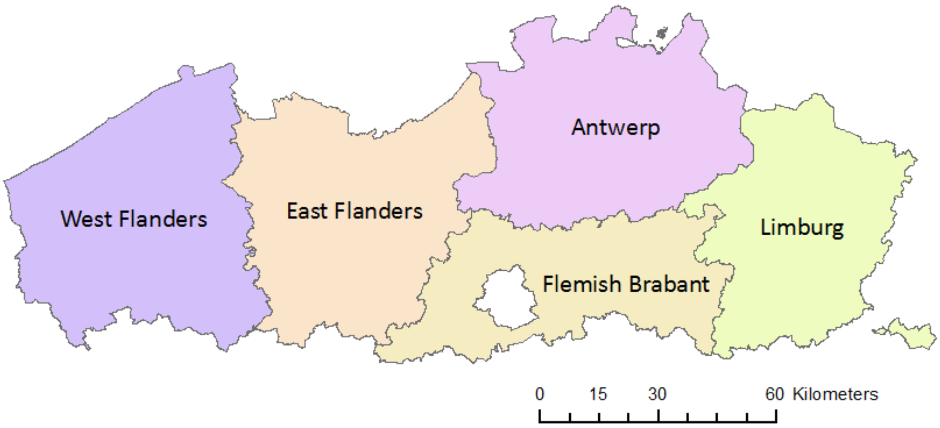


Figure 4 Provinces that Flanders has (Vriens et al., 2011)

Flanders also exhibits the typical features of western industrialized region (e.g., extensive industry, infrastructure and intensive agriculture) with population density of 431 citizens per square kilometre (Maes & Van Dyck, 2001).

3.1.2 Transportation in Flanders

Flanders has an outstanding transport infrastructure. The road network in Flanders is the densest one in the world (Flanders Investment & Trade, 2008), and it directly connects to those of other countries such as France, Germany, Luxembourg and the Netherlands. It allows goods to be transported from Flanders to most major European markets within 24h by road (Flanders Investment & Trade, 2008). Generally, the road network in Flanders can be classified into nine categories and their corresponding lengths are shown in table 8. The railroads in Flanders are the world's second densest rail network. In total there are 2,040 kilometres of tracks (Mestdagh et al., 2005). Flanders' navigable waterways extend over 1,580 kilometres (Mestdagh et al., 2005) and 1076 kilometres of them are used for commercial navigable purpose (Flanders Investment & Trade, 2008). Benefiting from the pivotal location in Blue Banana and in Golden Triangle of Europe, Flanders has an ideal position when it comes to logistics (Maes et al., 2009), and it is often called "crossroads of Europe".

Table 8 The categories of road network in Flanders and their lengths (Mestdagh et al., 2005)

Category	Length (km) in Flanders
Motorways	860
Roads like motorways	570
High roads	2100
Secondary roads	2550
Connecting roads	7770
Important local roads	1800
Local roads	23570
Access roads	19850
Other roads	410

Besides, in Flanders, the road includes passengers transport i.e. by car, by motorcycle etc., and freight transport i.e. by light (< 3.5 Mg) and heavy (> 3.5 Mg) trucks. The rail also includes passenger and freight transport. Yet, for navigable waterway, it is mainly used for freight transport. The policy measures for railway transport are made on a federal level while the measures for inland waterway are decided on a regional level.

3.2 ***Data collection and pre-processing***

In order to develop the multimodal transport network and optimise the allocation of LIHiD biomass to conversion facilities in Flanders, relevant data are collected as summarised in table 9.

Table 9 Identification of the required data characterising the biomass-for-bioenergy supply chain in Flanders

Object type	**Relevant content**	**Geographical dataset**	**Sources**
LIHiD biomass production site (grassland)	The location, productivities and related attributes for each type of grassland	Natuurpunt	Bervoets, (2008)
Conversion facilities	Locations and identification of digestion and composting plants	Compost producers on map (Data Compostproducenten op kaart)	Vlaamse Compostorganisatie VZW, (2011a)
Capacity of conversion facilities	Indication of conversion type and licensed capacity for each plant	Overview fermentation companies with quality control (Overzicht vergistingsbedrijven met kwaliteitscontrole)	Vlaamse Compostorganisatie VZW , (2011b)
Transportation network	Components of networks for highway and railway	Multi network street data (MultiNet Street Data)	Tele Atlas, (2003)
Navigable waterway network	Navigable waterway lines in Flanders	Indeling van de waterwegen van Waterwegen en Zeekanaal NV volgens CEMT klasse; Aanlegplaatsen die gebruikt kunnen worden als laad-en losplaatsen in het beheersgebied van nv De Scheepvaart	Waterwegen en Zeekanaal NV, (2011); Nv De Scheepvaart, (2011)
Railway terminals	The location of the transfer station	Terminals (terminals_tot_corr_A_lijstEV); Railway terminals in Belgium (kaart terminals 20110524)	Infrabel, (2011)
Waterway terminals	The location of the waterway transfer points and the type of goods which can be loaded or unloaded for each terminal	New loading and unloading on Flemish waterways (Nieuwe laad- en losinstallaties op de Vlaamse waterwegen); Inland containers in Flanders (Binnenvaartcontainerterminals in Vlaanderen)	Promotie Binnenvaart Vlaanderen, (2011a); Promotie Binnenvaart Vlaanderen, (2011b)

3.2.1 Biomass production site

3.2.1.1 Data description

According to the multiple benefits reported by Bioenergy Information from Cornell University (2006), grasses are considered as an efficient and fast growing solar energy collector regardless of geographical restriction. They can grow on the marginal lands ill suited for continuous row crop production or open rural land with relative fewer inputs compared with other annual crops (BERC, 2009). Considering these traits and intensive land use for agriculture in Flanders (Maes & Van Dyck, 2001), LIHiD grasslands are chosen as the production sites. Furthermore, LIHiD grass has a large potential to be developed in future as one primary biomass source.

The shapefile named "actnatkort2H_region" indicates the grasslands managed by Natuurpunt and located in Flanders (See table 9). Natuurpunt, whose objective is to manage the natural resources for future challenges, collects data based on literature research and field survey (Bervoets, 2008). According to the database, Natuurpunt manages 4198 dispersed polygons of grasslands in Flanders with a total area of 3734.59 hectare. Table 10 displays the key attributes stored in this shapefile. The classification of grasslands with their proportion is shown in figure 5. It is straightforward that the grasslands in Flanders maintained by Natuurpunt are dominated by permanent grasslands (75%), dotter grasslands (13%) and mesophilic meadows (7%).

Table 10 The key attributes of obtained biomass data (_COL1 = type of grassland (symbology of Biologische Waarderingskaart), PROD_MIN = minimum productivity (in Mg ha^{-1} year^{-1}), PROD_AVG =average productivity (in Mg ha^{-1} year^{-1}), PROD_MAX = maximum productivity (in Mg ha^{-1} year^{-1}) and OPP_HA = grassland area (in ha))

FID	Shape	_COL1	PROD_MIN	PROD_AVG	PROD_MAX	Biomass	OPP_HA
0	Polygon	Hp	4	6	8	grass	0.47
1	Polygon	Hc	3	4	7	grass	1.32
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4187	Polygon	Hp	4	6	8	grass	0.79

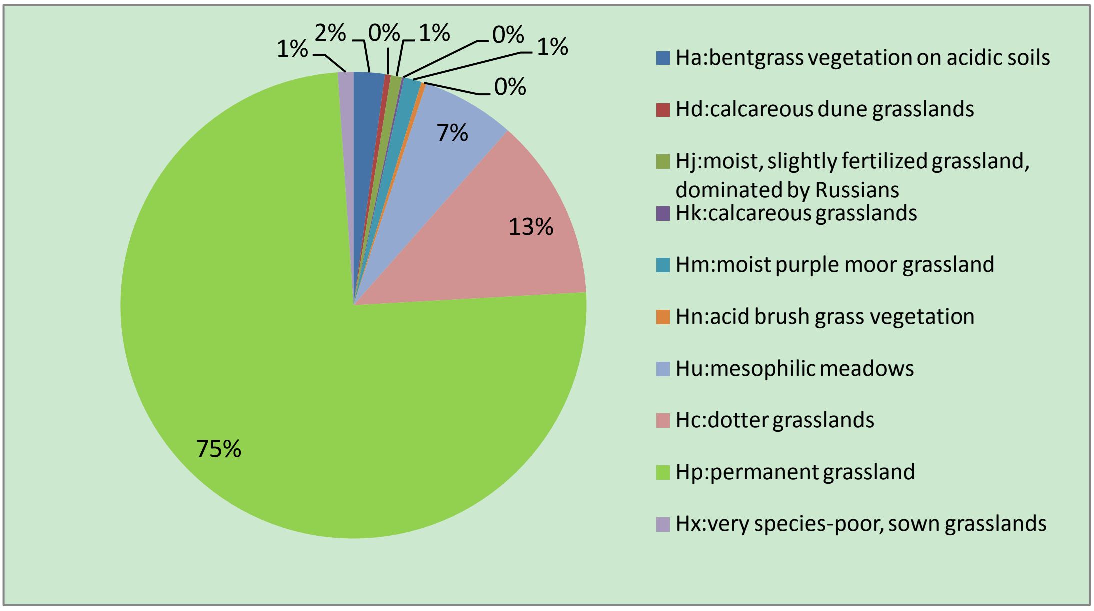


Figure 5 Distribution of grasslands managed by Natuurpunt according to the grass land types described in the Biological Valuation map (Vriens et al., 2011)

3.2.1.2 Data pre-processing

Due to the existence of some overlapping areas from the original source (e.g. the small highlight polygon located in the big highlight polygon in the left part of figure 6), the function Eliminate of ArcGIS 10.0 is applied to remove these intersection parts and simultaneously decrease the total amount of polygons to 2697 by merging polygons with neighbouring ones sharing the longest border (Figure 6). To determine the key attributes of the new created polygons, a Spatial Join is applied. For example, if a new area contains more than one previous data, the lower one is assigned to this new polygon. The new area is calculated by the function of Calculate Geometry with the unit of hectare.

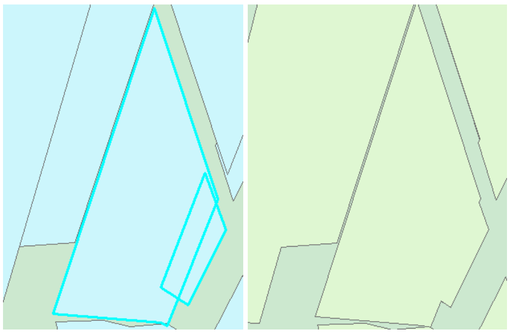


Figure 6 Comparison between pre-processing data (left) and the data after eliminating the overlapping areas (right)

To store the estimated usable amount of grass, a new attribute named "production" is created. Due to a series of restrictions (e.g., soil carbon maintenance and loss during the transport), not all biologically available grass can be used for energy production. The simply generic model of Shi et al. (2008) is therefore applied to estimate the reasonable or usable quantities of grass for bioenergy production. The equation is constructed as follows:

$$Q = A * P * r * (1 - c - l), \qquad (1)$$

Where:
Q = the usable amount of grasslands (in Mg year^{-1});
A = the production area of grasslands (in ha);
P = the average productivity of grasslands (in Mg ha^{-1} year^{-1});
r = the ratio of usable biomass for energy production;
c = the leaving ration of grasslands considered from environmental aspect;
l = the losing part ration of grasslands during the whole logistics process.

The product from multiplying area (A) by average productivity (P) indicates the biologically available amount of biomass. Parameter “r” represents the ratio of usable biomass for energy production. For grasslands, this parameter equals to 1 (Shi et al., 2008). While for other biomass such as crops, the value of r is relatively lower because only their residues (e.g., straws and stems) are used for energy production (Shi et al., 2008). The value of parameter “c” refers to a part of biomass should be left at production site to preserve the habitat and soil quality, estimated as 0.5 (Shi et al., 2008). The fraction “l” is used for calculating the loss during the whole process (e.g., harvesting loss) (Shi et al., 2008). For grasslands, fraction “l” is estimated to be 0.05 (Shi et al., 2008).

Like many authors did (Panichelli & Gnansounou, 2008; Perpina et al., 2009; Shi et al., 2008; Yeh & Chow, 1997; F. Zhang, Johnson, & Sutherland, 2011), the grassland polygons are converted into points located within the original polygons, by applying the function Feature to Point of ArcGIS 10.0 and simultaneously checking the “inside” option. Note that these grassland points are used only for subsequent network analysis to provide the rough location for each piece of grassland or assume the sites where the harvested grasses can be loaded. Thus, these points do not have a particularly realistic meaning. Besides, to avoid topological problems like self-intersection during the conversion process, the function of Repair Geometry is suggested to be firstly applied.

3.2.2 Conversion facilities

From VLACO (2011, see table 9 in the beginning of part 3.2), 36 biomass conversion facilities are selected with the conversion type of “anaerobic digestion”, because its suitability for grass conversion (See table 4) as well as it is proven to be commercially used (Iakovou et al., 2010; McKendry, 2002b). In this research, these facilities are treated as the destinations in the allocation process. Considering the replacement of grass for energy crops, organic-biological waste and agricultural waste, the capacity of each conversion facility is calculated by summarising these licensed capacities. If the corresponding capacity is a range rather than a fixed number, the average value is preferred.

3.2.3 Transportation network

Two data sources are available to represent the transportation network in Flanders: NAVTEQ NAVSTREETS and Tele Atlas Multinet street data. Both datasets are professional datasets (Zielstra & Zipf, 2010), widely used for commercial applications, and are quarterly updated.

Our choice is based on our research target (i.e. build transportation network) rather than the judgement that which is more comprehensive or more accurate, although there has some tests or disputes in public (e.g. NAVTEQ versus Tele Atlas: http://www.gpsreview.net/navteq-vs-tele-atlas/). For this master thesis research, the major transportation data (i.e. road network and railway network) are attained from the data of Tele Atlas (2003), and the reasons are fourfold. First of all, its attributes are highly related to the attributes required in the Network Analyst extension of ArcGIS (e.g. one way attributes, average speed attributes, functional road attributes, time attributes etc.) and thus are directly usable to construct a network. Secondly, its absolute accuracy measures 10 metres inside and 25 metres outside built up areas indicating a high-quality dataset (Tele Atlas, 2003). Furthermore, the road network includes nine levels, i.e. motorway, major roads, other major roads, secondary roads, local connecting roads, local roads of high importance, local roads, local roads of minor importance and other roads, allowing users to choose data at different levels. Last, the Tele Atlas dataset is accompanied by comprehensive English documentations.

3.2.3.1 Road network

Based on the original data source (Telenet Multinet street data in 2003), the highway network and junctions for five provinces of Flanders are selected and merged. To clearly explain the final framework for road network, an entity-relation (ER) model (Figure 7) is displayed to show the main entities as well as main attributes and their relations. As figure 7 illustrates, lines and junctions are the major entities of the road network. Both of them have an elevation feature. Compared with a single elevation value (ELEV) of junction, each line has two elevation values for its two ending points, namely, F_ELEV (F = from) and T_ELEV (T = to), indicating the elevations of the start and end points. And, based on the same elevation, lines are connected together adhered to the corresponding junctions. Except elevation feature, each line also has other attributes. ONEWAY indicates the drive direction and VT is short for vehicle types. Both of them are regarded as restrictions to manage drive flows in road network and are available in the Multinet dataset. Other attribute fields (i.e. energy consumption (FUEL_CSP), CO_2-emissions (CO_2) and economic costs) of roads' segments are added to the available dataset. These values for each line are calculated based on the distance field (METERS) available in the Multinet dataset and relevant data from table 5. Besides, the feature of time spending is obtained from the original dataset of road system (MINUTES). Moreover, as we mentioned before, the road network in Flanders includes nine levels (See last paragraph or table 8), from the highest class (value zero) to the lowest one (value eight). But only the functional road classes above six, namely, from motorway to local road of high importance, are considered into the network system of this research because of their significant roles in the whole allocation process and already large dataset (in total 195,054 line and point of data) (Figure 8).

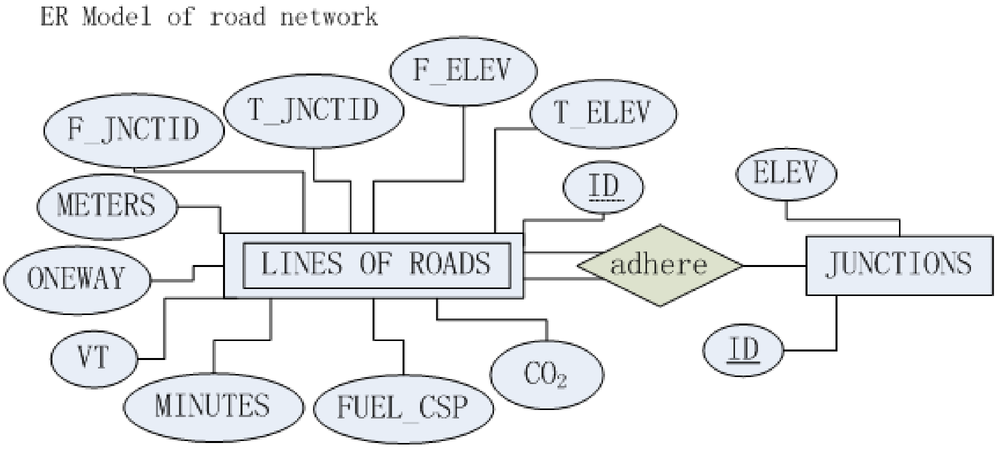


Figure 7 Entity-Relationship model with two entities (lines of roads and junctions), and their main attributes (VT = vehicle type, ELEV = elevation, FUEL_CSP = energy consumption and CO_2 = CO_2-emissions)

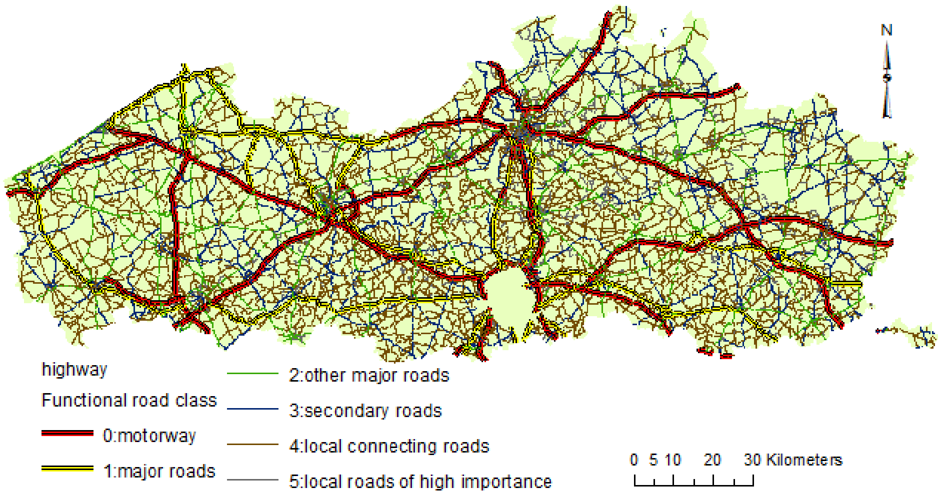


Figure 8 Road network in Flanders (limited to the 6 highest functional classes)

3.2.3.2 Railway network

In the Telenet Multinet Street data (2003), the railway network is delineated as line features for five regions in Flanders. These data are merged to form an integrated railway system. In order to pinpoint the terminals and transfer sites, the data obtained from Infrabel (map showing the freight terminals in Belgium (2011) and a spreadsheet with the addresses of freight terminals) (See table 9) are digitised by the GEOREFRENCING function of ArcGIS 10.0. This implies that the locations are less accurate because of rough comparison and lack of detailed address data of railway network itself. As a result, 38 points are added as transfer locations where the grass can be unloaded from other modes to train or unloaded from train to other modes. Also, their corresponding elevations are attached. Then, the values of new created attributes (i.e. minutes, energy consumption (MJ Mg^{-1}), CO_2-emissions (g Mg^{-1}) and economic cost (Euro Mg^{-1}) of each railway segment are calculated based on its length and relevant data displayed in table 5. A similar ER model as the road network applied is also suitable for railway network. The railway system in Flanders combined with possible transfer locations is shown in figure 9. It is clear that the majority of transfer points are located in the cities of Antwerp, Ghent, Mechelen and Oostende.

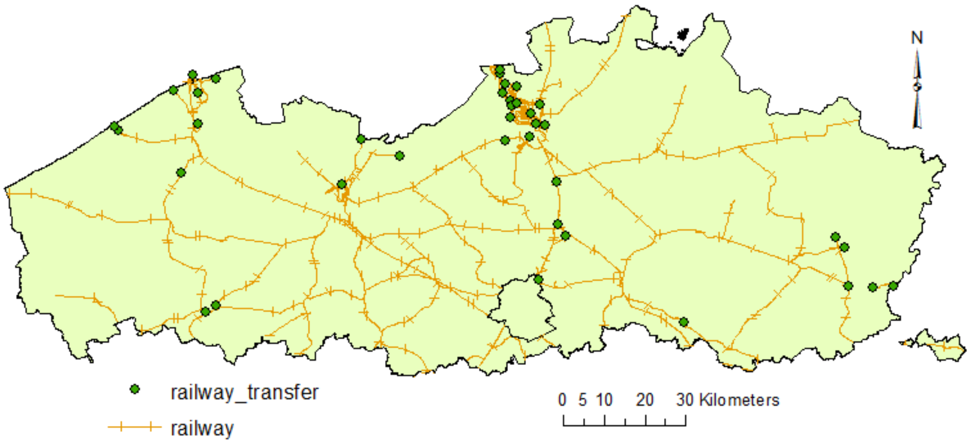


Figure 9 Railway network in Flanders with transfer sites

3.2.3.3 Waterway network

Because the Telenet Multinet Street data (2003) only includes a part of the waterway network in Flanders, data for this part are obtained from "NV De Scheepvaart" and "Waterwegen en Zeekanaal NV". The obtained line shapefiles present the navigable waterways in Flanders characterised by their names, administrators and the different permissions of transported weight. The locations of the terminals and transfer points are distracted from the map of "Inland containers in Flanders (2011)" (http://www.binnenvaart.be/nl/waterwegen/kaart_containers.html) and the map of "New loading and unloading on Flemish waterway (2011)" (http://www.binnenvaart.be/nl/waterwegen/kaart_kaaimuren.html). However, these terminals are not suitable for loading all types of goods and they are classified into several categories such as liquid goods, piece goods, bulk and waste etc. Therefore, only the transfer points with the type of goods like bulk and waste are considered and as a result 45 terminals are selected. Their corresponding elevations are also attached. The created fields for energy consumption, CO_2-emissions, economic cost as well as time spending are determined by procedure similar to the one applied to the railway network. A similar ER model as road network applied is also obtained, where transfer points and lines as major entities are linked by elevation feature. Figure 10 presents the navigable waterway network in Flanders combined with possible transfer sites, classified by their different dimension ranges.

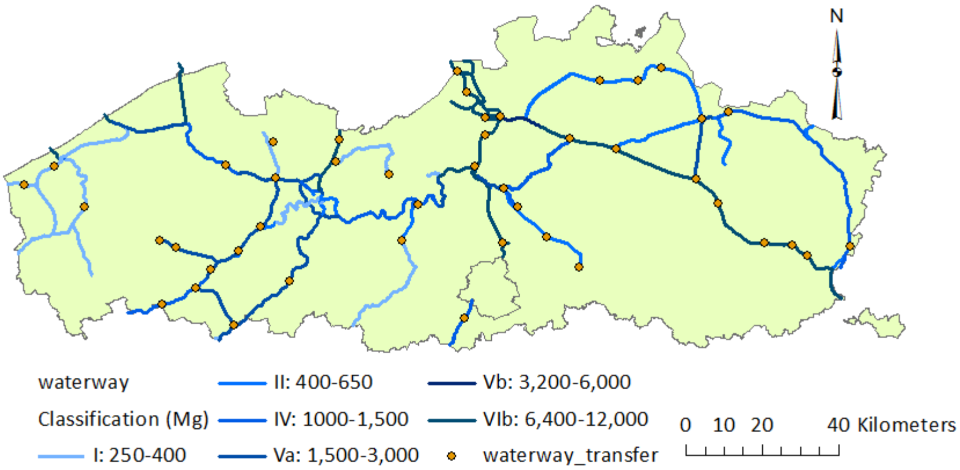


Figure 10 Waterway network in Flanders with possible transfer points

3.3 *Procedure to develop a multimodal network by means of ArcGIS software*

When unimodal transportation networks are available, a multimodal transportation network in Flanders can be build. The procedure is introduced in this part, and the general steps are presented in figure 11.

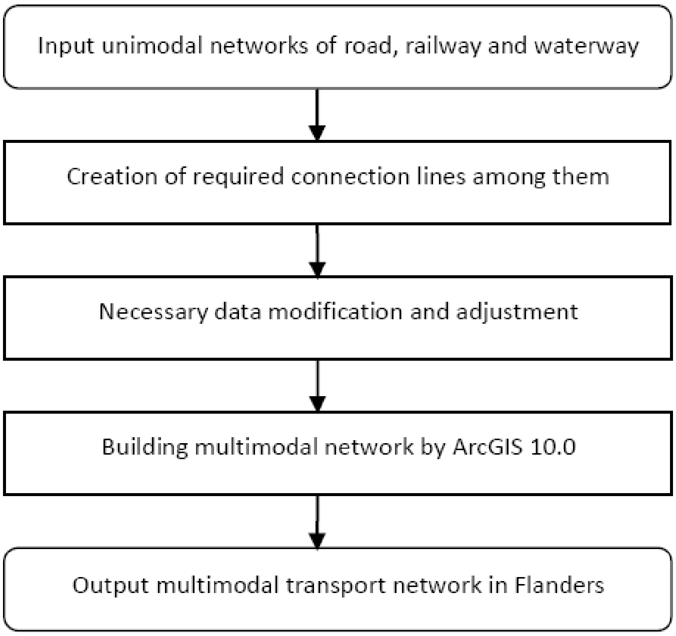


Figure 11 A flow chart of multimodal network development

3.3.1 Input unimodal networks of road, railway and waterway

The individual development of unimodal network is not necessary, because they can be constructed during the process of multimodal development. Thus, only the relevant features are needed to be input. These required data comprises the line shapefiles of road network, railway network and navigable waterway network, and the junctions of road network, and the transfer points of railway and waterway networks.

3.3.2 Connectivity between unimodal networks

To develop the multimodal network, the connectivity between the unimodal networks i.e. road network, railway network and waterway network, is required. In order to link unimodal networks by transfer points between road and railway as well as road and waterway, functions of Near, Merge and Points to Line are applied. As a result, each transfer point of the railway network and waterway network is lined to the nearest junction of the road network (Figure 12). Besides, the comparison among the source maps highlights the possible linkages between the terminals of the waterway network and the railway network at four locations in Flanders, namely, Antwerp, Mechelen, Ghent and Hasselt. Therefore, seven lines are created to connect the transfer points of railway network and waterway network located in these regions.

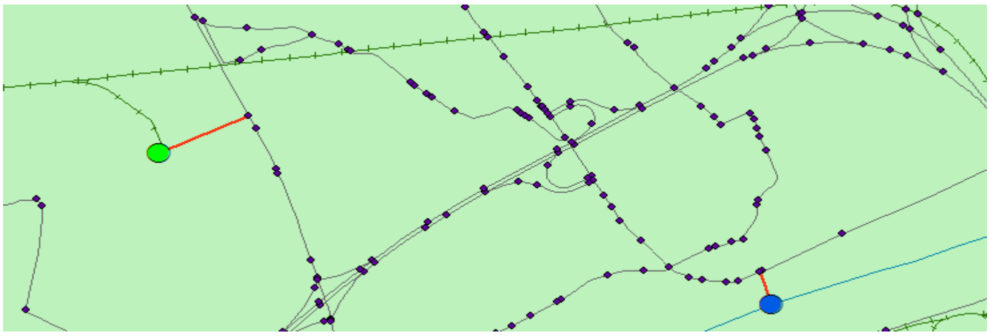


Figure 12 Connectivity between unimodal networks (green line = railway, grey line = road, blue line = waterway, green dot = transfer site of railway, and blue dot = transfer site of the waterway, red line = connection line between different networks)

Moreover, the final objective of this research is to allocate all grasslands to conversion facilities. Therefore, the connections between the production sites and the road network need to be determined. Besides, due to no conversion facilities are located nearby the transfer points of railway and waterway (the shortest distance is more than 600m), the connections between conversion facilities and road network are also needed. Thus, a similar procedure as applied to connect the transfer points of the railway network to road network is applied. When a region has a high concentration on grasslands, it is possible that the same nearest node of road network is selected by different grasslands. All created connection lines are treated as being part of road network, named with “connecting road”. Their distances are calculated by Calculate Geometry function, and other attributes such as energy consumption, CO_2-emissions and economic cost are calculated based on the field of distance and relevant data in table 5. Besides, their corresponding elevations are attached.

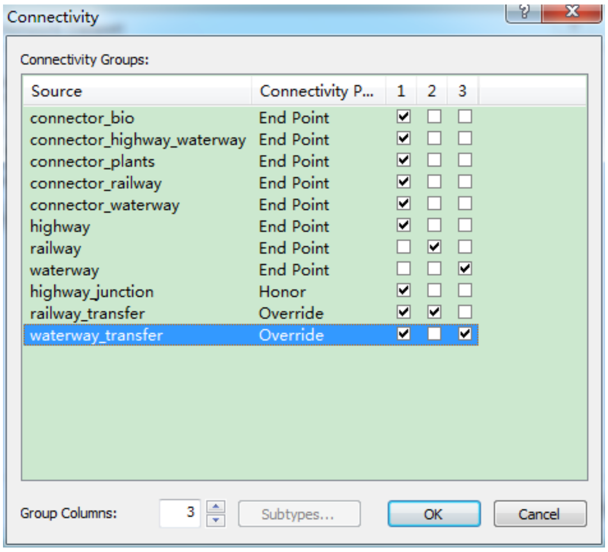
3.3.3 Data modification

Before constructing the multimodal network, three topics require attention and modification. First of all, the geographical spatial gap between Voeren (i.e. little light grey area located in the middle right position in figure 3) and the rest of Flanders. Although Voeren belongs to Flanders, it is impossible to allocate any grassland in Voeren to a conversion facility because no conversion facilities exist in Voeren and no connection exists between this region and the main area of Flanders. Therefore, two lines based on the main roads in both regions are created to integrate the Voeren to the main region of Flanders. Secondly, considering that railway and waterway are always operated at regional level rather than local level, their corresponding parts in the Brussels region are taken into account. Finally, some grassland sites turn out to be isolated because they are assigned to the nearest nodes of the road network and the restrictions attached to connection lines (e.g. one way or vehicle type) limit their accessibility. Thus, these grassland sites are deleted and their quantities are assigned to the nearest grassland sites. As a result, the number of grassland points decreased from 2697 to 2657.

3.3.4 Creation of the multimodal network

ArcGIS 10.0 software and its Network Analyst extension are used to create the multimodal network. Before building the network, it is necessary to create a new file geodatabase to store all feature datasets that include lines shapefiles of road, railway and waterway network, and point shapefiles corresponding to the junctions of road network, and transfer points of railway and waterway network.

Then, a new network dataset is constructed by completing the pop-up screens in the “create network dataset” function. First, the connectivity relation among these features is defined as illustrated in figure 13. Three groups are built to store road, railway and waterway system separately. Since the junctions of road belong to road system and are only attached to road network, they are checked in road column (1) with the role of “honor”. In other words, the lines of road take a leader role to decide the connectivity. However, transfer points of railway and waterway not only work for their individual network, but they are also treated as key points to connect their individual network to road network. Thus, they are checked in two related columns with the role of “override”. The connectivity between two or more networks depends on these points. Besides, there are also two options for line features, i.e., “end point” and “any vertex”. Considering the connectivity may only occur at the end points of lines rather than any crossing points of lines, the former one (end point) is preferred.

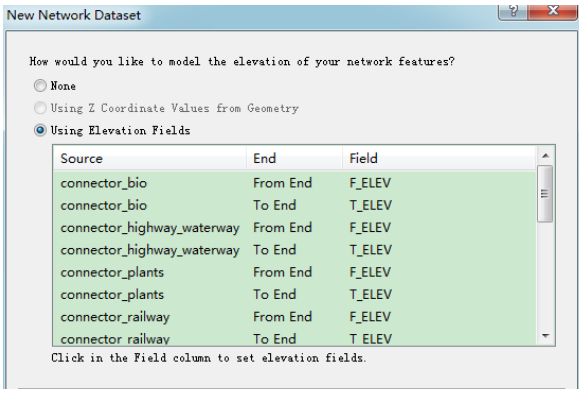


Source	Connectivity P...	1	2	3
connector_bio	End Point	☑	☐	☐
connector_highway_waterway	End Point	☑	☐	☐
connector_plants	End Point	☑	☐	☐
connector_railway	End Point	☑	☐	☐
connector_waterway	End Point	☑	☐	☐
highway	End Point	☑	☐	☐
railway	End Point	☐	☑	☐
waterway	End Point	☐	☐	☑
highway_junction	Honor	☑	☐	☐
railway_transfer	Override	☑	☑	☐
waterway_transfer	Override	☑	☐	☑

Group Columns: 3

Figure 13 The connection table installation

Besides, considering spatial complex of road network, elevation fields are necessary to be used (Figure 14). For example, changing direction is possible when crossing at the same level, while it is not possible when the crossing involves a bridge or a tunnel. Thus, the elevation among multimodal network is regarded as a spatial indication to judge the connectivity leading to a possible direction change. In other words, a feasible changing direction only occurs at the crossing with the same elevation.



How would you like to model the elevation of your network features?

○ None

○ Using Z Coordinate Values from Geometry

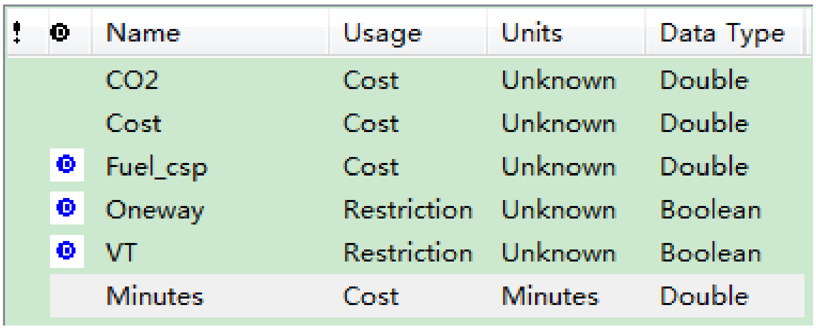
● Using Elevation Fields

Source	End	Field
connector_bio	From End	F_ELEV
connector_bio	To End	T_ELEV
connector_highway_waterway	From End	F_ELEV
connector_highway_waterway	To End	T_ELEV
connector_plants	From End	F_ELEV
connector_plants	To End	T_ELEV
connector_railway	From End	F_ELEV
connector_railway	To End	T_ELEV

Click in the Field column to set elevation fields.

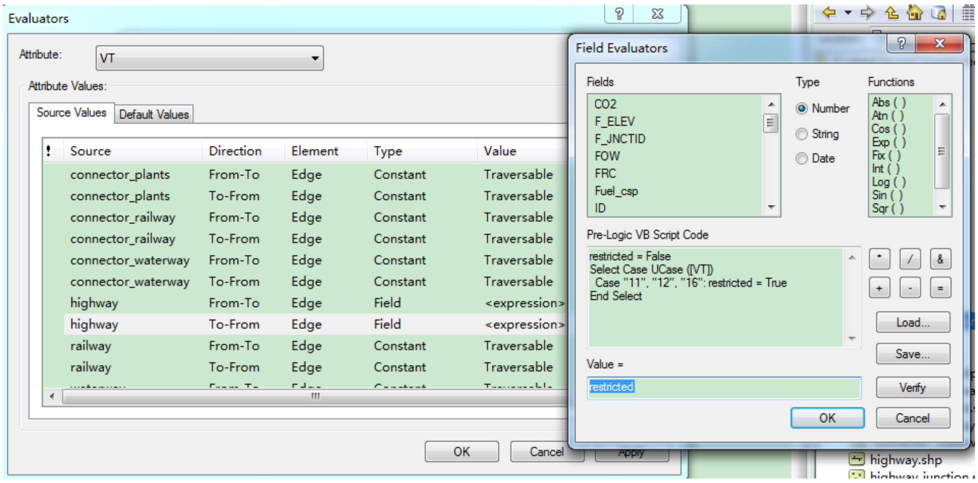
Figure 14 The elevation field for all features is used to construct the network dataset

The following step is to decide the evaluators of the network, i.e. to specify the attributes and restrictions of the multimodal network. Two restrictions are included to limit the flow along the road (Figure 15). One restriction encompasses the attribute "one way" which is used to decide the allowed drive direction (i.e., open in both direction, in positive direction, in negative direction or closed in both directions). And, the other is "vehicle type" indicating that some roads can only be served by specific vehicle types e.g. taxi and passenger cars rather than trucks. Both of them are implemented by short Visual Basic scripts. Due to ArcGIS software only takes "one way" restriction into account, a similar programming is written and is applied for "vehicle type" restriction (Figure 16). In addition, considering the double way feature of railway freight transport and waterway transport, no specific restrictions are attached to their networks. The other attributes i.e. energy consumption, economic cost, minutes and CO_2-emissions are treated as "cost attributes". It means that, these four values are available as input when each line of road, railway or waterway is used or passed.



!	◉	Name	Usage	Units	Data Type
		CO2	Cost	Unknown	Double
		Cost	Cost	Unknown	Double
	◉	Fuel_csp	Cost	Unknown	Double
	◉	Oneway	Restriction	Unknown	Boolean
	◉	VT	Restriction	Unknown	Boolean
		Minutes	Cost	Minutes	Double

Figure 15 The attributes of multimodal network



Attribute: VT

!	Source	Direction	Element	Type	Value
	connector_plants	From-To	Edge	Constant	Traversable
	connector_plants	To-From	Edge	Constant	Traversable
	connector_railway	From-To	Edge	Constant	Traversable
	connector_railway	To-From	Edge	Constant	Traversable
	connector_waterway	From-To	Edge	Constant	Traversable
	connector_waterway	To-From	Edge	Constant	Traversable
	highway	From-To	Edge	Field	<expression>
	highway	To-From	Edge	Field	<expression>
	railway	From-To	Edge	Constant	Traversable
	railway	To-From	Edge	Constant	Traversable

Type: ● Number ○ String ○ Date

Pre-Logic VB Script Code

```
restricted = False
Select Case UCase ([VT])
 Case "11", "12", "16": restricted = True
End Select
```

Value = restricted

Figure 16 The parameters of vehicle type restriction

Based on the previously key steps, the multimodal transportation network in Flanders can be constructed by clicking the confirmation button. The whole building process takes around fifteen minutes.

3.4 *Scenario analysis*

After the multimodal transportation network is built, the following objectives are:

- to explore whether and how a multimodal transportation network can be used to optimise the allocation of biomass to the conversion facilities considering single and multiple objectives;
- to assess the sensitivity of the allocation of biomass for parameters defining the multimodal transportation network and for parameters defined in the location-allocation procedure.

The LA-tool from the ArcGIS 10.0 toolbox as presented in the literature review was used to allocate the grass to the anaerobe digesters in Flanders for different scenarios. In total, forty-three scenarios are developed which can be classified into three research stage. The first research stage is primarily related to whether and how multimodal transportation can be involved to optimise the allocation of biomass considering single objective. Firstly, considering transfer operations bring extra cost (See 2.3.2.2 part of literature research), the first two cases are developed associated with examining the influence of transfer cost. Besides, according to the accumulation way of these evaluators (i.e., energy consumption, cost and CO_2-emissions) are related to both quantity and transport distance (See table 5), transport distance is chosen as a second interesting parameter to be assessed. Then, the second research stage focuses on assessing the sensitivity of the allocation of biomass for parameters defining the multimodal transportation network (modalities of network) and parameters defined in the location-allocation procedure (limitation of conversion facilities). Simultaneously, a conversion limitation for each conversion facility is also considered together with modalities to obtain a more comprehensive understanding how these two parameters affect the allocation. The contribution of Matlab software is also required. Last research stage is to explore the effects on allocation of biomass to bioenergy conversion facilities, caused by single and multiple objectives in terms of energy efficiency.

3.4.1 Influence of transfer cost

Based on multimodal transportation network built for Flanders, the influence of transfer cost is determined by optimising the allocation of grasses from the grasslands to anaerobe digesters in terms of energy efficiency without (scenario 1.1) and with (scenario 1.2) transfer cost. As shown in table 11, HRW indicates a combination network of highway, railway and waterway.

Table 11 The contents of scenario 1.1-1.2 and relevant restrictions

Scenario	Transfer cost	Transport distance	Modality	Objective
1.1	No	True	HRW	Optimise energy efficiency
1.2	Considered	True	HRW	Optimise energy efficiency

All previous prepared data including grasslands, conversion facilities and multimodal network are applied, combined with the Location-Allocation analysis available in the Network Analyst software. The operation procedure of the first scenario (1.1) without consideration of transfer cost is rather simple. After loading the multimodal network established previously, a new location-allocation layer can be opened in the Network Analyst extension and shows in the left screen (Figure 17). Then, grasslands are imported as demand points and conversion facilities are loaded as facilities.

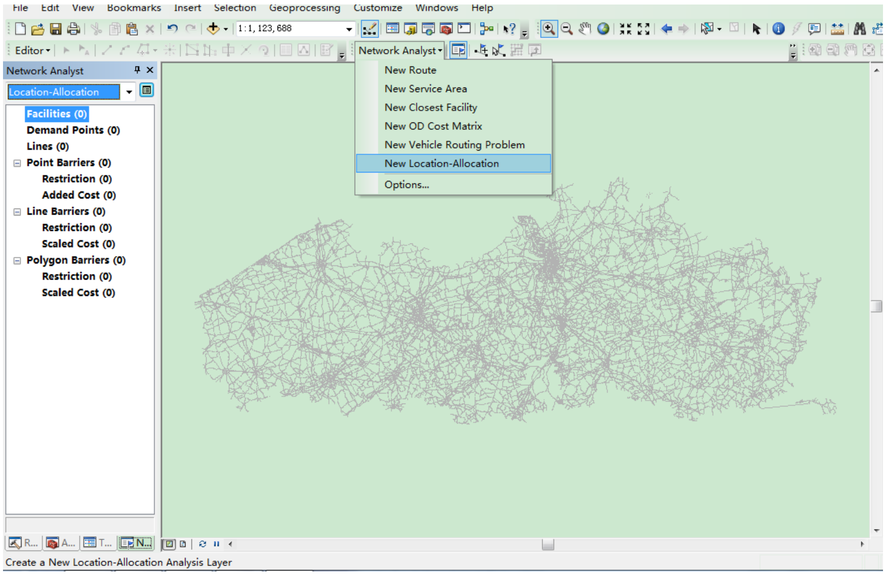
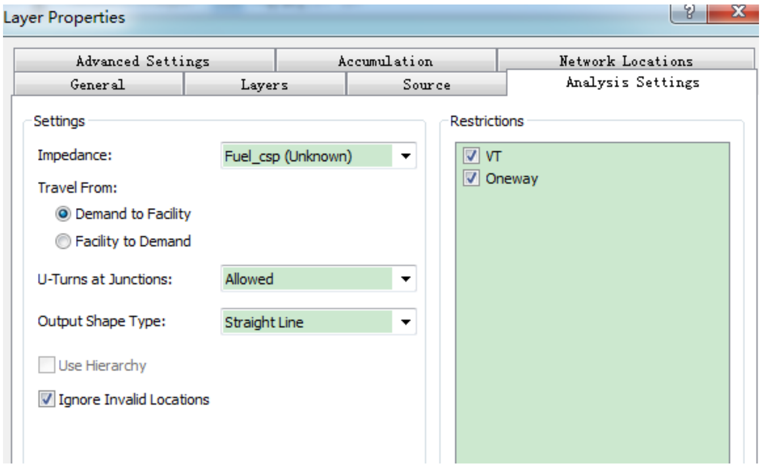


Figure 17 Creation of a new task of location-allocation analysis

Next, settings associated with impedances, restrictions and accumulated indications etc. are given in this created location-allocation analysis layer to serve the allocation process. The basic one is to make sure the energy consumption attribute is chosen as the impedance and the orientation of allocation is from demand sides to facilities, namely, from grasslands to conversion facilities (Figure 18). And, the restrictions i.e. “oneway” and “vehicle type” (VT) as we mentioned before are also checked and applied. Then, considering that our objective is to minimise the total energy consumed, the “minimise impedance” is therefore selected as the problem type, and the number of “facilities to choose” is 36 (Figure 19). Last, all attributes of interest such as energy consumption, CO_2-emissions, economic cost and time expenditure, should be checked in the accumulation layer to make sure that all of them are accumulated and stored during the allocation process. Then, a computation of allocation is implemented based on the semi-randomized algorithm mentioned in section 2.4.2, and it takes about 30 minutes to yield results.



Impedance: Fuel_csp (Unknown)

Travel From:
● Demand to Facility
○ Facility to Demand

U-Turns at Junctions: Allowed

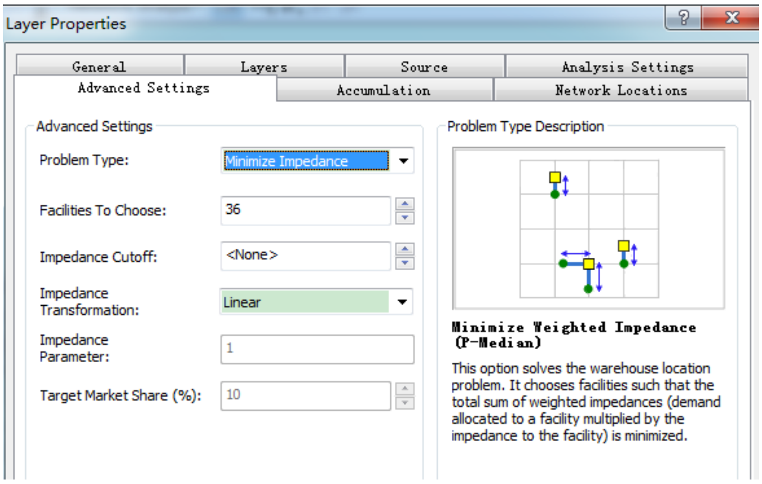
Output Shape Type: Straight Line

☐ Use Hierarchy

☑ Ignore Invalid Locations

☑ VT
☑ Oneway

Figure 18 Basic settings for location-allocation



Problem Type: Minimize Impedance

Facilities To Choose: 36

Impedance Cutoff: <None>

Impedance Transformation: Linear

Impedance Parameter: 1

Target Market Share (%): 10

Minimize Weighted Impedance (P-Median)

This option solves the warehouse location problem. It chooses facilities such that the total sum of weighted impedances (demand allocated to a facility multiplied by the impedance to the facility) is minimized.

Figure 19 Define the problem type of allocation and number of conversion facilities

For the second scenario (1.2), transfer costs are involved. So, it is necessary to change the expressions of cost attributes belonged to multimodal network firstly as explained in part 3.3.4. The importance is that, the costs of transfer such as energy consumed, CO_2-emissions, time spending and extra-economic cost, are attached to the connection lines of each transfer points of train and boat rather than to the transfer points themselves. The main reason is that, compared with single attribute of points, the lines have explicit direction attributes, e.g., “from-to” and “to-from”. Thus, two different values based on different directions can be used. Simultaneously, the cost of initial loading from grasslands and final unloading at conversion facilities is also taken into account, and this total value is attached to the final connecting lines of conversion facilities. Due to its properties or expressions of attributes are modified, the multimodal transportation network must be build again. Then, it can be applied and performed with the same steps that scenario 1.1 did, to yield results.

3.4.2 Influence of transport distance

As highlighted in the literature review, the advantage of freight transport by train and ship over truck appears at relatively larger transport distances. The major reason can be explained as the relatively higher transfer cost (e.g., energy consumption) of train and boat (See table 7) weakens their competiveness at short distances (Table 5). Thus, how a multimodal transportation network can be used to optimise the biomass allocation in terms of energy efficiency is also associated with transport distance. In order to obtain larger transport distances, the true distances (scenario 1.2) are multiplied by 2, 3, 5, 7, 10, and 20 to result in six case studies’ context (Table 12). To provide a more straight view of how original transport distances are altered, the total waterway distance as an example is also illustrated in table 12. Besides, the transfer cost is attached in the same way that scenario 1.2 did. And, the multimodal transportation network is build again due to its properties have been modified. Then, these six allocation processes are performed in a similar way as scenario 1.1 did.

Table 12 Scenarios studied to examine the sensitivity of multimodal network to transport distance

Scenario	**Transfer cost**	**Transport distance (based on true distance)**	**Total waterway distance as example (km)**	**Modality**	**Objective**
1.3	Considered	Multiplied by 2	2244.68	HRW	Optimise energy efficiency
1.4	Considered	Multiplied by 3	3367.02	HRW	Optimise energy efficiency
1.5	Considered	Multiplied by 5	5611.70	HRW	Optimise energy efficiency
1.6	Considered	Multiplied by 7	7856.38	HRW	Optimise energy efficiency
1.7	Considered	Multiplied by 10	11223.42	HRW	Optimise energy efficiency
1.8	Considered	Multiplied by 20	22446.84	HRW	Optimise energy efficiency

3.4.3 Effect of network modality and conversion limitation

Apart from the examination of whether and how multimodal transportation network including road, railway and waterway can be used to optimise the allocation of biomass in terms of energy efficiency, its advantage over other combinations of modalities of transportation network is also interesting to be analysed. To ensure the involvement of the railway network and waterway network under the consideration of transfer cost, the setting of case 1.7 is chosen for this analysis. In other words, the true distances in the multimodal transportation network in Flanders are multiplied by 10. Besides, considering other biomass types competing with grass for the limited conversion capacity of each conversion facility, different fractions of the capacity of the available conversion facilities are also taken into account. Thirty-two scenarios are developed based on each of four networks (i.e., road network, road and railway network, road and waterway network, and a combination of road, railway and waterway network) combined with eight situations of capacity availability (i.e., 100%, 50%, 20%, 10%, 5%, 3%, 2% and 1.5%) (See table 13). The complex case studies of multimodal network (2.25-2.32) are described in detail. All other scenarios follow the similar procedures and minimise the total energy consumption.

Table 13 Thirty-two scenarios developed to test the influence of modality

Scenario	Modality	Capacity availability	Scenario	Modality	Capacity contribution
2.1	H	100%	2.17	HW	100%
2.2	H	50%	2.18	HW	50%
2.3	H	20%	2.19	HW	20%
2.4	H	10%	2.20	HW	10%
2.5	H	5%	2.21	HW	5%
2.6	H	3%	2.22	HW	3%
2.7	H	2%	2.23	HW	2%
2.8	H	1.5%	2.24	HW	1.5%
2.9	HR	100%	2.25	HRW	100%
2.10	HR	50%	2.26	HRW	50%
2.11	HR	20%	2.27	HRW	20%
2.12	HR	10%	2.28	HRW	10%
2.13	HR	5%	2.29	HRW	5%
2.14	HR	3%	2.30	HRW	3%
2.15	HR	2%	2.31	HRW	2%
2.16	HR	1.5%	2.32	HRW	1.5%

Because the existing function of location-allocation lacks a restriction to consider the destination's capacity, the function of Origin-Destination (OD) Cost Matrix available in Network Analysis (ArcGIS 10.0) is applied coupled with a short Matlab programme. First, a new OD Cost Matrix analysis layer is created (Figure 20) after loading the multimodal network with transfer cost attached (see scenario 1.2). Then, grasslands are imported as origins and conversion facilities are loaded as destinations. Before clicking the solving button, the layer properties are examined to make sure that the energy consumption is chosen as an impedance indication (as figure 18 did) and it is accumulated during the calculation process (checked in accumulation layer property).

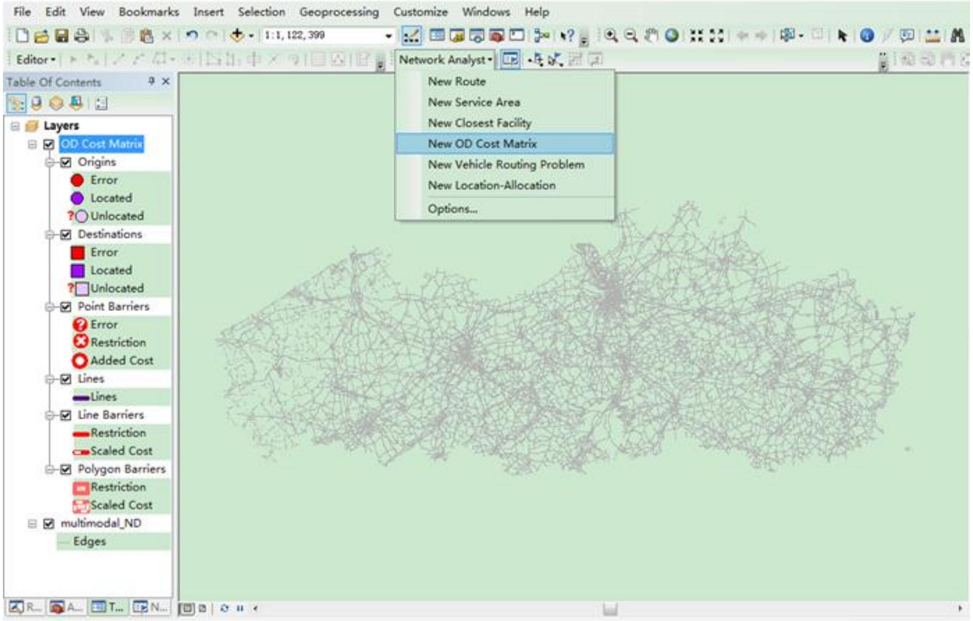


Figure 20 Creation of a new OD cost matrix by ArcGIS 10.0

When calculation is done (taking almost half an hour), an attribute table including 95652 (2657*36) records is obtained. This table contains the total energy consumption of each grass allocated to each conversion facility, ranked by original sequence of grassland sites and the energy consumed from minimum to maximum. And, the corresponding destination is also recorded. Then, destinations and total energy consumption, these two columns are exported into MATLAB, stored as one dimensional array and named as “des” and “energy” separately. Since no direct way to export data from table installed in ArcGIS to MATLAB, Microsoft Office Excel 2007 is applied as an intermedium to achieve this target. Namely, these 95652 records are imported to excel firstly, and then they are read into MATLAB.

Apart from loading “des” and “energy” mentioned above, the harvestable biomass production at each grassland site and the amount of biomass (capacity) required at each conversion facility are also imported into MATLAB and called “pro” and “capacity” separately. The allocation process is based on the priority of the minimum energy consumption. After one grassland site is assigned to one conversion facility, the capacity of this conversion facility is updated with subtracting allocated grassland value from current capacity. If the production at the biomass production site exceeds the current capacity of assigned conversion facility, it will be relocated to the next site based on energy consumption rank until the suitable one is found. To ensure that all grasslands are distributed, an array named “temp” is created to store the undistributed ones. The allocation process is repeated for eight capacity limitations. Figure 21, an N-S flow chart, presents the algorithmic procedure implemented in MATLAB to achieve this objective.

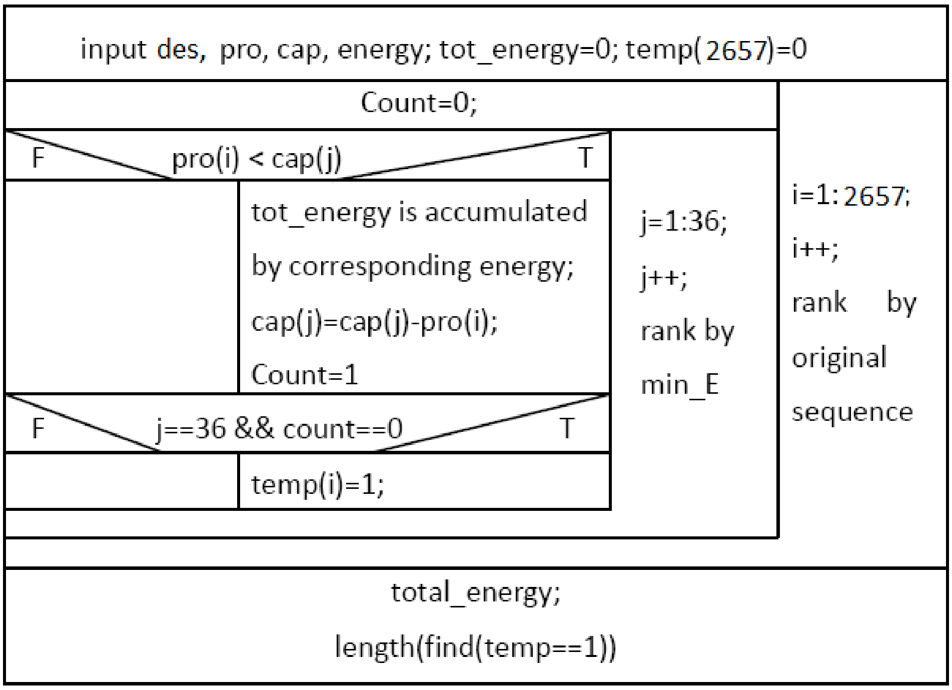


Figure 21 An N-S chart of allocation process in MATLAB

The allocation process based on other networks i.e., road network, road and railway network, and road and waterway network, are manipulated in the same way. But, each of them should be built firstly (See part 3.3.4), and then is set with the same transport distance as scenario 1.7 did where the transfer cost is also attached, and last is applied into the same procedures as mentioned above.

3.4.4 Effect of objective

Apart from the previous scenarios where allocation is defined to minimise energy consumption, the minimisation of CO_2-emissions (case 3.1) and the minimisation of cost (case 3.2) are also interesting to be examined. Two scenarios are developed in which respectively cost and CO_2-emissions are minimised for the biomass-for-bioenergy supply chain. Simultaneously their corresponding energy consumptions are calculated. These scenarios are still based on the distances in Flanders multiplied by 10. Also, it is assumed that the availability of conversion facilities for LIHiD biomass is 100%. The operation procedures are the same as mentioned in 3.4.1, except for changing the impedance to total economic cost and total CO_2-emissions separately.

Moreover, all scenarios analysed so far optimise one single criterion. Therefore, it is interesting to examine how the allocation of biomass will be effected when multiple criteria (scenario 3.3) are considered. Energy consumption, economic cost and CO_2-emissions are treated as three objectives. First of all, all values of these three criteria are normalised by dividing each value by the correspondingly largest value. A rule that the smaller is the better is obeyed. Then, considering from the research objective and environmental aspect, both energy consumption and CO_2-emissions are given the weight of 0.4, and remaining fraction (0.2) is assigned to total cost. The problem type of impedance chosen is to minimise a combination of these values. Correspondingly, the total expenditure of energy is recorded.

4 Results

4.1 *Grasslands in Flanders*

The general profile of grassland points maintained by Natuurpunt in Flanders is shown in figure 22. The total quantity of harvestable grasslands is 13,775.6 Mg year^{-1}. Although there is not so many grassland points located in the province of West Flanders, the grass production of this region managed by Natuurpunt is the second largest one among others (Table 14). And, the province with the least grass production is Flemish Brabant region (Table 14), although it has many grassland dots shown in figure 22. The largest grass production is located in Limburg. Besides, the territorial area for each province and their corresponding grass areas are also provided in table 14 to further discussion.

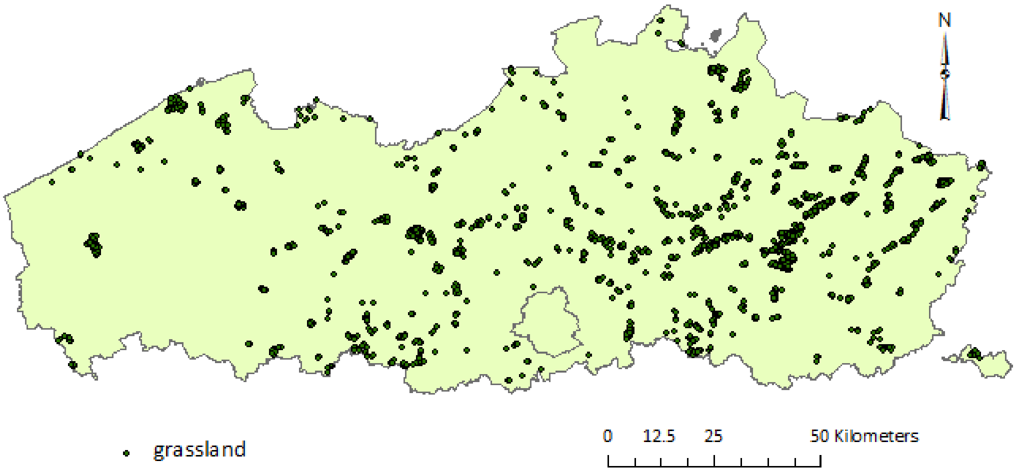


Figure 22 A general profile of grassland sites in Flanders

Table 14 Territorial area of each province in Flanders and their corresponding grass areas and productions in nature reserves managed by Natuurpunt (Vriens et al., 2011)

Province	**West Flanders**	**East Flanders**	**Flemish Brabant**	**Antwerp**	**Limburg**
Grass area (in ha)	863.55	596.85	506.56	665.54	1102.09
Territorial area (in ha)	316929	300781	211870	287559	242761
Grass production (Mg year^{-1})	3466.5	2063.7	1785.4	2311.5	4148.53

4.2 *Conversion facilities*

The locations of conversion facilities in Flanders are shown in figure 23. Although only the conversion type of anaerobe digester is considered, their related possible capacities vary from 500 Mg per year to 150,000 Mg per year and the total potential conversion reaches 1,364,520 Mg per year. Besides, most facilities with large conversion capacities are located in West Flanders. To some extent, their locations are opposite to the distribution of grassland points mentioned, especially when Limburg is considered. This is explained by the fact that LIHiD biomass is not the main feedstock for these facilities. Also, the region surrounding Brussels is significantly devoid of conversion facilities.

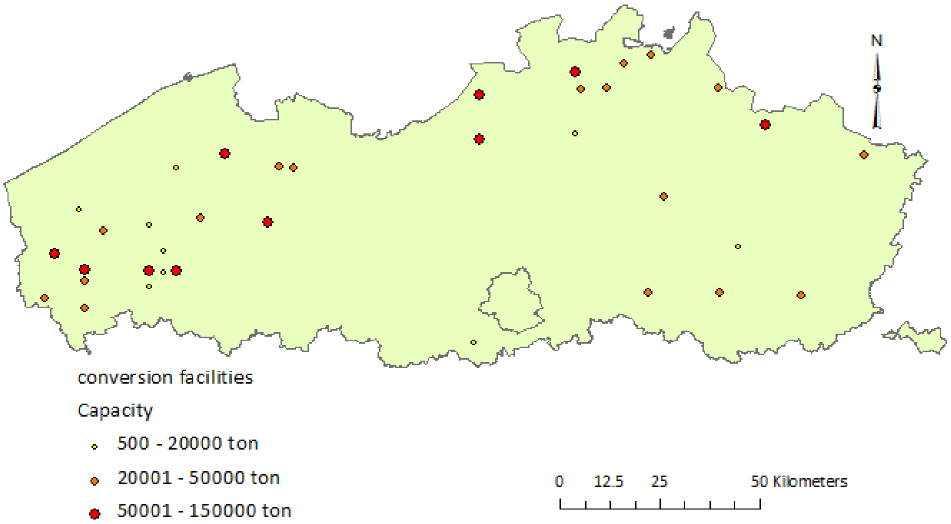


Figure 23 Conversion facilities located in Flanders

4.3 *Multimodal transportation network of Flanders*

The resulting multimodal transportation network of Flanders is shown in figure 24. It combines road network, railway network and waterway network and their attributes, e.g., energy consumption, CO_2-emissions and economic cost per segment. The transfer points of railway and waterway are key junctions used to keep the connectivity among unimodal networks. It is clearly visible that Voeren has been connected to the rest of Flanders, and parts of railway and waterway located in the Brussels region are integrated.

The lengths of road, railway and waterway obtained from this multimodal network are shown in table 15. Compared with the reported values derived from other datasets and mentioned in previous part (part 3.1.2), the results shown in table 15 keep the same order of magnitude, indicating the good quality of this multimodal transportation network in Flanders.

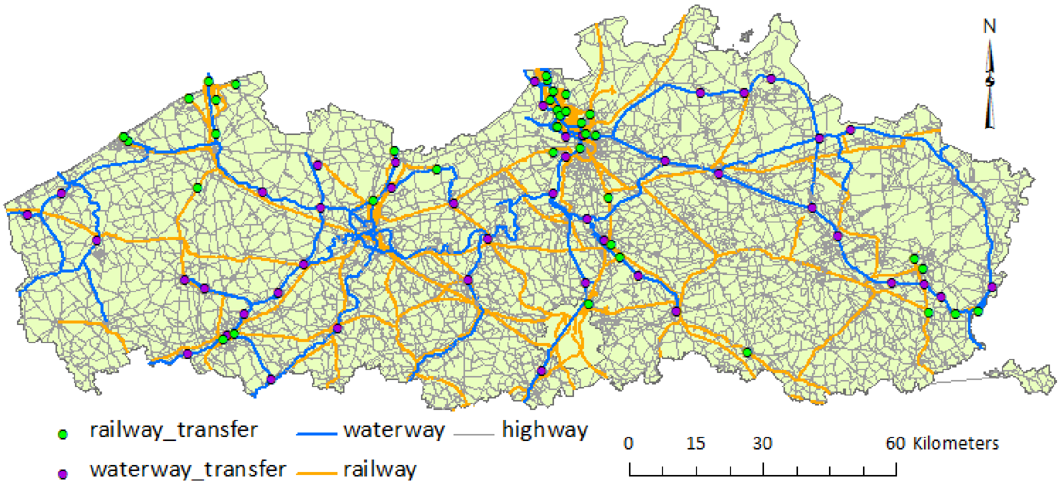


Figure 24 Multimodal transport network of Flanders

Table 15 Total length of included road, railway and waterway in multimodal transport network

	Road	Railway	Waterway
Total length (km)	17448.69	2402.22	1122.34

4.4 *Sensitivity analysis*

4.4.1 Effect of transfer cost

The allocation results without and with the consideration of transfer cost are respectively displayed in figure 25 and figure 26. And, the corresponding involvements of roadway, railway and waterway during these processes are illustrated in table 16 (in the next section). Other attributes i.e. energy consumption, cost and CO_2-emissions are shown in table 17 (in the next section).

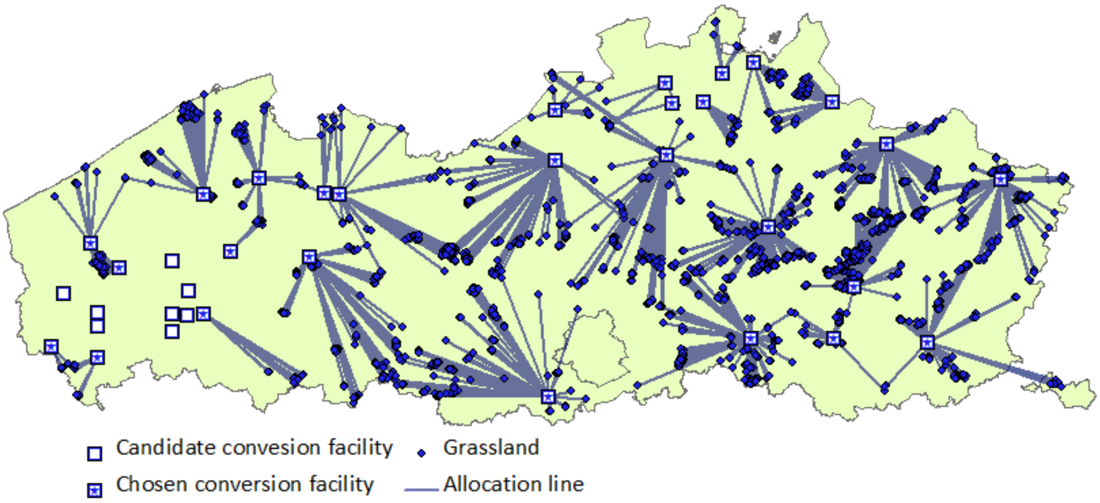


Figure 25 Allocation results without transfer cost consideration

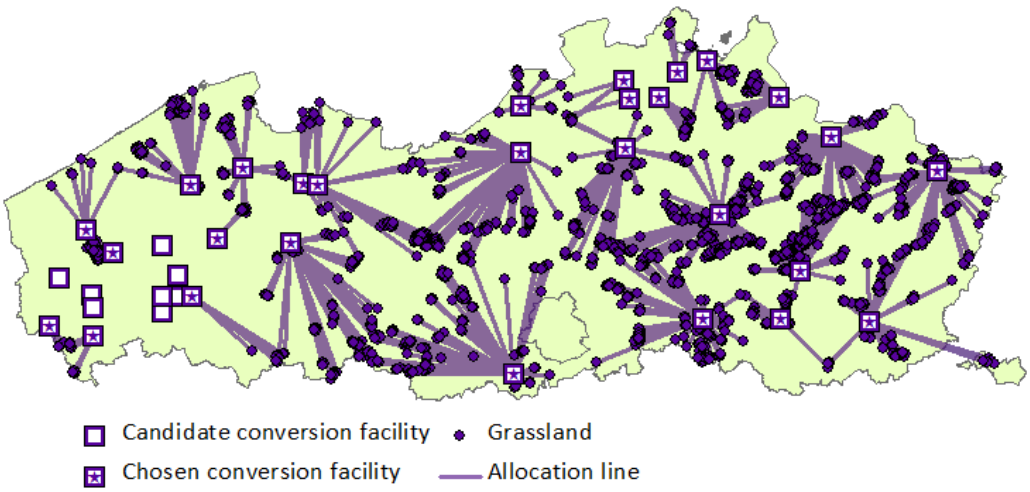


Figure 26 Allocation results with transfer cost consideration

4.4.2 Effect of transport distance

Table 16, reveals the relation between the transport distance and the involvements of three kinds of modes as well as the effects caused by transfer cost in the previous section. Other information associated with these eight scenarios, such as energy consumption, CO_2-emissions and economic cost is presented in table 17. Since most of them do not change the allocation destinations leading to a similar outcome, the results of these eight scenarios (including previous two) are illustrated in appendix (Part 8.1).

Table 16 The involvement of road, railway and waterway and associated transfer numbers for these eight scenarios

Case study	Road		Railway		Waterway		Total (km)	Number of transfer
	Distance (km)	%	Distance (km)	%	Distance (km)	%		
1.1	46811.16	0.92	1426.92	0.03	2699.28	0.05	50937.36	370
1.2	48824.57	1.00	0	0	0	0	48824.57	0
1.3	96771.40	0.99	1094.94	0.01	0	0	97866.34	44
1.4	142982.49	0.96	2762.25	0.02	2779.75	0.02	148524.49	132
1.5	236570.13	0.95	5350.30	0.02	7323.08	0.03	249243.51	190
1.6	330449.61	0.94	8064.60	0.02	11479.43	0.03	349993.64	212
1.7	471082.31	0.94	11896.97	0.02	18813.79	0.04	501793.07	244
1.8	939174.51	0.93	25655.57	0.02	45605.26	0.05	1010435.34	296

Table 17 Other attributes of these eight scenarios

Case study	Number of grassland sites	Number of conversion facilities used	Energy consumption (GJ)	CO_2-emissions (Mg)	Time consumption (day)	Total cost (k €)
1.1 (*1)	2657	28/36	309.76	14.96	41.20	20.86
1.2 (*1)	2657	28/36	391.85	16.40	34.20	56.91

Case study	Number of grassland sites	Number of conversion facilities used	Energy consumption (GJ)	CO_2-emissions (Mg)	Time consumption (day)	Total cost (k €)
1.3 (*2)	2657	28/36	712.46	31.26	69.28	81.15
1.4 (*3)	2657	28/36	1030.11	46.14	111.14	104.05
1.5 (*5)	2657	28/36	1655.52	75.90	191.73	147.61
1.6 (*7)	2657	28/36	2277.10	105.77	270.89	190.03
1.7 (*10)	2657	28/36	3208.04	150.67	392.67	253.19
1.8 (*20)	2657	28/36	6308.81	300.28	804.17	462.76

4.4.3 Effect of modality and capacity

Table 18-21 displays the minimum energy consumption for each case study based on road (Table 18), road + railway (Table 19), road + waterway (Table 20) and road + railway + waterway (Table 21) separately related with eight different available proportions of conversion facilities for grass.

Table 18 Minimum energy consumption allocation based on road network

Case study (availability)	2.1 (100%)	2.2 (50%)	2.3 (20%)	2.4 (10%)	2.5 (5%)	2.6 (3%)	2.7 (2%)	2.8 (1.5%)
Energy consumption (GJ)	3298.63	3298.63	3298.63	3452.8	3584.3	3893.65	4608.48	5870.24

Table 19 Minimum energy consumption allocation based on road + railway network

Case study (availability)	2.9 (100%)	2.10 (50%)	2.11 (20%)	2.12 (10%)	2.13 (5%)	2.14 (3%)	2.15 (2%)	2.16 (1.5%)
Energy consumption (GJ)	3246.9	3246.9	3246.9	3409.68	3559.37	3864.42	4561.68	5729.72

Table 20 Minimum energy consumption allocation based on road + waterway network

Case study (availability)	2.17 (100%)	2.18 (50%)	2.19 (20%)	2.20 (10%)	2.21 (5%)	2.22 (3%)	2.23 (2%)	2.24 (1.5%)
Energy consumption (GJ)	3259.96	3259.96	3259.96	3414.13	3545.62	3840.89	4518.27	5665.91

Table 21 Minimum energy consumption allocation based on road + railway + waterway network

Case study (availability)	2.25 (100%)	2.26 (50%)	2.27 (20%)	2.28 (10%)	2.29 (5%)	2.30 (3%)	2.31 (2%)	2.32 (1.5%)
Energy consumption (GJ)	3208.04	3208.04	3208.04	3370.82	3520.51	3816.28	4484.07	5611.37

As shown in figure 27, the general uptrend for each network accompanied with the lower available proportion is significantly apparent. Besides, it is evident that the smallest energy consumption with all capacity limitations always comes from the multimodal transportation network (road + railway + waterway), and correspondingly the largest one always comes from where only the road network is involved. It indicates that, with a specific transport distance, multimodal transportation network does work in terms of energy efficiency.

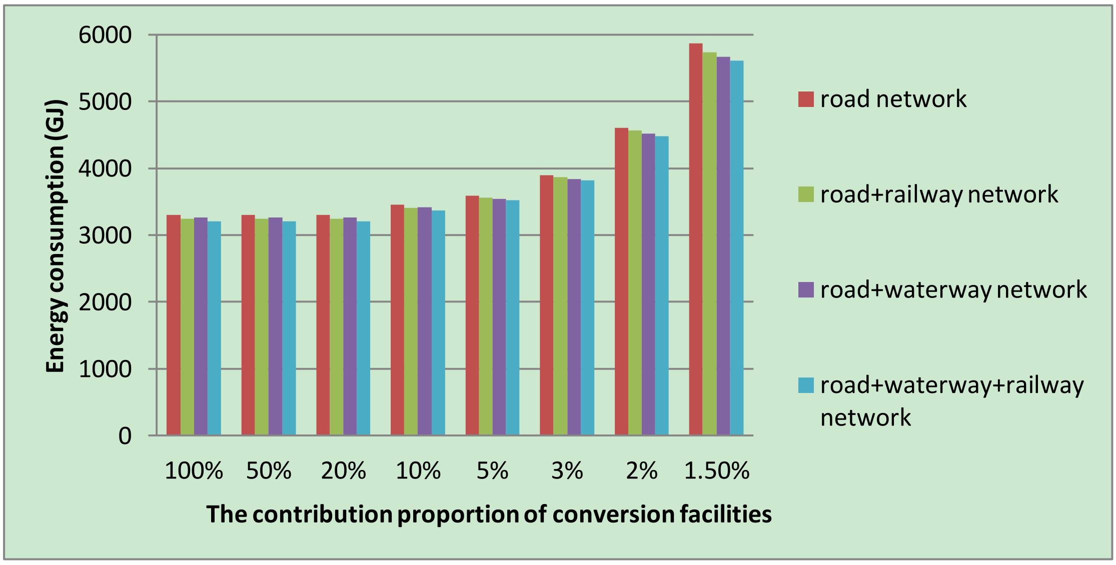


Figure 27 A relation between the available proportion of conversion facilities and energy consumption for four kinds of modes

Since location-allocation procedure of ArcGIS does not take into account the capacity limitations from destination, only four allocation outcomes (i.e., 2.1, 2.9, 2.17 and 2.25) are graphically presented in appendix (Part 8.2). Here, the most distinctive figures (the results of case 2.1 and case 2.25) are merged and displayed in figure 28.

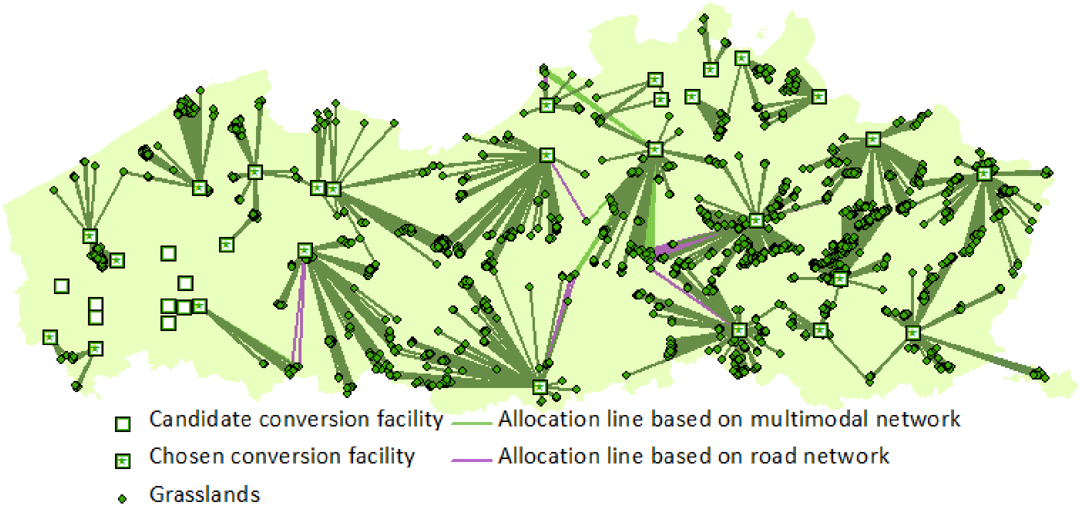


Figure 28 Comparison between the allocation in road network (2.1) and multimodal network (2.25)

4.4.4 Effect of objective

Figure 29 shows the total energy consumed following the criteria of minimum energy consumption, minimum CO_2-emissions (3.1), minimum economic cost (3.2) and multiple criteria based on three factors (i.e., energy consumption, CO_2-emissions and economic cost) (3.3). Besides, it should be noticed that the interval of y-axis is 10 GJ rather than 1000 GJ did in figure 27. Furthermore, their corresponding allocation results (3.1-3.3) are also illustrated in appendix part 8.3.

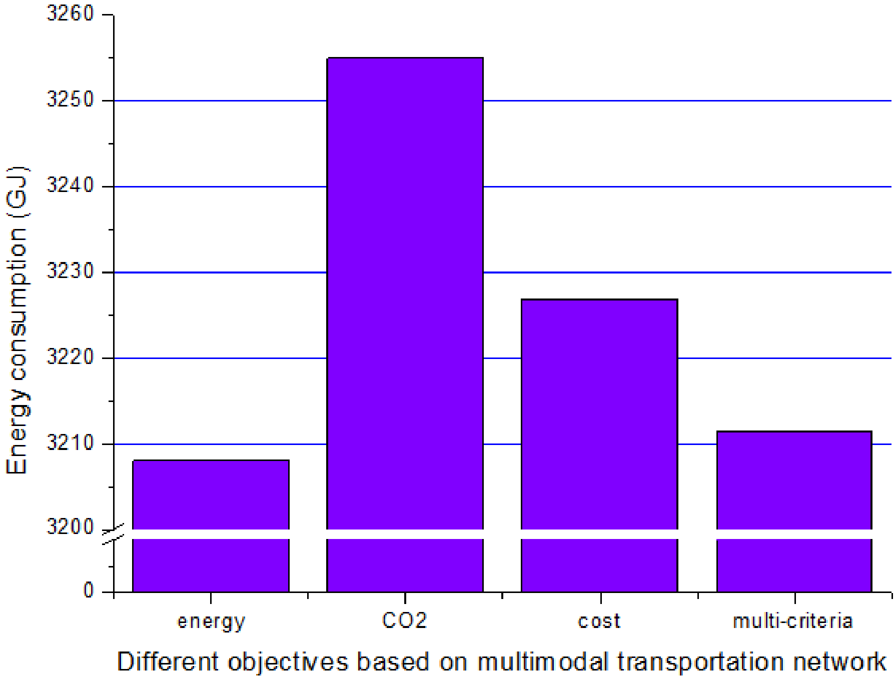


Figure 29 Energy consumption based on other allocation priorities

5 Discussion

5.1 *Location of grasslands and conversion facilities*

5.1.1 Biomass production

Although grasses are treated as an efficient and fast growing solar energy collector regardless of geographical restriction, the distribution of grasslands in Flanders maintained by Natuurpunt still emerges some patterns as figure 22 shows. Firstly, many of the grassland sites tend to be clustered together. Besides, compared with figure 24 (multimodal transportation network in Flanders), most of the sites are located away from the major traffic infrastructure. Furthermore, uneven regional production of grasslands primarily associated with different magnitudes of the production area is also presented. It should be noticed that although there are not so many grassland sites located in West Flanders (Figure 22) managed by Natuurpunt, the production of grass there is the second largest among other regions (Table 14). The major reason can be explained by the fact shown in table 14 that, West Flanders has large grassland areas as well as it obtains the largest territorial area. Benefiting from the largest grassland area managed by Natuurpunt, Limburg has the largest grass production although its territorial area is relatively small (Table 14). In the other three regions (East Flanders, Flemish Brabant and Antwerp), the production area doesn't differ that much as visualised on the figure or statistical data presented.

Compared with the value of annually harvestable grassland in Flanders (8,070.2 Mgy^{-1} – 21,574.5 Mgy^{-1} and the average production is 14,454.3 Mgy^{-1}) published by Bervoets (2008), the value of harvestable grasslands found in this research is 13,775.63 Mgy^{-1} which is located in reported scope and is very close to the average value.

5.1.2 Conversion facilities

As shown in figure 23, it is interesting to find that, most conversion facilities are located out of the Flemish Diamond region. The major reason may be associated with the social, economic and environmental considerations. For example, some pollution produced from conversion facilities may reduce the life quality. Thus, they should avoid locating in densely populated regions as much as possible. Besides, compared with other services industry, conversion facilities are often located in the suburban zone because of lower cost-effectiveness. Furthermore, some of them are concentrated in the same region (e.g., West Flanders) to benefit from agglomeration economy. The conversion capacity of each province in Flanders is shown in table 22. West Flanders has the largest potential conversion capacity which is more than double of the one in Limburg. It could be related to its significant role in agricultural production in Flanders. Besides, compared with other regions, Flemish Brabant has a significantly smaller conversion capacity.

Table 22 Conversion capacity for each province in Flanders (VLACO, 2011)

Province	West Flanders	East Flanders	Flemish Brabant	Antwerp	Limburg
Conversion capacity (Mg year^{-1})	547,350	274,000	76,900	247,270	219,000

5.1.3 Comparison

When table 14 and table 22 are compared, the idea mentioned in the part 2.3.2 that local conversion is not always possible although it is preferable from economic aspect is confirmed here. For example, the largest production of grass managed by Natuurpunt is in Limburg. However, its local conversion capacity is not high in comparison with other provinces like East Flanders, Antwerp, and especially West Flanders. The locations of the largest production grass region (Limburg) and the largest potential conversion region (West Flanders) are mismatched from the geographical point of view. After all, the location of conversion facilities is influenced by many factors not directly related to the location of the biomass. Some influencing factors are transportation network, topography, water resources, environmental resources and population centres (Sadi Mesgari et al., 2006). Based on currently mismatched locations between grasslands and conversion facilities, the optimisation of transportation is therefore undoubtedly urgent and crucial.

5.2 *Sensitivity analysis*

5.2.1 Influence of transfer cost

Based on table 16, the distinction shown in first two cases is caused by considering of transfer cost. The scenario 1.1 assumed that transfer from one mode to another one is without additional cost, successfully involves the multimodal transportation and leads to a lower energy consumption (table 17). However, when transfer energy consumption is taken into account, only the road network which has the least transshipment cost, is used. This situation indicates that whether multimodal transportation network can be used to optimise the allocation of biomass to conversion facilities is related to transfer cost consideration. The higher transfer cost from railway and waterway compared with those of road transport, weakens their competitiveness and even drives them out in a specific transport distance. Thus, without any transfer cost consideration, the minimal energy consumed by allocating grasslands to conversion facilities in Flanders is 309.76 GJ, successfully making full use of multimodal transportation network. However, when transfer cost is involved, the multimodal transportation network totally loses its advantages in the scale of Flanders. As a result, the least energy consumed by the same allocation process leads to a larger value of 391.85 GJ, whereby all transport is via the road.

Besides, to clearly display the different outcomes of allocation without and with transfer cost consideration, figure 25 and figure 26 are combined to form figure 30. As shown in figure 30, it is straightforward that transfer cost not only directly reduces the possible usage of train and ship mentioned, but it also indirectly leads to some destinations changed (i.e. the pure green lines). The suggestions are twofold. One is that, when higher transfer cost of train or ship is sited, the previous allocation based on train or ship has to change into road transport. The other one is that, without transfer cost consideration, grasslands located nearby transfer points of train or ship have more chances compared with others to be transported to further conversion facilities with lower energy consumption. In other words, these grasslands have lower opportunity costs to use multimodal transportation network compared with others far away from the transfer points of train or ship.

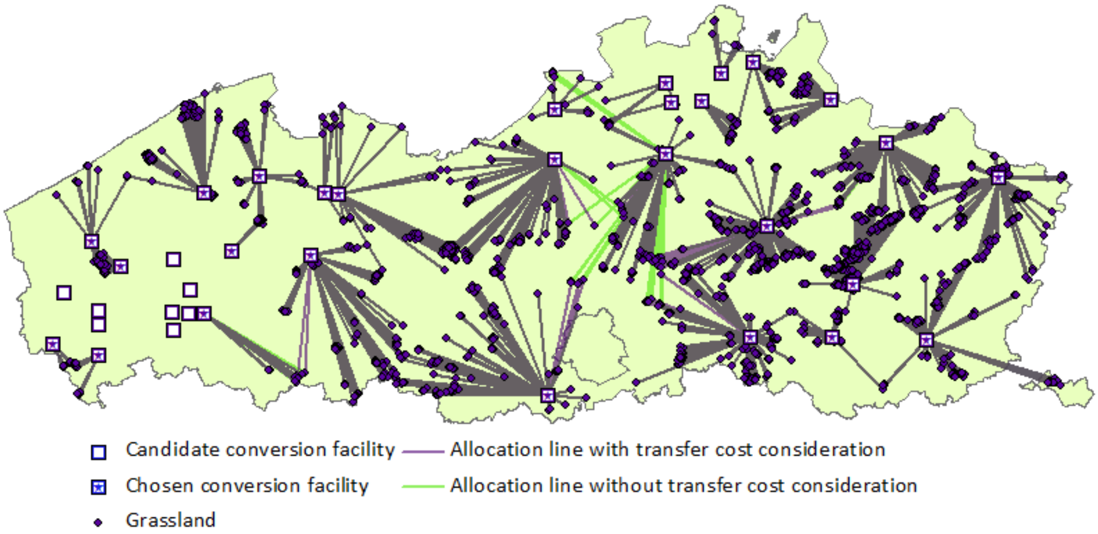


Figure 30 Comparison between the outcomes of allocation without and with transfer cost consideration

5.2.2 Influence of transport distance

When transport distance becomes larger (case 1.3-1.8), the usage of railway comes earlier than waterway benefiting from its relatively lower transfer cost compared with ship's. However, when the waterway is applied and the transport distance continues to increase, its involved proportion is gradually increasing rather than being stable as railway. Simultaneously, the number of transfers is increasing (Table 16). In order to obtain a more straight view of different involvements of three networks under these cases (including the previous two), figure 31 is portrayed. It is straightforward that for all cases, the road transport occupies the largest proportion, always more than 90%. And, its peak (100%) occurs for the true distance with transfer cost consideration. With the increasing transport distance involved, the contribution of road is slightly decreasing but still larger than its value from the first scenario. The decreasing usage part of road network is compensated by increasing usage of railway and waterway. The proportion of railway usage (red part in figure 31) after it involves, is relatively stable. The proportion of waterway usage (green part in figure 31) gradually increases accompanied with larger transport distance.

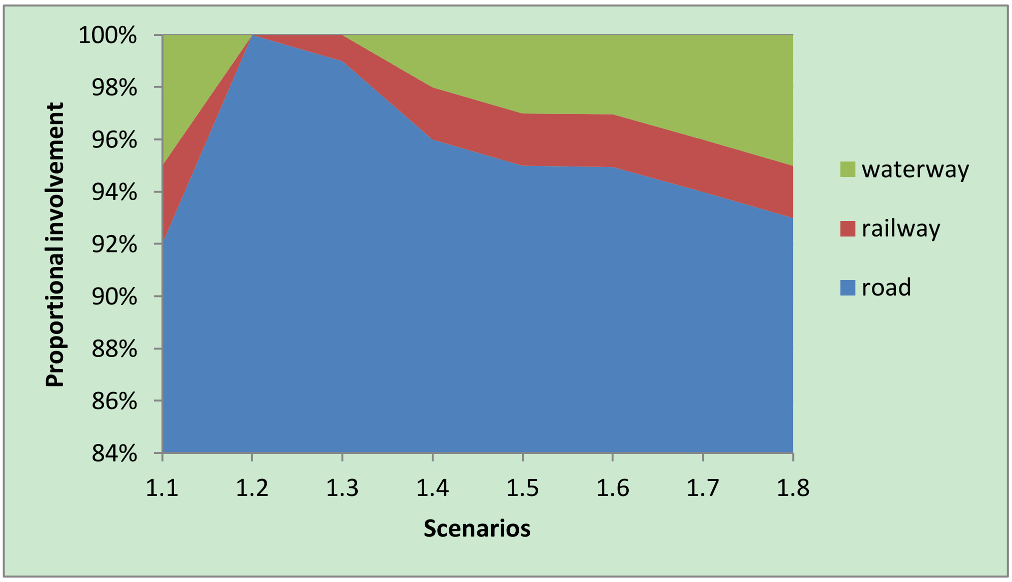


Figure 31 Involvement degrees of road, railway and waterway for different scenarios

In addition, the priority of road, train and ship considered from the view of energy efficiency also follows the sequence mentioned in literature research (i.e. road firstly, then train and the last is ship). But based on these eight scenarios, it is not enough to provide any explicit threshold for the profitable usage of each mode rather than their priority.

Besides, due to the total assumed availability of conversion facilities (1,364,520 Mgy^{-1}) is almost ten times of the total production of grasslands in Flanders (13,775.6 Mgy^{-1}) managed by Natuurpunt, there are always 28 out of 36 conversion facilities used (Table 17). At the same time, the values of other indications such as energy consumption, CO_2-emissions and time spending are not doubled as the same degree as the transport distance did.

Based on these eight scenarios, several suggestions can be given. First of all, a higher transfer cost could limit the choices for other modes rather than road, in a relatively short distance; secondly, whether and how multimodal transportation network can be used to optimise the biomass-for-bioenergy supply chain in terms of energy efficiency, is related to the transfer cost and transport distance as well as the locations of grasslands; then, compared with railway, the benefit from the usage of waterway requires a larger distance; last, the role of road in freight transportation is significant.

5.2.3 Effect of modality and capacity

Based on Flanders (10 times of true distances), different modalities combined with capacity limitation of conversion facilities are examined. From figure 27, it is clear that under all cases with varied capacity limitations, the usage of only road network always keeps the highest energy consumption while multimodal network involving road, railway and waterway always consumes the least energy. There is no uniform conclusion for the other two modalities, because their differences are small. When the available capacity of conversion facilities is within 100%-10%, energy consumed based on a combined network of road and waterway is larger than those from a combined network of road and railway (Table 19-20). However, when conversion capacity from conversion facilities is very limited such as only 5% or even less, a combined network of road and railway expends more energy than road and waterway (Table 19-20). Thus, when capacity of conversion facilities is significantly limited, waterway transport has more advantages over railway transport because longer distances are implicated and required. According to figure 27, it is also clear that a higher capacity limitation of conversion facilities requires higher energy consumption for each modality. And, the influence of capacity limitation on energy consumption is significantly crucial especially when available capacity is very small like 5%. It indicates that many harvested grasses are forced to be transported to a conversion facility far away because of no available conversion facility nearby. In addition, compared with the factor of network modality, the limitation of conversion facilities has more impacts on minimum energy consumption.

Furthermore, as shown in figure 28, multimodal transportation network compared with unimodal network (i.e., road network), provides good opportunities for transporting over longer distances with lower energy consumption. From pure green lines in figure 28 indicating the new destinations in multimodal transportation network displays, grasslands are allocated to further conversion facilities but without increasing the energy consumption. In other words, based on multimodal transportation network, conversion facilities also have more options of feedstock sources compared with only road freight transportation.

Some suggestions, based on this specific scale, are given. In the first place, multimodal network combining road, railway and waterway can minimise the energy consumption compared with other modalities; next, only the transport by using road network is the worst choice considered from energy consumption point of view; thirdly, the capacity limitation of destinations can lead to much higher energy consumption especially when it is very significant; also, compared with network modalities, the factor of capacity limitation has a lager influence on energy consumption; last, multimodal transportation network provides the opportunity for longer transport with less energy consumed and the significant limitation of conversion facilities.

5.2.4 Effect of objective

Different objectives lead to various energy consumptions. First of all, as figure 29 shows, energy consumption based on these three objectives are all larger than the outcome for minimum energy consumption. Besides, compared with results of minimum economic cost and multiple criteria, larger energy is consumed to minimize the CO_2-emissions. The major reason can be traced from table 5, indicating that train is the least CO_2-emissions vehicle but not the least energy consuming. However, ship is the most ideal transport vehicle no matter from cost or energy consumption aspects. Thus, scenario objected to minimum CO_2-emissions aiming at the usage of train transport rather than ship, brings higher energy consumption compared with other two studies. Besides, compared with scenario of minimum cost, approximate 15GJ energy can be saved if allocation process follows multiple criteria objective, which assigns the weight of 0.4 to both energy consumption and CO_2-emissions and the weight of 0.2 to economic cost.

5.3 *Energy balances*

Although the created multimodal transportation network does work in Flanders without transfer cost consideration and saves energy consumption in larger transport distance with transfer cost consideration, a relevantly interesting question should be asked is that whether these grasses deserve being transported to the conversion facilities. In other words, if their final energy production is smaller than energy consumed by transporting, it is not worth to allocate them. Due to an anaerobe digestion is considered, the grass is firstly converted to biogas and then the biogas is used in a combined heating and power to produce heat and electricity (ODE-Vlaanderen, 2012). According to the quantities of harvestable grass in Flanders per year managed by Natuurpunt (13,775.63 Mg year^{-1}) and the biogas yield of grass is 180 Nm^3 Mg^{-1} and 1 Nm^3 biogas has a heating value of 23 MJ Nm^{-3} as well as the efficiency of a combined heating and power (85%) mentioned in section 2.3.1.5.2, the total harvestable grass in Flanders per year managed by Natuurpunt can yield a heating value of 48,476.3 (=13,775.63 * 180 * 23 * 85% * 10^{-3}) GJ, which significantly surpasses the energy consumed by allocating grasses to conversion facilities in Flanders without transfer cost consideration (309.8 GJ) as well as with transfer cost consideration (391.8 GJ). It is surprising to find that the "energy consumed during the transportation / energy output from grass" is 0.8% (= (391.8/48,476.3) * 100%), less than 1%. However, according to the findings by Börjesson (1996), the "biomass transportation part / output biomass energy production" is small as well. Although he did not mention about LIHiD biomass, there is the data about reed canary grass and clover-grass ley, and their respective values are 0.55% and 1.4%. Besides, it also should be mentioned that, according to the section 2.3.1.5.2 in literature research, the conversion values can vary depending on data source, which indicating that different types of grass, different regions of grass and other factors (e.g., temperature and moisture) will lead different results. Thus, this ration should be further researched, although it confirms that the use of grass for the production of bioenergy is promising.

In addition, it must be noticed that, the transportation part researched here is only partial aspect involved in the biomass-for-bioenergy supply chain. Many challenges do exist. On the one hand, as mentioned in literature research (Figure 1), the whole biomass-for-bioenergy supply chain compromises several other actors (e.g., pre-processing, storage and conversion) and these procedures also consume energy. On the other hand, grass and other LIHiD biomass are only part of the overall supply of biomass which to some extent they can be mixed and processed together in the conversion plant. Thus, this research likes a case study while in reality the situation is much more complex in terms of energy efficiency.

5.4 *Limitations*

There are two major limitations associated with this research which should be mentioned. The first one is that, the capacity of the vehicles (truck, train and ship) has not been considered and the reasons are twofold. First of all, the each piece of grassland managed by Natuurpunt in Flanders is generally small. Less than 5% of them provide a quantity of grass exceeding the capacity of a truck (19 Mg). Secondly, some of near sites with small quantities can be collected and transported together. So, when capacity of vehicles is considered, more uncertainties will be involved. But, it also confirms again that, in reality, the transportation itself could be rather complex. The other point is that, in this study only grass produced in natural resources of Natuurpunt are considered. Other resources of grass and LIHiD-biomass (e.g., road waste) are not considered, just as import or export of biomass. Simultaneously, the availability of conversion facilities for grass conversion is assumed rather than explicit indication. In reality, it can be assumed by a mix of LIHiD-biomass or leads a competition among LIHiD-biomass.

From the technical point of view two remarks must be made. First, the result from location-allocation function is near-optimal. This means that, in reality, it may not the exact optimum solutions. Secondly, to solve complex allocation issues, network analysis combined with mathematical programming is required (Panichelli & Gnansounou, 2008; Tittmann, Parker, Hart, & Jenkins, 2010).

6 Conclusion

The general objective of this research was threefold. First of all, to find out how to build a consistent multimodal transportation network based on different unimodal transportation networks and considering attributes and restrictions related to energy consumption, costs and CO_2-emissions during the allocation of biomass to conversion facilities. The second objective explored whether and how the multimodal transportation network can be used to optimise the allocation of biomass to conversion facilities in the biomass-for-bioenergy supply chain considering single (minimal energy consumption) and multiple objectives (i.e., a minimum combination value considered from energy consumption, costs and CO_2-emissions). The third objective was to assess the sensitivity of the allocation of biomass to the conversion facilities to the definition of the multimodal transportation network or the definition of the location-allocation procedure.

To achieve these objectives, the required data were collected from literature where the motivation of this study is also confirmed. Considering social, economic and environmental aspects, biomass as an alternative for fossil fuel in the future is promising. Simultaneously, because of impossibility of local conversion of biomass, the optimisation of transportation in the biomass-for-bioenergy supply chain is crucial.

By using ArcGIS 10.0 software, a multimodal transportation network in Flanders was successfully built based on three unimodal transportation networks (road network, railway network and navigable waterway network). The key attributes (energy consumption, costs and CO_2-emissions) are assessed from literature and the restrictions (drive direction and vehicle type) realized by VB scripts were also attached. Through the location-allocation analysis function of ArcGIS and crucially relevant parameters (e.g., problem definition and standardisation of data), the developed multimodal transportation network can be applied to optimise the allocation of biomass to the conversion facilities considering the single and multiple criteria.

From the analysis of scenarios using the created multimodal transportation network of Flanders for allocating all LIHiD-grass biomass produced annually in the nature reserves managed by Natuurpunt to the available bioenergy production sites with the objective of minimising energy consumption for transportation, it is concluded that:

- Road is in all scenarios the major transportation mode;
- Minimal energy is consumed when transshipment costs are not incorporated;
- The incorporation of transhipment costs in the procedure leads to the avoidance of rail and waterway transport.

From scenarios using a derived network in which the transportation segment lengths have been artificially magnified, it is concluded that:

- The contribution of waterway transportation is gradually increasing with the scale factor but remains low;
- The contribution of railway transportation remains limited to 2%;
- The energy consumed, CO_2-emissions, time use and total cost are not merely proportional to the distance travelled since the share of the three transportation modes is important.

From scenarios using a network scaled with factor 10 for distance and assuming that the available capacity of the conversion plants ranges from 100% to 1.5% it is concluded that the lower the available capacity, the more energy must be consumed to allocate the biomass to the conversion plants. Furthermore, the multimodal network always leads to the lowest amount of energy consumed in comparison with a unimodal road network or with bimodal networks (road-rail or road-water). Finally it was found that the energy consumed over the 10-fold magnified multimodal network when three criteria were optimised simultaneously rather than the single energy consumption, was very close to the minimal value and lower than in case CO_2-emissions or costs would be minimised.

Finally, two hints are provided for further research. The first one is to further examine the threshold for the advantage usage of different modes. Namely, to assess where the transport distance exceeds that train or ship has more profitable compared with others. And, the other one is to optimise the allocation of biomass to bioenergy conversion facilities from the whole supply chain aspect in which other operations mentioned in literature research (e.g., collection, pre-processing and storage) are all involved. After all, the sustainable development of biomass for bioenergy supply chain should consider all actors involved rather than transport part, although transportation plays a significant role.

7 References

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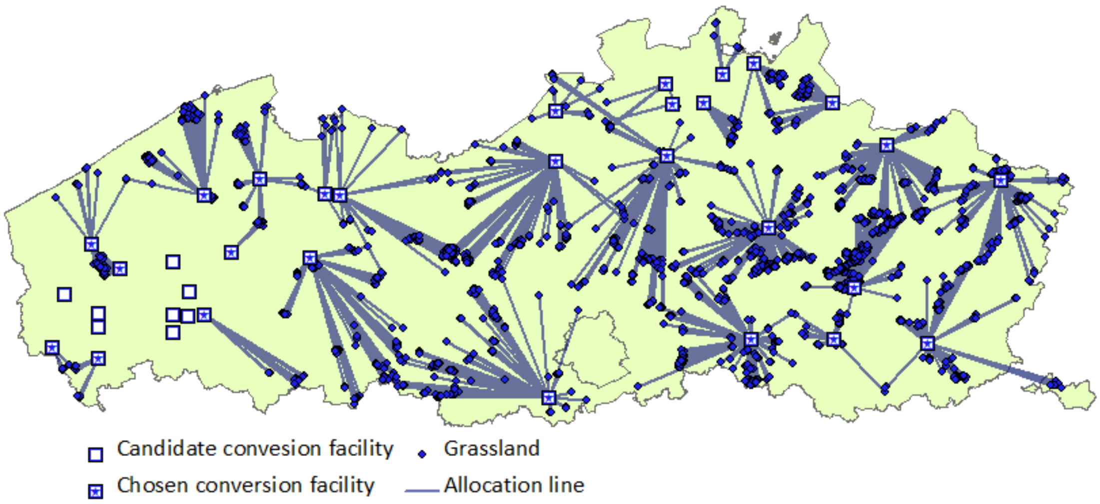
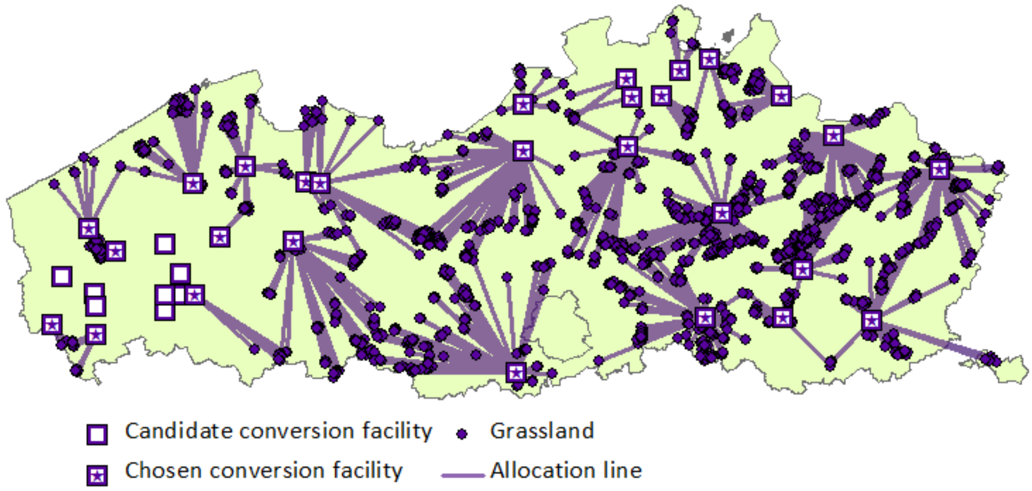
8 Appendix

8.1 *Transfer cost and transport distance*

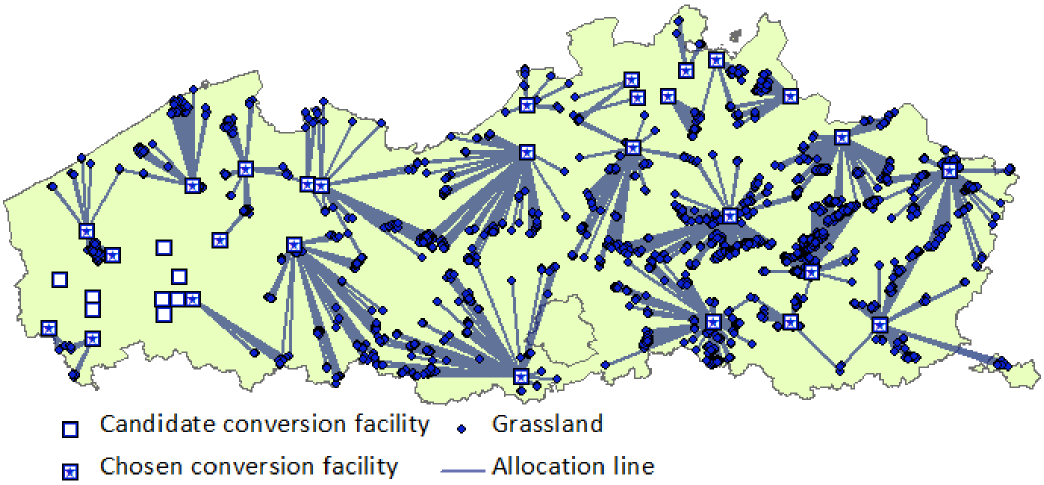
8.1.1 Scenario 1.1: allocation without transfer cost consideration



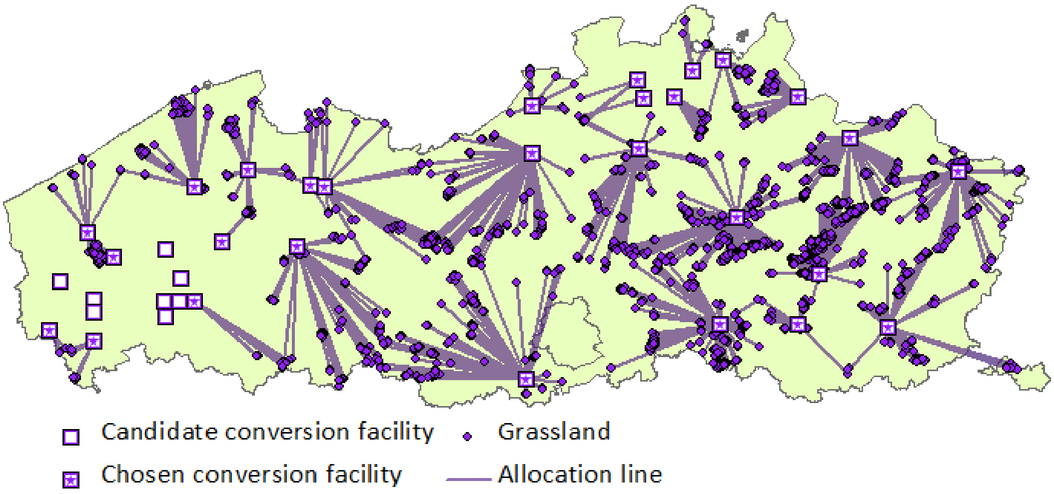
8.1.2 Scenario 1.2: allocation with transfer cost consideration



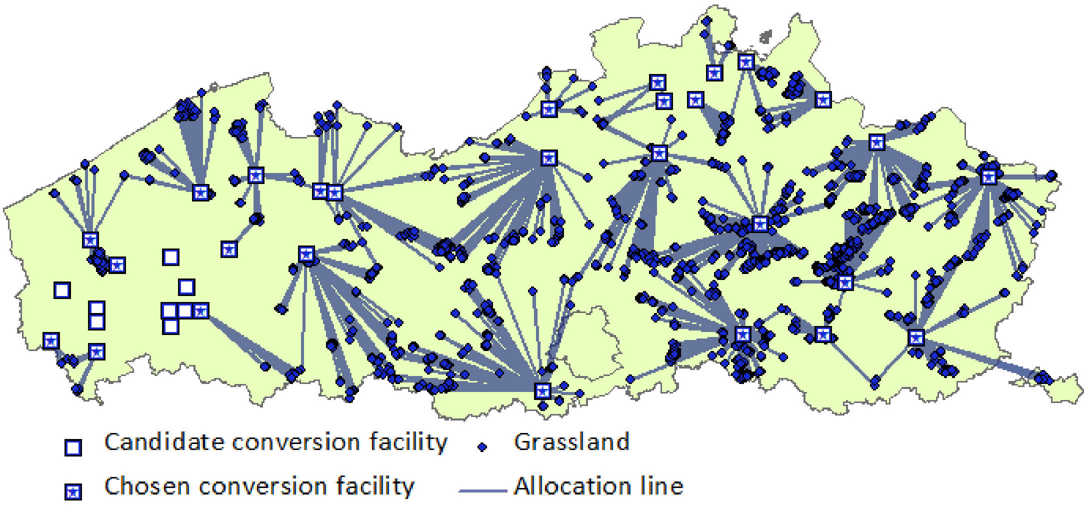
8.1.3 Scenario 1.3: allocation based on true distances multiplied by 2



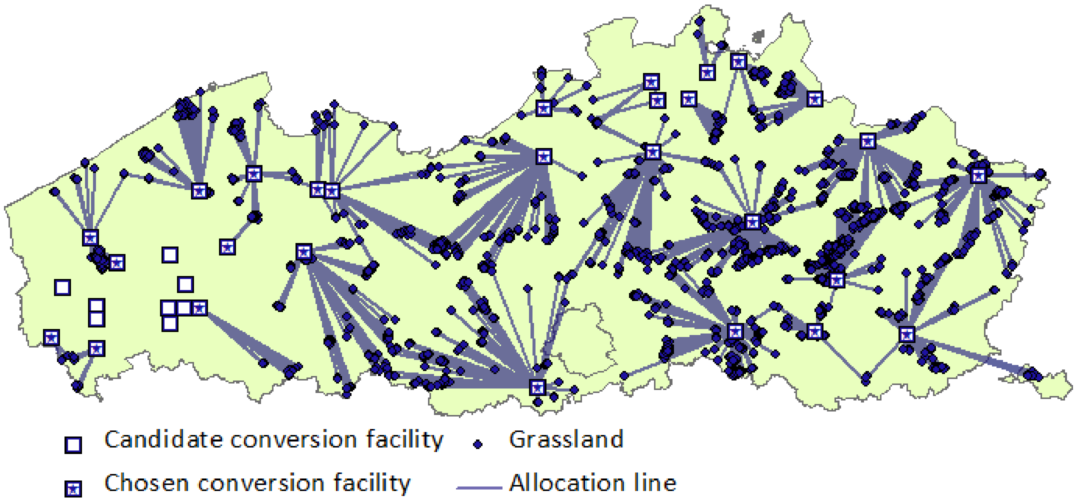
8.1.4 Scenario 1.4: allocation based on true distances multiplied by 3



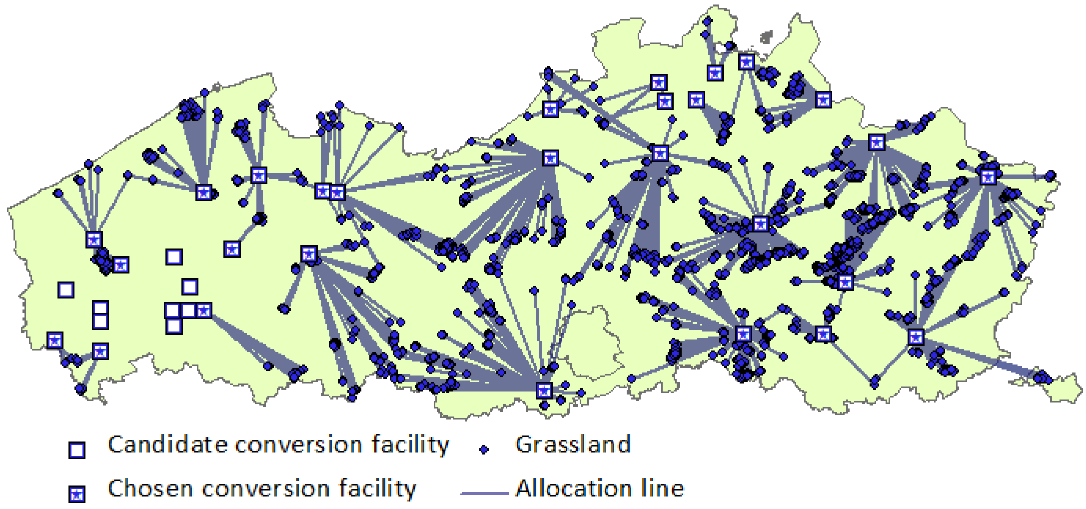
8.1.5 Scenario 1.5: allocation based on true distances multiplied by 5



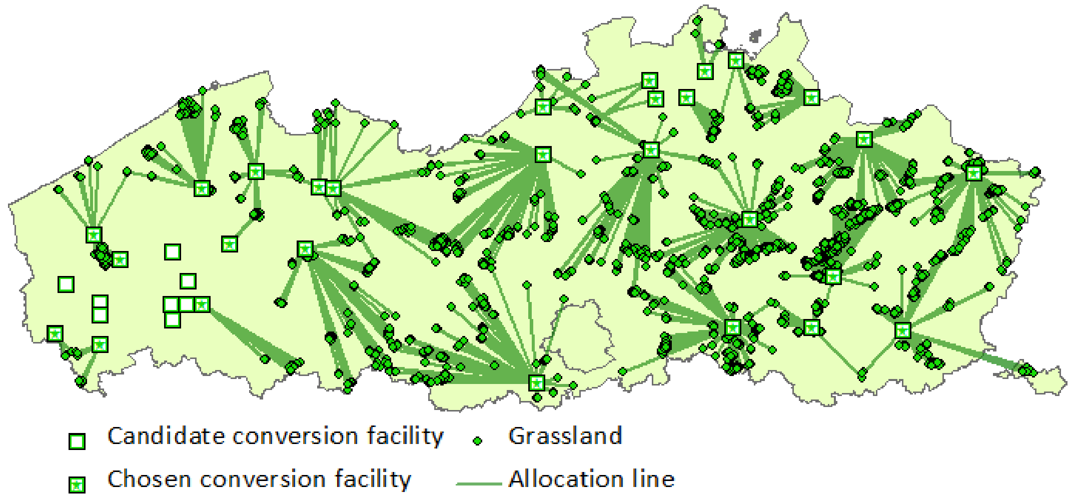
8.1.6 Scenario 1.6: allocation based on true distances multiplied by 7



8.1.7 Scenario 1.7: allocation based on true distances multiplied by 10

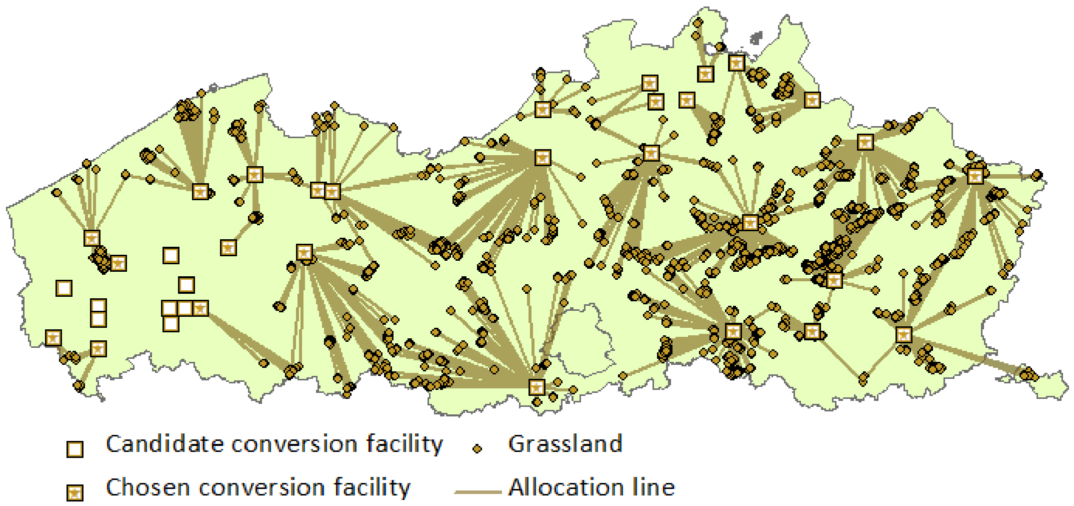


8.1.8 Scenario 1.8: allocation based on true distances multiplied by 20

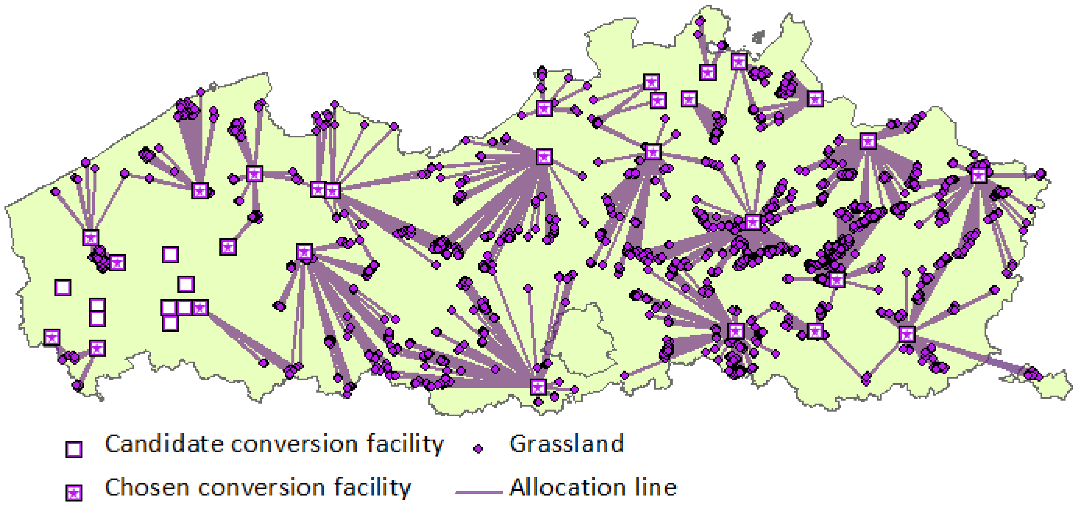


8.2 ***Modality***

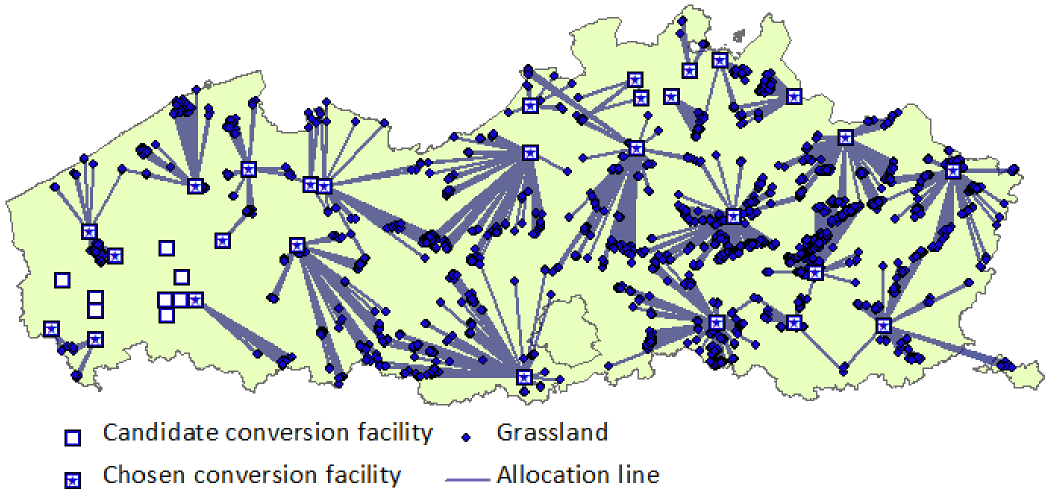
8.2.1 Scenario 2.1: allocation based on road network



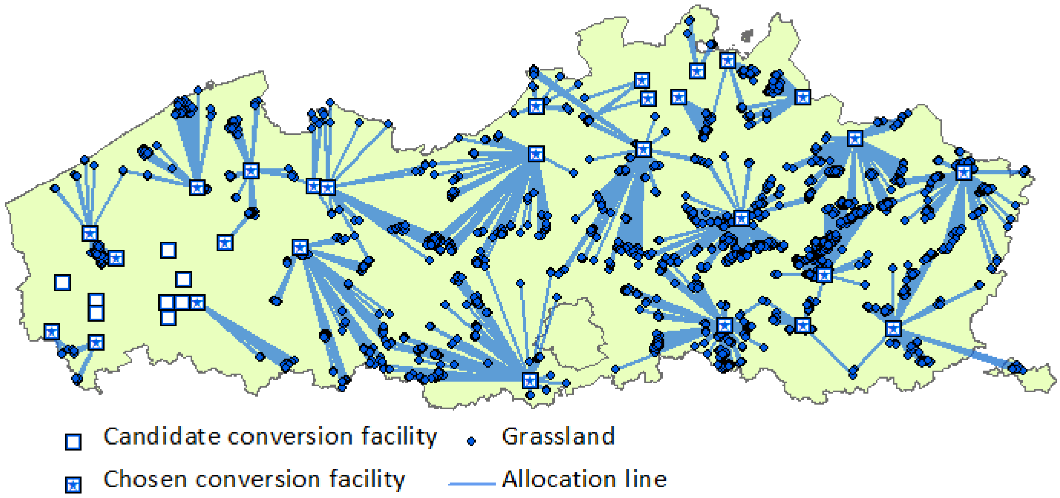
8.2.2 Scenario 2.9: allocation based on road + train networks



8.2.3 Scenario 2.17: allocation based on road + waterway networks

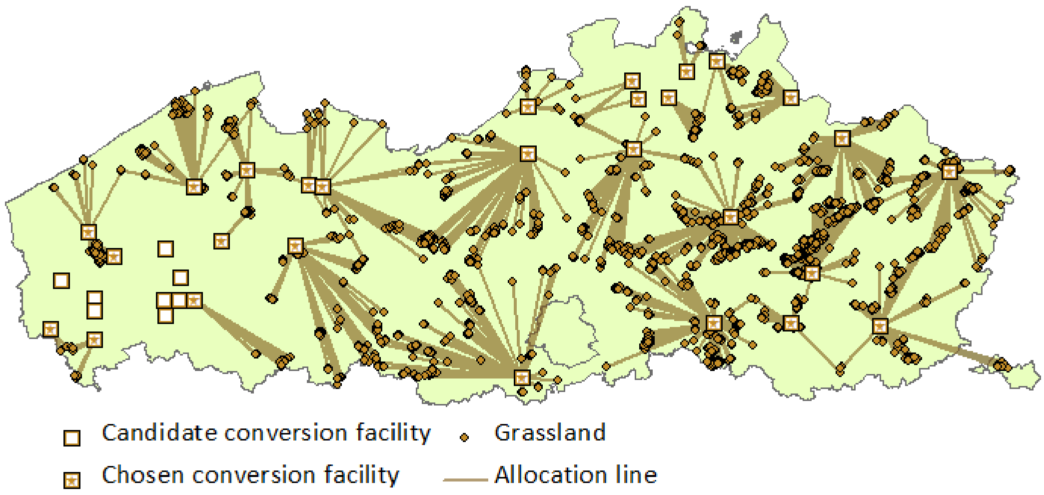


8.2.4 Scenario 2.25: allocation by road + railway + waterway networks

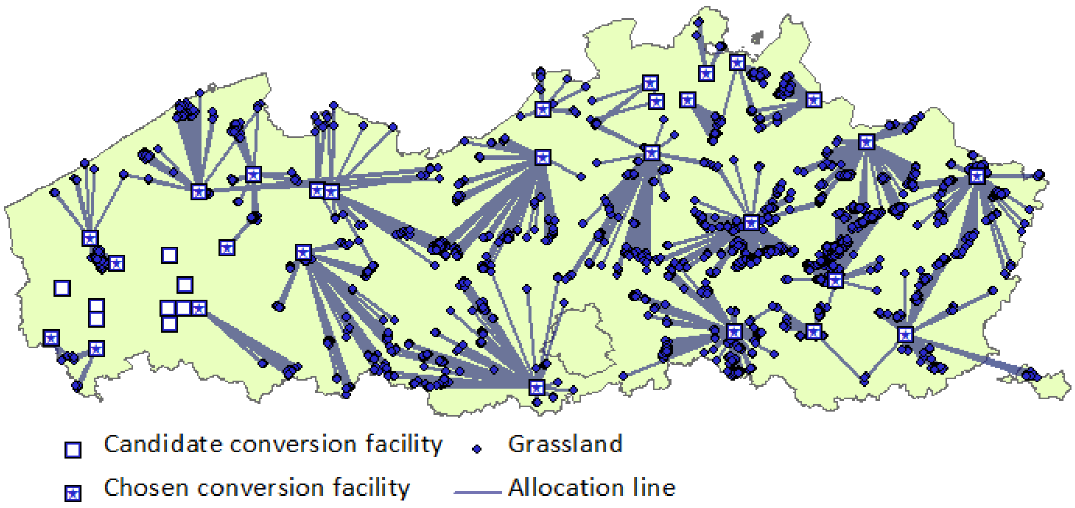


8.3 *Objectives*

8.3.1 Scenario 3.1: minimum CO_2-emissions



8.3.2 Scenario 3.2: minimum economic cost



8.3.3 Scenario 3.3: multiple criteria