Application of Agent-Based Modeling in Multi-Source Biomass Supply Chain Purchase Planning and Scheduling for a Power Plant

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ABSTRACT

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Sahar Esmaeilzadeh

Renewable energies play a pivotal role in social, political and environmental affairs of every country. Numerous reports state that among all the renewable options, biomass is one of the most sustainable alternatives. However, biomass-fired energy plants face several unintended potential consequences. The cost and risk burden on facility managers is an issue given the lack of historical data on life-cycle operation and maintenance of technologies.

With the advancement of computational capabilities, Agent-Based Modeling and Simulation (ABMS) is rapidly replacing conventional simulation techniques. Creating a successful simulation model can support the enhancement of logistical efficiency. The most common simulation technique used in biomass supply chain management is System Dynamics (SD). SD modeling in nature is highly abstract and therefore inadequate to consider the complete biomass supply chain structure and all related detail and information.

Agent-Based Modeling and Simulation (ABMS) can act as an add-on to complement SD simulation method. In this thesis, the fundamentals of ABMS are combined with SD simulation technique in order to overcome many limitations of current modeling and simulation practices. ABMS is a bottom-up modeling techniques where actors and participants of the system are given attributes and their behavior is encoded as a set of rules. Currently the applications of ABMS in biomass supply chain management is limited and few in numbers, however, this technique is gaining the interest of many specially in the field related to supply chain management.

A simulation model for the process of biomass purchase scheduling, planning and management for a power plant is developed. The model establishes a holistic approach in absence of knowledge of BSC system's behavior and provides a reusable base that facilitates modeling various scenarios and measuring their performance through simulation. To address the challenges, four different scenarios have been designed and implemented. First scenario analyzes the outputs of the system in case of an increase in the scale of the operation. In the second scenario, the acceptable biomass types have been limited to only woody and high quality types. In the third scenario, storage method has been improved and combined with hot air treatment method. As for the forth scenario, ambient storage method as the cheapest method with high deterioration rate has been investigated. The results of these scenarios have been reported and individually evaluated. By conducting a comparison analysis between these scenarios and the base scenario, their advantages and disadvantages have been assessed. The third scenarios is identified as the most favorable.

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LIST OF ABBREVIATIONS

AB	Agent Based
ABMS	Agent Based Modeling and Simulation
AI	Artificial Intelligent
AHP	Analytic Hierarchy Process
BPI	Biomass Performance Indicator
BSM	Biomass Scenario Model
BSCM	Biomass Supply Chain Management
CLD	Casual Loop Diagram
CSCMP	The Council of Supply Chain Management Professionals
EDI	Electronic Data Interchange
FTL	Full Truck Load
GIS	Geographic Information Systems
LCA	Life Cycle Assessment
MC	Moisture Content
MCDM	Multi Criteria Decision Making
MAUT	Multi-Attribute Utility Theory
SCM	Supply Chain Management
SD	System Dynamics

CHAPTER 1: INTRODUCTION

1.1 General Overview

Renewable energies play a pivotal role in social, political and environmental affairs of every country. Numerous reports states that among all the renewable options, biomass is one of the most sustainable alternatives [3]. However, biomass-fired energy plants face several unintended potential consequences. The cost and risk burden on facility managers is an issue given the lack of historical data on life-cycle operation and maintenance of technologies [1].

Essentially, simulation is an attempt to imitate real life or a hypothetical situation. Creating a successful simulation model can support the enhancement of logistical efficiency and it often leads to more realistic planning. The most common simulation technique used in biomass supply chain management is System Dynamics (SD). SD modeling in nature is highly abstract and therefore inadequate to consider the complete biomass supply chain structure and all related detail and information.

Agent-Based Modeling and Simulation (ABMS) can act as an add-on to complement SD simulation method. In this thesis, the fundamentals of ABMS is going to be combined with SD simulation technique in order to overcome many limitations of current modeling and simulation practices. ABMS is a bottom-up modeling techniques where actors and participants of the system are given attributes and their behavior is encoded as a set of rules. Currently the applications of ABMS in biomass supply chain management is limited and few in numbers, however, this technique is gaining the interest of many specially in the field related to supply chain management.

1.2 Problem Statement

The heterogeneous nature of biomass along with the complexities rising from seasonality and scattered geographical distribution of biomass sources turns biomass supply chain management into one of the most complex management problems. Dealing with these challenges requires an extensive and intelligent decision-making support tool. The vast majority of studies adopt system dynamics as their approach and because of the complexities, they end up over-simplifying the problem or limiting themselves to a fraction of the biomass supply chain for example the strategic level.

The increased complexity of this system dictates the need for developing an extensive and comprehensive tool. This is where ABMS comes into play as a modeling tool that can integrate analytic and heuristic decision processes. This research aims to create an application based on AB approach to manage the biomass supply chain planning and scheduling of a power plant given multiple biomass types and sources with seasonal characteristics.

1.3 Research Objectives

The main objective of this thesis is to model and simulate the process of biomass supply chain scheduling, planning and management using an ABMS approach to overcome limitations of current approaches and enhance current practices with a particular emphasis on:

1. Establishing a holistic approach in the absence of knowledge of BSC system's behavior. ABMS is considered a bottom-up approach, meaning behaviors are defined

in an individual level. This trait permits an important advantage: construction of models without knowing the global interdependencies. A comprehensive AB model can be developed by merely identifying all the participants and their behaviors.

2. Overcoming the low logistical efficiency as the key barrier in development and advancement of biomass-based energy production systems. ABMS provides a reusable base that enables rapid development of customized decision support tools and consequently facilitating modeling various scenarios and measuring their performance through simulation. This eases the ability of decision makers to quantitatively assess the risk and benefits and enhance the performance of the system.

1.5 Thesis Outline

This thesis is comprised of five chapters. Chapter 1 is a general introduction to the topic which includes the problem statement, research objectives and the thesis outline. Chapter 2 summarizes the literature review related to the current status and prospects of biomass resources overall and with a focus on modeling and simulation techniques in particular. In chapter 3 a step-by-step procedure is provided on how to develop an AB model for biomass supply chain scheduling and purchase planning. Chapter 4 represents the implementation of the proposed simulation model, Chapter 5 outlines the conclusions and contributions of this research work at-hand.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Overview

In this chapter current status and prospects of biomass resources along with the potentials and barriers of using biomass as energy source is investigated. Moreover, it aims to highlight the modeling and simulation techniques used in BSCM by inspecting their applications and identifying their limitations.

2.2 Biomass and Bioenergy

In the era we live, renewable energies play a pivotal role in social, political and environmental affairs of every country [2]. Among all the renewable options, biomass is one of the most sustainable alternatives for future [3]. From a social aspect, biomass has the potential to foster rural economic development [4] by creating jobs and income, it will benefit rural diversification and will boost regional development [5]. Furthermore, benefits of biomass rise from enhancing energy security [5]. Fossil fuels will inevitably reach their limits within the foreseeable future [2]. By reducing dependency on oil exporter countries the risks of this fragile energy supply can be averted [3]. Environmentally speaking, the energy sector is the highest contributor to human-related greenhouse gas emissions [6].

Renewable energies are considered an effective tool to achieve domestic GHG emissions reduction of 40% by 2030 and 80% by 2050 compare to 1990 levels [2]. Substituting fossil fuels with biomass can be beneficial to climate change mitigation [4]. In many studies it has been stated that using bioenergy products potentially has lower environmental impacts comparing to their petroleum counterparts [7]. Biomass sources, in their growing cycle, perform carbon by carbon fixation processes. This means they convert inorganic CO_2 to organic compounds [8], and it has the ability to be produced and consumed on a CO_2-neutral base [2]. However, some LCA studies suggest that biomass fuels are not always carbon-neutral as it was assumed before [9]. Researchers hypothesize that conversion of grasslands or woodlands into energy crop farm or forest monocultures might lead to a great amount of GHG emission [5]. Also, this can cause irreversible harms to the sensitive soil and lead to desertification in the long run [5]. In addition, emissions caused by handling and transportation of biomass rises some concerns too. An analysis done by Longo et al. (2015) [10] shows that the highest energy and environmental impacts are caused by the operation step. The importance of sustainable management and handling of biomass can be concluded form this result.

Biomass is a safe, secure, sustainable and affordable energy source [10]. In contrast to other renewable alternatives, biomass has three important advantages. Firstly, biomass offers an energy inventory which enables us to use it on-demand to generate energy also may be used for optimizing the power grid by providing peak load services [5]. Secondly, biomass is a versatile energy source, it can be used for electricity generation, heat production, also as fuel for transportation [11]. Thirdly, biomass is abundantly found in nature. Based on definition, any organic matter derived from plants or animals on a renewable basis is considered biomass [3], therefore, every product and by-product of agricultural activities such as energy crops, agricultural residues, manure and silvicultural origin such as wood and forestry residues. The issue with forestry source is inaccessibility of forests during months of the year that energy demand is quite high [6]. This definition also includes Industrial residues and municipal organic waste, though at present biomass from this origin plays a subordinate role in bioenergy production [5].

Canada's forest area is 347,069,000 hectares which comprises 37% of the world's certified forests [36]. Currently, nearly 85% of the Canada's wood pellets are exported to Europe rather than used in Canada. This is partly because Canada has abundant supplies of fossil fuels and diversifying the energy mix is not essential for Canada as much as EU [38]. However, forest-based bioenergy has become increasingly an attractive alternative of fossil fuels for Canada because of the environmental and economic needs [37]. Canada is one of 17 countries that participate in the research activities of International Energy Agency (IEA) Bioenergy, and more research is planned to be done in this field [37].

If we are looking at distributing alternative energy in Canada, biomass would be a proper answer for following reasons. First, Canada is abundant with various types of biomass sources. Second, adequate advancement of district heating systems in Canada. The history of district heating systems in Canada goes back to 19th century and it is growing progressively [14]. Biomass energy generating technologies are easily integratable with the infrastructure of existing hydro and district heating systems [7].

The contribution of forest biomass to Canada's energy supply was 3 to 4% in the 1970s, this number has been increased to 5–6% in 2018 [37]. A rapid expansion of bioenergy industry is expected in the coming decades. The need to integrated methodological approaches which will enable us to link different decision levels, including strategic, tactical and operational levels, and overcome the complexities of biomass supply chain is evident.

The accomplishment of this task we allow us to lower the costs, reduce the environmental impacts per functional unit and gain more social benefits [7].

2.4 Challenges Ahead

Biomass supply chain has several distinctive characteristics that distinguish it from a typical supply chain [11]. Designing a cost-effective and time sensitive supply chain system which can ensure steady delivery of high-quality products is the main challenge for bioenergy industry [7]. Unlike petroleum, biomass sources are geographically scattered [5]. These sources are seasonally available and there are uncertainties in the amount of supply [6, 11]. Additionally, biomass raw materials are heterogeneous and have unpredictable quality [6]. Biomass of each source has a specific set of properties which vary significantly from one source to the other [7]. Properties such as shape, size, density, moisture content and energy density differs. Method of storage and handling also affects these properties [6]. These properties are also affected by seasonality [7]. These characteristics create a volatile and risk vulnerable supply chain [6] and contribute to the complexity of biomass supply logistics [4].

Biomass raw material has low density and also a low heating value which is partially caused by high moisture content. These characteristics create an increased need for transportation and handling equipment as well as storage space [11]. Storing a large amount of biomass over a lengthy period of time adds significantly to the costs [4], and choosing a cheap storage method leads to notable material loss and further reduction of the quality [11].

There are concerns that usage of starch-based and edible feedstocks as biomass may lead to implications on food supply and price. By using cellulosic biomass adverse impacts on food supply can be avoided [7]. Further, competing land use between biomass production for food, material, and energy arises some challenges most seriously in developing countries [5].

2.4.1 Transportation

The location of biomass harvest and collection is usually different than the bio-power plant location, so transport efforts are required [5]. Biomass network and transportation simulation manages schedules, latencies, capacities and loading/unloading/processing times [12]. The logistic system of biomass could include large number of equipment pieces and different transportation methods [6]. Transportation takes a much larger piece in biomass supply chain cost pie [7]. It is reported by [6] that transportation cost can account for 50% of the total delivery cost in some cases. Also, report [11] concludes that 20-50% of biomass delivery cost is due to transportation and handling activities.

Transport emissions are directly related to transport distances and to the mode of transportation. Studies show that biomass traded over a long distance would still be beneficial to the environment if modern transport modes are used [5]. For example, Forsberg (2000) [32] in his research validates the transportation of biomass from Scandinavia to Holland. Thornley (2008) [33] states that lorry transports' contribution to nitrogen oxides and particulate emissions is much less in comparison to in-field harvesting and transportation operations.

Low energy density and high water content contributes to make biomass cost-prohibitive and unstable for long distance transport from an operational point of view [7]. Because of the low transportation density, both weight and volume capacity limits should be considered in transportation vehicles [7], although due to low density of all biomass types the volume capacity of the vehicle will be the ultimate limitation [11].

Transportation activities also entails social impacts. The frequent traffic of trucks may easily provoke resistance of citizens and affected communities [5]. Social issues have high impact on investment decisions and the land use for this purpose [3].

2.4.2 Storage

Reasons such as frequently scattered geographical distribution of biomass and short harvest season induce the necessity of having a buffer capacity to ensure continual and reliable supply of feedstock for bioenergy plants [2, 5].

There are various methods for storage of biomass resources. Storage costs mainly depend on the location and method of storage as well as the volume of biomass to be stored and duration of storage [5]. To determine the volume of biomass to be stored, Rentizelas et al. (2009) [11] assumes a 20-day full load operation of the energy plant as safety inventory and the size of the storage space required is determined by the maximum yearly biomass inventory level. Main risks of storing biomass are (1) biomass quality degradation and (2) dry matter losses. Biomass with a reduced quality can lead to a mass without yield [5]. Severity of dry matter loss depends on the number of storage steps and the storage duration [5]. Usually a linear monthly rate of material loss, varied by storage technology used, is assumed [7].

The type of biomass feedstock also influences the severity of these effects (for example, pellets have insignificant dry matter loss) [5]. To determine the appropriate mode of storage, the tradeoff between storage costs and material loss should be analyzed [7]. As the cheapest method, ambient storage leads to significant cost reduction at the storage and handling stage. However, primarily because of presence of high water content, biomass degradation, heating value reduction, and potential health risks are the side effects of this method [7]. Closed storage methods can be used to improve quality of biomass if combined with treatment methods like hot air drying capabilities [7] even by using exhaust heat from the facility [5]. Biomass inventory location can be on-field or next to the biomass power plant or in an intermediate place between these two [11]. In most cases of the relevant research work, the cheapest storage solution is chosen neglecting the positive effects of a more sophisticated storage method [11].

2.4.3 Treatment Methods

Treatment processes can be done at the biomass production site, a mediator location, or at the site of bioenergy plant. Treatments are done generally for the purpose of creating a product with higher density and efficiency and reducing deterioration rates. It can be mere mechanical manipulations such as crushing, bundling or grinding or hold more sophisticated mechanisms such as ensiling, drying, palletization, torrefaction, and pyrolysis [5].

The effects of biomass drying during storage is significant when biomass has high moisture content (usually 40-50%). It prevents problems such as quality degradation, material loss, fire danger and formation of microbes dangerous to human health [11].

Baling is a primary technology for forest residues and energy crops. Baling increases biomass density, hence, facilitates handling and transportation, additionally reduces the risks of deterioration [5]. Chipped biomass can directly be used in bioenergy plants or it can be turned into pellets for easier transportation and storage purposes. Palletization provides a higher quality product; the only drawback is its higher costs [5].

2.5 Biomass Logistics and Supply Chain Management

Mentzer et al. (2001) [34] defined the supply chain as "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer". Julka et al. (2002) [13] names three common features of entities: They are 1) Dynamic, 2) Distributed, and 3) Disparate.

The Council of Supply Chain Management Professionals (CSCMP) defines logistics management as "that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements." [27]. The logistics of biomass has an important role in bioenergy supply chain efficiency making allowance for integration of time-sensitive feedstock collection, storage, and delivery operations into efficient and reliable supply systems that deliver consistently high-quality biomass [7]. In Gold & Seuring (2011) [5] logistics is identified as a critical constraining factor of bioenergy supply chain.

The research topics in logistics and supply chain management have been traditionally associated with inventory management, forecasting, transportation and network optimization [3]. Research community has shown more interest towards strategic decisions in biomass supply chain compared with tactical and operational decisions [2]. It is still not clearly answered that which decisions should be made on the strategic, tactical and operational levels for developing waste biomass supply chain networks [2]. However, in the literature, strategic level decisions usually include the design of supply chains such as location, technology and capacity, and tactical and operational level includes decisions related to the flow of material and production planning [6]. Yue et al. (2014) [7] classifies strategic and operational levels according to the temporal continuation of their influences. Based on this classification, strategic decision level includes optimization of the selection of biomass suppliers, the location of conversion facilities, assignment of customer serving areas, and transportation links that connect different sites and deliver the biomass/biofuel across the supply chain network. The operational level includes three levels:

1) Optimization of planning (such as the development of robust forecasting model, multi-year strategy for capacity expansion and process retrofit, multi-period targets for purchase, sales and production, etc.),

2) Optimization of scheduling (includes the efficient and timely allocation of equipment units, raw materials, and human labors to fulfill the external and internal orders), and,

3) Optimization of control (involves real-time monitoring and adjustment of process parameters to meet the required quantity and quality of the products).

Design of overall biomass supply coordinates several main operations including harvesting and collection, storage, transport, and pre-treatment techniques [5]. Management of these operations becomes a critical issue because of the complex and uncertain environment of the problem [4, 3]. The complexity of biomass supply chain involves different players and products that are affected by biomass characteristics making bioenergy generation costlier than the conventional energy sources [6]. Systematically designing and optimizing the entire bioenergy supply chains, from strategic to operational levels in a cost-effective, robust and sustainable way is a significant challenge in research. By overcoming this challenge, the transition towards large-scale use of bioenergy will be accelerated [7].

A typical biomass supply chain for energy production comprises of these general system components and discrete processes [11, 2]:

1) Biomass harvesting and collection (from single or several locations),

2) Pre-treatment (a tactical level decision [2]),

3) Storage (in one or more intermediate locations),

4) In-field transport,

5) Road transport and

6) Energy conversion

Gold et al. (2011) [5] subdivides the issues of creating such model into two sections: (1) supply chain architecture and (2) tools for enhancing supply chain functioning. Swaminathan et al. (1998) [15] proposes a framework for the development of supply chain models. They categorize issues into three classes:

1) Configuration: deals with issues related to supply chain structure considering factors like lead time, transportation cost, and currency fluctuations.

2) Coordination: involves routine activities like materials flow, distribution, inventory control, and information exchange.

3) Contracts: deals with strategic affairs such as supplier reliability, number of suppliers, quantity discounts, demand forecast mechanisms, and flexibility to change commitments.

Some researchers have divided biomass supply chain into two separate goals; first analysis the system for sustainable products (it takes the design of products into account), and the second one analysis for sustainable operations. This approach constitutes challenges in the way of integration of different levels of the supply chain [3]. It is necessary to identify the entities and flows in order to make supply chain decisions and manage all critical relationships both upstream and downstream in their supply chains [13]. This calls for modeling them to understand the supply chain, as well as monitoring and managing the overall performance [13]. Bioenergy modeling analytical needs were identified by Fontes & Freires (2018) [3]:

1. The need for holistic model,
2. The need to understand the value of coordinated decisions
3. The need to support technology investment decisions
4. The need to assess the impacts of incentives.

Iakovou et al. (2010) [2] states that the complexity of multi-level supply system of biomass determines the need of a comprehensive supply chain management approach. Gold et al. (2011) [5] states the necessity of taking the whole system into account and comprehending all the components such as biomass resources, supply systems, conversion technologies, and energy services. Yue et al. (2014) [7] confirms the need for this comprehensive model that considers all the components across the entire biomass supply chain and allows us to effectively integrate the long-term strategic decisions with short-term operational ones. Fontes & Freires (2018) [3] affirms that integration of different processes and levels into one model can improve the biomass supply chain performance.

2.5.1 Multi Biomass Approach

Providing energy and hot water to buildings via a centralized district energy system has several advantages over decentralized ones [14]: they have (1) higher energy and performance efficiencies as a result of implementing advanced equipment and a professional maintenance, (2) lower lifecycle costs, (3) improved augmented control over environmental impacts.

Existing a clear rule of "economy of scales" in bioenergy industry is not automatically true. Having a larger bioenergy plant requires higher amount of biomass to satisfy the related demands and the increased costs of logistics and transportation of low density biomass feedstock to the point of processing can offset the benefits [7].

However, in Gold & Seuring (2011) [5] economy of scale is named as the main incentive for aiming for a large-scale biomass energy plant. However, since transportation costs of biomass account for a significant portion of the biofuel supply chain, bioenergy plants may not necessarily benefit from the economy of scale [7]. The scale of the optimum processing plant is directly affected by the available biomass feedstock per unit area surrounding the plant and consequently the transportation costs [5].

Biomass supply chain has a complex and uncertain environment [3, 11]. One of the reasons for this uncertain environment is that biomass supply is affected by weather conditions, insect populations, plant diseases, and farmers planting decisions [4]. Using multi-biomass approach might be effective to decrease these uncertainties.

Most biomass-to-bioenergy research works consider a single type of biomass as their source. Limiting the feed supply to one feedstock with a seasonal availability induces the need of storing large amounts of biomass for a significant time period, which leads to added inventory costs [2]. A multi-biomass approach can significantly ease these problems [11]. Iakovou et al (2010) [2] suggest the development of a multi-biomass system, aiming at reducing the storage space requirements. Rentizelas et al. (2009) [11] reveals the cost reduction potential of the multi-biomass approach in by achieving a 15–20% cost reduction by using two biomass sources. Iakovou et al (2010) [2] in their study express that to minimize the share of capital costs, widening the operational window of biomass logistics by combining multiple-biomass chains is required. A major reason for the limited amount of research done on multi-biomass approach is the rising complexities of logistics when a variety of biomass streams are involved. There are issues that require more detailed study such as organizational aspects, variations in availability, storage and backup fuel [11]. Furthermore, Iakovou et al (2010) [2] acknowledges the need for developing more sophisticated supply chain planning and coordination methodologies as opposed to the well-explored traditional ones.

Maintaining a profitable and ecologically sustainable biomass system requires an elaborate selection of types and quantity of biomass to purchase and a well-thought geographical mapping of the suppliers and procession sites [5].

2.6 Background and Methods of Modeling in Bioenergy SC

2.6.1 Advantages and Benefits of Modeling

Meadows (1980) [35] says: "A model is simply an ordered set of assumptions about a complex system. It is an attempt to understand some aspect of the infinitely varied world". Modeling and optimization tools can play an important role in optimizing the supply chain network by identifying cost-effective and sustainable pathways, hence, helping us to bypass experimental trials [7]. Two critical barriers in the way of further utilization of bioenergy industry are the costs and complexity of its logistics operations [2, 5]. As illustrated in Figure 1, bioenergy production is a complex system with many components in several segments namely biomass resources (wood, agricultural and energy crops, by-products, wastes [5], supply systems (different harvesting methods, transportation requirements and operation and handling needs, such as chipping, storing and loading), conversion technologies (through thermochemical (combustion, gasification, pyrolysis and liquefaction), bio-chemical and

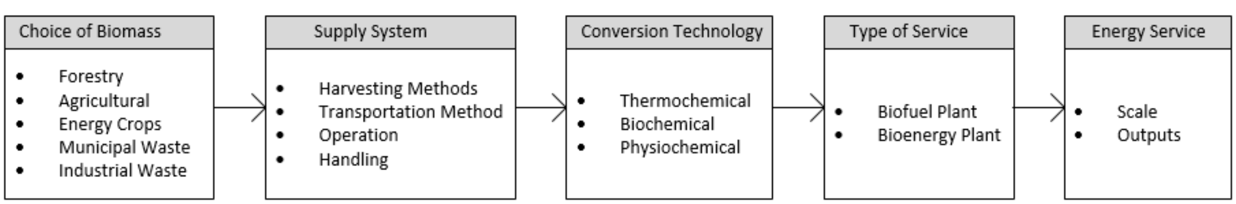


Figure 1 - Biomass Supply Chain adopted from Shabani et al. (2013) [6]

physicochemical processes [2]), and energy services (manifold in size). These components can be merged in many unique combinations which makes direct comparisons between different bioenergy systems difficult. It is possible to secure and expand biomass supply by innovative management technics and strategies [5]. Improving the supply chain performance by using analytical tools is the key to overcome the main barriers to the development of bioenergy industry [3]. Through simulations we can assess effects of different alternatives (such as adding new sources, choosing among candidate suppliers, facility locations, technology options, transport modes, etc.) over the potential of industry growth under environmental, economic and social conditions [3].

Yue et al. (2014) [7] suggests these characteristics for a holistic optimization model for biofuel supply chain: multi-scale, multi-perspective, and multi-criterion. Because of several uncertainties and complexities both micro and macro prospective of biofuel supply chain should be incorporated in decision-making tools. Regarding to this uncertainties, Iakovou et al (2010) [2] points out the unresolved challenge of designing a supply chain management model adoptable to the local and inter-regional conditions such as the existing infrastructure, geographical allocation of collection areas, the current regulatory and techno-economic environment, and competition among consumers. Regarding to the mentioned key barriers, non-technical issues rather than technical issues create a bottleneck for bioenergy industry. Enhancement of logistical efficiency is expected through new software systems and analytical tools [5].

2.6.2 Mathematical Modeling and Simulation

Mathematical models, in particular multi-objective optimization techniques, can be adopted in order to achieve the optimum design based on the objective functions and manage the supply chain [6]. Since there is a tradeoff between economic, environmental and social performances of the supply chain as well as the risks associated with design and operation, a multi-objective technique is required to deal with this conflict of interests [7]. These models are effective especially when the entire components of the supply chain in different segments such as biomass resources, supply systems, conversion technologies and energy services, and different levels of decision, such as strategic, tactical and operational, are integrated [6].

Optimization techniques have a vast range of applications including bioenergy industries. However, mainly, economic objectives were considered in these models [6]. For example, Freppaz et al. (2004) [43] used a mixed integer programming method to maximize annual profit (revenues from sale of energy minus costs such as harvesting, transportation, installation and maintenance, and energy distribution). As the limitation of this research work, the environmental impacts of using forest biomass and biomass growth dynamics have not been taken into account. Rentizelas et al. (2009) [44] focuses on optimizing a bioenergy supply chain and conversion facility with the ultimate target of satisfying the energy demand in the most financially efficient manner. In this research work, in order to overcome the limitations of the implemented non-linear optimization method and to find a global optimum of the problem, they have used a two-step algorithm. In the first step, an optimization method defines a good solution to the problem. In the second step, to further enhance the solution, the solution is used as the starting point of another optimization method. Incapability of the model to incorporate the effects of uncertainty is named as a limitation for this model.

Yue et al. (2014) [7] states that interpreting various activities, even across multiple sectors, into equations in the constraints or objective functions might seem appealing and easy, however, formulating a comprehensive and detailed model might be computationally intractable. Their solution for this problem is to take advantage of the properties of the supply chain system (e.g., network structure, spatial scale) and to drop off components with negligible influences on the optimization objectives. Another critical drawback of mathematical modeling is that although optimization of the supply chain using this method might be possible, yet they cannot capture the dynamic aspects of bioenergy systems [4].

2.6.3 LCA Approach

Life-Cycle Assessment is the most used method for analyzing renewable energies and it is considered as the most comprehensive approach to conduct and environmental impact assessment [3]. The official and ISO-definition of LCA is: the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [41].

LCA represents an important methodology for a complete assessment of the impacts of a product, however, it has been traditionally separated from economic analysis. For this reason, the influence and relevance of LCA for decision making are limited [40]. Current methods of GHGs accounting and water footprinting, highly simplify LCA and are considered insufficient to understand the dynamic interrelationships between the environmental and ecological impacts as well as their implications for resource consumptions 39]; complementary methods are required in order to deal with the limitation [3].

2.6.4 Multi-Criteria Approach

It is evident that aside from economic aspects of implementing a bioenergy plant, environmental and social impacts of different alternatives should be considered too. The need to incorporate different factors and viewpoints of various actors promotes the use of multi-criteria decision making (MCDM) methods [14]. According to Ghafghazi et al. (2010) [14], the prerequisites of conducting a MCDM method are:

1) Defining the problem clearly,

2) Identifying all the realistic alternatives,

3) Defining the actors involved in the decision making,

4) Selecting the evaluating criteria,

5) Evaluating each alternative, and,

6) Selecting a MCDM method.

Multi-Attribute Utility Theory (MAUT), Analytic Hierarchy Process (AHP), PROMETHEE and ELECTRE are the most commonly used MCDM methods in the area of renewable energy planning [24, 14].

2.7 Simulation Models in Bioenergy SC

2.7.1 System Dynamics Approach

Traditional methods based on operation research models cannot deal with some problems related to the multi-level complex interactions involving economic, environmental and social elements, along with analytical components such as performance and cost assessing aspects. To build an adequate supply chain model three elements are required:

people, observation and systems-knowledge [3]. Dynamic behavior is intrinsic in complex social and multidisciplinary systems such as bioenergy production [17] and using simulation-based approaches are recommended in order to obtain an enhanced understanding of the bioenergy supply system [3].

Attentions have been drown to SD approach due to the growing interest in the holistic perspective of the biofuel supply chain [3]. SD modeling is developed by an electrical engineer Jay W. Forrester in the 1950s and has been used for strategic energy planning and policy analysis since 1970s [3]. His work integrates concepts of feedback control theory and digital computation. Mathematically, it is a system of differential equations [12] and permits disequilibrium modeling [16]. Forrester describes it as "the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise". These models should be simulated over a long enough time period so that transient behavior can be played out. This time period usually is either five times the longest time delay or four times the sum of time constants around the dominant loop [16]. To stablish a SD model, it is necessary to define the system boundary. Forrester describes the system boundary as hypothetical line that encloses the system and no influences from outside of this line are necessary for generating the particular behavior being investigated.

SD is a powerful method which takes time factor into account of analyzing relations between components of a complex system [3]. It can demonstrate the behavior of a system with complex relations using feedback loops, and delays [4] and by elucidating variations, multiple players and interdependencies among different systems and processes, this simulation method can improve management of industry processes whose behavior is essentially dynamic. Materials, information and finance flows can be managed and coordinated. Through sensitivity and “what-if” analyses SD applications allow us to evaluate the impacts of various scenarios [3].

However, this approach can only enable us with a macro prospective over the system [4]. The items aggregated in a same stock are indistinguishable, they do not have individuality, and this leads to a high level of abstraction [12]. Several complex relationships between variables from different environments as well as feedback loops and delays cause a high level of complexity in macro problems [4].

Most researchers have applied system dynamics in the specific topics such as market behavior, future market shares, bio economy, energy policies and CO_2 emissions [3]. For example, Nasiri et al. [45] uses a SD model to perform what-if scenarios and sensitivity analysis in order to investigate different choices of biomass boiler technology. They identify the optimal energy generation capacities and schedules for biomass and backup boilers, including optimal levels of biomass ordering and storage under a renewable heat incentive scheme in the UK. Their research shows that even with the availability of incentives, there would be no motivation to go for a better performing biomass boiler technology or a more efficient biomass fuel option.

SD and its applications have been classified into three classes: Biomass Scenario Model (BSM), Scenario Analysis Process, and Hybrid Modelling [3]. The Biomass Scenario Model was designed to extensively evaluate biomass-to-biofuel supply chain, identifying the points of leverage and providing theatrical insights to support biofuel industry’s growth. The outcomes of this approach have demonstrated the need for substantial policy intervention and the importance of coordinating investment, land use expansion and incentive management [3]. It was initially designed to accelerate deployment of biofuels in the U.S and was focused on distribution logistics, dispensing stations, fuel use and, vehicle modules, however, due to the complexities of the system and limitations related to the input data, its application has been limited to a fraction of supply chain. Comprehensive implementation of this approach is conditioned to a greater comprehension and understanding of the system. The Scenario Analysis Process is an effective method for expanding the knowledge and understanding of the system behavior by analyzing different scenarios in a variety of contexts, yet, it does not have forecasting capabilities and it requires another tool to complement the simulation methods [3]. The Hybrid Modelling Framework consolidates multiple tools to assess complex system problems.

2.7.2 Agent-based Approach

Because of the increasing complexities in supply chain management problems and its distributed nature, necessity of using AI have become evident [13]. Electronic Data Interchange (EDI) and Distributed Databases are recognized as important technological advancements that possibly will boost supply chain performance [15]. Borshchev & Filippov (2004) [12] notes that within the last few decades, while generally no new ideas have been added to the traditional simulation methods such as System Dynamics, the software engineering world has made a huge progress in approaching the complexity of systems. Agent-Based approaches have been preferred with an aim to create an extensive intelligent decision-making tool to address the shortcomings [13]. Since supply chain management is fundamentally concerned with coherence among multiple decision makers, a multi-agent based approach is a natural choice [15]. Existing System Dynamics models can be remodeled using Agent-Based approach. This would facilitate further enhancements to capture much more complicated behavior, dependencies and interactions, hence, providing us with a deeper insight of the system [12].

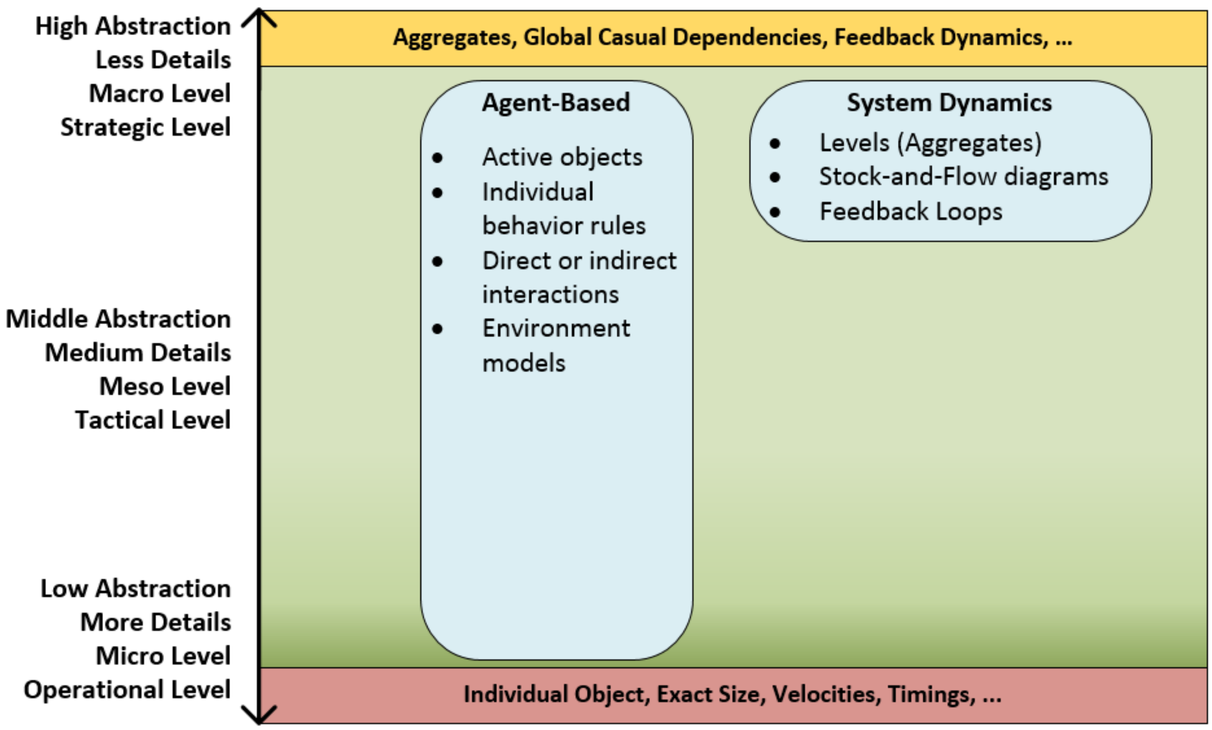


Figure 2 - Simulation Methods on Abstraction Level Scale. Adopted from Fontes & Freires (2018) [3]

In order to model a sustainable bioenergy production, a holistic approach with inherent capabilities to reveal interrelationships and interactions is required [17]. Contradictory to System Dynamics, defining a global system behavior is not required in Agent-Based approach. This method is considered a bottom-up approach, meaning behaviors are defined in an individual level. This trait permits an important advantage: construction of models in the absence of the knowledge about the global interdependencies. Merely knowing the individual behavior of the system components is sufficient. How thing affect each other and the global behavior of the system will be revealed after the construction of the Agent-

Based model. This also leads to an easier model refinement processes as normally only local changes are required [12].

Another advantage of this approach is that it provides a reusable base of domain-specific primitives that enables rapid development of customized decision support tools. This means that it requires much less effort (few hours instead of few months) to model various scenarios and measure their performance through simulation. This eases the ability of decision makers to quantitatively assess the risk and benefits. Furthermore, using agents makes it possible to integrate analytic and heuristic decision procedures and incorporate supply, process, and demand uncertainty. Multi-agent approach is a framework capable of combining of analytical and simulation models and it is befitting to study both the static and dynamic aspects of problems [15].

Julka et al. (2002) [13] identifies necessary features for a modern day supply chain decision support system and presents an Agent-Based framework based on them. These features are as the following:

1. Knowledge encapsulation (knowledge includes material and information flow details, information on the structure of various entities, their working, and their relations with other entities organized in a manner that aids addition, deletion, modification and easy access),
2. Intelligent inference (for efficient query handling),
3. Connectivity (capable of being constantly updated with the latest information),
4. Flexibility (responsive to not only 'what is', 'how much' and 'when' queries but also 'what-if' scenarios),

5. Collaboration and scalability (to avoid a large number of changes in case two different systems need to be merged).

In Agent-Based approach, behaviors of the agents are specified using state charts proposed by David Harel [12]. Fontes & Freires (2018) [3] comments that Agent-Based modeling is a useful add-on to the older approaches and not a substitution.

2.7.3 Hybrid Models

Sustainable development is a complex and multidimensional phenomenon and cannot be completely managed by current tools, specifically for problems that require a micro and macro analysis of the system behavior. The need to integrate methodological approaches is evident [3]. The increasing demand for an integrative and holistic framework have caused modelers to look at Agent-Based and combined approaches to get deeper insight into complex systems [12].

Hybrid modeling is an effective approach to prevail over the weaknesses and limitations generated by disjointed bottom-up and top-down modelling. Agent-Based modeling as a bottom-up and inductive approach and System Dynamics as a top-down and deductive approach are the most appropriate approaches that can be combined by the support of cyber-infrastructure to explore the various “what if” scenarios [3].

CHAPTER 3: METHODOLOGY

3.1 Chapter Overview

The need for a comprehensive and holistic model is identified in the previous chapter as a requirement to address the problems of BSCM. In this chapter a framework is proposed to create a simulation model for BSCM.

As the first step, the scope of the work and the boundaries of the model have been defined. Afterwards, participants of the AB model and their associated attributes have been proposed. Based on this recognition, a corresponding database design have been laid out. Furthermore, the Environment in which the agents interact is defined,

3.2 ABMS for BSCM

ABMS is a bottom-up modeling approach. Model elements are built before the process is studied as whole. As it is illustrated in Figure 3, prior to implementation of the simulation model the following six-step procedure has been carried out:

1) Defining the Scope of the Model: The boundary and objective of the model is delineated. All the participants and players which significantly or insignificantly contribute to the operation been identified,
2) Determining Participants and Their Characteristics: Characteristics and attributes of the participants have been established,
3) Database Design: A database structure has been designed to contain the identified characteristics,
4) Environment: The environment in which the system operates has been settled,

5) BSC Process Identification: The overall process and the mechanism in which the participants interact has been outlined in detail,

6) Modeling Platform Determination: The most suitable tool for this particular simulation problem has been determined.

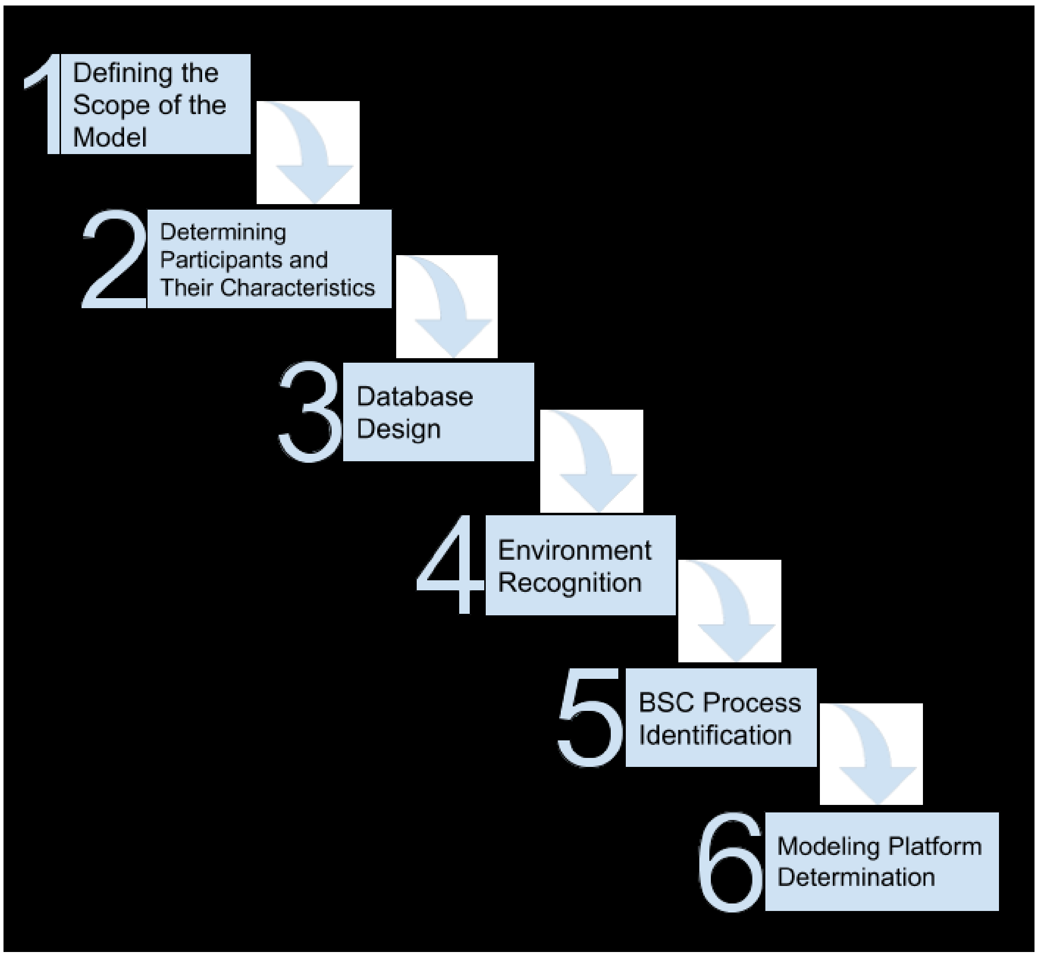


Figure 3 – The Implemented Procedure for Creating BSCM Simulation Model

3.2.1 Scope of the Model

The AB model in this research work is aimed to incorporate the heterogeneous nature of the biomass (density, moisture content, etc.) along with seasonality and the scattered geographical distribution of biomass sources into the logistics management of a biomass-fired power plant. The logistic operations and processes include scoring, ranking, selection, transportation, treatment, storage and consumption of biomass. Creation of a reusable foundation is intended in order to assist the heuristic approach of exploring different scenarios.

Beneficial to achieving realistic behaviors and results within the defined scope, a list of players and elements are selected to be included in the model. The following selection is based on the literature review conducted in chapter 2 and the objective of this research work:

1. The bioenergy power plant: The energy conversion center which has a monthly biomass intake and daily biomass usage.
2. Supplier: They represent the geographical dispersion of biomass resources and produce a specific type of biomass with a seasonal rate.
3. Variety of biomass types: Defines different types of biomass with energy content as well as physical and environmental attributes in detail.
4. Transportation method: Is characterized by the maximum load capacity, price and emission rates.
5. In-transit biomass: When a biomass load is purchased can go through different phases before reaching the inventory.
6. Inventory: The size and the method of storage is on dispute. It effects the cost rate and material quality and degradation.
7. Treatment plants: They are accessible in defined locations and perform treatment operations on the biomass with a price rate.
8. Demand: Is a pattern based on the service size of the power plant and the atmospheric conditions of the location.

9. Purchase plan: Is required as a percussion for high demand months and to consider the inaccessibility of the roads in harsh conditions of winter months.

3.2.2 Participants and Their Characteristics

Based on the scope of the model, a list of participants and their properties is arranged. The surrounding factors are taken into consideration to the best possible ability. In Table 1, each participant is presented together with a set of characteristics that define their behavior in the model.

Table 1 – Major Participants of a BSCM System and Their Attributes

PARTICIPANT	PROPERTIES
The Bioenergy Power Plant	Energy Production Capacity (kWh), Demand (kWh), Satisfied Demand (kWh), Purchase Plan (kWh), Satisfied Purchase Plan (kWh), Max Acceptable Moisture Content (%)
Supplier	Name, Longitude, Latitude, Production Rate (kg/month), Weather Effects (%/month), Biomass Type, Moisture Content (%), Min Trade (kg), Transportation Method
Biomass Type	Name, LHV (kWh/kg), Carbon (%), Lowest Density (kg/m^3), Highest Density (kg/m^3), Base Price ($/100kg), Deterioration Rate (%/month)
Transportation Method	Transportation Cost ($/km), max Weight FTL (kg), max Volume FTL (m^3), Carbon Emission (kg/km)
In-Transit Biomass	Origin Supplier, Initial Batch Amount (kg), Current Amount (kg), Batch Moisture Content (%), Batch LHV (kWh/kg), Batch Density (kg/m^3), Deterioration Rate (%/month)

Inventory	Storage Method Related Deterioration Rate (%/month), Occupied Storage Space (m^3), Max Occupied Storage Space (m^3), Storage Cost Rate ($/$m^3$/month), Cumulative Storage Cost ($),
Treatment Plant	Name, Longitude, Latitude, Treatment Cost ($/kg)
Demand Pattern	Month, Demand (kWh)
Purchase Plan	Month, Purchase Plan (kWh)
Weather Effects	Month, Weather Effect (%)

3.2.3 Database Design

The next step of developing the ABMS is to design a relational database and gather required data. A relational database is a collection of organized and interrelated data in the form of tables and relations. As it is shown in the Figure 4, the gathered data is divided into subject-based tables and primary keys which uniquely identifies every records of the table are specified. Crow's Foot notions have been used to define the relationships between the tables; different shapes at the ends of the lines represent the cardinality of the relationship.

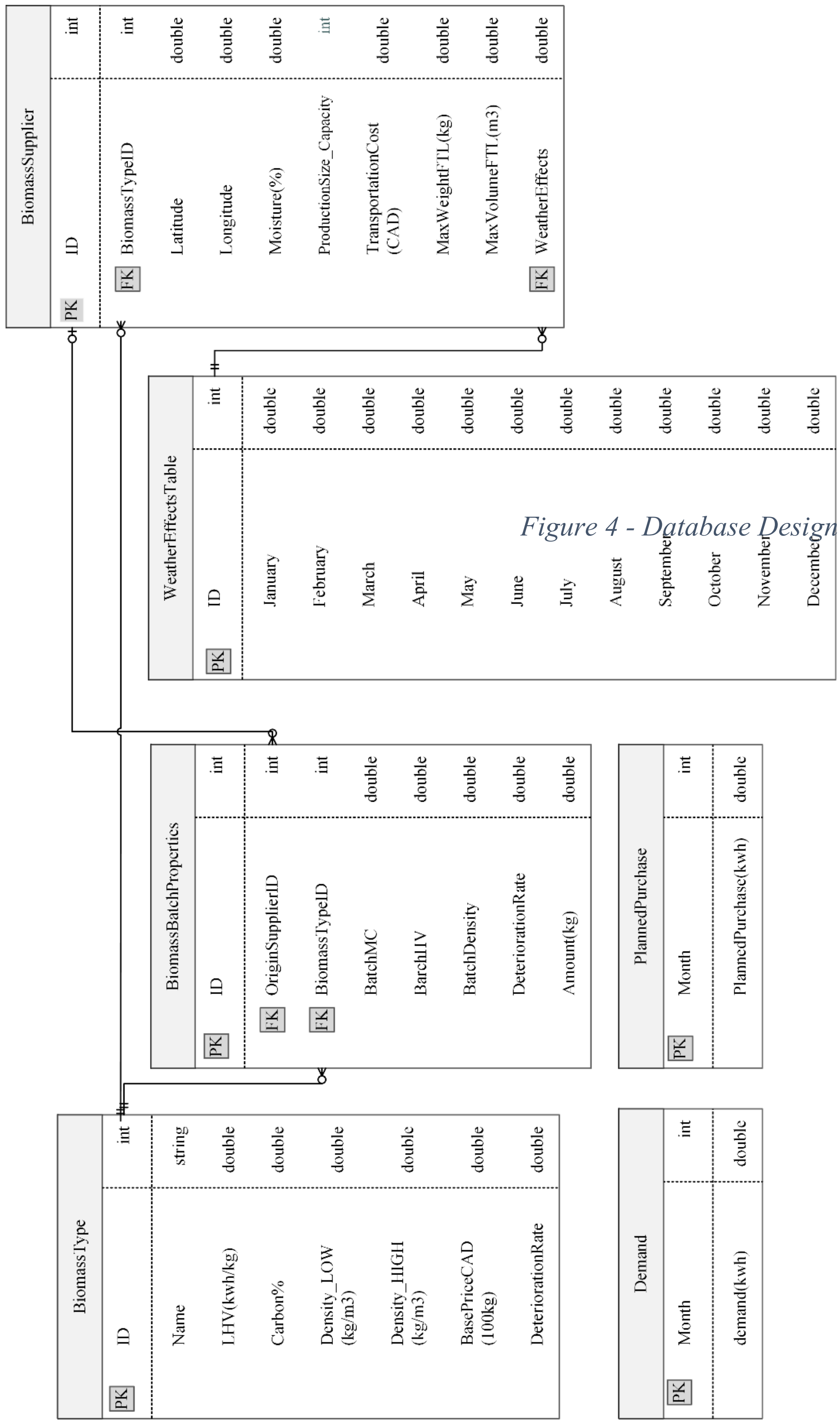


Figure 4 - Database Design for the proposed model

3.2.4 Environment

Agents live and interact in a platform that in AB terms is called an environment. A realistic and sufficiently detailed view of the environment is necessary to understand and anticipate effects of this environment on the model in general and on agents in particular.

To address the geographical dispersion nature of biomass resources, Geographic Information Systems (GIS) is chosen as the environment for the BSCM simulation model. GIS is a system in a form of a map with multiple layers which is designed to capture, store, analyze, manage, and present all types of geographical data. GIS can be employed to visualize the spatial configuration of biomass resources, treatment plants and storage spaces. Geographical distances can be precisely measured between any two agents living in a GIS environment and therefore identifying the shortest route between them.

3.2.5 BSC Process Identification

At this step of the model creation, now that the participants are identified and their characteristics are determined and their environment is recognized, the operations of the system can be investigated.

As it is mentioned in the problem statement, the focus of this thesis and the simulation model is to facilitate the planning and scheduling aspect of the biomass supply chain management. In the simulation model, suppliers' biomass production is formulated through a monthly production rate which seasonally changes. At the start of every month, the available biomass sources will be listed and ranked regarding to their economic costs such as purchase, transportation, treatment and storage (storage cost is calculated for a period of one month) and environmental costs such as transportation and combustion emissions. Based on Clarke & Preto (2011) [31], the energy content of most dry biomass fuels fall in the narrow range of 7,300–8,000 BTU/lb. Hence, in this model, the benefits and values of different types of biomass has not been taken into consideration for the ranking purpose.

Purchase requests will be sent to the top ranked suppliers until the purchase has reached to this month's planned amount and will be transported and stored in the inventory. Meanwhile based on the energy demand of the day, batches of biomass will be transferred to the furnace and will be consumed. State of the system including costs, emissions and inventory levels should be available at every point of simulation. This goes on until the designated simulation period ends.

3.2.6 Modeling Platform Determination

The first object-oriented programming language ever developed is named SIMULA 67 [28] and as its name suggests it was designed for creating simulation models. Currently, common object-oriented languages such as Java, C# and C++ are used for doing simulation.

To avoid writing many lines of code, there are simulation modeling tools that provide built-in libraries to facilitate modeling for users. These tools differ from each other in various criteria such as coding aspects, visual aspects, flexibility in representing agents, executing actions, efficiency, input/output capabilities, and analysis capabilities [29].

AnyLogic 8.2.3 [30] is selected as the simulation development tool. In consideration, AnyLogic is a Java-based software that can combine multiple paradigms including SD and AB. With the help of additional Java code, highly customized and flexible models could be developed using this software.

CHAPTER 4: IMPLEMENTATION

4.1 Chapter Overview

This chapter presents the implemented simulation model and describes its components. Main class is the top-level agent of the model which integrates all model other agents and manages the interaction between them. Major simulation actions are performed in this agent class.

All the agents along with their building components are explained in this chapter. At the end a numerical experiment has been conducted to demonstrate the performance of the developed model.

4.2 Database Tables and Input Data

AnyLogic software has built-in integrated database to read input data and write simulation output. The input data is imported into the model from excel. Composition of the database tables are shown in Figure 5. Using this database allows the model to read parameter values and configure models and also create parameterized agent populations. Flowchart activities, events, state chart transitions, message passing are saved in model execution logs.

Result of the simulation is highly correspondent to the input of the model. The input data should be adequately detailed to capture all influential properties of the participants. Through a comprehensive literature review at chapter 2 participants of a BSCM system and their properties have been identified.

Ministry of Agriculture, Food and Rural Affairs of Ontario [31] provides a detailed information on the properties of common biomass fuels in Ontario. Geographical mapping details of biomass suppliers, effects of the season on their production rate and the exact properties of the biomass that they are producing are unavailable. The lack of such data compels this simulation model to be an exploratory model with certain assumptions about the above mentioned information. However, a series of scenario analysis will be conducted to test the impact of some of the key assumptions. All data sets and the associated assumptions are provided in Appendix A.

Composition of the imported database tables and the execution logs are presented in Figure 5. Details and organization of these database tables are demonstrated in Table 2.

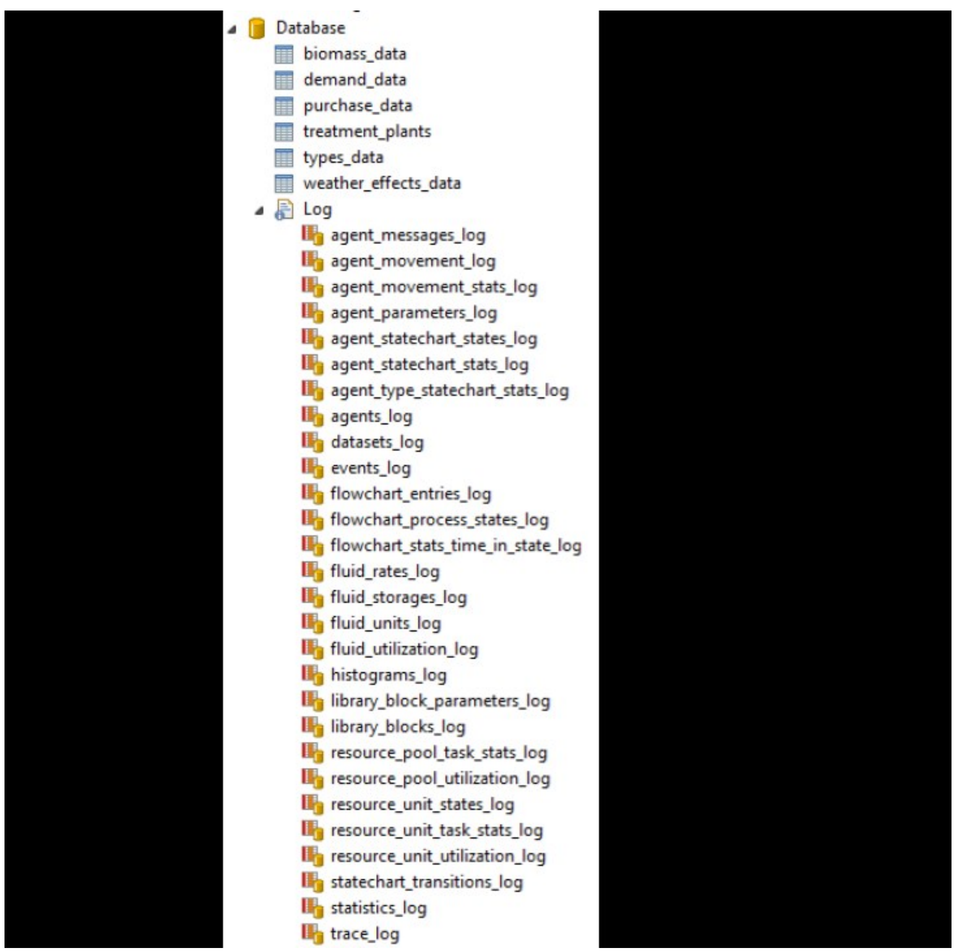


Figure 5 - Composition of the Database

Table 2 - Organization of the database

Table	Columns	Description
biomass_data	id	A unique id number for each supplier.
	name	Name of the supply center.
	lat	Latitude of the location.
	lon	Longitude of the location.
	mc	Moisture content of the product.
	size	Scale of the production: demonstrated by numbers 1, 2 or 3.
	type	Foreign key id from types_data table.
demand_data	month	One of 12 months of the year.
	Demand_kwh	Predicted demand of biomass in kWh by the biomass power plant.
purchase_data	month	One of 12 months of the year.
	planned_purchase	To compensate the delays and road blockage in winter, purchases are planned to be done one to three months ahead.
treatment_plants	name	Name of the treatment facility.
	lat	Latitude of the location.
	lon	Longitude of the location.
types_data	name	Name of the biomass type.
	kwh_per_kg	Energy content of the biomass.

	ash	Ash percentage.
	carbon	Carbon percentage.
	density_low_kg_m3	The lowest recorded density.
	density_high_kg_m3	The highest recorded density.
	base_price_cad_100kg	Common price for per 100kg.
	deterioration_rate	Deterioration percentage per month
weather_effects_data	id_type	Foreign key id from biomass_type table.
	month1 . . . month12	A percentage speculation the effects of weather conditions on the production rate for each month.

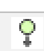
4.3 Main Class

Main class is the top-level agent of the model. It is the first Class that is constructed, its parameters are set up, and its functions are called. It is the integration point of all the model components. The GIS map is set up inside the main class. This Class creates the population of agents and manages the interactions between them as well as the environment. Furthermore, producing final results and performing analysis are also the main class's duties.

Major elements used in the BSCM simulation model are presented in Table 3.

Table 3 - AnyLogic Elements Used in the Model

Symbol	Element
Agent Elements	

	Agent
	Parameter
	Variable
	Collection
	Excel Connectivity Tools
	Function
	Event
	Connector
	Link to Agent
	State Chart Entry Point
	State
	Transition
	Branch
	Final State
System Dynamics Elements	
	Stock
	Flow
	Link
Action Chart Elements	
	Action Chart Start Point
	Code
	Decision
	Local Variable

	While Loop
	Do While Loop
	Return
Animations	
	Bio power plant
	Supplier
	Biomass Treatment Center
	Truck

4.3.1 GIS Environment

As it shown in Figure 6, the GIS environment for this model is zoomed to Canada. It enables the model to display and manage maps in a model. Bio-power plant agent, suppliers and treatment plants will be set up in their defined longitude and latitude points on the map. This map uses AnyLogic server as the routing server. Truck agents will take the shortest routes in the network. The cumulative number of times that biomass has been purchased from a certain supplier will be shown on top of the supplier animation (it is shown by <text> in the Figure 6).

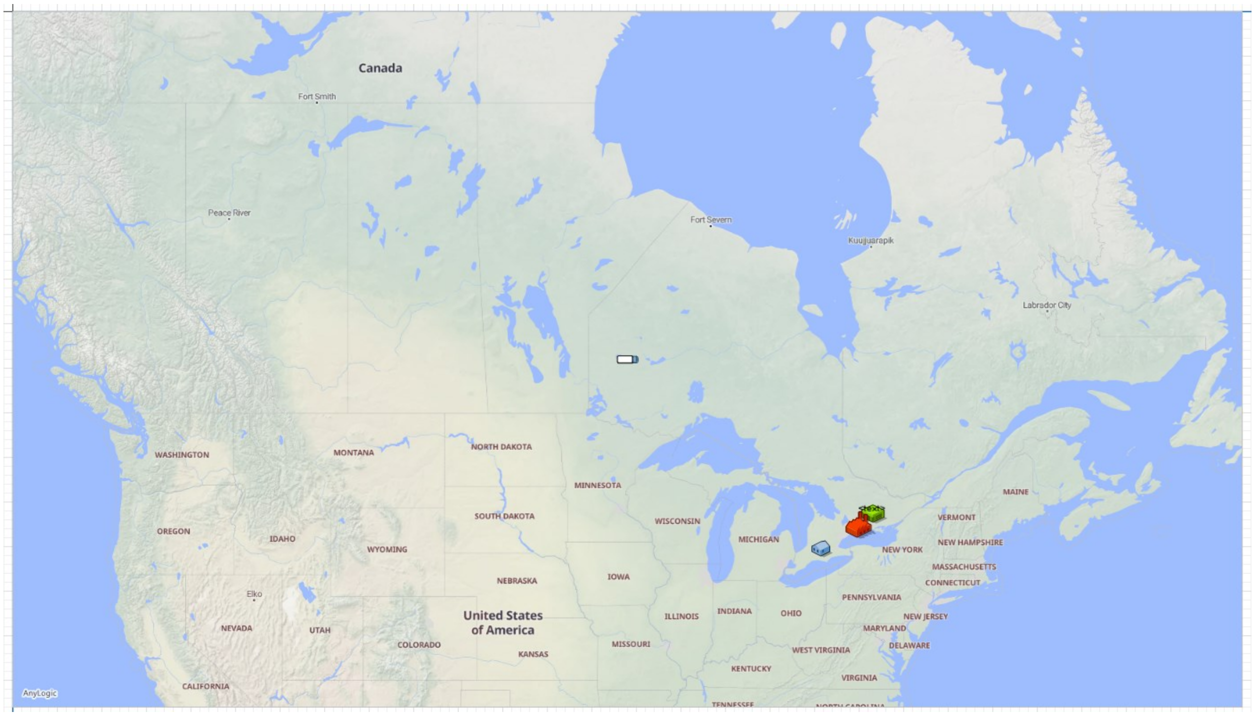


Figure 6 - GIS Environment

4.3.2 Agents, Parameters and Variables

Main class includes several agents, parameters, and variables. These elements are listed and descripted in Table 4. Certain agent populations are created in the main class and they live and interact in its environment. Additionally, global parameters are defined in the main class by reasons of giving them a unified value and allowing other agents to access them easily. Variables are used to contain characteristics of the objects that are changing over time or to store the results of model simulation.

Table 4 - List of Agents, Parameters and Variables of the Main Class

Element	Description
biopowerPlant	Represents the single agent located in Quebec.

suppliers	Represents the group of suppliers. Agents' parameters are set up from suppliers_data table.
treatmentPlants	Represents the group of treatment plants. Agents' parameters are set up from treatment_plants table.
biomassBatch	Represents the purchased load of biomass. This type of agent will be populated during the simulation as purchase requests are sent.
maxAcceptableMC	Maximum acceptable level of MC. Biomass with a lower MC does not require treatment.
TruckEmissionRate	Carbon emission rate of a full truck per kilometer.
storageEmissionRate	Storage related carbon emissions per month.
minSellGolobal	Minimum amount of biomass purchase in kg.
transportation CostPerMeter	Transportation cost per meter.
TreatmentCostPerKg	Treatment cost per kg.
cumulativeBiomass TransportationCost	Cumulative biomass transportation cost.
cumulativeBiomass PurchaseCost	Cumulative biomass purchase cost.
cumulative TreatmentCost	Cumulative treatment cost.
exceptionNot EnoughBiomass	"Not enough biomass available" exception error (text message).

4.3.4 Events, Functions and Action Charts

The Events used in the main class are depicted in Table 5. In the BSCM simulation model a lot of actions happen in a cyclic manner (monthly or daily). To schedule an action at some particular moment of time, Event element is used. When an Event is triggered, a function or action chart is called. Functions that conduct calculations of economic and environmental scoring, ranking of suppliers, selecting and delivering purchase requests and fulfilling the daily demand are triggered using these Event elements.

Table 5 - Main Class Events

Event	Action
triggerRanking	At the start of every month calls rankingChart() action chart.
triggerDailyUsage	At the Start of every day calls setDailyUsage() action chart.
triggerSelection	Start of every month calls selectionChart() action chart.
triggerEcoEnvScoring	At the start of every month calls: 1. standardScoreEconomical() function, 2. standardScoreEnvironmental() function,

Functions return the value of an expression each time the user calls it from the model. Functions are helpful when the same function will be used in multiple occasions in the model. A list of the functions active in the main class is presented in Table 6. These functions are in charge of calculating standardized scores for each supplier based on their economical and environmental performances.

Table 6 - Main Class Functions

Function	Function Body
standardScore Economical	Calculates a standardized score for each supplier based on their economical performance.

	``int N = suppliers.size(); double ecoCost_Ave = 0; double ecoCost_Dev = 0; for (Supplier s: suppliers) ecoCost_Ave += s.economicalCost/N; for (Supplier s: suppliers) ecoCost_Dev += pow((s.economicalCost - ecoCost_Ave),2)/ (N-1); ecoCost_Dev = sqrt(ecoCost_Dev); for (Supplier s: suppliers) s.ecoCost_STANDARD = (s.economicalCost - ecoCost_Ave)/ecoCost_Dev;```
standardScore Environmental	Calculates a standardized score for each supplier based on their environmental performance. ```int N = suppliers.size(); double envCost_Ave = 0; double envCost_Dev = 0; for (Supplier s: suppliers) envCost_Ave += s.environmentalCost/N; for (Supplier s: suppliers) envCost_Dev += pow((s.environmentalCost - envCost_Ave),2)/ (N-1); envCost_Dev = sqrt(envCost_Dev); for (Supplier s: suppliers) s.envCost_STANDARD = (s.environmentalCost - envCost_Ave)/envCost_Dev;```

Action Charts visually defines a function. They are structured block charts allowing defining algorithms graphically in the style of structured programming. They express algorithms using sequencing, selection, and iteration and perform data processing or calculations. There are three action charts present in the main class and their description is as follows:

Action Chart 1: rankingChart

This action chart is triggered by ⚡ triggerRanking event. When it is called it sorts the biomass suppliers based on their Biomass Performance Indicator (BPI). This action chart is shown in Figure 7 and described in detail in Appendix B, Table 30. This action chart basically iterates between the suppliers and sorts them based on their score; the higher the score, the lower the rank.

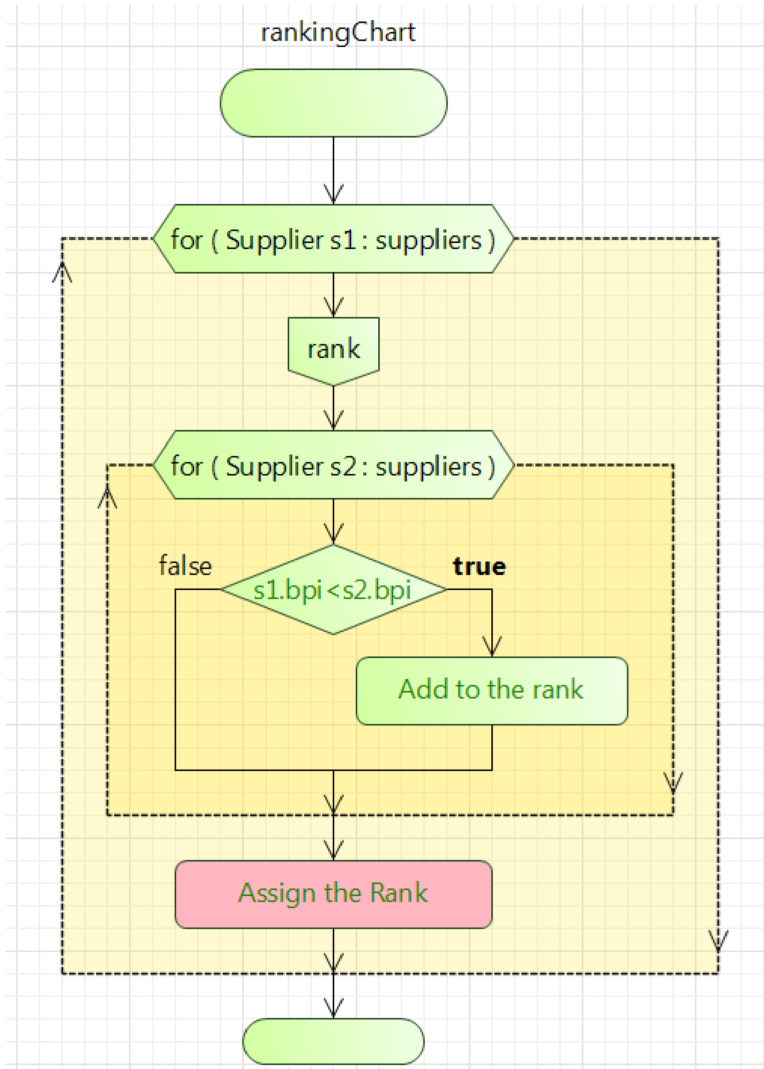


Figure 7 - rankingChart Diagram

Action Chart 2: selectionChart

This action chart is shown in Figure 8 and described in detail in Appendix B, Table 31. selectionChart is activated by triggerSelection event and it follows these steps:

1. A local variable named desiredRank with the initial value of 1 is created.
2. By using a For-loop, the supplier with a rank equal to the desiredRank is selected.
3. A local variable named purchaseStep is created with the initial value equal to the minSellGlobal parameter.
4. At this point, the chart checks the selected supplier's inventory to see if it has equal or more than purchaseStep amount.
5. If the condition is true, selectionChart sends a purchase request to the suppliers. It also determines the number of trucks needed depending on the maximum weight or volume of a full truck load (FTL). It adds the overall transportation cost, price of the purchased biomass and if required, treatment costs respectively to cumulativeBiomassTransportationCost, cumulativeBiomassPurchaseCost, and cumulativeTreatmentCost variables. The total energy content of the purchased biomass is also added to the satisfiedPurchase variable.
6. If the condition is false, the chart moves on to the next top ranked supplier until the satisfiedPurchase is equal or greater than plannedPurchase.
7. If ahead of satisfying the purchase plan, desiredRank variable's value reaches to the total number of the suppliers, it means that a cycle of iteration has been completed and the available suppliers are not able to satisfy the planned purchase. At this point the action chart adds an exception error text to exceptionNotEnoughBiomass specifying the amount of shortage and the month.

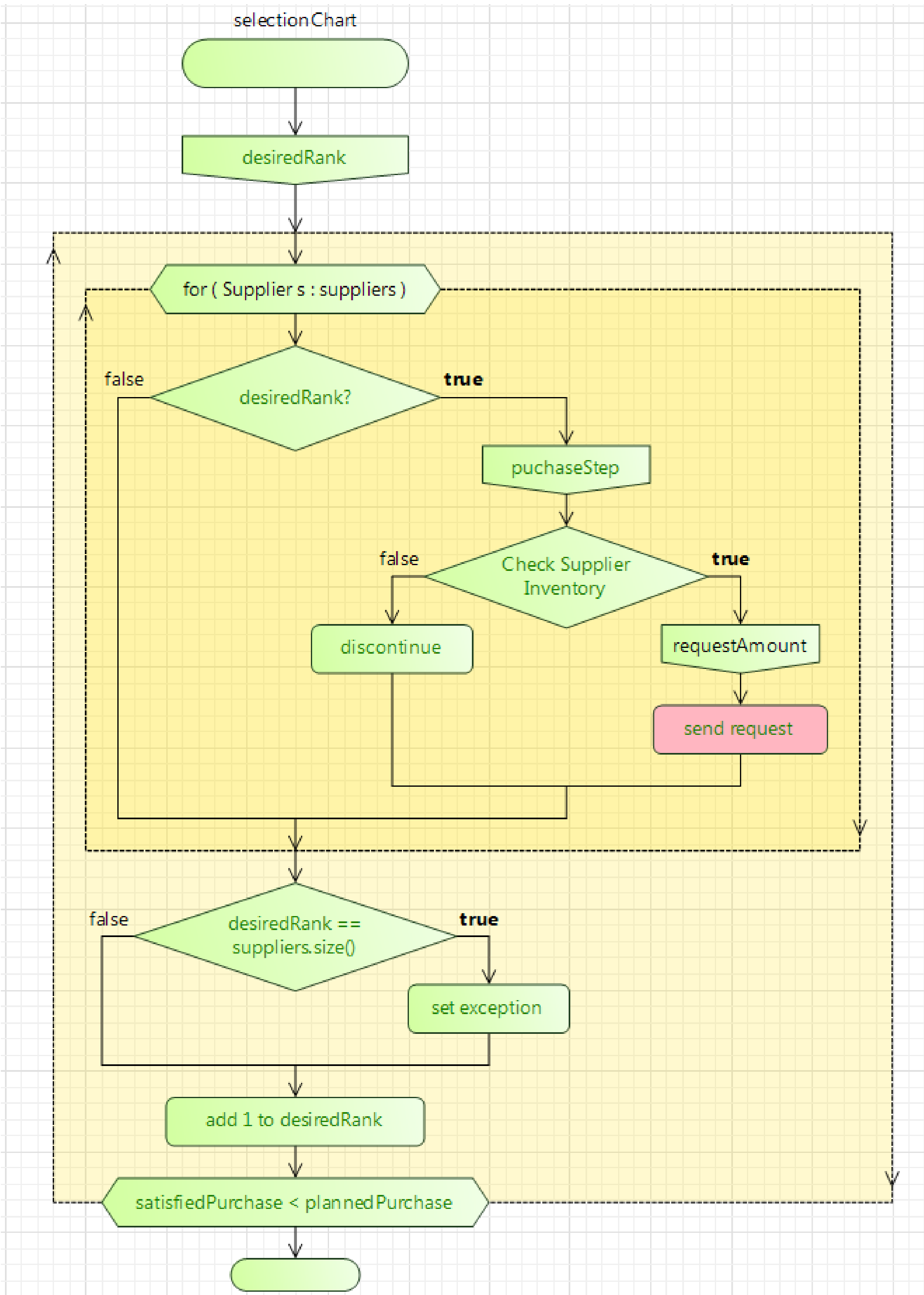


Figure 8 - selectionChart Diagram

Action Chart 3: setDailyUsage

This action chart is triggered by ⚡ triggerDailyUsage event. It determines the daily demand of biomass by dividing the monthly demand of biomass into the number of days in the month. Then it monitors the inventory and selects the type of biomass with the highest rate of deterioration rate, sends a message to the inventory to consume biomass of the selected type by the amount of daily need. Using a For-loop it iterates between the suppliers until the dailyNeed is satisfied. This action chart is shown in Figure 9 and is described in detail in Appendix B, Table 32.

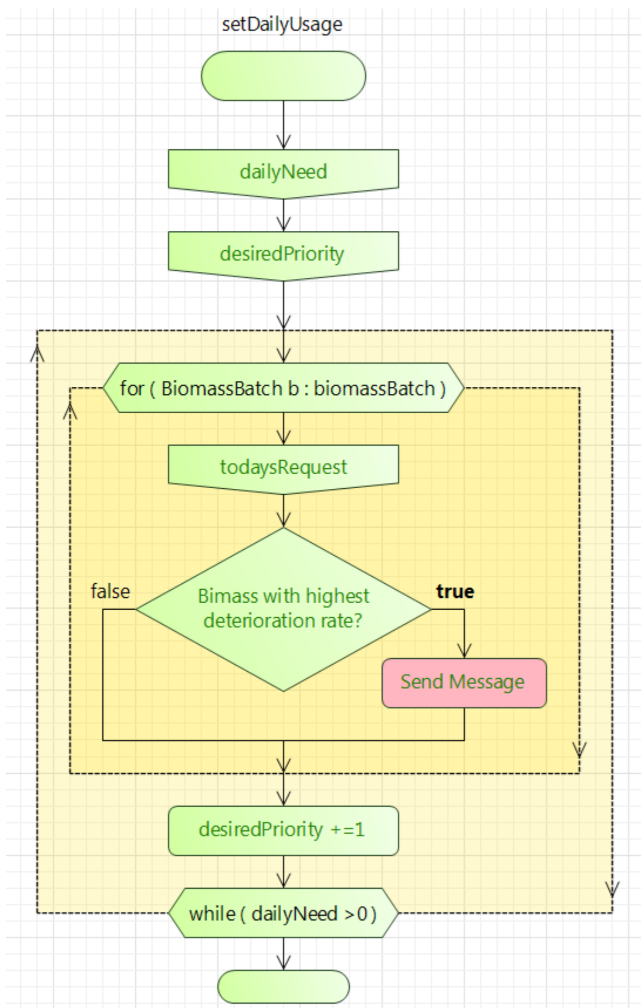


Figure 9 - setDailyUsage Diagram

4.4 Agent Classes

Beside the main class, BSCM simulation model has eight more classes. They represent the players and effective factors of the system. Each of these classes have their own parameters, variables and internal calculations. Subsections 4.4.1 ~ 4.4.8 discuss each of these agent classes individually.

4.4.1 Supplier Agent

This agent class holds a population of suppliers created based on the biomass_data database. Parameters, variables and agents existing in this class are explained in detail in Table 7. Based on these parameters and variables, the behavior of each supplier agent will be decided.

Table 7 - Parameters, Variables and Agents of the Supplier Agent

Element	Description
biomassType	Represents the list of biomass varieties stored in the database.
weatherEffects	Represents the list of factors of production effected by weather conditions stored in the database.
name	Name of the supply center.
size	Scale of the production: demonstrated by numbers 1, 2 or 3.
mc	Moisture content of the product.
type	A number referring to one of the defined types of biomass.
transportCost	Transportation cost per meter.
lat	Latitude of the location.

lon	Longitude of the location.
minSell_Kg	Minimum amount of biomass allowed to purchase in kg.
productionRate	Represents the maximum production rate per month of the facility set based on the size parameter and set at the start up by setProductionRate function.
biomassTypeAgent	This variable holds a member of biomassType agents according to the type parameter
biomassTypeName	Descriptive name of the biomass type.
weatherEffectsAgent	This variable holds a member of weatherEffects agents according to the type parameter
products	Represents the amount of biomass present in the supplier's inventory.
bpi	Biomass performance indicator.
rank_bpi	Rank of the supplier based on the bpi factor.
seasonEffects	Seasonal effect on the biomass production rate
density	Density of the product.
deteriorationPercentage	Monthly deterioration percentage.
priorityOfUse	Represents the priority that a biomass type has to be used after stored in the inventory. Equals to 1/ deteriorationPercentage.
economicalCost	Economical cost of a minimum purchase.
environmentalCost	Environmental cost of a minimum purchase.
ecoCost_STANDARD	A standardized score of economical cost of a minimum purchase.

envCost_STANDARD	A standardized score of environmental cost of a minimum purchase.
numberOfPurchasesDone	Represents the number of times that a trade has been done with the supplier during the simulation.

There are a number of events and functions present in this class as it is shown in Table 8. These functions set the variables based on the primary parameters of the agent. For this purpose, biomassType and weatherEffects agents are used as a point of reference. Moreover, seasonChange event is triggered every month and sets the monthly seasonEffects variable. The setProducts event applies the influence of the season on the production rate

Table 8 - Events and Functions of the Supplier Agent

<table>
<tr><th>Event/Function</th><th>Action</th></tr>
<tr><td>setProductionRate</td><td>Assigns a value to productionRate variable based on the size parameter using a uniform distribution.
Function body
<pre>
if (this.size == 0){
    this.productionRate = uniform(0, 250);
    this.presentation.setScale(0.5, 0.5, 0.5);
    }
else if (this.size == 1){
    this.productionRate = uniform(250, 500);
    this.presentation.setScale(0.75, 0.75, 0.75);
    }
else
    this.productionRate = uniform(500, 750);
</pre></td></tr>
<tr><td>setBiomassTypeAgent</td><td>Assigns an agent as biomassTypeAgent variable and sets the biomassTypeName.</td></tr>
</table>

<table>
<tr><td></td><td>

Function body

```
for( BiomassType b: biomassType)
    if (b.num == this.type)
        biomassTypeAgent = b;

biomassTypeName = biomassTypeAgent.name;
```

</td></tr>
<tr><td>setWatherEffectsAgent</td><td>

Assigns an agent as weatherEffectsAgent variable.

Function body

```
for( WeatherEffects w: weatherEffects)
    if (w.no == this.type)
        weatherEffectsAgent = w;
```

</td></tr>
<tr><td>setVariables</td><td>

Assigns a value to density, deteriorationPercentage and priorityOfUse.

Function body

```
this.density =
uniform(biomassTypeAgent.densityLowKgM3,
        biomassTypeAgent.densityHighKgM3);
this.priorityOfUse = biomassTypeAgent.priorityOfUse;
this.deteriorationPercentage =
        1/biomassTypeAgent.priorityOfUse;
```

</td></tr>
<tr><td>seasonChange</td><td>

At the start of every month assigns a value to seasonEffects.

Action

```
if (getMonth() == 0)
    seasonEffects = weatherEffectsAgent.month1;
if (getMonth() == 1)
    seasonEffects = weatherEffectsAgent.month2;
if (getMonth() == 2)
    seasonEffects = weatherEffectsAgent.month3;
if (getMonth() == 3)
    seasonEffects = weatherEffectsAgent.month4;
if (getMonth() == 4)
    seasonEffects = weatherEffectsAgent.month5;
if (getMonth() == 5)
    seasonEffects = weatherEffectsAgent.month6;
if (getMonth() == 6)
    seasonEffects = weatherEffectsAgent.month7;
if (getMonth() == 7)
    seasonEffects = weatherEffectsAgent.month8;
if (getMonth() == 8)
    seasonEffects = weatherEffectsAgent.month9;
if (getMonth() == 9)
    seasonEffects = weatherEffectsAgent.month10;
if (getMonth() == 10)
    seasonEffects = weatherEffectsAgent.month11;
if (getMonth() == 11)
    seasonEffects = weatherEffectsAgent.month12;
```

</td></tr>
<tr><td>setProducts</td><td>At the start of every month assigns a value to products.</td></tr>
</table>

	Action `products = productionRate * seasonEffects;`

When a supplier agent is selected by the selectionChart to do trade action, it receives a request message from the main class to prepare the order. This logic is structured using a state chart. This state chart is shown in Figure 10 and described in detail in Table 9. The initial state of every supplier is “producing”. When a message is received and the transaction is triggered, a new agent from the type of biomassBatch with the attributes of the mother agent is created. Shortly after that the supplier agent goes back to the “producing” state.

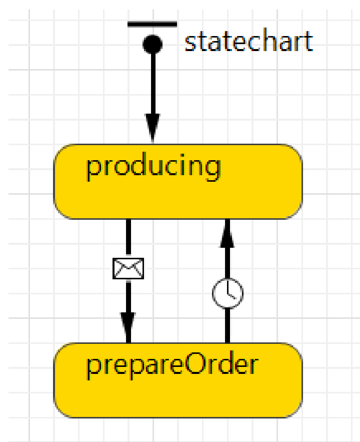
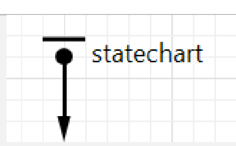
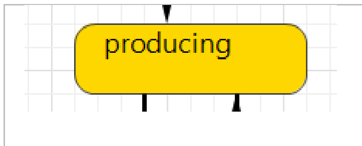
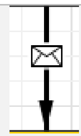
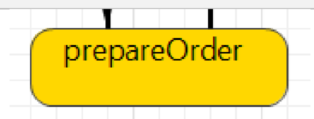
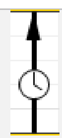


Figure 10 - supplier State chart

Table 9 - Elements of supplier Statechart

Element	Description
	Represents the state chart entry point.

<table>
<tr><td>
</td><td>A simple state that all the suppliers initially fall in.</td></tr>
<tr><td></td><td>This transaction is triggered by message. When a supplier agent receives a request from the main class, it creates a biomassBatch agent with attributes of its biomass product. The amount in kg is specified in the message.
Action:
<pre>main.add_biomassBatch(this.mc,
                      biomassTypeAgent.kwhKg,
                      density,
                      this,
                      msg,
                      deteriorationPercentage,
                      priorityOfUse);</pre></td></tr>
<tr><td>
</td><td>Supplier starts to prepare the order.</td></tr>
<tr><td></td><td>After a short while (one day) the supplier goes back to producing state.</td></tr>
</table>

Furthermore, this class has an action chart named ecoEnvCostCalculator that calculates the economic and environmental costs of buying a unit of biomass. This action chart is shown in Figure 11 and described in detail in Appendis B, Table 33. This chart executes these steps:

1. Creates bocal variables named economicalCost and environmentalCost.
2. Compares the product’s moisture level is with the maximum acceptable moisture level of the power plant.

3. If the moisture level is higher than the acceptable level, the chart identifies the nearest located treatment plant, calculates the transportation cost and emissions of transporting the product from the suppliers location to the treatment plant and from the treatment plant to the power plant. These costs are added to the economicalCost and environmentalCost variables.
4. If the moisture level is lower than the acceptable level, the transportation cost and emissions of transporting the product from the supplier’s location to the power plant are calculated and added to the economicalCost and environmentalCost variables.
5. A local variable named storageCost created and it holds the cost of storing the product for one month.
6. The storage cost and the combustion emission are respectively added to the economicalCost and environmentalCosts.These values will be used in order to rank the supplier.

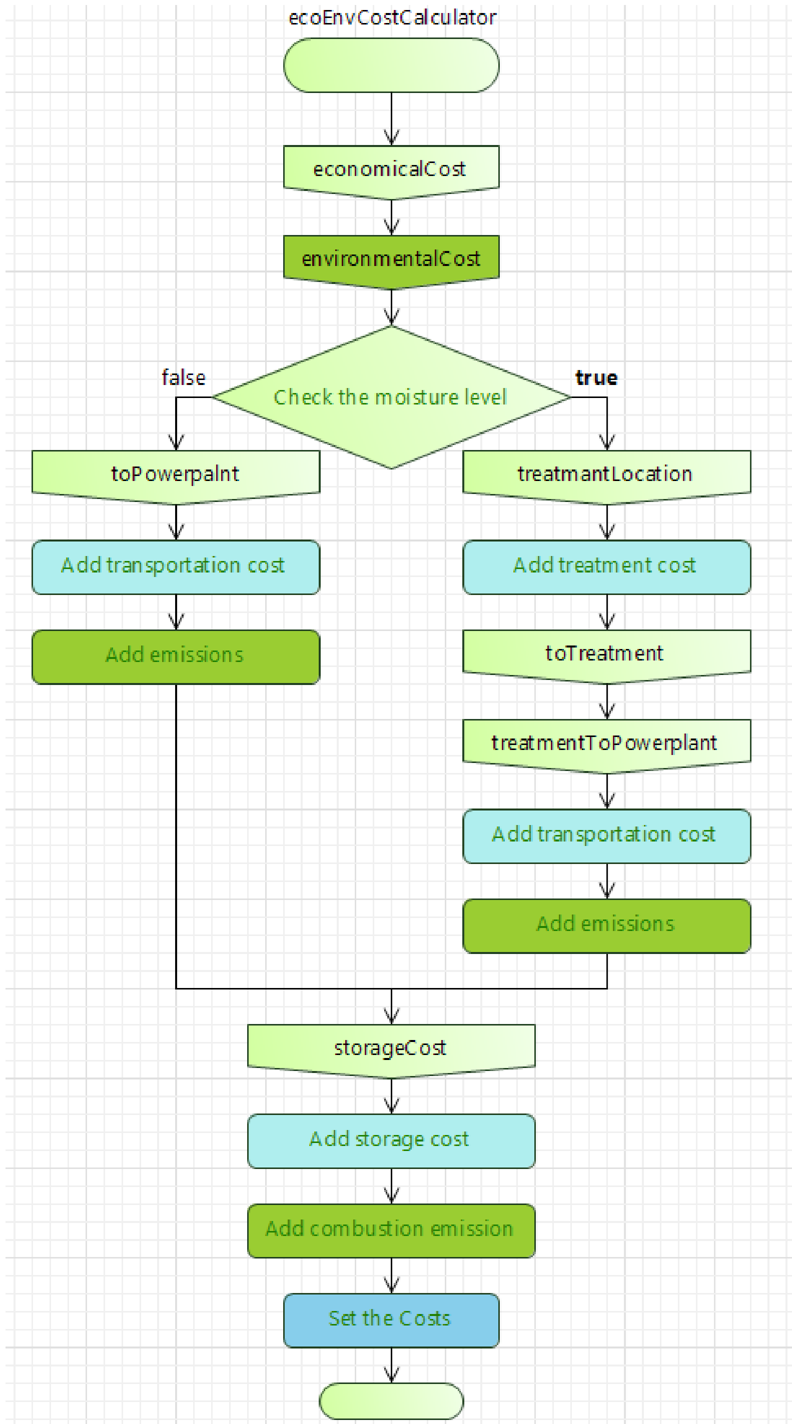


Figure 11 - ecoEnvCostCalculator Diagram

4.4.2 biopowerPlant Agent

This single agent represents the bioenergy power plant. Variables and agents existing in this class are explained in detail in Table 10 - List of Agents, Parameters and Variables of the biopowerPlant AgentThe agents have been used as a list to hold the monthly value of the demand and planned purchase. The variables are controlling elements and will be measured during the simulation.

Table 10 - List of Agents, Parameters and Variables of the biopowerPlant Agent

Element	Description
demand	Represents the demand data stored in the demand_data table.
purchasePlan	Represents the purchase plan stored in the purchase_data table.
demand_kwh	The amount of biomass in kWh that the biopower plant demands.
satisfiedDemand	The amount of consumed biomass in kWh.
plannedPurchase_kwh	The amount of biomass in kWh that is planned to be purchased.
satisfiedPurchase	The amount of purchased biomass in kWh.
storageCostRate	Represents the cost of storing 1 m^3 of biomass for a month.
occupiedStorageSpace	The occupied storage space in m^3.
exceptionDemandNotMet	“Not enough biomass in the storage” exception error (text).

Table 11 demonstrates the event elements used in this class. These two events are triggered every month to assign the new demand and planned purchase values to their corresponding variables.

Table 11 - Events used in the biopowePlant Agent

<table>
<tr><th>Event</th><th>Action</th></tr>
<tr><td>setDemand</td><td>

At the start of every month checks if the privious month's demand has been met or not. And then assigns a value to demand_kwh.

Action

```
if (satisfiedDemand < demand_kwh)
    this.exceptionDemandNotMet +=
    "Demand Not Met for month " + getMonth() +"\n";

for ( Demand d : demand)
    if (getMonth() == d.month-1)
        demand_kwh = d.demandKwh;

satisfiedDemand = 0;
```

</td></tr>
<tr><td>setPurchase</td><td>

At the start of every month carries over the unsatisfied amount of planned purchase to this month. Then assigns a value to plannedPurchase_kwh.

Action

```
satisfiedPurchase = satisfiedPurchase - plannedPurchase_kwh;

for ( PurchasePlan p : purchasePlan)
    if (getMonth() == p.month-1)
        plannedPurchase_kwh = p.plannedPurchase;
```

</td></tr>
</table>

In order to calculate the storage cost, it is required to capture the dynamic nature of it. Therefore, a stock and flow diagram has been used in the biopowerPlant agent class as shown in the Figure 12.

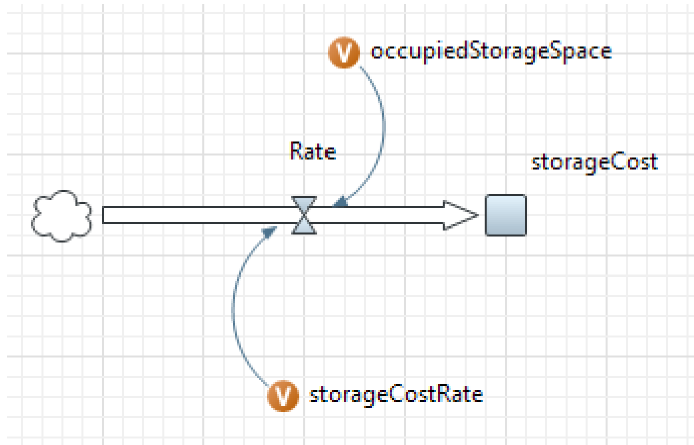


Figure 12 - Stock and Flow Diagram for biopowerPlant Agent

Method of storage determines the value of the storageCostRate variable which indicates the cost per month for every m^3 of the occupied storage space. Storage cost is defined as a stock with an inflow named Rate which is calculated using formula (1).

$$(1) \qquad Rate = \text{storageCostRate} * \text{occupiedStorageSpace}/30$$

4.4.3 Biomass Batch Agent

Parameters and variables of this agent class are explained in detail in Table 12. biomassBatch agent class represents an initially empty population of agents. When a supplier agent receives a purchase request, it creates a biomassBatch agent with attributes of the purchased product located in the supplier's coordination.

Table 12 - Parameters and variables of biomassBatch Agent

Element	Description
batchMC	Moisture content of the biomass batch.
batchHV	Heating value of the biomass batch per kg.
batchDensity	Density of the biomass batch.

originSupplier	Origin of the biomass batch.
deteriorationPercentage	Monthly deterioration percentage.
CompetativePriorityOfUse	The priority that the biomass batch has to be used after stored in the inventory. Equals to 1/ deteriorationPercentage.
initialBatchKg	Initial amount of the biomass batch in kg.
activateDeath	A binary variable initially with the value of 1.

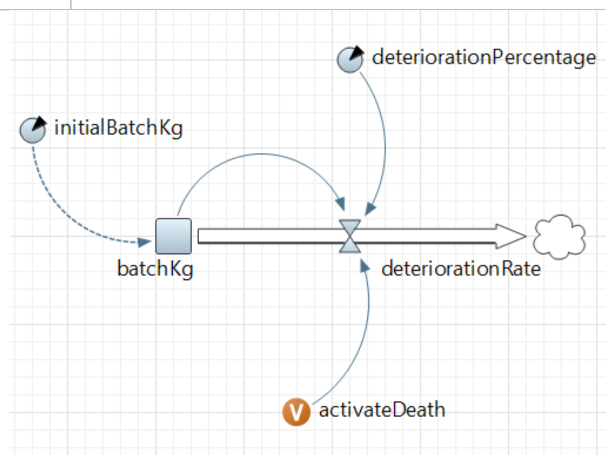


Figure 13 - Stock and Flow Diagram for biomassBatch Agent

Effects of deterioration rate is calculated using a stock and flow diagram as shown in the Figure 13. A stock named batchKg with the initial value of the purchased biomass batch represents a batch of biomass stored in the inventory. Based on the type of the biomass a value is assigned to deteriorationPercentage. The outflow is defined by deteriorationRate which is calculated using formula (2):

(2) $$deteriorationRate = \text{batchKg} * \text{deteriorationPercentage}/100/30 * \text{activateDeath}$$

A biomassBatch agent from birth to death goes through different states. Figure 14 represents the state chart of this agent as implemented in BSCM simulation model. Appendix B, Table 34 explains the elements of this state chart in detail. A purchased biomass unit is either directly transported to the power plant or first it takes a route to the nearest treatment plant and then is moves to the inventory in the power plant's location. The unit of biomass is stored in the inventory until it receives a message by the setDailyUsage action chart and it is moved to the burner to be consumed and it is turned into ash and is disposed.

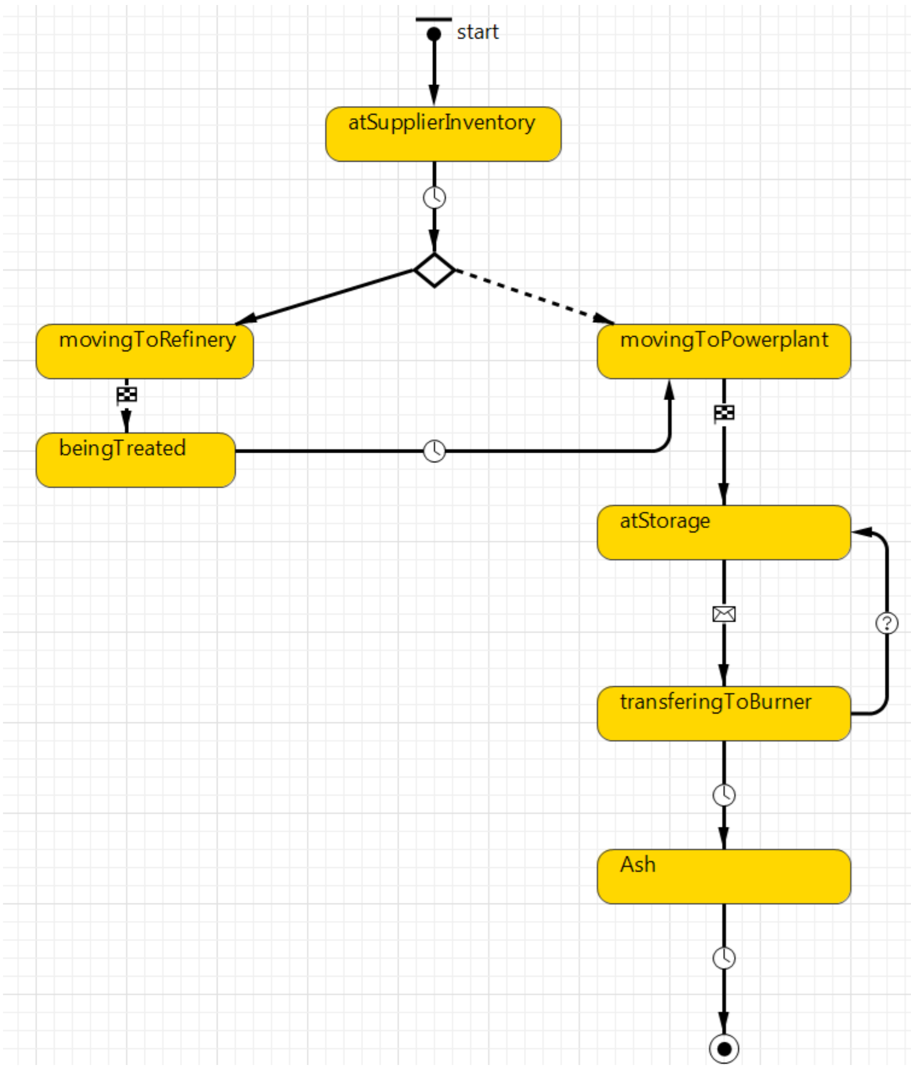


Figure 14 - biomassBatch State Chart

4.4.4 Treatment Plant Agent

This Agent represents the treatment plants. Elements used in the construction of the treatmentPlant agent are displayed in Table 13. These elements hold the basic information about the treatment facility such as its name and geographical coordination and the cost rate of the service.

Table 13 - Elements used in treatmentPlant Agent

Element	Description
name	Name of the treatment facility.
lat	Latitude of the location.
lon	Longitude of the location.
treatmentCost	Cost of treatment per kg of biomass.

4.4.5 Biomass Type Agent

This agent hold the information of different types of biomass as a population of agents as declared in the types_data database. Table 14 presents the parameters used in this class. This agent is used as list to hold the information, making it possible for the supplier agent to draw data from it during the set-up.

Table 14 - Elements used in biomassType Agent

Element	Description
id	A unique number assigned as an identifier.
name	Descriptive name of the biomass type.

kwhkg	Energy content per kg.
ash	Ash percentage.
carbon	Carbon percentage.
densityLowKgM3	The lowest recorded density.
densityHighKgM3	The highest recorded density.
basePriceCad100kg	Common price for per 100kg.
deteriorationRate	Deterioration percentage per month

4.4.6 Weather Effects Agent

This agent is constructed based on the data stored in weather_effects_data table. Parameters used in this agent class are displayed in Table 15. A weatherEffects agent is assigned to every supplier and the information stored in it is accessed every month by the supplier agent.

Table 15 - Elements used in weatherEffects Agent

Element	Description
id	An id number pointing to a unique id number in the biomass_type table.
month1	A percentage speculation the effects of weather conditions on the production rate in January.
month2	A percentage speculation the effects of weather conditions on the production rate in February.

month3	A percentage speculation the effects of weather conditions on the production rate in March.
month4	A percentage speculation the effects of weather conditions on the production rate in April.
month5	A percentage speculation the effects of weather conditions on the production rate in May.
month6	A percentage speculation the effects of weather conditions on the production rate in June.
month7	A percentage speculation the effects of weather conditions on the production rate in July.
month8	A percentage speculation the effects of weather conditions on the production rate in August.
month9	A percentage speculation the effects of weather conditions on the production rate in September.
month10	A percentage speculation the effects of weather conditions on the production rate in October.
month11	A percentage speculation the effects of weather conditions on the production rate in November.
month12	A percentage speculation the effects of weather conditions on the production rate in December.

4.4.7 Demand Agent

This agent is constructed based on the data stored in demand_data table and it holds predicted demand of biomass in kWh by the bioenergy power plant for every month. Parameters of this agent are displayed in Table 16. This agent lives inside the biopowerPlant agent and its information is accessed every month by this agent.

Table 16 - Elements used in demand Agent

Element	Description
month	One of 12 months of the year.
demandkwh	Amount of energy in kWh.

4.4.8 Purchase Plan Agent

To compensate the delays and road blockage in winter, purchases are planned to be done few months ahead. purchasePlan agent represents the required data which is stored in purchase_data table. Parameters constructing this agent are displayed in Table 17. Similar to the demand agent, purchasePlan agent lives in the biopowerPlant agent and is used every month to access information.

Table 17 - Elements used in purchasePlan Agent

Element	Description
month	One of 12 months of the year.
plannedPurchase	Amount of energy in kWh.

4.5 Results

BSCM simulation model offers both simulation output data and simulation runtime data. When lunching the model, using a simulation experiment enables us to create animation for the model and simulate it for a specified time with the visualization. An experiment has been conducted based on a hypothetical database provided in Appendix A. Simulation time starts at the beginning of spring (April) and runs for one year.

Figure 15 displays the composition of the GIS map at the end of this experiment. As it has been explained before, the numbers on top of a supplier's animation indicates the number of times that the supplier has been selected for conducting a purchase. Table 18 is a detailed version of the amount of purchase load in kg for each biomass type in each month.

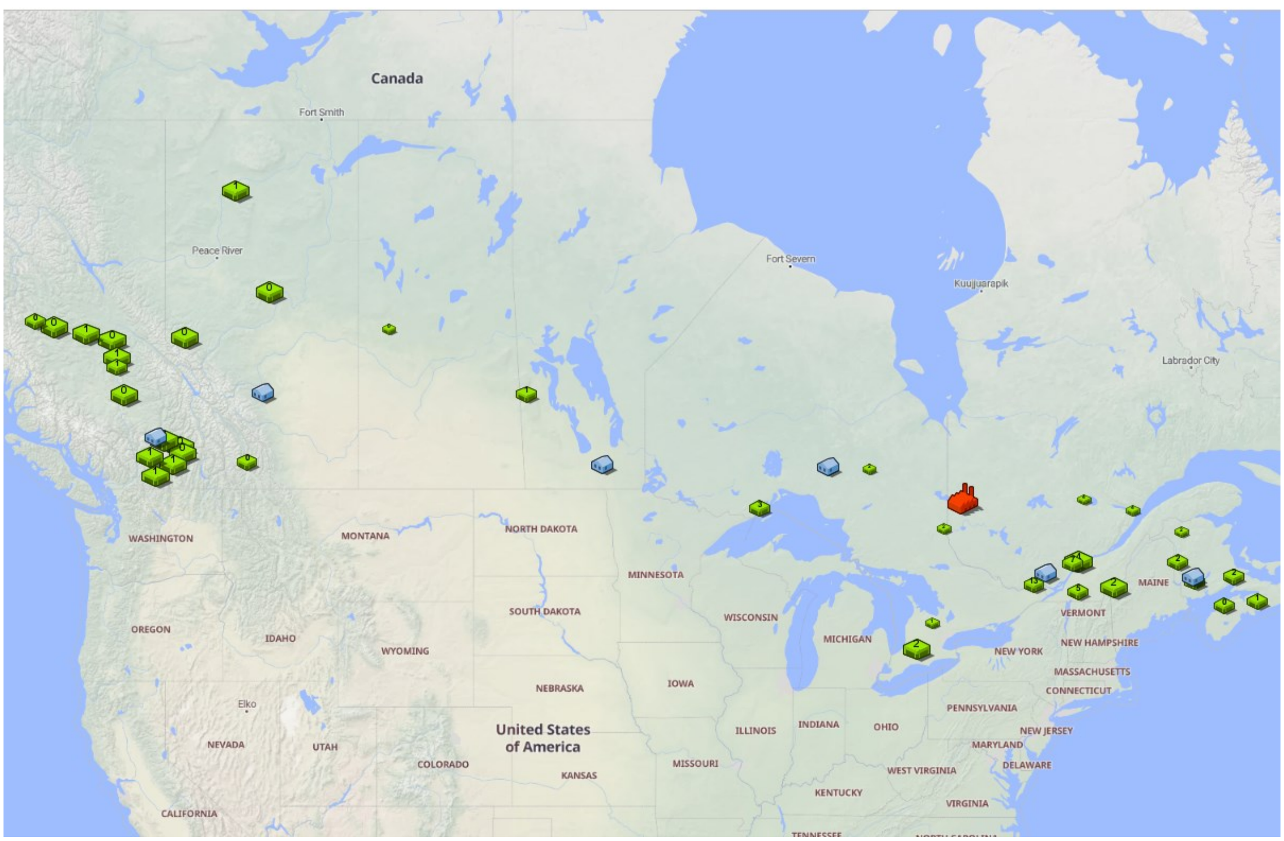


Figure 15 - GIS Finishing Composition

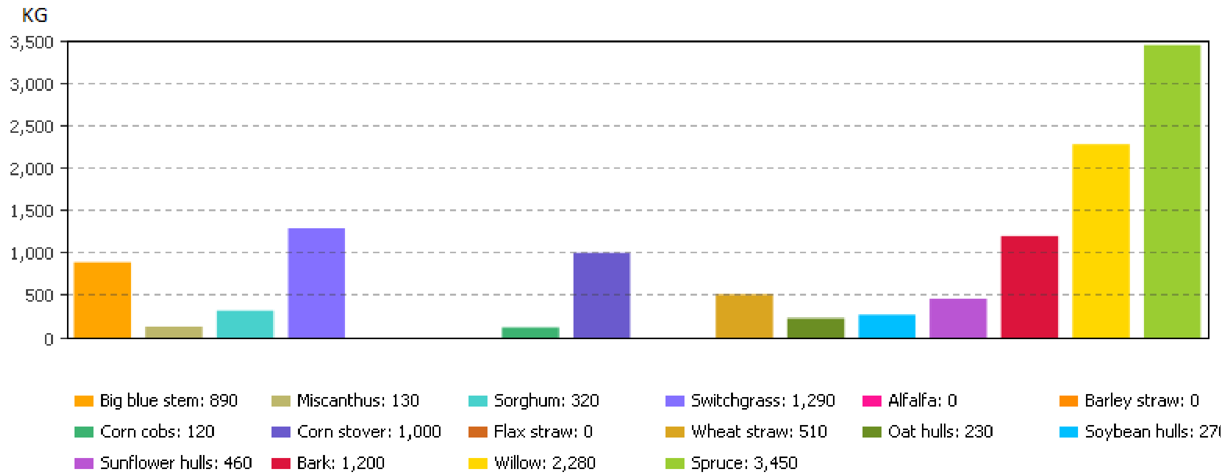


Figure 16 - Bar Chart of Cumulative Purchase in kg

Figure 16 is a bar chart presenting cumulative amount of purchase in kg from each type of biomass. Woody biomass has taken most of the total purchases. Woody biomass has a higher energy and material density; these attributes make this type of biomass economically favorable. The other reason is that the suppliers of woody biomass in the database generally have a higher production rate, therefore a higher availability rate.

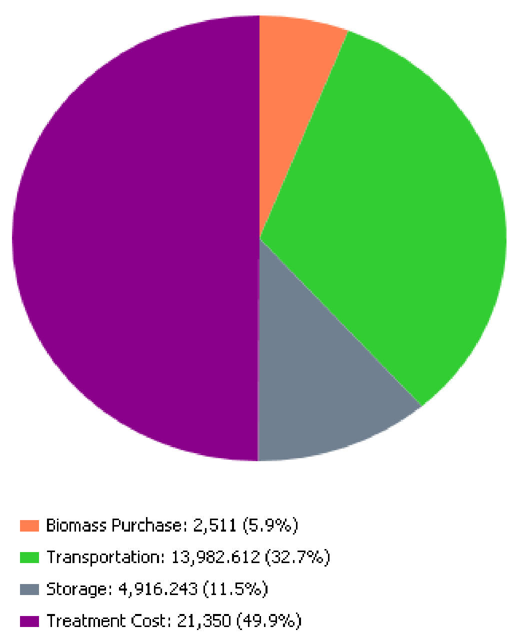


Figure 17 - Pie Chart of the Costs

According to Figure 17 treatment cost has the highest impact of the total cost. The necessity of doing a treatment operation on a purchased biomass batch depends on the quality of the biomass and also the max acceptable moisture content percentage sat by the power plant equipment. The need for treatment and the consequence costs are incorporated in the initial scoring and ranking of the biomass products.

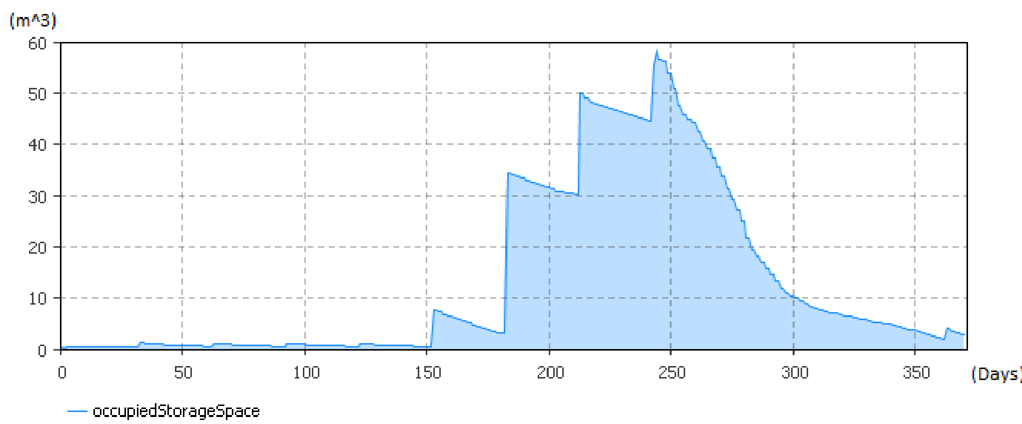


Figure 18 - Time-Plot Chart for Occupied Storage Space

Figure 18 presents the history of the occupied space of the storage in the time horizon. During the simulation, logistic figures can be followed real-time. Figure 19 depicts the fluctuations of demand and purchase plan and their rate of satisfaction. As is apparent from the figures, all purchases are done according to the plan and the model has not encountered any shortage of biomass.

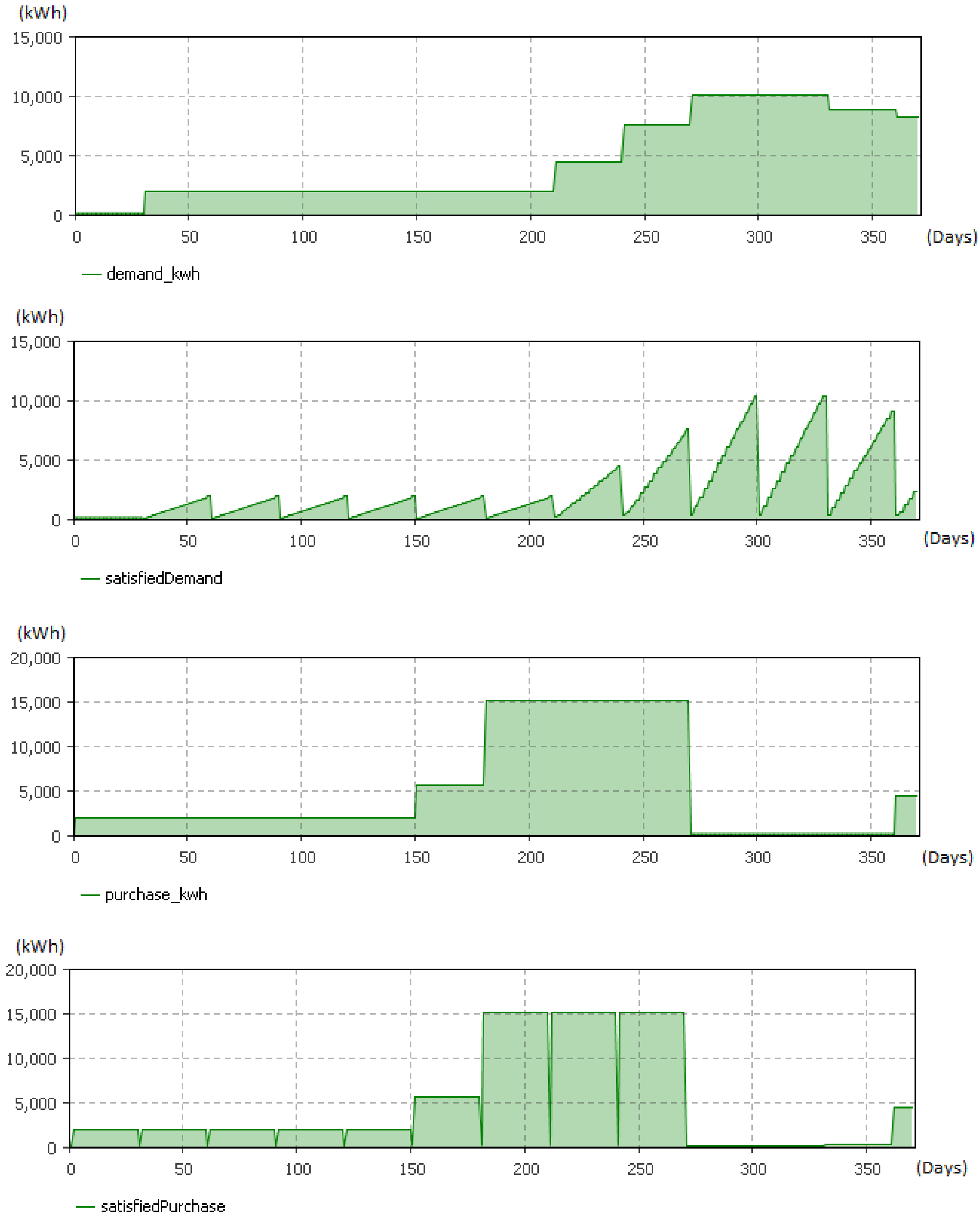


Figure 19 - Time-Plot Charts for the Initial Run

Table 18 - Purchase Load (kg) for Selection of Biomass Types in Each Month

Month	Big blue stem	Miscanthus	Sorghum	Switchgrass	Alfalfa	Barley straw	Corn cobs	Corn stover	Flax straw	Wheat straw	Oat hulls	Soybean hulls	Sunflower hulls	Bark	Willow	Spruce
January	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
February	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
March	-	-	-	-	-	-	-	-	-	-	-	-	80	100	210	50
April	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	300
May	-	-	-	60	-	-	-	-	-	-	-	-	-	-	-	300
June	-	-	-	50	-	-	-	-	-	-	-	-	-	-	-	300
July	-	-	-	50	-	-	-	-	-	-	-	-	-	-	-	300
August	330	-	-	450	-	-	-	-	-	-	-	-	-	-	-	300
September	280	-	190	360	-	-	80	40	-	250	-	10	220	-	360	80
October	140	-	90	270	-	-	40	20	-	130	-	-	80	700	10	80
November	70	50	40	-	-	-	-	-	-	-	230	260	80	-	70	400
December	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

4.6 Verification and Scenario Analysis

This section is dedicated to test and validate the developed BSCM simulation model. Verification in Pohekar & Ramachandran (2004) [24] is defined as "the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model". This includes code verification by determining if the code correctly implements the intended algorithms and also solution verification meaning the accuracy in which the algorithms solve the mathematical-model equations for the specified quantity of interest.

Effective validation of a complex simulation model can be very difficult. Without sufficient and reliable data, it is not possible to perform result validation through comparisons of outputs against the real world. For this reason, the proposed model is an exploratory simulation model and what presented here as verification entails series of what-if scenarios to determine what drives the model's behavior and to ensure that the simulated system is acting according to the modeler's logic.

4.6.1 What-If Scenario 1: Increasing the Biomass Intake

Through the literature review presented in chapter 2, it has been elucidated that BSC does not necessarily follow the economy of scale rules. Economic feasibility of building a power plant in a certain scale is tightly related to the available biomass per area ratio. This scenario has been constructed to analyze the outputs of the system in case if the scale of operation is so large that the suppliers of biomass in the specified geographical boundary are not able to satisfy the power plant's demands. For this purpose, the biomass intake has been increased by 50% compared to the initial run.

Figure 20 shows the finishing composition of the GIS map. It indicates a shortage about 4200 kWh at the 11th month of the simulation run. The model has purchased all the available biomass from the established suppliers but still it has failed to satisfy the purchase plan.

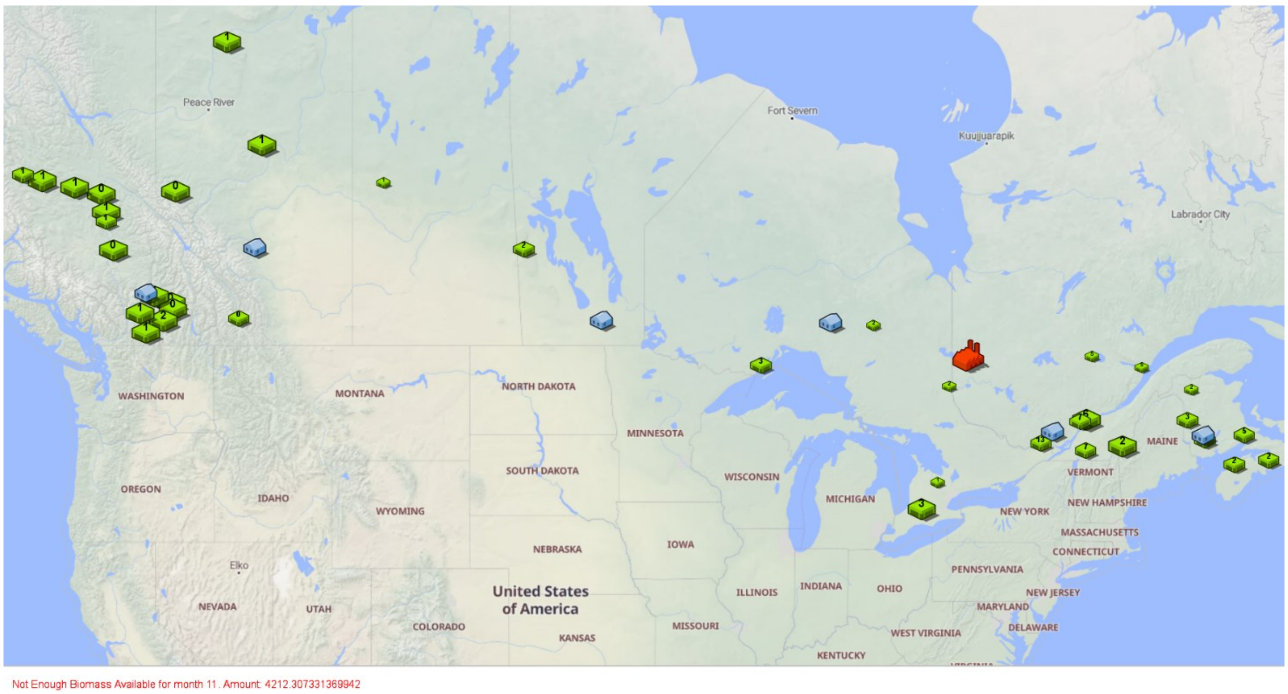


Figure 20 - Scenario 1: GIS Finishing Composition

Figure 21 display the proportions of all the purchases. Woody biomass has been the most contributing source. This figure is expounded with more detail in Table 19.

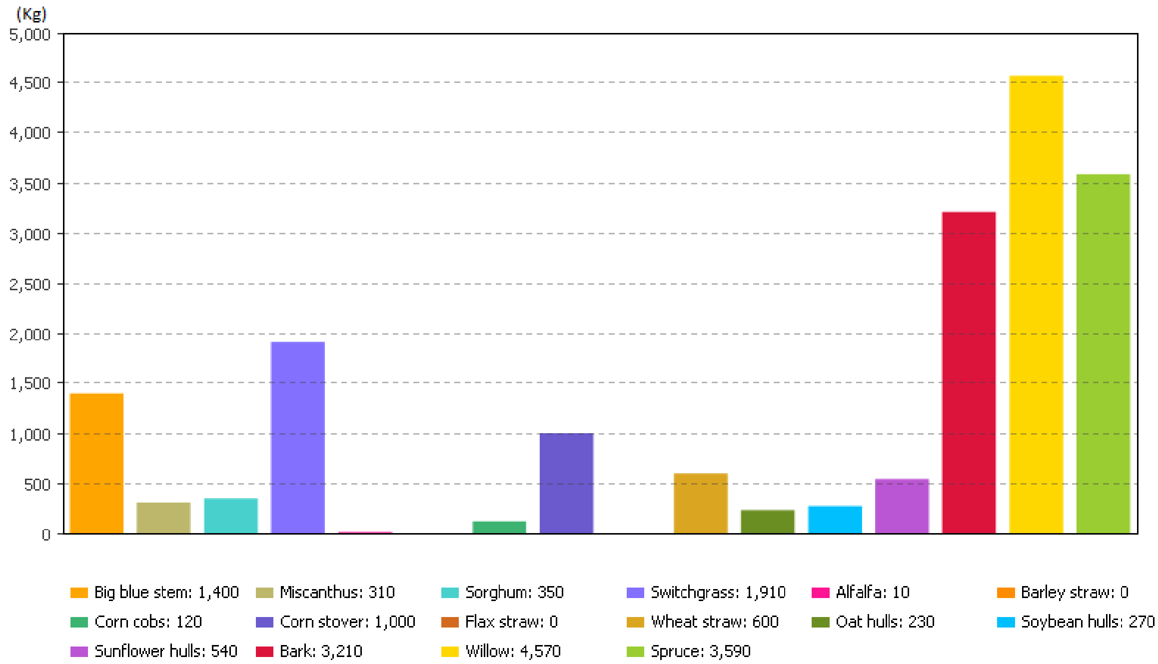


Figure 21 - Scenario 1: Bar Chart of Cumulative Purchase in kg

Figure 22 display the relative proportions of the costs. Share of treatment cost has increased compare to the initial results. The model has been force to buy all the available biomass, high quality and low quality, in order to satisfy the demand.

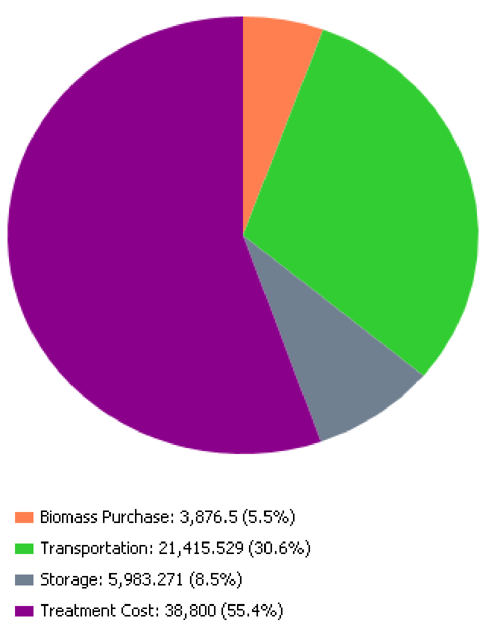


Figure 22 - Scenario 1: Pie Chart of the Costs

Figure 23 shows the occupied storage space in the timeline of the simulation run. The maximum of the occupied space has been increased from $58m^3$ in the initial run to $65m^3$ in this scenario which shows about 12% ((58-65)/58 ≈ -0.12) increase.

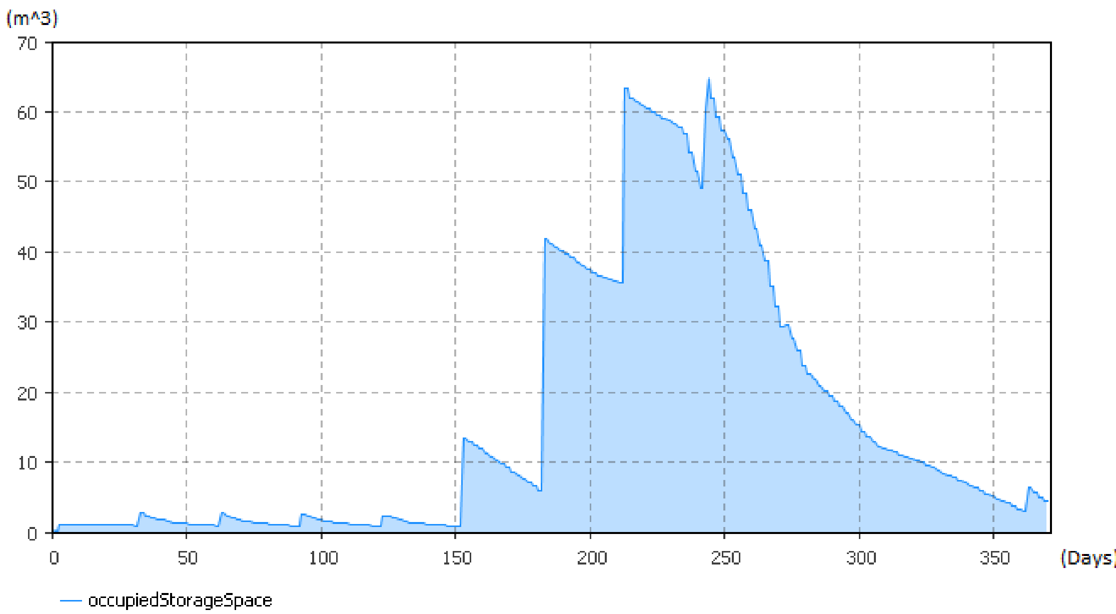


Figure 23 – Scenario 1: Time-Plot Chart for Occupied Storage Space

Figure 24 simply shows the fluctuation of the demand and purchase plan along with their satisfaction progression. The shortage of biomass has manifested in the satisfiedPurchase time plot as the negative load.

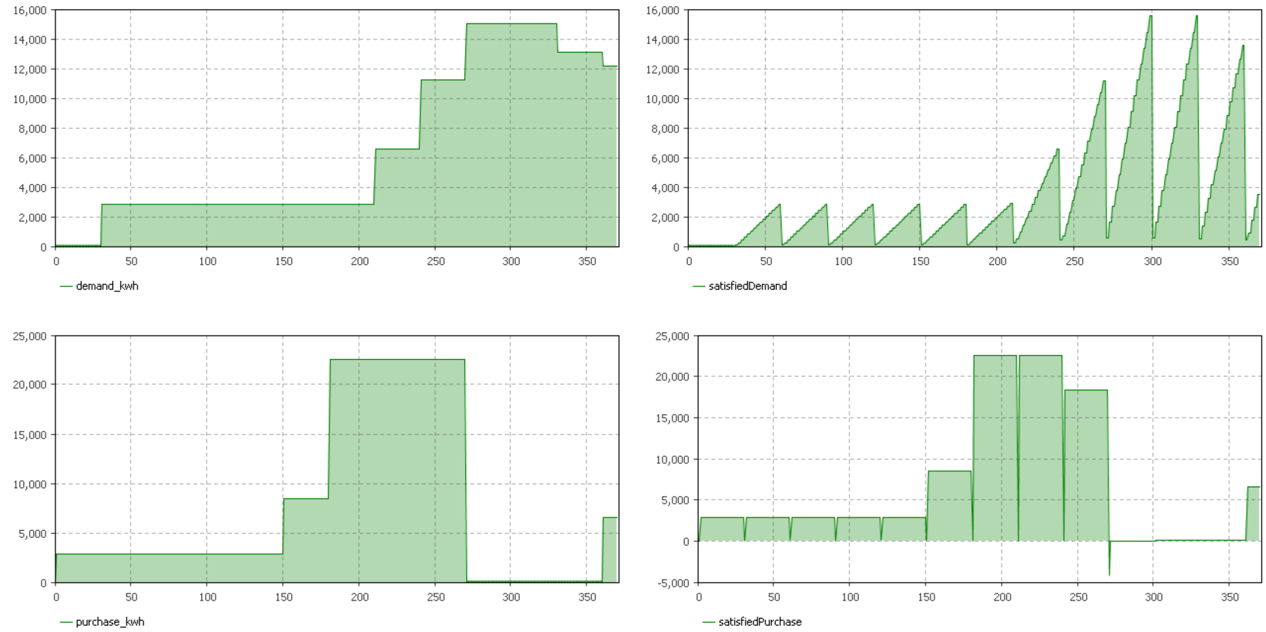


Figure 24 – Scenario 1: Other Time-Plot Charts

Table 19 - Scenario 1: Purchase Load (kg) for Selection of Biomass Types in Each Month

Month	Big blue stem	Miscanthus	Sorghum	Switchgrass	Alfalfa	Barley straw	Corn cobs	Corn stover	Flax straw	Wheat straw	Oat hulls	Soybean hulls	Sunflower hulls	Bark	Willow	Spruce
January	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10
February	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10
March	-	-	-	-	-	-	-	-	-	-	-	-	80	420	100	50
April	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	300
May	60	-	-	180	-	-	-	-	-	-	-	-	-	-	-	300
June	50	-	-	180	-	-	-	-	-	-	-	-	-	-	-	300
July	-	-	-	230	-	-	-	-	-	-	-	-	-	-	-	300
August	710	-	-	450	-	-	-	-	-	-	-	-	-	-	150	300
September	280	-	190	360	-	-	80	40	-	260	-	10	220	10	400	80
October	140	90	90	270	10	-	40	20	-	80	-	-	80	310	400	80
November	20	50	30	-	-	-	-	-	-	-	230	260	80	-	330	400
December	-	-	-	-	-	-	-	-	-	-	-	-	80	-	240	30

4.6.2 What-If Scenario 2: Limiting Biomass Types to Biomass with High Energy Content

In the literature review, multi-biomass option has been proposed as a possible solution for ensuring the continuous biomass supply securing demand satisfaction. This scenario is designed to test this statement. The initial model has been built on multi-biomass concept and it considers 16 different types of biomass. In this experiment the available types of biomass have been limited to only woody products which are considered high quality biomass.

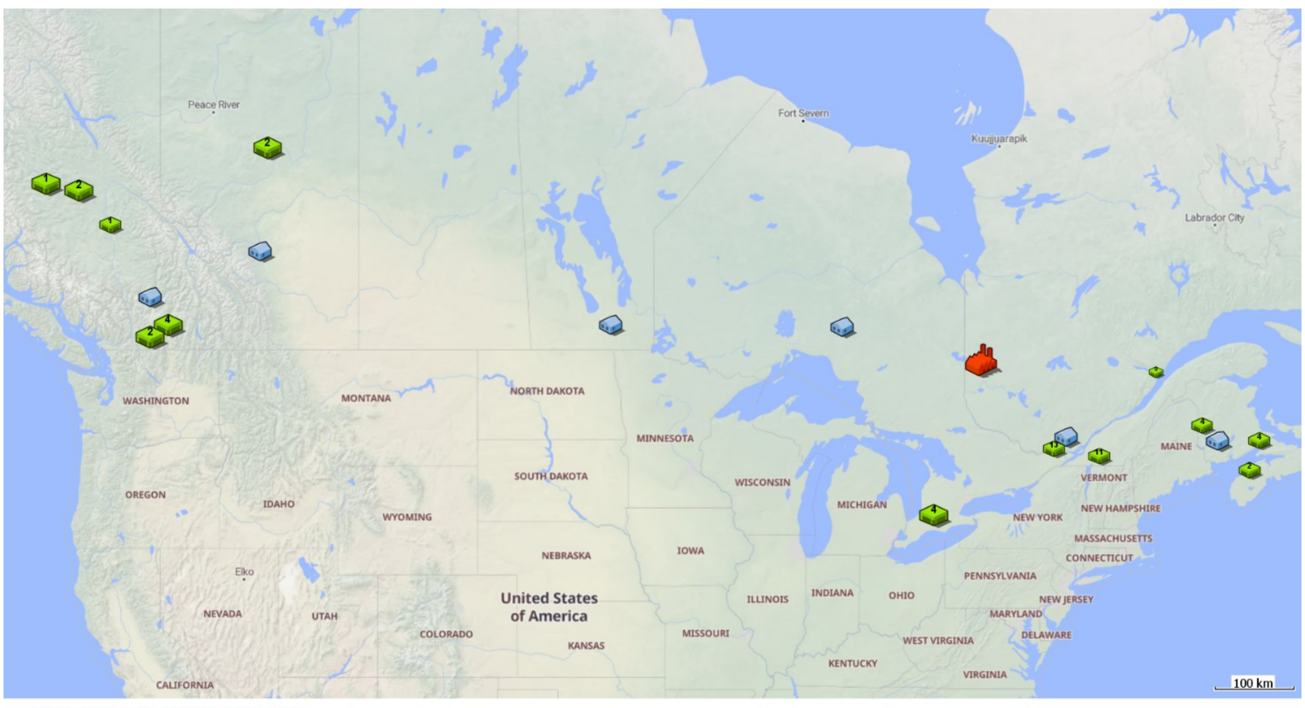


Figure 25 - Scenario 2: GIS Finishing Composition

Figure 25 shows the geographical positioning of the remaining suppliers. The model has encountered a shortage of biomass with the energy value of 1400 kWh in month 11.

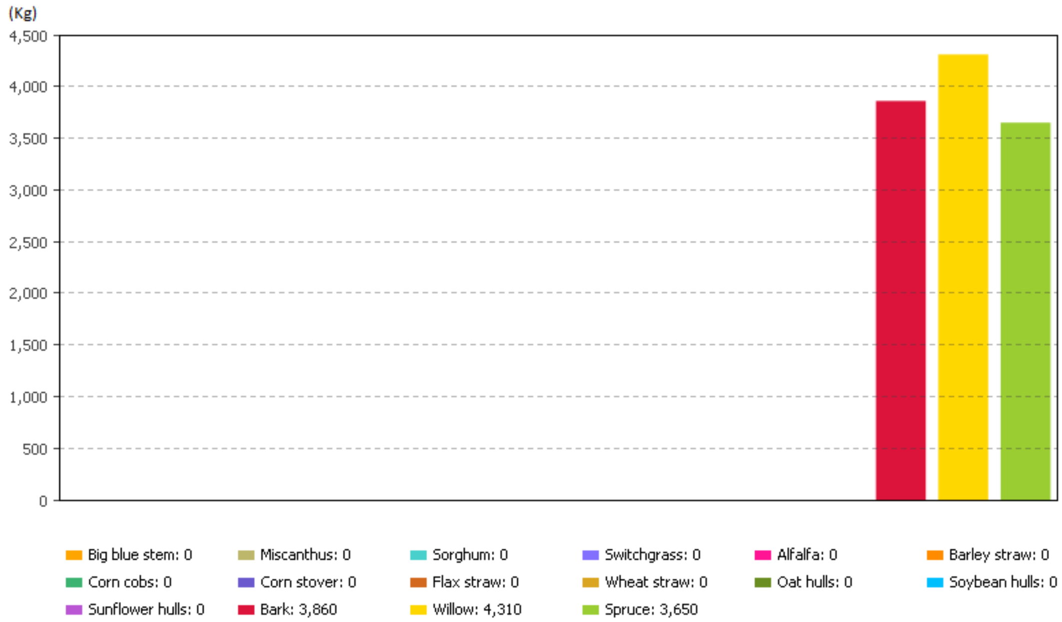


Figure 26 - Scenario 2: Bar Chart of Cumulative Purchase in kg

According to Figure 27, treatment cost is the highest contributor to the total cost. Transportation and storage costs show a significant decrease due to the denser nature of the woody biomass, however, purchase cost of the biomass shows about 34% increase (from the initial 2,511$ to 3,353$).

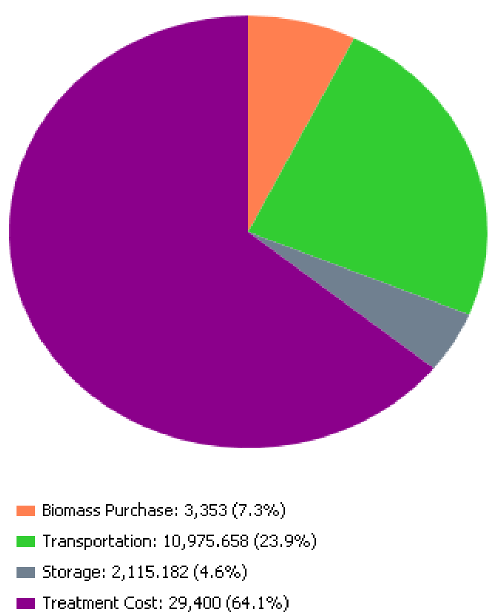


Figure 27 - Scenario 2: Pie Chart of the Costs

According to Figure 28, the maximum of the occupied space of the inventory is about $19m^3$ which compare to the initial $59m^3$, there is a significant ((58-19)/58 ≈ 67%) decrease. This number also explains the apparent storage cost reduction displayed in Figure 27.

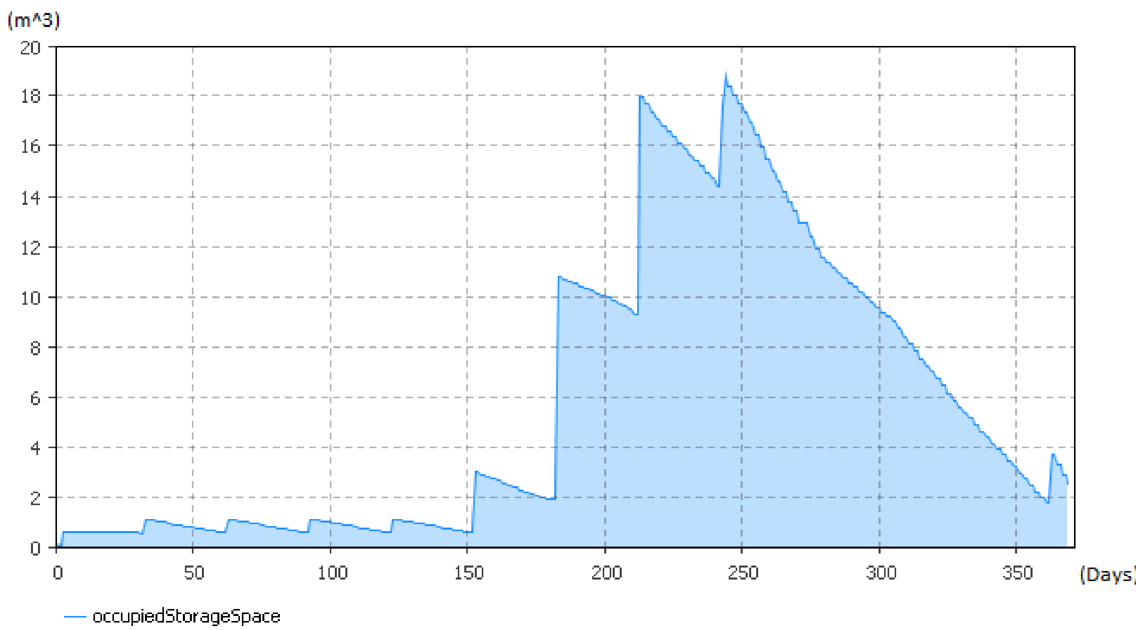


Figure 28 - Scenario 2: Time-Plot Chart for Occupied Storage Space

Progress of demand and purchase together with their satisfaction advancement is presented in Figure 29 and matches the expectations.

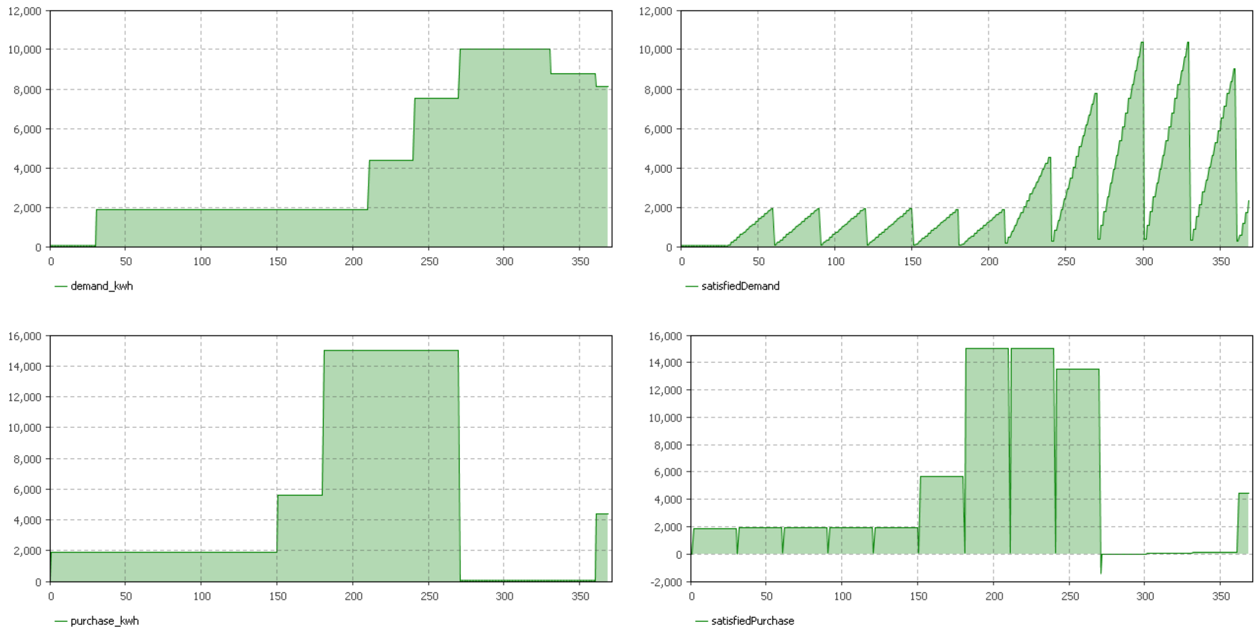


Figure 29 - Scenario 2: Other Time-Plot Charts

Table 20 - Scenario 2: Purchase Load (kg) for Selection of Biomass Types in Each Month

Month	Big blue stem	Miscanthus	Sorghum	Switchgrass	Alfalfa	Barley straw	Corn cobs	Corn stover	Flax straw	Wheat straw	Oat hulls	Soybean hulls	Sunflower hulls	Bark	Willow	Spruce
January	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10
February	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10
March	-	-	-	-	-	-	-	-	-	-	-	-	-	200	210	50
April	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	300
May	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	300
June	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	300
July	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	300
August	-	-	-	-	-	-	-	-	-	-	-	-	-	40	360	80
September	-	-	-	-	-	-	-	-	-	-	-	-	-	240	400	80
October	-	-	-	-	-	-	-	-	-	-	-	-	-	240	400	80
November	-	-	-	-	-	-	-	-	-	-	-	-	-	-	330	400
December	-	-	-	-	-	-	-	-	-	-	-	-	-	-	140	10

4.6.3 What-if Scenario 3: Improving Storage Method and Increasing the Maximum Acceptable MC

According to the literature, choosing a proper method of storage is one of the critical challenges in BSCM. Different methods have been reviewed in chapter 2. In most cases of the relevant research work, the cheapest storage solution is chosen neglecting the positive effects of a more sophisticated storage method. Combining hot air drying treatment with the storage method has been speculated to be a comparatively advantageous choice.

This scenario is designed in order to investigate this statement. In order to bring to bear a high storage cost, the storageCostRate variable has been increased by 50%. Accordingly, the maxAcceptableMC parameter has been increased from the initial 40% to 60%. Deterioration rate has remained negligible.

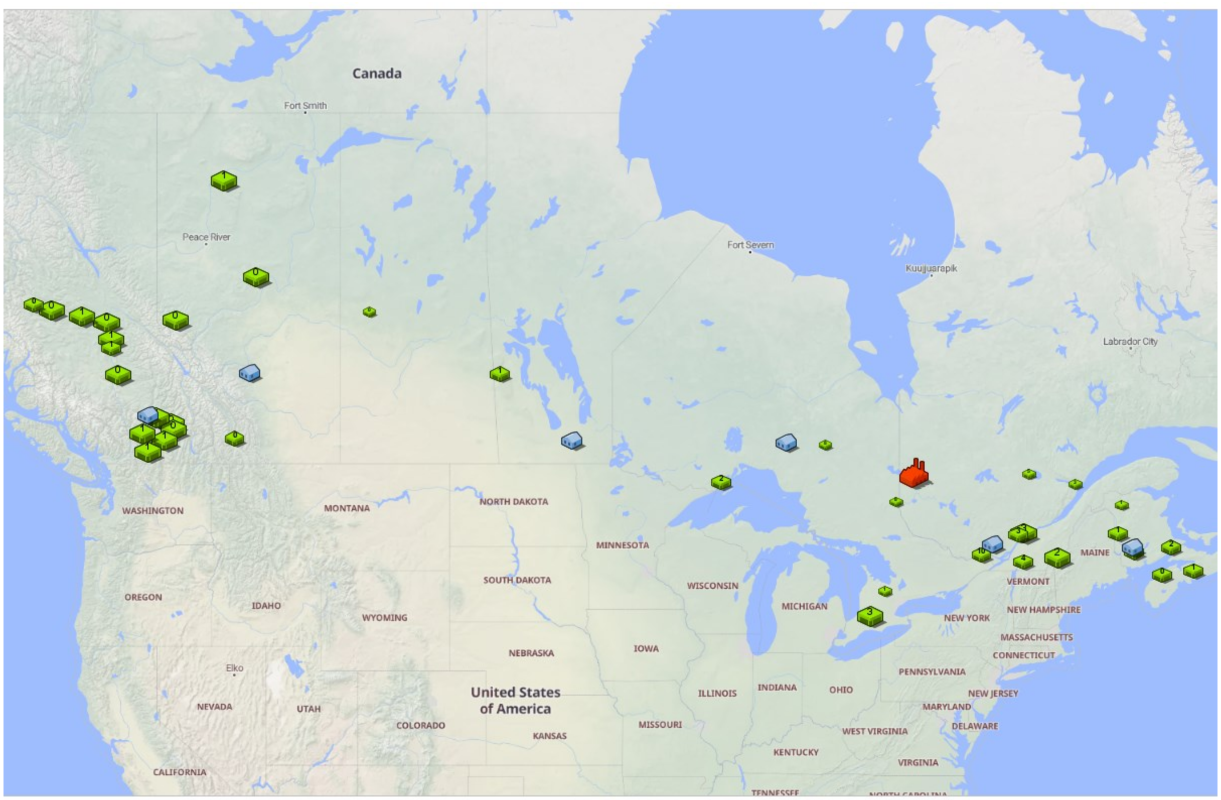


Figure 30 - Scenario 3: GIS Finishing Composition

Figure 31 displays a slight increase of the share of non-woody biomass among the total purchases. Table 21 demonstrates the variations in precise detail.

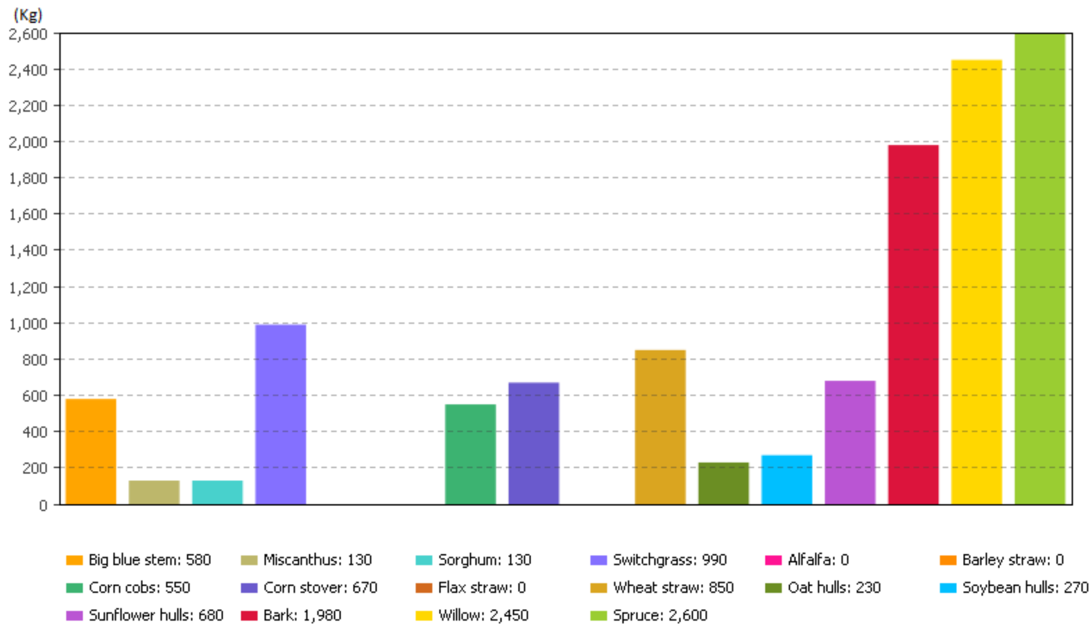


Figure 31 - Scenario 3: Bar Chart of Cumulative Purchase in kg

Figure 32 reports 0 as the treatment cost. As expected, the model has decided to only purchase the biomass with no need for a prior treatment. Storage cost shows about 33% ((4916-6550)/4916 ≈ -0.33) increment compare to the initial simulation run.

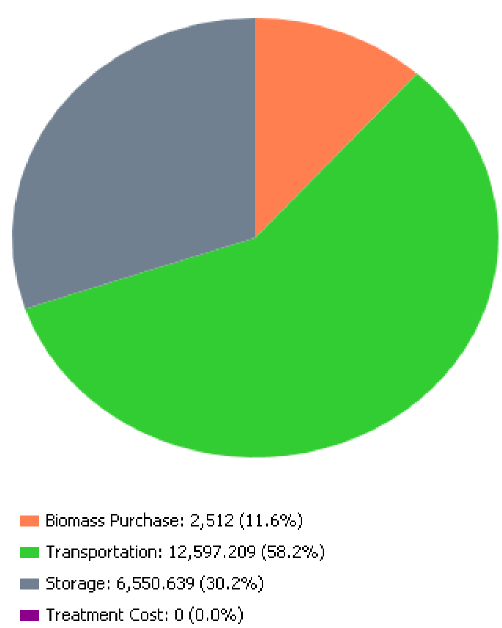


Figure 32 - Scenario 3: Pie Chart of the Costs

Evaluating Figure 33 demonstrates that implementing this scenario instead of the initial assumptions will result in about 16% ((58-49)/58 ≈ 0.16) reduction of the maximum needed storage space. This result can be explained with the logic behind the selection method. Since the storage cost rate has been increased, a higher score will be assigned to the biomass with a higher density and hence a lower storage cost. For this reason, the model will tend to decrease the occupied storage space.

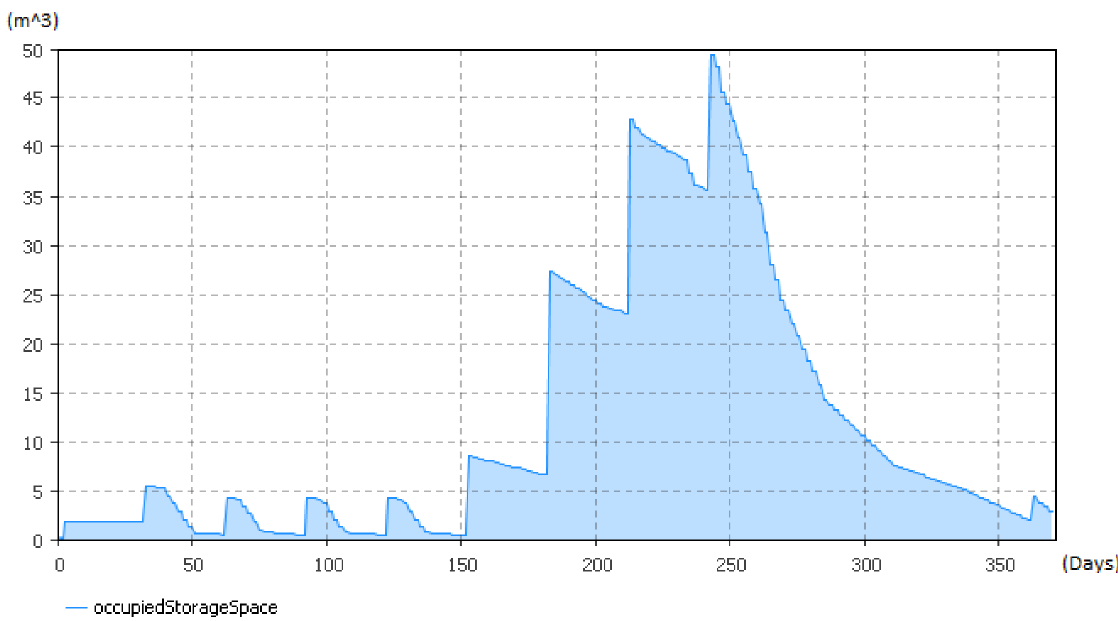


Figure 33 – Scenario 3: Time-Plot Chart for Occupied Storage Space

Time-plot charts of this scenario are presented in Figure 34. They follow a predicted pattern.

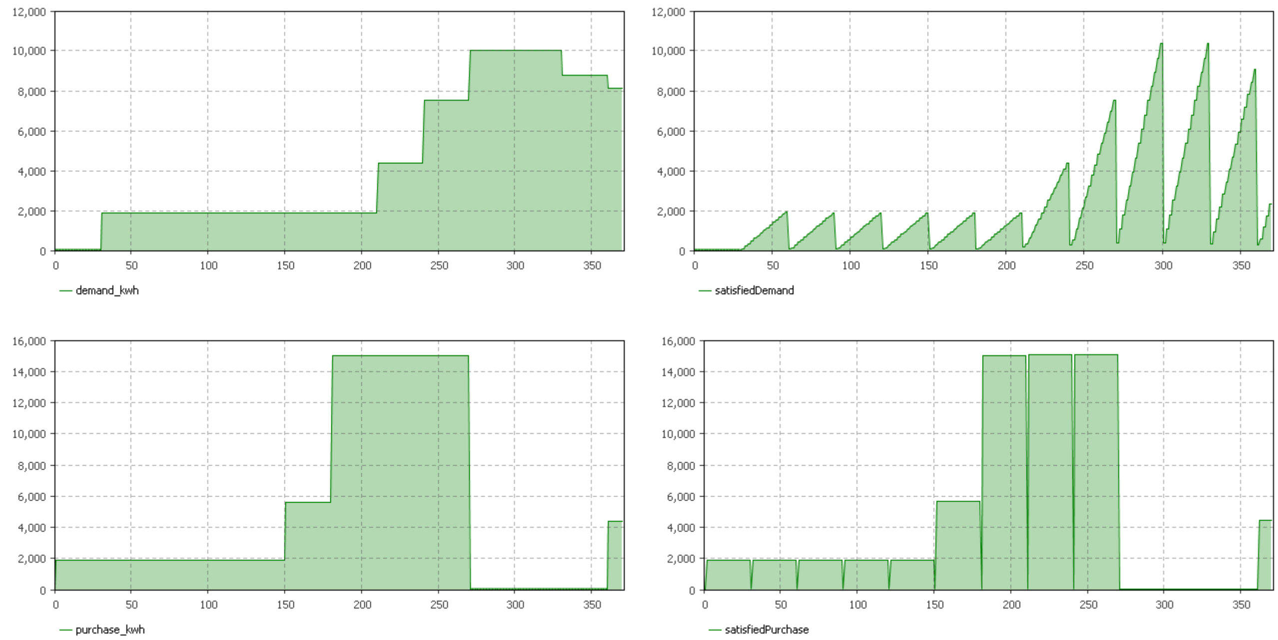


Figure 34 - Scenario 3: Other Time-Plot Charts

Table 21 - Scenario 3: Purchase Load (kg) for Selection of Biomass Types in Each Month

Month	Big blue stem	Miscanthus	Sorghum	Switchgrass	Alfalfa	Barley straw	Corn cobs	Corn stover	Flax straw	Wheat straw	Oat hulls	Soybean hulls	Sunflower hulls	Bark	Willow	Spruce
January	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
February	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
March	-	-	-	-	-	-	-	-	-	-	-	-	80	330	210	180
April	-	-	-	-	-	-	50	-	-	40	-	-	-	-	-	270
May	-	-	-	-	-	-	70	-	-	110	-	-	-	-	-	180
June	-	-	-	-	-	-	70	-	-	110	-	-	-	-	-	180
July	-	-	-	-	-	-	80	-	-	110	-	-	-	-	-	170
August	-	-	-	360	-	-	80	-	-	110	-	-	220	-	-	300
September	280	-	-	360	-	-	80	340	-	90	-	10	220	700	360	80
October	140	-	90	270	-	-	40	20	-	130	-	-	80	250	20	80
November	20	50	40	-	-	-	-	-	-	-	230	260	80	-	280	160
December	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

4.6.4 What-if Scenario 4: Choosing a Less Effective Storage Method with High Deterioration Rate

This experiment is designed in order to analyze the tradeoff between the storage cost and material loss. Ambient storage which is the cheapest method is chosen for the storage mode. In order to adjust the initial assumptions of the simulation according to this scenario, the storageCostRate has been reduced effectively by 90% and the deterioration rate is increased by 40%. Purchase plan has been increased accordingly to compensate the loss of matter and energy.

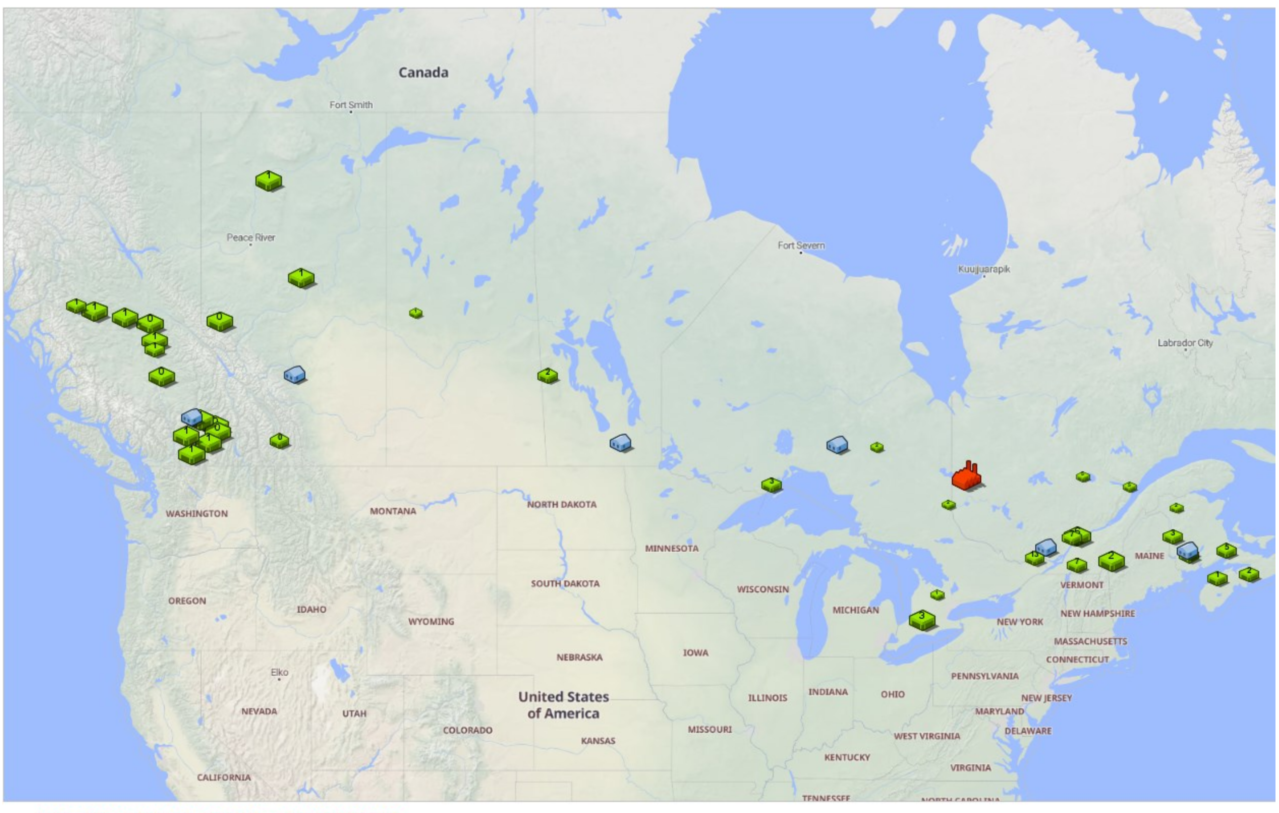


Figure 35 - Scenario 4: GIS Finishing Composition

Figure 35 presents the positioning of the suppliers and the frequency of purchase from each of them. This figure also reveals a shortage with the value of 2710 kWh for month 11.

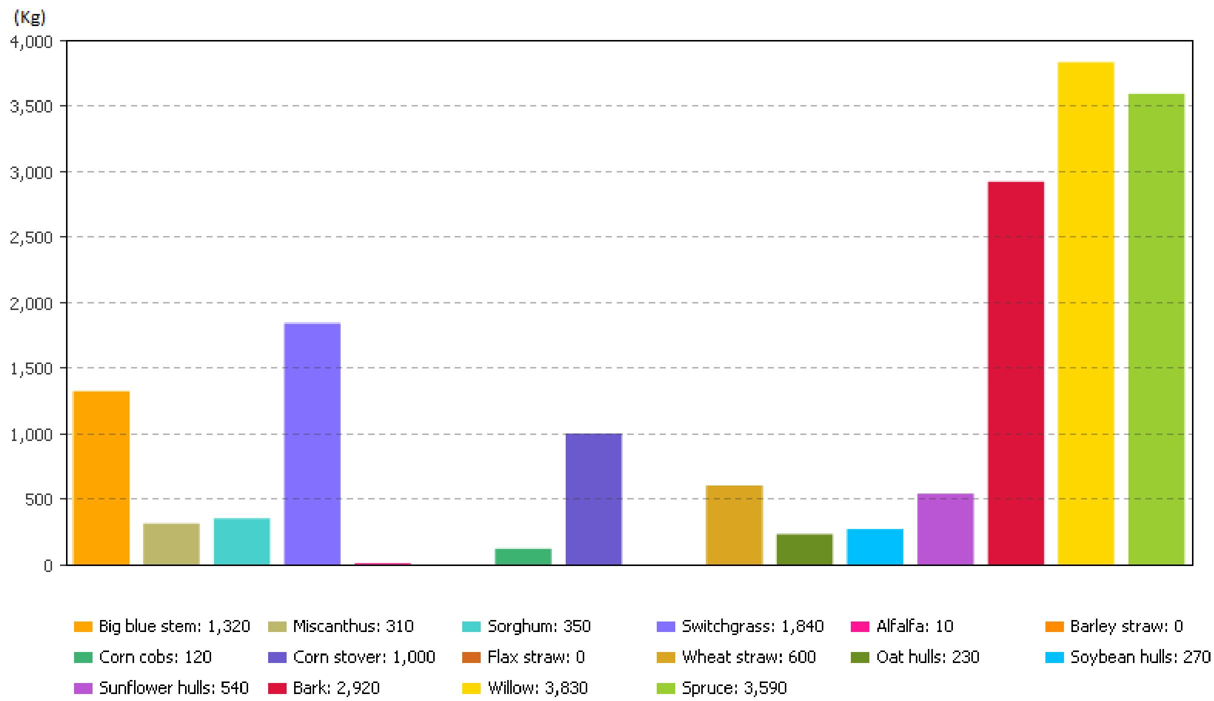


Figure 36 - Scenario 4: Bar Chart of Cumulative Purchase in kg

As expected Figure 36 indicates an overall increase in purchase of different types of biomass. The altered purchase plan is accounted for this increment.

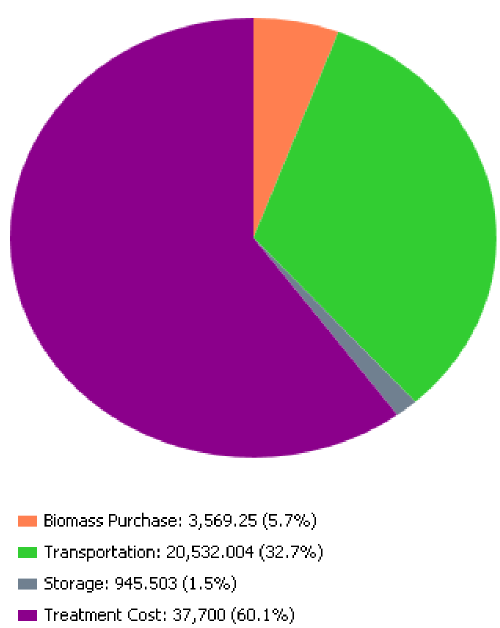


Figure 37 - Scenario 4: Pie Chart of the Costs

As presented in the Figure 37, storage cost shows a significant reduction of about 81% ((4916-945)/4916 ≈ 0.81). As expected the other costs have generally increased.

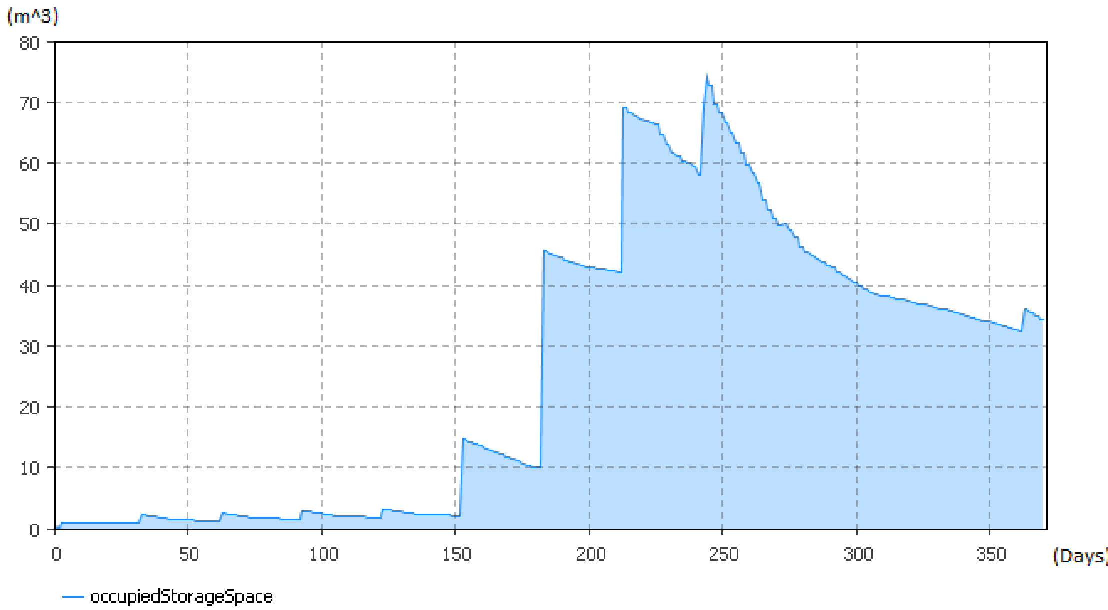


Figure 38 - Scenario 4: Time-Plot Chart for Occupied Storage Space

According to Figure 38, the maximum occupied storage space has increased by 27% ((58-74)/58 ≈ -0.27) from the initial run. Also this diagram indicates that a larger amount of biomass has been kept in the storage for a lengthy time. The buffered biomass can explain this outcome.

Figure 39 shows the status of the control time-plot charts. As anticipated, they follow the usual patterns.

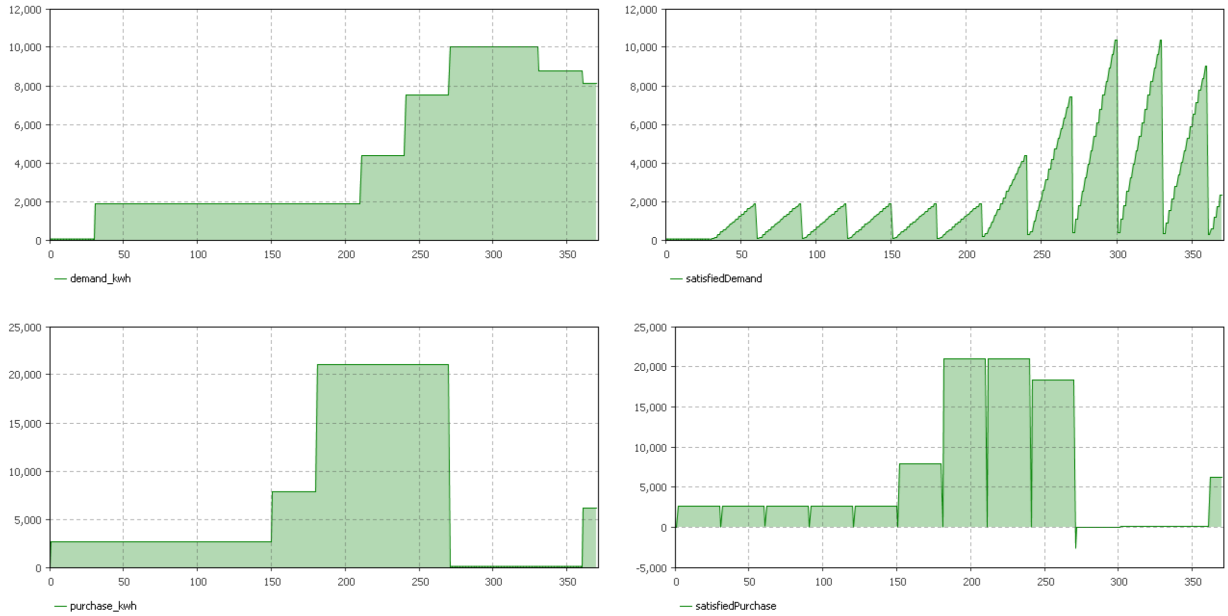


Figure 39 - Scenario 4: Other Time-Plot Charts

Table 22 - Scenario 4: Purchase Load (kg) for Selection of Biomass Types in Each Month

Month	Big blue stem	Miscanthus	Sorghum	Switchgrass	Alfalfa	Barley straw	Corn cobs	Corn stover	Flax straw	Wheat straw	Oat hulls	Soybean hulls	Sunflower hulls	Bark	Willow	Spruce
January	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10
February	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10
March	-	-	-	-	-	-	-	-	-	-	-	-	80	420	20	50
April	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	300
May	20	-	-	180	-	-	-	-	-	-	-	-	-	-	-	300
June	10	-	-	180	-	-	-	-	-	-	-	-	-	-	-	300
July	-	-	-	200	-	-	-	-	-	-	-	-	-	-	-	300
August	710	-	-	450	-	-	-	-	-	-	-	-	-	-	50	300
September	280	-	190	360	-	-	80	40	-	260	-	10	220	700	140	80
October	140	90	90	270	10	-	40	20	-	80	-	-	80	30	400	80
November	20	50	30	-	-	-	-	-	-	-	230	260	80	-	330	400
December	-	-	-	-	-	-	-	-	-	-	-	-	80	-	130	30

4.6.5 Comparing Results of the Scenarios

Table 23 presents the major costs and system performance indicators of the different scenarios and experiments implemented in the BSCM simulation model.

In Scenario 1 the scale of operation has been increased by 50% and naturally it has the highest total cost. This scenario entails unfavorable results since the available biomass supply cannot answer this scale of energy production. Encountering energy shortage is imminent in this scenario.

Despite the significant cost reduction at the storage level, scenario 4 stands in the second highest place for the total costs. Choosing a poor storage method has led to many adverse outcomes. Purchase cost, treatment cost and consequently transportation cost are relatively very high in this scenario. Moreover, system has been unable to satisfy the designated demand.

Scenario 2 shows an acceptable performance. Buying denser biomass products has led to a comparative minimum transportation cost. As a consequence, required storage space and hence the storage cost is low also. However, narrowing the choices to a few biomass types has limited the available biomass supplies and caused a failure in demand satisfaction.

Scenario 3 represents itself as the most favorable choice. This scenario has the minimum total cost compare to the others. These results signify the positive effects of choosing a more sophisticated storage method.

Table 23 - Detailed Comparision Between Scenarios

Scenario / Parameter	Initial Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Cost	42,759.85	70,075.3	45,943.84	21,659.85	62,746.76
Purchase Cost	2,511.00	3,876.50	3,353.00	2,512.00	3,569.25
Transportation Cost	13,982.61	21,415.53	10,975.66	12,597.21	20,532.01
Storage Cost	4,916.24	5,983.27	2,215.18	6,550.64	945.50
Treatment Cost	21,350.00	38,800.00	29,400.00	0	3,7700.00
Max Storage Space (m^3)	58	65	19	49	74
Energy Shortage (kWh)	0	4,212.31	1,465.41	0	2,719.83

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

This research work investigated potentials and barriers of using biomass as energy source. To enhance the potentials of bioenergy industry, an ABMS model capable of conducting a detailed analysis of the BSC system is proposed. The core idea of the model relies on the power of AB techniques on handling the complexities induced by considering multiple biomass types and sources in the management of a biomass supply chain network.

In turn, an in-depth literature review was conducted to investigate current status and prospects of biomass resources overall and with a focus on modeling and simulation techniques in particular. The existing models, their limitations and applicability were investigated. The ABMS method was investigated by studying its principal elements such as agents, GIS map environment, interactions and functions in industrial engineering and supply chain management. Limitation of traditional methods were illustrated to highlight the need of ABMS in management of biomass supply chain network.

Moreover, a simple step-by-step procedure was provided on how to develop an AB model for biomass supply chain scheduling and purchase planning according to the author's perception of the BSCM mechanism and AB technique. Then, the development of a comprehensive AB model for a bioenergy power system consisting of a bio-power plant, suppliers, treatment plants, transportation system and an inventory was demonstrated. The model governs the process logistics, scoring and ranking technique, information sharing, and biomass properties. In addition, agents' types, attributes, roles and operation logic were discussed in detail.

An object-oriented simulation application in JAVA language was developed as an implementation of the proposed AB model for biomass supply chain management. The proposed model was simulated for a biomass power plant in Quebec with multiple scenarios experimented to analyze outcomes of different managerial choices and assumptions.

5.2 Research Contributions

The key contribution of this research work is modeling and simulating the process of biomass supply chain scheduling, planning and management. This model establishes a holistic approach in absence of knowledge of BSC system's behavior and provides a reusable base that facilitates modeling various scenarios and measuring their performance through simulation. This eases the ability of decision makers to quantitatively assess the risk and benefits and enhance the performance of the system.

To address the challenges, four different scenarios have been designed and implemented. First scenario analyzes the outputs of the system in case of an increase in the scale of the operation. In the second scenario, the acceptable biomass types have been limited to only woody and high quality types. In the third scenario, storage method has been improved and combined with hot air treatment method. As for the forth scenario, ambient storage method as a cheap method with a high deterioration rate has been investigated. The results of these scenarios have been reported and individually evaluated. By conducting a comparison analysis between these scenarios and the base scenario, their advantages and disadvantages have been assessed. The third scenarios has been identified as the most favorable. The results suggest that the model generates meaningful sets of data for biomass purchase and usage planning along with the possible costs and benefits.

Moreover, the key players and influential factors in the BSC structure has been pinpointed and low logistical efficiency of the supply chain has been identified as the key barrier in the development of biomass-based energy production systems.

5.3 Research Limitation

The limitations of the proposed framework can be summarized in the following points:

- The model's focus is limited to purchase planning and scheduling part of biomass supply chain logistics.
- The emissions related to the biomass production and material handling have not been considered.
- Biomass producers are assumed to be willing to supply biomass without expecting any long-term commitments.
- Accidents and delays during the transportation are not considered.
- Validation of the proposed model was done through scenario analysis. Validating the model and its outcomes through comparison with a real case was not in the scope of this thesis.

5.4 Future Work and Recommendation

The current proposed model could be extended by including many other activities and details such as harvesting methods, biomass production processes, storage handling activities, biomass combustion techniques, and long-term contracts. By accomplishing this objective, an extensive economic analysis along with a comprehensive LCA analysis could be possible.

A comprehensive field study is recommended in order to geographically map the biomass suppliers of the selected location. Gathering a database consisting of their detailed production rates and patterns and the properties of their products is essential in the interest of achieving a comprehensive and advantageous simulation results.

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Appendix A: Database used in BSCM Simulation Model

Table 24 - Appendix A: Data Set of Biomass Suppliers (biomassData Table)

ID	Location (city)	Prov	Lat	Lon	MC_%	size	type
1	Grand Cache	AB	53.90755	-118.968	52	2	6
2	La Crete	AB	58.14868	-116.364	26	2	2
3	Slave Lake	AB	55.26771	-114.591	28	2	14
4	Prince George	BC	53.83124	-122.735	54	2	5
5	Strathnaver	BC	53.28351	-122.495	29	2	1
6	Burns Lake	BC	54.22611	-125.752	52	2	15
7	Armstrong	BC	50.44291	-119.2	36	2	9
8	Williams Lake	BC	52.11633	-122.129	46	2	7
9	Quesnel	BC	52.98174	-122.495	52	1	15
10	Coldstream	BC	50.23633	-119.108	55	2	5
11	Houston	BC	54.38555	-126.723	50	1	3
12	West Kelowna	BC	49.86089	-119.594	27	2	15
13	Kamloops	BC	50.65273	-120.046	46	2	11
14	Vanderhoof	BC	54.01449	-124.051	55	1	1
15	Vanderhoof	BC	54.02597	-124.09	22	2	16
16	Merritt	BC	50.10472	-120.787	31	2	12
17	Swan River	MB	52.12819	-101.28	39	1	2
18	Bristol	NB	46.47166	-67.5711	46	1	14
19	St-Quentin	NB	47.51338	-67.3776	21	0	8
20	Tracyville	NB	45.76655	-66.6844	21	1	10
21	Weldon	NB	45.9452	-64.6924	26	1	15
22	Summerford	NL	49.49282	-54.8165	46	0	10
23	Milford	NS	45.05538	-63.4462	55	1	2
24	Lawrencetown	NS	44.90071	-65.1812	49	1	14
25	New Liskeard	ON	47.6267	-79.6748	58	0	10
26	Thunder Bay	ON	48.35864	-89.2353	23	1	3
27	St. Marys	ON	43.29511	-81.0766	44	2	14
28	Hearst	ON	49.67194	-83.5343	54	0	7
29	Lac-Megantic	QC	45.57524	-70.8731	39	2	8
30	Sacre-Coeur	QC	48.26813	-69.898	24	0	16
31	St-Felicien	QC	48.64012	-72.4191	60	0	13
32	Shawinigan-Sud	QC	46.50522	-72.7177	45	2	1
33	Papineauville	QC	45.66078	-75.0256	37	1	16
34	Meadow Lake	SK	54.13566	-108.406	30	0	5
35	Skookumchuck	BC	49.91485	-115.767	20	1	4
36	Princeton	BC	49.467	-120.493	20	2	15
37	Melancthon	ON	44.23558	-80.2851	51	0	12
38	St-Paulin	QC	46.42651	-73.0162	21	1	4

Table 25 - Appendix A: Data Set of Biomass Types (typesData Table)

No	Name	kwh/kg	Ash%	Carbon%	density_LOW (kg/m3)	density_HIGH (kg/m3)	Base_Price_CAD (100kg)	PriorityOfUse
1	Big blue stem	5.181811115	6.1	44.4	24	111	8.5	1
2	Miscanthus	5.330416671	2.7	47.9	24	111	8.5	4
3	Sorghum	4.677844448	6.6	45.8	24	111	8.5	3
4	Switchgrass	5.123015004	5.7	45.5	49	266	8.5	2
5	Alfalfa	4.803836115	9.1	45.9	34	323	8	6
6	Barley straw	4.832911115	5.9	46.9	24	111	5	7
7	Corn cobs	5.121722782	1.5	48.1	170	297	10	5
8	Corn stover	5.143044449	5.1	43.7	50	130	8	8
9	Flax straw	5.046127782	3.7	48.2	24	111	8	10
10	Wheat straw	4.981516671	7.7	43.4	24	111	9	9
11	Oat hulls	5.143044449	5.1	46.7	70	200	13.5	13
12	Soybean hulls	4.987977782	4.3	43.2	70	200	13	12
13	Sunflower hulls	5.511327782	4	47.5	70	200	14	11
14	Bark	5.448008893	1.5	47.8	200	280	25	14
15	Willow	5.524250004	2.1	50.1	400	600	30	16
16	Spruce	5.362722227	0.4	48.3	600	750	30	15

Table 26 - Appendix A: Data Set of Effects of Seasons on Biomass Production Rates (weatherEffectsData Table)

No	January	February	March	April	May	June	July	August	September	October	November	December
1	0	0	0	0	0.6	1	1	1	0.4	0.2	0.1	0
2	0	0	0.4	0.8	1	1	0.8	0.6	0.4	0.2	0.1	0
3	0	0	0	0	0	1	1	0.6	0.4	0.2	0.1	0
4	0	0	0	0	0.4	1	1	1	0.8	0.6	0	0
5	0	0	0	0	1	1	1	1	1	0.4	0	0
6	0	0	0.4	0.8	1	1	1	1	0.4	0	0	0
7	0	0	0	0.7	0.9	1	1	1	1	0.5	0	0
8	0	0	0	0.7	0.9	1	1	1	1	0.5	0	0
9	0	0	1	1	1	0.5	0	0	0	0	0	0
10	0	0	0	0.4	1	1	1	1	0.8	0.4	0	0
11	0.4	0.4	0.4	0.4	0.4	0.4	1	1	1	0.4	0.4	0.4
12	0.4	0.4	0.4	0.4	0.4	0.4	1	1	1	0.4	0.4	0.4
13	0.4	0.4	0.4	0.4	0.4	0.4	1	1	1	0.4	0.4	0.4
14	0	0.6	0.6	1	1	1	1	1	1	1	0	0
15	0.4	0.6	0.6	1	1	1	1	1	1	1	0.6	0.4
16	0.4	0.6	0.6	1	1	1	1	1	1	1	0.6	0.4

Table 27 - Appendix A: Data Set of Biomass Demand (demandData Table)

month	demand_KWH
1	2000.0016
2	1750.0014
3	1625.0013
4	875.0007
5	375.0003
6	375.0003
7	375.0003
8	375.0003
9	375.0003
10	875.0007
11	1500.0012
12	2000.0016

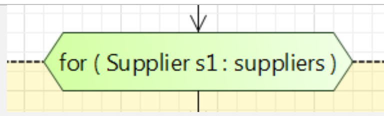
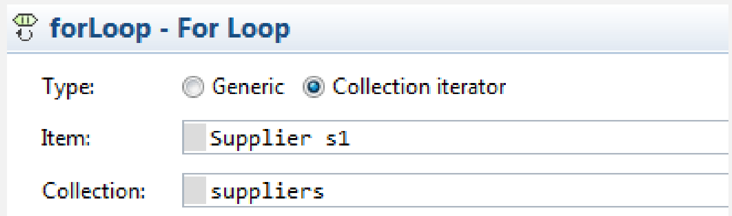
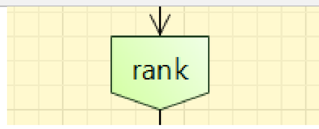
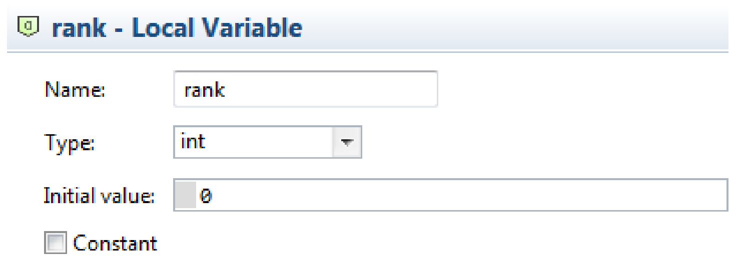
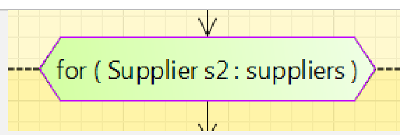
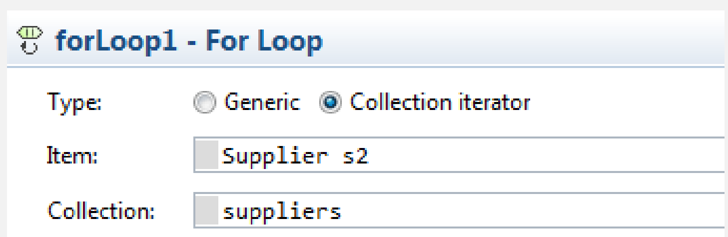
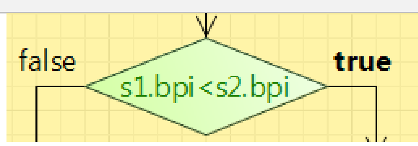
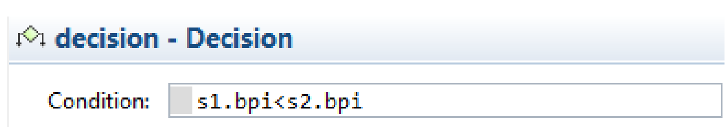
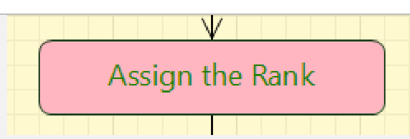
Table 28 - Appendix A: Data Set of the Planned Purchase (purchaseData Table)

month	Planned_Purchase
1	0
2	0
3	875.0007
4	375.0003
5	375.0003
6	375.0003
7	375.0003
8	1125.005
9	3000.0003
10	3000.0012
11	3000.0016
12	0

Table 29 - Appendix A: Scale of Production

Size	Scale of Production (kg per month)
0	Assigned based on a Uniform distribution on the interval [0,250)
1	Assigned based on a Uniform distribution on the interval [250,500)
2	Assigned based on a Uniform distribution on the interval [500,750)

Table 30 - Appendix B: rankingChart Elements

Element	Action
	Iterates between all the suppliers 
	Creates a local variable called "rank". 
	Iterates between all the suppliers 
	The supplier with the lower pbi passes this condition. 
	Supplier's rank is increased by 1.

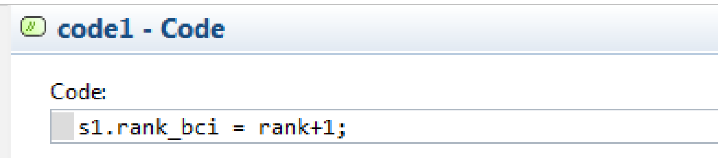
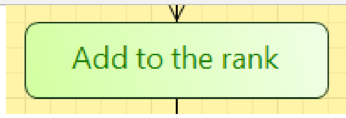
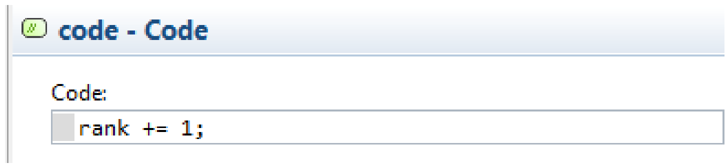
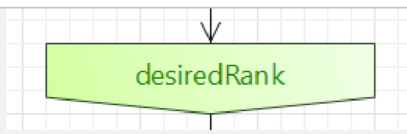
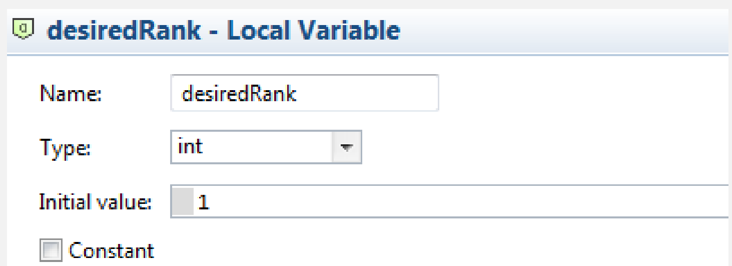
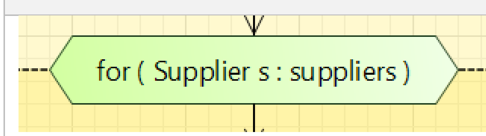
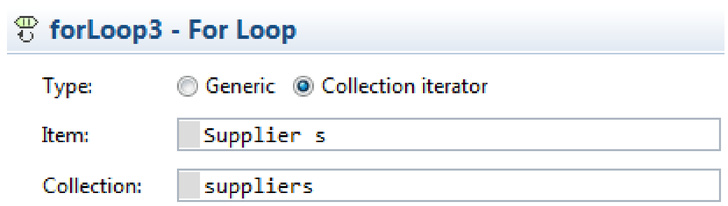
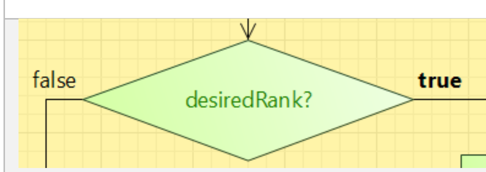
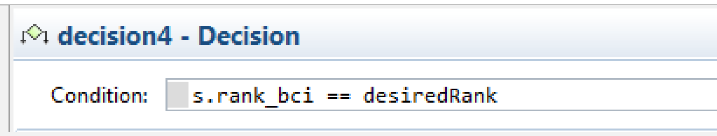
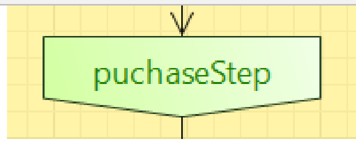
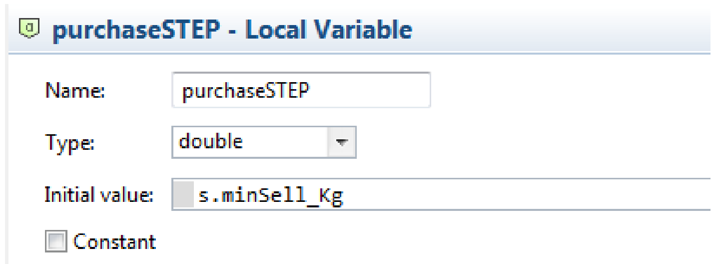
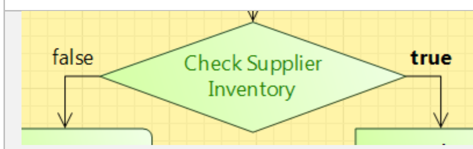
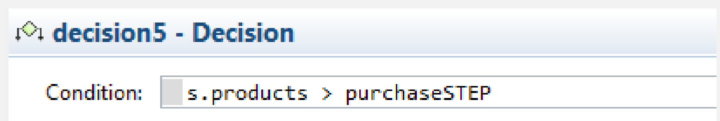
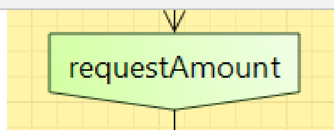
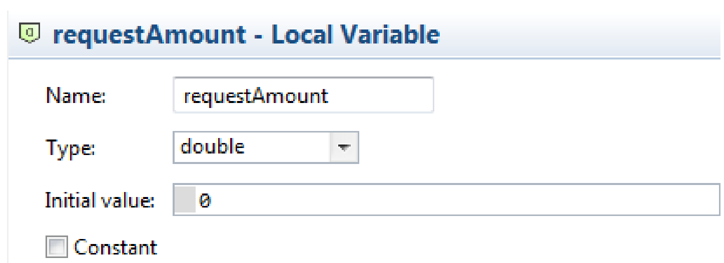
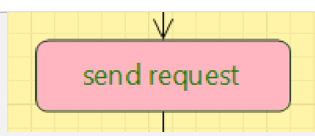
	
	Moves on to the next rank. 

Table 31 - Appendix B: selectionChart Elements

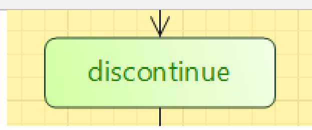
Element	Action
	Creates a local variable called "desiredRank" with initial value of 1. 
	Iterates between all the suppliers 
	Checks if the supplier's rank is equal to the desiredRank.

	
	Creates a local variable called "purchaseStep". 
	Checks if the supplier's inventory has enough biomass to make a trade. 
	Creates a local variable called "requestAmount". 
	Sends a purchase request to the selected supplier.

code4 - Code

Code:

```
do  {
    requestAmount += purchaseSTEP;
    biopowerPlant.satisfiedPurchase +=
    s.minSell_Kg*s.biomassTypeAgent.kwhKg;
    s.products -= purchaseSTEP;
    } while (s.products >= purchaseSTEP);

deliver(requestAmount,s);
s.numberOfPurchasesDone +=1;

int n = (int) max(requestAmount/s.maxWeightFTL_Kg,
        requestAmount/s.density/s.maxVolumeFTL_m3) + 1;

this.numTruckTest = n;

this.cumulativeBiomassTransportationCost +=
 n * s.overallTransportationCost;
this.cumulativeBiomassPurchaseCost +=
 s.biomassTypeAgent.basePriceCad100kg/100*requestAmount;

if(s.mc > this.maxAcceptableMC)
    this.cumulativeTreatmentCost +=
     s.treatmentCost*requestAmount;

for (int i = 0; i < 16; i++)
    if (s.type == i+1)
        this.purchaseData.set(i,
        purchaseData.get(i)+requestAmount);
```

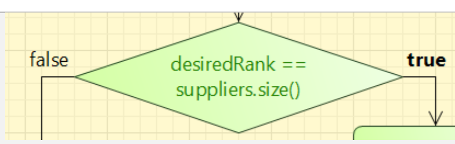


When the purchasePlan is satisfied, stops the process.

code2 - Code

Code:

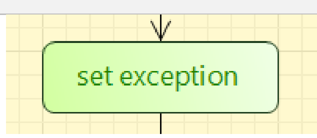
```
break;
```



Condition is true when an iteration has been conducted between all the suppliers.

decision2 - Decision

Condition: `desiredRank == suppliers.size()`



Sets an error message to the variable exceptionNotEnoughBiomass.

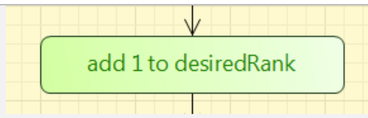
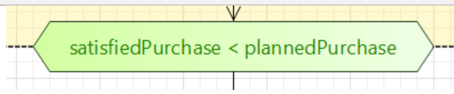
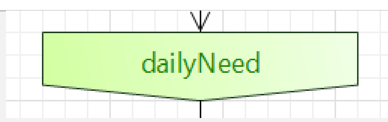
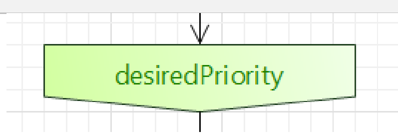
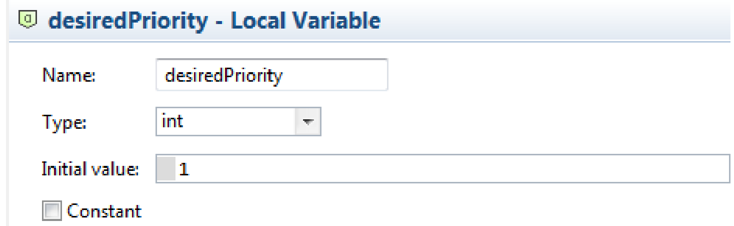
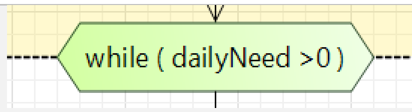
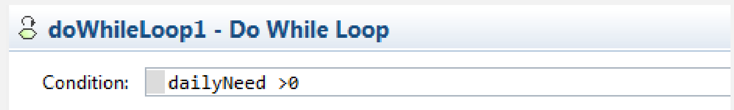
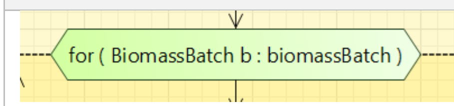
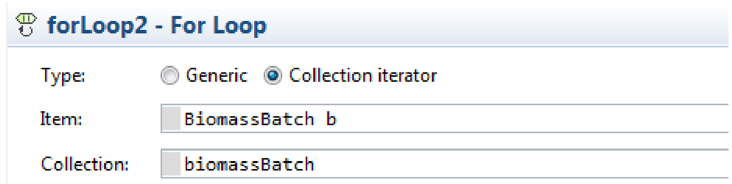
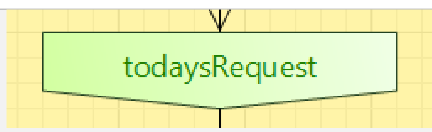
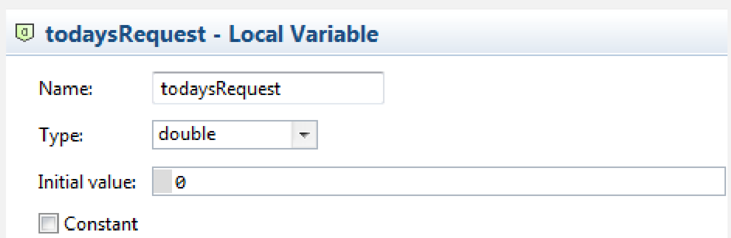
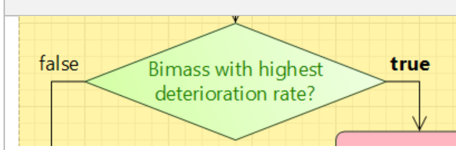
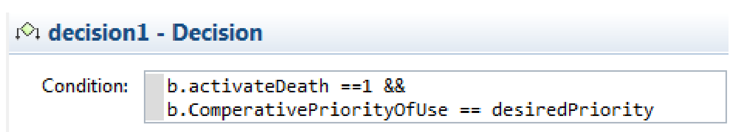
	code7 - Code Code: `double i = biopowerPlant.plannedPurchase_kwh -` `        biopowerPlant.satisfiedPurchase;` `this.exceptionNotEnoughBiomass +=` `    "Not Enough Biomass Available for month " + getMonth() +` `    ". Amount: " + i + "\n";` `break;`
	Increases the desired rank by 1. **code5 - Code** Code: `desiredRank +=1 ;`
	Repeats the process until plannedPurchase has been satisfied. **doWhileLoop - Do While Loop** Condition: `biopowerPlant.satisfiedPurchase < biopowerPlant.plannedPurchase_kwh`

Table 32 - Appendix B: setDailyUsage Elements

Element	Action
	Creates a local variable called "dailyNeed" **dailyNeed - Local Variable** Name: dailyNeed Type: double Initial value: `this.biopowerPlant.demand_kwh/28` ☐ Constant
	Creates a local variable called "desiredPriority"

<table>
<tr><td></td><td>
</td></tr>
<tr><td>
</td><td>Conducts the process as long as the dailyNeed is positive.

</td></tr>
<tr><td>
</td><td>Iterates between all the biomass batches in the inventory.

</td></tr>
<tr><td>
</td><td>Creates a local variable called “todaysRequest”

</td></tr>
<tr><td>
</td><td>The biomass with higher deterioration rate passes this condition.

</td></tr>
</table>

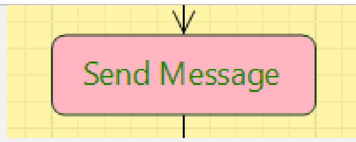
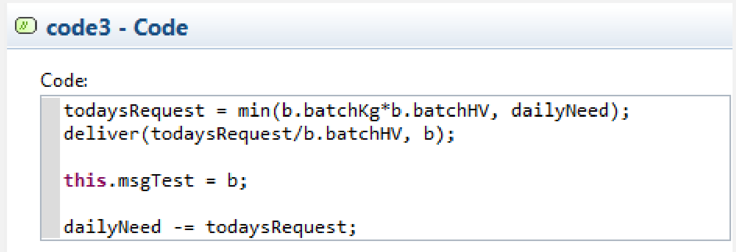
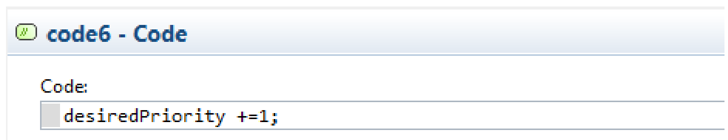
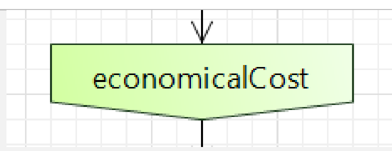
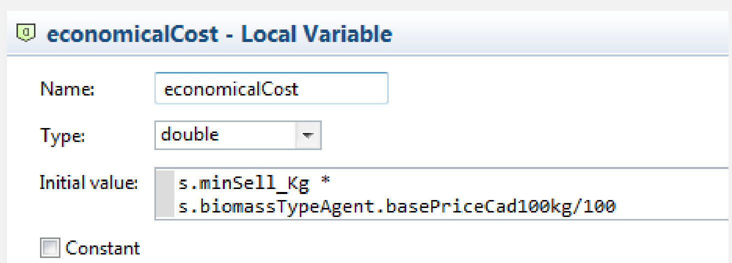
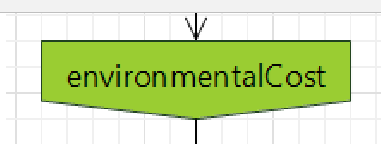
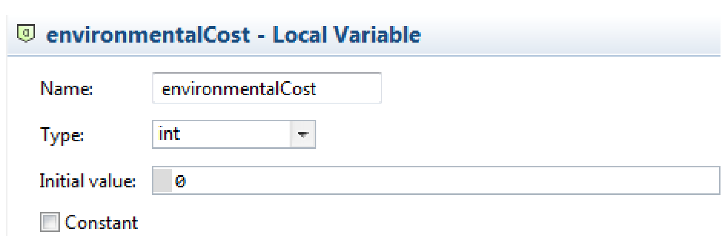
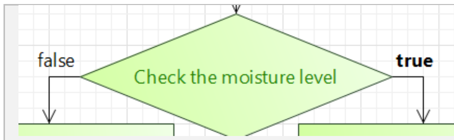
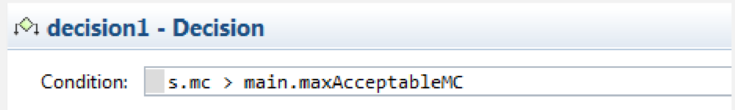
<table>
<tr><td>
</td><td>Sends a message to consume a specified amount from the selected biomass type.

</td></tr>
<tr><td>
</td><td>Increases the desiredPriority rank by 1.

</td></tr>
</table>

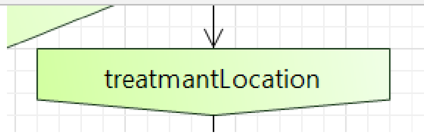
Table 33 - Appendix B: ecoEnvCostCalculator Elements

<table>
<tr><th>Element</th><th>Action</th></tr>
<tr><td>
</td><td>Creates a local variable called “economicalCost”.

</td></tr>
<tr><td>
</td><td>Creates a local variable called “environmentalCost”.

</td></tr>
</table>

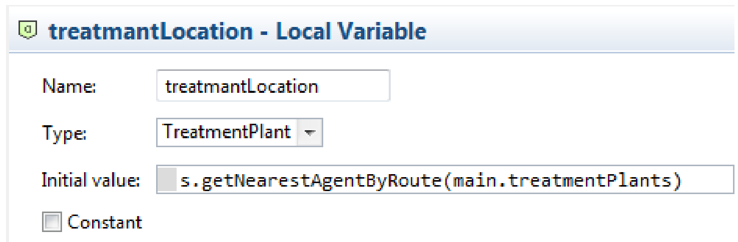


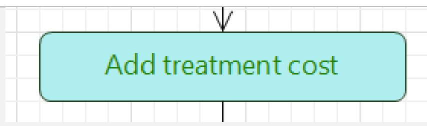
Checks if the supplier's product has an acceptable MC.



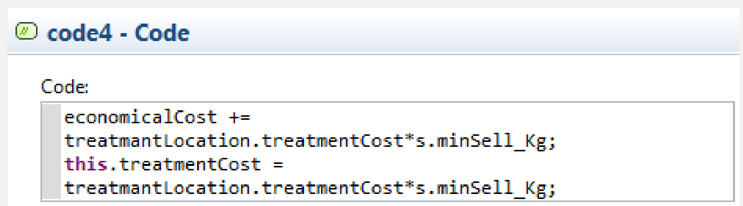


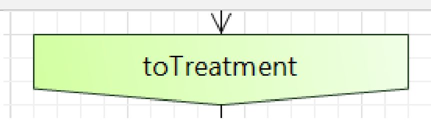
Creates a local variable from the treatmentPlant type called "treatmentLocation"



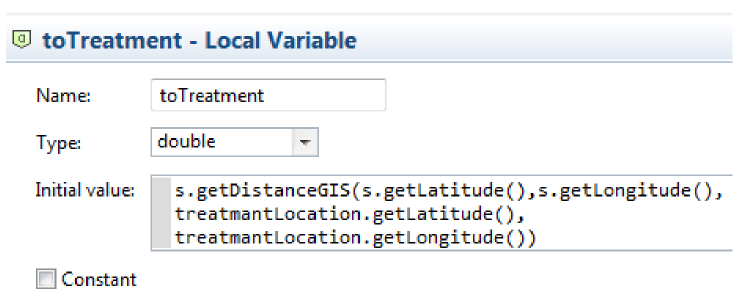


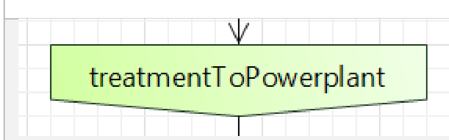
Adds treatment cost to economicalCost.



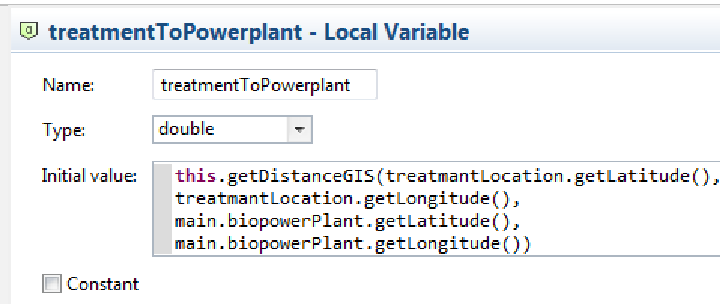


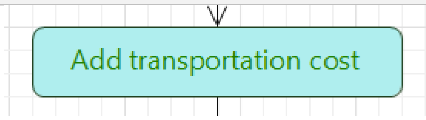
Creates a local variable called "toTreatment" with the initial value of the distance between the supplier and the nearest treatment plant's location.



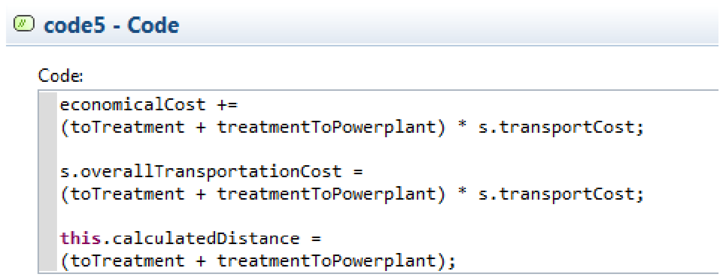


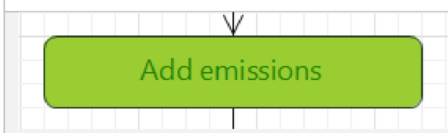
Creates a local variable called "treatmentToPowerplant" with the initial value of the distance between the nearest treatment plant and the power plant's location.



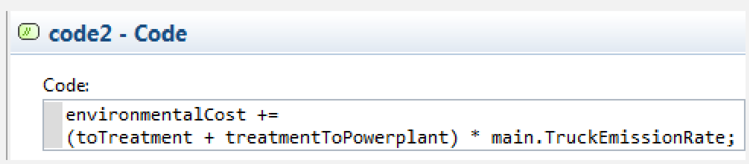


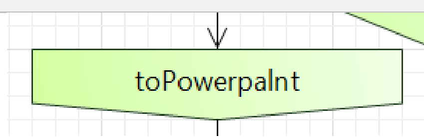
Calculates the transportation costs and adds it the economicalCost.



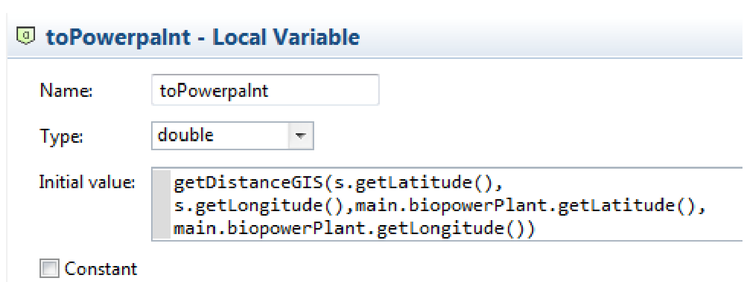


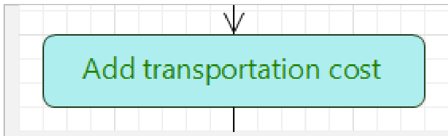
Calculates the transportation related emissions and adds it to the economicalCost





Creates a local variable called “toPowerplant” with the initial value of the distance between the supplier and the power plant’s location.



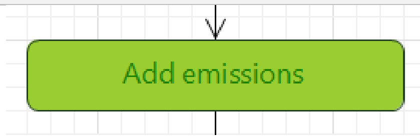


Calculates the transportation costs and adds it the economicalCost.

code6 - Code

Code:

```
economicalCost += toPowerpalnt*s.transportCost;

s.overallTransportationCost = toPowerpalnt*s.transportCost;
this.calculatedDistance = toPowerpalnt;
```

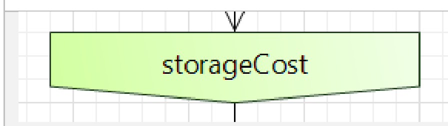


Calculates the transportation related emissions and adds it to the economicalCost

code1 - Code

Code:

```
environmentalCost += toPowerpalnt * main.TruckEmissionRate;
```



Calculates the cost of storing the product for one month and store it in a local variable called storageCost.

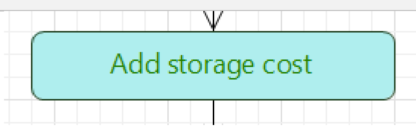
storageCost - Local Variable

Name: storageCost

Type: double

Initial value: `s.minSell_Kg/s.density*BiopowerPlant.storageCostRate`

☐ Constant

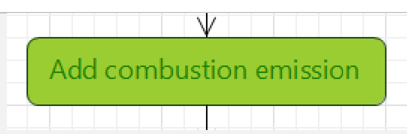


Adds the storage cost to the economicalCost.

code - Code

Code:

```
economicalCost += storageCost;
```



Adds the combustion emissions to the environmentalCost.

code8 - Code

Code:

```
economicalCost +=
s.biomassTypeAgent.carbon * 0.01 * s.minSell_Kg;
```

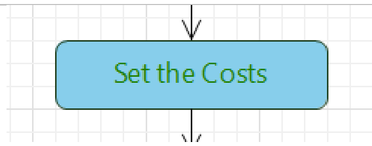
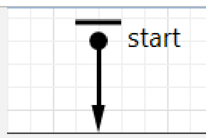
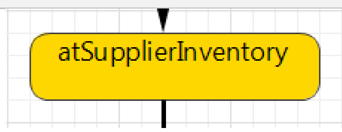
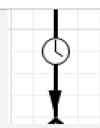
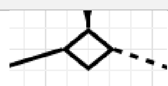
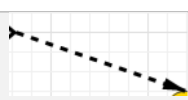
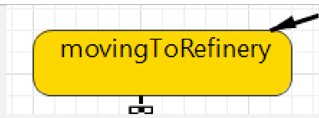
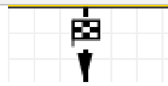
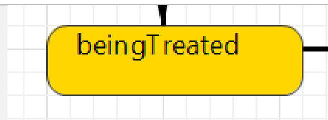
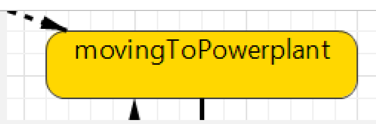
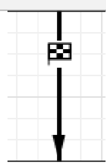
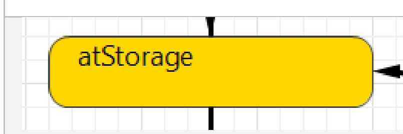
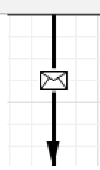
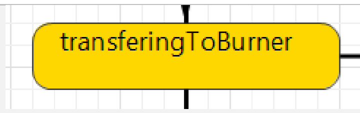
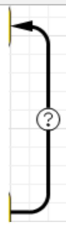
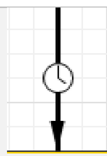
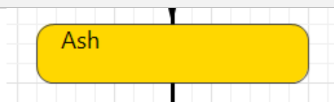
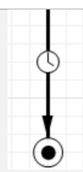
	Calculates the economic and environmental costs. code7 - Code Code: `s.economicalCost = economicalCost;` `s.environmentalCost = environmentalCost;`

Table 34 - Appendix B: Elements of biomassBatch State Chart

Element	Action
	Represents the state chart entry point.
	Purchased biomass is in the supplier's inventory/
	Purchased biomass (biomass batch) is being prepared to be shipped. This transition is triggered by timeout.
	Represents a transition branching and/or connection point. Regarding to batch's MC it will be either transported to a treatment plant or the biopower plant.
	The default transition that makes the agent move towards the biopower plant. Action: `moveTo(main.biopowerPlant);`
	If batchMC is greater than maxAcceptableMC, biomass batch moves toward the nearest treatment plant.

	Condition: `this.batchMC>=main.maxAcceptableMC` Action: `moveTo(this.getNearestAgentByRoute (main.treatmentPlants));`
	Biomass batch is moving to the treatment plant.
	This transition is activated at agent's arrival.
	At this state, the biomass batch is being treated and its MC will be reduced 40%. Exit action: `this.batchMC = 0.40 * this.batchMC`
	This transition is triggered when the treatment is done. Biomass batch starts moving towards the biopower plant. Action: `moveTo(main.biopowerPlant);`
	Biomass batch is moving towards the biopower plant.
	This transition is activated at agent's arrival. The batch's volume is added to the occupied space of the inventory. Action: `BiopowerPlant.occupiedStorageSpace += initialBatchKg/batchDensity;` `this.presentation.clear();`
	Biomass batch is stored in the inventory.
	This transaction is activated when setDailyUsage action chart sends a message to transfer a specified amount of the biomass to the burner.

	Action: `this.batchKg -= msg;` `main.biopowerPlant.occupiedStorageSpace -= msg/batchDensity;` `main.biopowerPlant.satisfiedDemand += batchHV * msg;`
	Biomass is being transferred to the burner.
	After satisfying the demand the remaining biomass, if any, it goes back to atStorage state.
	Biomass is being consumed.
	Biomass has turned into ash. At this phase activateDeath variable is set to 0.
	Biomass batch's life time ends.