Canadian Journal of Forest Research
Revue canadienne de recherche forestière

**Forest biomass supply chain optimization for a biorefinery
aiming to produce high-value bio-based materials and
chemicals from lignin and forestry residues: A review of
literature**

Journal:	<i>Canadian Journal of Forest Research</i>
Manuscript ID	cjfr-2016-0336.R2
Manuscript Type:	Review
Date Submitted by the Author:	01-Nov-2016
Complete List of Authors:	Dessbesell, Luana; Lakehead University, Faculty of Natural Resources Management Xu, Chunbao (Charles); Institute for Chemicals and Fuels from Alternative Resources (ICFAR), Department of Chemical and Biochemical Engineering, Western University Pulkki, Reino; Lakehead University, Faculty of Natural Resources Management Leitch, Mathew; Lakehead University, Faculty of Natural Resources Management Mahmood, Nubla; Institute for Chemicals and Fuels from Alternative Resources (ICFAR), Department of Chemical and Biochemical Engineering, Western University
Keyword:	biomass-to-energy, biomass-to-materials and chemicals, economic optimization, lignocellulosic residues, value-added bio-based products

SCHOLARONE™
Manuscripts

Forest biomass supply chain optimization for a biorefinery aiming to produce high-value bio-based materials and chemicals from lignin and forestry residues: A review of literature

Luana Dessbesell^{a*}, Chunbao (Charles) Xu^{b*}, , Reino Pulkki^a, Mathew Leitch^a, Nubla Mahmood^b

^aLakehead University, Faculty of Natural Resources Management, Braun Building, BB1007D - 955 Oliver Rd, Thunder Bay, ON P7B 5E.

^b Institute for Chemicals and Fuels from Alternative Resources (ICFAR), Department of Chemical and Biochemical Engineering, ICFAR, Rm. 108 and Room CMLP 2335, Western University

Email: ldessbes@lakeheadu.ca (L.D); nmahmoo2@uwo.ca (N.M); mathew.leitch@lakeheadu.ca (M.L); rpulkki@lakeheadu.ca (R. P.); and, cxu6@uwo.ca (C.X).

**Corresponding authors: ldessbes@lakeheadu.ca (L.D) Phone: (807) 766 -7127 and, cxu6@uwo.ca (C. X.) Phone: 519-661-2111 ext. 86414. Fax: 519-661-4016*

19 **Abstract**

20 Technological development has enabled the production of new value-added products from
21 lignocellulosic residues, such as lignin. This has allowed the forest industry to diversify its
22 product portfolio and maximize the economic returns from feedstock, while simultaneously
23 working towards sustainable alternatives to petroleum-based products. Although previous
24 research has explored industrial-scale production opportunities, many challenges persist
25 including the cost of woody biomass and its supply chain reliability. While numerous studies
26 have addressed these issues, their emphasis has traditionally been on bioenergy, with little
27 focus on biochemicals and biomaterials/bio-products. This review seeks to address this gap
28 through a systematic study of the work recently reported by researchers. A lot of work has
29 been published from United States and Canada with an emphasis on bioenergy production
30 (84.8%), 4.6% of the work is focused on biomass-to-materials or chemicals, and 10.6%
31 addressed both. Between 2012 and 2015, the majority of published research is focused on
32 “biomass-to-materials and chemicals” and both “biomass-to-energy and biomass-to-materials
33 and chemicals”. This fact highlights recent interests in diversified biorefinery portfolios.
34 However, further work concerning forest biomass supply chain optimization, and new high-
35 value bio-based materials and chemicals is necessary.

36

37 **Keywords:** biomass-to-energy, biomass-to-materials and chemicals, economic optimization,
38 lignocellulosic residues, value-added bio-based products.

39 **1. Introduction**

40

41 Countries around the world are adopting laws/policies intended to lower Greenhouse
42 Gas (GHG) emissions, which results in an increasing interest in alternative renewable sources
43 for producing bioenergy, biochemicals, and biomaterials. Despite this interest, according to
44 the International Energy Agency (IEA), oil, natural gas and coal still account for almost
45 81.7% of the world’s current primary energy supply (Bell et al. 2014). Moreover, many
46 industrial chemicals and synthetic materials are still dependent on petroleum-derived
47 products (Kurian et al. 2013). For instance, 42% of the petroleum revenue came from
48 chemicals, plastic and rubber. Surprisingly, this category consumes only 4% of petroleum
49 (Werpy, 2009).

50 As an alternative feedstock to petroleum-based products, lignocellulosic biomass has
51 been recognized as a promising resource for the production of non-energy commodities, such
52 as chemicals, fibres, plastics and construction materials because of its chemical properties
53 and abundance (Fahd et al. 2011; Iqbal et al. 2013; Isikgor and Becer 2015). Additionally,
54 lignocellulosic biomass provides means of helping the forest sector transition into a more
55 diverse, market-driven industry, while concurrently improving its environmental footprint
56 (Thiffault et al. 2014). Thus, the biorefining approach has become a favourable pathway to
57 obtain value-added products from forest and mill residues. The biorefinery concept is defined
58 by the IEA - Task42 Biorefining, as the “sustainable and synergetic transformation of low-
59 value biomass into marketable food and feed ingredients, products (chemicals, materials) and
60 energy (fuels, power, heat)” (Bell et al. 2014).

61 In this context, researchers have been working intensively to improve biomass
62 conversion technologies towards commercial-scale facilities (Hughes et al. 2013). However,
63 despite the increased efficiency of the technology in the last decade, ongoing challenges

64 related to the feedstock logistics and biomass valorization have resulted in only a small
65 number of operational industrial biorefineries (Kurian et al. 2013).

66 While the biorefinery concept has emerged as an alternative way to petroleum
67 dependence, the rising demand for biomass from the traditional forest industry and the
68 emerging bioproducts industry have increased the complexity of multilevel supply systems.
69 This creates a need for the integrated biomass supply chain management (BSCM) approaches
70 (Iakovou et al. 2010). Therefore, a method for designing profitable biomass supply chains
71 (BSC), which can also accommodate these aforementioned challenges, is vital to the long-
72 term economic viability of this emerging industry (Sukumara et al. 2014; An and Wilhelm
73 2014).

74 The development of an efficient BSC to provide a low-cost biomass feedstock
75 requires detailed investigation and analysis. In recent years, there have been an increasing
76 number of literature reviews on BSC. The following summarizes the subjects addressed by
77 recent review papers:

- 78 • main concerns related to bioenergy BSC and logistics (e.g. Gold and Seurig, 2011 and
79 Kurian et al. 2013);
- 80 • effect of different feedstocks types on the BSCM (e.g. Iakovou et al. 2010 and Kurian
81 et al. 2013);
- 82 • multi-criteria decision-making methods were addressing problems arising within the
83 bioenergy sector (e.g. Scott et al. 2012);
- 84 • bio-fuel BSC under uncertainties (e.g. Awudu and Zhang, 2012);
- 85 • deterministic and stochastic models applied in bioenergy value chain optimization
86 (e.g. Shabani et al. 2013);
- 87 • assessment and optimization of forest biomass supply chain (FBSC), considering
88 economic, social and environmental aspects (e.g. Cambero and Sowlati, 2014);

- 89 • development of energy BSC optimization frameworks (e.g. Elia and Floudas, 2014).
90 Strategic challenges and issues with design, planning, and management of BSC (e.g.
91 Mafakheri and Nasiri, 2014); and,
92 • multi-scale modeling and optimization of BSCs (e.g. Yue et al. 2014).

93 Additionally, there are a number of literature reviews regarding thermochemical
94 technologies and the opportunities associated with lignocellulosic biomass (e.g. Iqbal et al.
95 2013; Isikgor and Becer 2015). While studies examining FBSC and conversion technologies
96 to produce bio-based value-added products are quickly evolving, a review covering those
97 subjects is very limited or missing.

98 To fill this gap in the literature, this work endeavours to answer some questions such
99 as “What products shall be targeted in a biorefinery based on FBSC optimization?” To
100 accomplish this, the remainder of this work is organized into two sections. The first part
101 outlines recent advancements in conversion technologies and bio-based products from forest
102 residues focusing on lignin. The second part presents a systematic review of FBSC studies.
103 This paper contributes to the body of knowledge by: (i) summarizing recent achievements in
104 the production of bio-based products from lignin and forest residues; (ii) providing an
105 overview of BSC studies, based on their year of publication, research objectives, country of
106 origin and journal; and, (iii) identifying the bioproducts targeted in the FBSC optimization
107 studies and summarizing the number of articles that addressed bio-based materials and
108 chemicals.

109

110 **2. Methods**

111

112 *2.1 Narrative literature review*

To provide the background information on thermochemical technologies to produce value-added bio-based chemicals and materials from lignin and forest residues a narrative review was performed in the first section of this paper.

A narrative review is a combination of published information, where it typically summarizes the contents of each paper (Green et al. 2001). In this first section we focused on the research work done by the research team of the Institute for Chemicals and Fuels from Alternative Resources (ICFAR) and Lignoworks (The NSERC Biomaterials and Chemicals Strategic Research Network: <http://www.icfar.ca/lignoworks/>) in Canada, which have significantly contributed to the Canadian forest industry by generating alternative products and technologies from forest and mill residues.

Publications from Canada were reviewed in this paper; the country is one of the leading countries in research in this field, and can provide a considerable number of papers satisfying a narrative review to cover the topic.

2.2 Systematic literature review

In this section, the literature on supply chain optimization is collected through a search and screening of research and literature review papers that address different components of the BSC. Secondly, a systematic review is presented, based on the process described below.

The systematic review helps to identify the difference between real and presumed knowledge through mapping out areas of uncertainty, determining in what fields little research has been done and identifying topics in which more research is necessary (Petticrew and Roberts 2006). The systematic review followed five main steps: identifying key terms/words, locating/searching literature, checking publications applicable to the topic, classifying the literature and writing the literature review.

The keyword “biomass* supply* chain*” was searched in the ISI Web of Knowledge (WOK), resulting in the retrieval of 979 documents. All database years of ISI were taken into consideration, and the results were saved in End Note Web for external review and verification (a complete list of documents can be obtained by contacting the first author). The data were then entered into Microsoft Excel for analysis. The review focused on English language peer-reviewed literature documenting FBSC technical and economic optimization. Therefore, to be included the paper had to be considering at least one forest-based feedstock also perform a BSC techno-economic optimization.

3. A narrative literature review on alternative sources and thermochemical technologies for production of bio-based chemicals and materials

3.1 Alternatives sources for bio-based products

Energy crops, forest and agriculture biomass residues are renewable resources that can potentially offset future petroleum shortages while decreasing GHG emissions and not compromising food supply (Bell et al. 2014). Lignocellulose is a major structural component of woody and non-woody plants and consists of cellulose, hemicellulose and lignin (Menon and Rao 2012).

Cellulose constitutes more than 40% of the wood and is present mainly in the secondary cell walls (Sjöström 1993). Hemicelluloses are heteropolysaccharides that also function as supporting materials in the cell walls (Sjöström 1993). Lastly, “Lignin is a complex three-dimensional biopolymer of aromatic alcohols” (Ferdosian et al. 2014). After cellulose, lignin is the second most abundant renewable natural polymer, accounting for between 15% and 40% of stem wood, depending on species (Holladay et al. 2007; Novaes et al. 2010).

Recently, cellulose has become a source material for a variety of products, in addition to traditional products, such as pulp and paper. The cellulose and hemicellulose-derived carbohydrates can be refined into various value-added bio-based products, such as alcohols, esters and carboxylic acids, through so-called “sugar platform” biorefineries (Cheng et al. 2010). Moreover, the world’s first cellulose nano-crystalline plant was built in Canada with a capacity of one t·day⁻¹ (Hamel 2016).

Innovative technologies to create value-added and high-value bio-based products have led to improved usage of forest harvesting and mill residues, such as kraft lignin. The primary source of technical lignin is the pulp and paper industry (Mahmood et al. 2013). According to Moshkelani et al. (2013), the kraft lignin pulping residues can increase the revenue margin of mills through conversion into higher valued marketable products such as biofuels, synthetic gas and chemicals.

In the kraft pulping process, only 42% to 44% of softwood biomass after bleaching, and about 50% of hardwood is converted into pulp, and the residue (mainly hemicelluloses and lignin) is combusted in the recovery boiler (Moshkelani et al. 2013). Laurichesse and Avérous (2014) estimated that annual global production of lignin is over 70 million tonnes, around 95% of which is burned in recovery boilers for steam and power generation. Only about 5% of lignin (mainly lignosulphonate) is utilized for production of value-added bio-based products, such as dispersants, adhesives and surfactants.

Lignin is an exceptionally abundant raw material and, therefore, offers an opportunity for lignocellulosic biorefineries. According to Hughes et al. (2013), biorefining technologies are available to utilize and fractionate lignocellulosic feedstock to produce intermediate and final products (Hughes et al. 2013). However, there are a few kraft lignin plants in North America, including the Mead-Westvaco in South Carolina, USA, which produces approximately 20,000 t·yr⁻¹ of kraft lignin (Huang 2014). In 2013, Domtar started to produce

75 t·d⁻¹ of kraft lignin at its Plymouth, North Carolina plant (Huang 2014). A commercial-scale kraft lignin production plant with a targeted capacity of 30 t·d⁻¹ is under construction in Hinton, Canada based on the LignoForceTM system created by FPInnovations. Also, a lignin precipitation pilot plant, the first facility of its kind in North America, is installed at Resolute Forest Products in Thunder Bay, Ontario, with capacity for 100 kg·d⁻¹ (Canadian Biomass 2013).

Holladay et al. (2007) considered six scenarios where 225 million tonnes of lignin were utilized for power, transportation fuels, products and chemicals, both individually and in various combinations. When lignin is used for purposes other than power, the overall revenue increase is \$12-35 billion. However, significant technological development will be required to seize the full value benefit.

Research in non-traditional wood products that can be produced alongside traditional products has been playing a prominent role in expanding the current wood product portfolio, to take advantage of new market opportunities (Blair 2013). A biorefinery model proposed by the Canada Bio-pathways Project is based on extracting the largest possible value from a forest feedstock. Products originating from this process include both traditional and novel ones that satisfy the primary criteria that the highest possible value must be generated at every stage. Ordinarily, heat and power are a necessary part of the combination (Browne et al. 2011).

Specialty chemicals are said to be promising elements of a forest biorefinery products portfolio because they have the highest profit margins compared to pulp and paper products, and less competition within the market. This allows biorefineries to reduce their direct competition with well-established commodity petrochemical products (Mansoornejad 2012).

Browne et al. (2011) analyzed the relationship between annual market size and price of forest products. They concluded that the products with higher market price have a smaller

market size, and vice versa. For instance, polyphenols (biomass-derived specialty chemicals), have a market size of 10^4 kg per year, and a market price higher than US\$100/kg. In contrast, cellulose-based fibres have a world market of the order of 10^{11} kg, but regular sales prices are of the order of \$1/kg.

3.2 Thermochemical conversion technologies

Commercial scale conversion of lignocellulosic materials to value-added bio-based products is still a challenging proposal. According to Ghatak (2011), an upgraded technology for lignin isolation from black liquor, and breakthroughs in industrial chemistry and chemical technology for value-added products from lignin can profoundly improve a lignocellulosic biorefinery.

There are a number of conversion technologies available to convert biomass residues into a range of biofuels and chemicals (Srirangan et al. 2012). In this paper, a short overview of recent papers addressing lignin conversion technologies for chemicals and materials is presented. For an in-depth review the following papers are recommended: Zhang et al. 2010a; Srirangan et al. 2012; Iqbal et al. 2013; and, Shen et al. 2015. Additionally, particularly for lignin conversion technologies, particularly Pandey and Kim (2011), Huang (2014), and Laurichesse and Avérous (2014) are useful literature sources.

Biomass gasification is a sustainable process, which uses gasification agents such as air/oxygen, steam, CO_2 or their combinations for converting lignocellulosic biomass into low to medium Btu (British thermal unit) fuel gasses (Hurley et al. 2010). For Feng et al. (2015) there are two pathways to obtain renewable phenol alternatives. The first is to extract chemical components such as lignin and alkaline extractives from lignocellulosic biomass. The second is to convert lignocellulosic biomass via various thermochemical processes (i.e., phenolysis, liquefaction and pyrolysis) into phenolic bio-crude, bio-oil or pyrolysis oil.

Lignin can be degraded or decompose into oligomeric and monomeric phenolic compounds by different processes, such as hydrolysis and pyrolysis (Pandey and Kim 2011). These compounds then become potential sources of biophenols for replacing petroleum-based phenols in the production of phenol formaldehyde (PF) resins (Cheng et al. 2011).

Direct liquefaction is considered a favourable route for converting biomass into liquid fuels and value-added chemicals (Feng et al. 2015). High-pressure direct liquefaction technology was found to be superior when compared to pyrolysis technology as it produces liquid oils with much greater caloric values (Yang et al. 2009a). Bio-oil products from fast pyrolysis contain high contents of water and oxygen leading to relatively low heating values. In contrast, biomass direct liquefaction processes produce liquid oil products (bio-crude) of a greater heating value than those from pyrolysis bio-oils (Li et al. 2011).

Another growing technology is supercritical water (SCW) gasification, which utilizes supercritical water as the reaction medium. It is an innovative hydrothermal process that converts wet biomass material or aqueous organic waste directly into a valuable hydrogen (H₂)-rich syngas (Zhang et al. 2012).

Laurichesse and Avérous (2014) reviewed the chemical modification of lignin to produce bio-based polymers, can be classified it into the following main groups: lignin fragmentation or de-polymerization into phenolic or other aromatic compounds for fine chemistry; synthesis of new chemical active sites to impart new reactivity to lignin; and, functionalization of hydroxyl groups to enhance their reactivity or responsiveness. Pandey and Kim (2011), in their literature review on thermochemical conversions of lignin, concluded that pyrolysis, gasification, hydrogenolysis, chemical oxidation and hydrolysis under supercritical conditions are the major thermochemical methods studied with regard to lignin depolymerization.

Another recent literature review concerning valorization of lignin to produce

chemicals and materials was provided in a thesis by Huang (2014). The author concluded that: lignin is a rich source of aromatics, which can be obtained by liquefaction or depolymerization. These lignins have smaller molecular weight, less steric hindrance effects and more active functional groups, which are desirable for the synthesis of bio-based phenolic resins, polyurethane resins and epoxy resins. Pyrolysis lignin has low yields generating a considerable amount of char; and, hydrothermal liquefaction provides various benefits when compared to gasification, wet oxidation, and pyrolysis.

3.3 Potential bio-based products from lignin and woody biomass

The term bio-based product includes the traditional products of the forest industry and a variety of chemicals, plastics, additives, bio-based plastics, fibres, reinforced plastics and insulation materials (de Jong et al. 2012). Figure 1 summarizes the potential bioproducts from lignocellulosic materials identified by Iqbal et al. (2013). In this paper we further classify the BSC for final products according to EIA Bioenergy (Bell et al. 2014) definitions:

- Biomass-to-energy: power, heat and fuels;
- Biomass-to-materials and chemicals (non-energy) that can be further classified into two product groups: traditional wood, paper and textile products (e.g., cotton, pulp); and, synthetic chemicals and materials (e.g., plastics, fibres and nitrogen fertilizers).

This review focuses on the bio-based chemicals and materials from forest residues, highlighting the potential lignin bioproducts. Biomass to bioenergy and biofuels production is widely discussed in previous reviews, such as Hughes et al. (2013) and Williams et al. (2016). After an exhaustive screening, Kokossis et al. (2015) found that the promising products of a biorefinery portfolio are from C5 sugars, including the catalytic production of xylitol and C5 ethanol, C6 sugars, including C6 ethanol and Itaconic acid, and from lignin derivatives such as PF resins and polyurethanes.

Ferdosian et al. (2014, 2015) state that lignin may be the best candidate as a green alternative to bisphenol A for the production of epoxy resin because of its aromatic arrangement. Moreover, Mahmood et al. (2013) highlighted that kraft lignin is a source of polyols, due to lignin's particular phenyl propanol structure and aryl alkyl ether bonding. In the search for sustainable materials for building and construction, lignin was found to be a suitable substitute to phenol in the manufacturing of PF resins (Pandey and Kim 2011; Cheng et al. 2011).

Mahmood et al. (2013) propose a process that produced renewable polyols from kraft lignin with desirable characteristics for rigid polyurethane foam synthesis, such as low molecular weight, moderately high aliphatic hydroxyl number/functionality and high yields.

PF resins are most broadly used as wood adhesives in the manufacturing of engineered wood products (e.g., plywood, particle boards and fibreboards). They are also employed in a variety of industrial products, such as insulation, coated abrasives, paper saturation and floral foam (Cheng et al. 2011). Bio-based PF resins from lignin can reduce the industrial consumption of various petroleum derivative elements, such as phenol and bisphenol A, which have high toxicity and carcinogenic effects related to both environmental sustainability and human health (Wang et al. 2010; Zhang et al. 2015).

Considerable efforts have been made in phenolic resins production to replace petroleum-based phenol either entirely or partially with lignocellulosic biomass. Browne et al. (2011) analyzed lignin as a replacement for phenol in the synthesis of PF resins and carbon black, and as a feed for carbon fibre production processes considering lignin competitiveness against petroleum-based resins. Their findings indicate that lignin is capable of replacing up to 50% of the phenol in PF resins in the manufacture of plywood, and possibly 30% in other kinds of composite wood panels with no primary alterations in strength properties. Moreover, Feng et al. (2015) concluded that bark bio-crude and neat PF adhesive

were successfully blended to produce novel formulated bio PF adhesives. The authors found that the ratio depends on the bark species; they reached a ratio of 50:50 (wt/wt) for white birch bark, while white spruce bark bio-crude and neat PF adhesive, respectively. The formulation ratio was up to 75:25 (wt/wt). Cheng et al. (2011) studied wood bio-crude to replace phenol for the production of bio-based phenolic resol resins. They found that adding up to 75 wt% (weight percent) resulted in an efficient bio-based resol resin for plywood adhesives, which had comparable to better dry/wet bonding strength than the reference pure PF resin. Later, Cheng et al. (2013) tested phenolic resins and adhesives from lignin/forestry residuals applying a high substitution ratio of degraded lignin phenol-formaldehyde (DLPF) to substitute phenol in the synthesis of bio-PF resins. Plywood samples glued with organosolv lignin phenol-formaldehyde (OLPF) and DLPF adhesives (phenol replacement ratio up to 75 wt%) showed higher dry/wet tensile strengths than those of PF adhesives.

Zhang et al. (2015) demonstrated the use of kraft lignin as a promising curing agent for phenol-5-hydroxymethylfurfural (PHMF) resins for thermal stability and mechanical properties, for the purpose of fibreglass reinforced composite materials.

Within their literature review, Isikgor and Becer (2015) found that lignocellulosic biomass can be utilized as a raw material to generate more than 200 value-added chemical compounds, thereby proving the lignocellulosic biomass potential as a complementary platform to fossil resources. For example, other than bio-based PF resins/adhesives, bio-based rigid polyurethane foams were prepared by Mahmood et al. (2015) using hydrolytically depolymerized kraft lignin via direct replacement or oxypropylation of depolymerized kraft lignin. The resulting foam displays an excellent combination of physical, mechanical and thermal properties compared to the reference foam. Table 1 summarizes papers addressing lignocellulosic conversion to generate various bio-based products, chemicals and materials from lignin and forest residues (e.g., epoxy resins, polyols, adhesives and PF resins among

other materials and chemicals). The conversion technologies most studied for production of resin and adhesives are polymerization and liquefaction (Table 1).

Even though there has been significant advancement in forest biomass biorefining conversion technologies for value-added bio-based chemicals and materials, there are still several barriers limiting their adoption within the market. Among the barriers for implementation of commercial scale facilities, two key ones are logistical constraints associated with maintaining a consistent supply of woody feedstock and lignin, and the high capital costs of building a biorefinery (Blair 2013). Fortunately, many of these challenges can be addressed through a well-designed BSC (Gold and Seuring 2011; An et al. 2011; Zhang et al. 2014). A pivotally important task for developing a biorefinery is to create a reliable BSC for enough feedstock at a stable price. A BSC generally starts at the cultivation level (establishment and treatment of forest plantations and agricultural energy crops), going through harvesting, pre-processing, transportation, handling and storage, and ultimately ending at the final conversion unit, such as a biorefinery or bioenergy conversion plant (Ba et al. 2015).

A systematic design of the entire BSC network that considers all stages, from the production of forest and wood residues to the end-use of all bioproducts, is required to ensure that the economic and environmental benefits be optimized (Cambero et al. 2015). Therefore, an overview of BSCM and a systematic literature review of FBSC optimization based on literature papers up to October 6, 2015 are presented in the following section.

4. Systematic literature review on supply chain optimization studies and their targeted bio-based chemicals and materials

4.1 Supply chain optimization

A BSC integrates geographically dispersed facilities where raw materials, intermediate products or finished goods are acquired, transformed, stored, or marketed using transportation links that connect the facilities (Shapiro 2001; Chatfield et al. 2006).

According to Shapiro (2001), there are two categories of mathematical models used in supply chain optimization. The first type, known as descriptive models, includes forecasting, cost relationships, resource utilization relationships and simulation models. The second type, known as normative models or optimization models, are classified as linear, integer and non-linear programming (Moore and Weatherford 2001). Sharma et al. (2013) concluded that the majority of recent BSC papers utilize a mixed-integer (MIP) linear programming approach, an optimization approach. The MIP models are generalizations of linear programming models in which integer variables (most commonly the binary values of 0 and 1), are constrained to take on a non-negative integer value, whereas the remaining continuous variables are allowed to take on any non-negative values (Shapiro, 2001).

The BSC can be classified in three main planning scales: strategic, tactical and operational (Stadtler 2005; Shahi and Pulkki 2013). BSC Design (BSCD) and strategic planning consider a horizon of years, and involve, for example, network design, facility location(s) and process capacities. Alternatively, tactical planning and operational planning involve analyses on shorter time scales besides it commonly addresses inventory location and control, process scheduling and material flows. All scales should be analyzed collectively in an overall BSCD (Garcia and You 2015).

There have been an increasing number of papers addressing BSC optimization reported in some previous literature reviews. For instance, Shabani et al. (2013) analyzed 31 papers published prior to 2011. Their review focused on BSC design and analysis of bioenergy production. They concluded that environmental and social objectives should be included in the BSC models in addition to economic objectives. Cambero and Sowlati (2014)

reached the same conclusion. The BSC network models were reviewed by Shahi and Pulkki (2013) from the retrieved 22 papers. They found that there is a need for an integrated simulation-based optimization modeling approach in order to address uncertainties in the BSC demand and supply. In an exhaustive literature review, Elia and Floudas (2014) located 80 BSC studies regarding the production of heat, power and transportation fuels from coal, biomass and natural gas, both individually and in combination. They conclude that optimization models are most frequently applied; moreover, future studies considering multiple feedstock inputs (e.g. biomass and coal) with the focus on downstream operations and methods to address large-scale BSCs are necessary.

The most common objective of supply chain management is to minimize the total BSC cost. This includes: raw materials and other acquisition costs; inbound transportation costs; facility investment costs; direct and indirect manufacturing and distribution costs; inventory holding costs; inter facility transportation costs; and, outbound transportation costs (Shapiro 2001). The most effective approach to supply chain management is to maximize the net revenue by maximizing the revenue while minimizing total cost (Shapiro 2001)

An optimal BSCD is vital for the forest industries' long-term success. A forest biorefinery BSCD incorporates a wide range of biomass sources spreading out over vast geographic areas, and utilizes a variety of transport modes, ultimately generating a large number of potential BSC options. The main goal is to find the optimal logistical arrangement that minimizes annual system-wide costs, including harvesting, collection or purchasing costs, facility (storage, handling and fixed) costs, inventory holding costs and transportation costs, within the parameters of a predetermined set of requirements (Toka et al. 2010).

At the strategic level, the results from the BSCD become constraints for the aggregate planning that takes place at the tactical decision-making level. However, the BSCD not only has to be efficient on the expected conditions, but also robust and flexible enough to adapt to

potential changes in these circumstances (Toka et al. 2010). The number of studies addressing forest BSCD has increased rapidly. Table 2 presents a summary of four papers addressing BSCD. For more references, we refer to previous literature reviews: Sharma et al. (2013) which reviewed 32 papers, and Cambero and Sowlati (2014) with 54 papers.

Selecting the optimal location for the biorefinery site is an important decision that has a significant impact on the overall transportation cost (Ekşioğlu et al. 2009). The single and multi-facility methods for biorefinery location(s) require the knowledge of biomass feedstock locations (latitude and longitude), as well as biomass cost, availability and quality, and income from by-products (Johnson et al. 2012). Transportation costs are of prime importance when calculating the overall costs of biomass. Consequently, local or regional production of biomass is most favourable (Demirbas 2010).

The location problem has been addressed in some publications extensively. For a comprehensive review of BSC location models, we recommend Johnson et al. (2012). They examined the methods for optimally locating a forest biomass to a bio-fuel facility, reviewing 57 papers from 2005 to 2012 addressing this BSC problem. The authors also classified the methodology used in the papers, concluding that mixed integer programming (MIP) is the most applied method because it provides the most comprehensive assessment for locating biorefineries overall. Nonetheless, Shahi and Pulkki (2013) found that, in general, the problems solved with Linear Programming and MIP models often needed several over-simplifications to render them solvable; they suggest an integrated simulation-based optimization modeling approach as a better method. According to Kocoloski et al. (2011), locating facilities in a way that minimizes transport cost can reduce the overall cost significantly, as compared with uninformed employment.

The majority of the optimal location studies focus on bioenergy production, including fuels, heat and power (e.g. Leduc et al. 2008; Velazquez-Marti and Fernandez-Gonzalez

2010; Parker et al. 2010; Tittmann et al. 2010; Bai et al. 2011; Kim et al. 2011; Natarajan et al. 2012, 2014; Palander and Voutilainen 2013; Marvin et al. 2013; Pantaleo et al. 2014). However, some publications addressed BSC optimization for chemicals and materials production, including location problems. For example: e.g., Zhang and Wright (2014), Santibañez-Aguilar et al. (2015), Kokossis et al. (2015), Zhang et al. (2014), Sukumara et al. (2014), Dansereau et al. (2014) (Table 3).

4.2 The targeted products in biorefineries involving forest biomass supply chain optimization

It is evident that the number of published papers on economic optimization of FBSCs has increased significantly in the past 10 years (Figure 2 b). New challenges and more sophisticated models have been developed indicating the importance of efficient BSC design and the evaluation of production of various products: e.g., energy, materials and chemicals from forest biomass. Regarding the number of papers on BSC optimization, the Journal of Computer and Chemical Engineering published more papers than any other journal, with 13.8% of the total papers, followed by Bioresource Technology, Energy, and Biomass & Bioenergy, each accounting for 8% of the total papers (Figure 2 a). The United States (U.S.) (35%) and Canada (11%) contributed to more publications than any other country (Figure 2 c).

The Canadian forest products industry needs to diversify its portfolio to remain competitive, and the under-utilization of forest resources has lowered its competitiveness in the global market (Shahi and Pulkki 2013). A reliable BSCD is crucial to utilize the forest resources better and achieve their highest possible value. Hence, BSC optimization studies are essential for the introduction of high-value bio-based products. Once such BSC optimization studies are completed, analyses can be done to determine the most appropriate

strategies of fibre-use to maximize value generation based on current forest market conditions (Shahi and Pulkki 2013).

The relatively larger number of publications from Canada on BSC optimization indicates that the research community has endeavoured to explore solutions and alternatives for the Canadian forest industry. Additionally, the Canadian government, through Natural Resources Canada (NRCan), has supported development and implementation of bioenergy and biorefinery technologies (Paleologou et al. 2011). For instance, FIBRE (Forest Innovation by Research and Education) was founded in 2008 with the goal of developing innovative products, applications and processes, as well as policy for the forest industry (“FIBRE” 2016). Under the umbrella of FIBRE, there were seven research networks funded by NSERC (i.e., Value Chain Optimization Network, Bioconversion Network, Lignoworks, Sentinel Bioactive Paper Network, NEWBuildS, Innovative Green Fibre Network and For Value Net Network).

In the U.S., the Energy Independence and Security Act of 2007 (PUBLIC LAW 110–140—DEC. 19, 2007) and the U.S. Environmental Protection Agency (EPA) regulate the supply of renewable transportation fuels consumed through the Renewable Fuel Standard (RFS2) program. According to Zhang and Wright (2014), biorefiners, renewable fuel producers and other stakeholders are mandated to meet annual bio-fuel production and environmental requests to obey the RFS2. The large number of papers on BSC optimization from the U.S. highlights the efforts of American researchers in the production of various products using renewable feedstock replacing petroleum. Regarding renewable feedstock, there have been a variety of lignocellulosic sources explored within the literature, such as wood chips, energy crops, forest residues, agricultural residues, corn, switch grass, mill residues, and pulp and paper residues, among others. Studies focusing solely on wood as a primary feedstock comprised 44.6% of the publications collected in this work, while the rest,

55.5% are papers involving at least one non-wood feedstock source.

Biorefineries integrate biomass conversion processes to produce various products including fuels, power, heat, and value-added chemicals and materials. Their goals are to optimize the use of bioresources and minimize wastes, thereby maximizing benefits and profitability (Kokossis et al. 2015). According to the International Energy Agency, a biorefinery should produce at least one energy product and one non-energy product (Bell et al. 2014). From the papers reviewed, it can be inferred that there is a misunderstanding of the biorefinery concept, as some papers claimed biorefinery while it was producing only bioenergy.

Figure 3 presents a classification of the targeted products in the papers reviewed in this work. The majority of the papers (approx. 85% or 56 papers) focused on bio-energy and bio-fuels production. Only about 10% of the papers targeted both bio-energy, and bio-based materials and chemicals (such as specialty chemicals, pulp and wood products, newsprint products, lignin products, furfural and commodity chemicals). Finally, less than 5% of the papers focused solely on bio-based materials and chemicals. More specifically, the main products targeted were ethanol (~ 40%), electricity (~ 23%) and heat (~23%). However, none of the papers focused on the carbon black, PF and PU resins, epoxy resins and carbon fibre, discussed in a previous section of this article.

Overall, 10 papers were targeting bio-based materials and chemicals and bioenergy (Table 3). These papers were published between 2012 and 2015, implying the emerging research interest in this field in the last couple of years.

5. Conclusions

Lignocellulosic sources are one of the most promising renewable alternatives to fossil

fuels for the production of bio-based chemicals and materials as well as bioenergy and bio-fuels including transportation fuels, heat and power. Forest biomass can be used as a potential feedstock for biorefineries, which can ultimately help to ensure long-term environmental sustainability of the industry. Supply chain optimization has been addressed and emphasized in many publications. Although there are many literature review papers on biomass supply chains, some questions such as “What products shall be targeted in a biorefinery based on FBSC optimization?” have not yet been answered.

In this review paper, various lignocellulosic feedstock, potential products and conversion technologies were overviewed. FBSC optimization studies were then outlined. Finally, a systematic literature review was performed to discuss the target products of the BSC studies for biorefineries based on forest biomass. The major findings of the literature review may be summarized below:

(1) Novel thermochemical technologies have been developed over the years, which could diversify the forest industry portfolio by enabling the production of high-value products from forest biomass and mill residues. These technologies can contribute to increasing forest industry competitiveness, enhance the sustainability of the forest sector and decrease petroleum dependence.

(2) The BSC optimization has gained intensive attention in the past two years, in particular in the U.S. and Canada.

(3) The target products in the BSC studies published so far are mainly ethanol, electricity and heat, with little focus on bio-based chemicals and materials.

(4) A complete economic analysis and BSCD is crucial to the introduction of bio-based products into the market.

(5) There is a need for further studies focusing on biorefinery and supply chain optimization for the production of high-value bio-based materials and chemicals from forest

biomass.

Acknowledgments

The authors acknowledge the financial support from NSERC and the Ontario government through the Discovery Program, the NSERC/FPIInnovations Industrial Research Chair Program and the ORF-RE Program in Forest Biorefinery. One of the authors (L.D.) also wants to acknowledge Science without Borders and National Council for Technological and Scientific Development – Brazil for proving the scholarship for the PhD program.

Draft

References

- An, H., and Wilhelm, W.E. 2014. An exact solution approach based on column generation and a partial-objective constraint to design a cellulosic biofuel supply chain. *Comput. Chem. Eng.* **71**: 11–23. doi:10.1016/j.compchemeng.2014.07.011.
- An, H., Wilhelm, W.E., and Searcy, S.W. 2011. A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas. *Bioresour. Technol.* **102**(17): 7860–7870. doi:10.1016/j.biortech.2011.05.060.
- Awudu, I., and Zhang, J. 2012. Uncertainties and sustainability concepts in biofuel supply chain management: A review. *Renew. Sustain. Energy Rev.* **16**(2): 1359–1368. doi:10.1016/j.rser.2011.10.016.
- Ba, B.H., Prins, C., and Prodhon, C. 2015. Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective. *Renew. Energy*. doi:10.1016/j.renene.2015.07.045.
- Bai, Y., Hwang, T., Kang, S., and Ouyang, Y. 2011. Biofuel refinery location and supply chain planning under traffic congestion. *Transp. Res. Part B Methodol.* **45**(1): 162–175. doi:10.1016/j.trb.2010.04.006.
- Bell, G., Schuck, S., Jungmeier, G., Wellisch, M., Felby, C., Jørgensen, H., Stichnothe, H., Clancy, M., De Bari, I., Kimura, S., and others. 2014. IEA BIOENERGY Task42 BIOREFINING. IEA Bioenergy. Available from http://orbit.dtu.dk/ws/files/104275567/IEA_Bioenergy_Task42_Biorefining_Brochure_SEP2014_LR.pdf [accessed 23 October 2015].
- Blair, J. 2013. Development of forest biorefining in Canada: overcoming the feedstock barrier. Dissertation, Queen's University Kingston, Ontario.

- 573 Browne, T., Gilsenan, R., Singbeil, D., and Paleologou, M. 2011. Bio-energy and Bio-
574 chemicals Synthesis Report. IPInoovations. Available from
575 http://www.fpac.ca/publications/Bio%20Energy%20Final_En.pdf [accessed 7 August
576 2016].
- 577 Cambero, C., and Sowlati, T. 2014. Assessment and optimization of forest biomass supply
578 chains from economic, social and environmental perspectives – A review of literature.
579 *Renew. Sustain. Energy Rev.* **36**: 62–73. doi:10.1016/j.rser.2014.04.041.
- 580 Cambero, C., Sowlati, T., Marinescu, M., and Röser, D. 2015. Strategic optimization of forest
581 residues to bioenergy and biofuel supply chain: Forest biomass to bioenergy and
582 biofuel supply chain. *Int. J. Energy Res.* **39**(4): 439–452. doi:10.1002/er.3233.
- 583 Canadian Biomass. 2013. Learning About Lignin at CRIBE. Available from
584 <http://www.canadianbiomassmagazine.ca/news/learning-about-lignin-at-cribe-3970>
585 [accessed 8 August 2016].
- 586 Chatfield, D.C., Harrison, T.P., and Hayya, J.C. 2006. SISCO: An object-oriented supply
587 chain simulation system. *Decis. Support Syst.* **42**(1): 422–434.
588 doi:10.1016/j.dss.2005.02.002.
- 589 Cheng, S., D’cruz, I., Wang, M., Leitch, M., and Xu, C. (Charles). 2010. Highly Efficient
590 Liquefaction of Woody Biomass in Hot-Compressed Alcohol–Water Co-solvents [†].
591 *Energy Fuels* **24**(9): 4659–4667. doi:10.1021/ef901218w.
- 592 Cheng, S., D’Cruz, I., Yuan, Z., Wang, M., Anderson, M., Leitch, M., and Xu, C.C. 2011.
593 Use of biocrude derived from woody biomass to substitute phenol at a high-
594 substitution level for the production of biobased phenolic resol resins. *J. Appl. Polym.*
595 *Sci.* **121**(5): 2743–2751. doi:10.1002/app.33742.
- 596 Cheng, S., Wilks, C., Yuan, Z., Leitch, M., and Xu, C. (Charles). 2012a. Hydrothermal
597 degradation of alkali lignin to bio-phenolic compounds in sub/supercritical ethanol

- 598 and water–ethanol co-solvent. *Polym. Degrad. Stab.* **97**(6): 839–848.
599 doi:10.1016/j.polymdegradstab.2012.03.044.
- 600 Cheng, S., Yuan, Z., Anderson, M., Leitch, M., and Xu, C.C. 2012b. Synthesis of biobased
601 phenolic resins/adhesives with methylolated wood-derived bio-oil. *J. Appl. Polym.*
602 *Sci.* **126**(S1): E431–E441. doi:10.1002/app.35655.
- 603 Cheng, S., Yuan, Z., Leitch, M., Anderson, M., and Xu, C. (Charles). 2013. Highly efficient
604 de-polymerization of organosolv lignin using a catalytic hydrothermal process and
605 production of phenolic resins/adhesives with the depolymerized lignin as a substitute
606 for phenol at a high substitution ratio. *Ind. Crops Prod.* **44**: 315–322.
607 doi:10.1016/j.indcrop.2012.10.033.
- 608 Čuček, L., Martín, M., Grossmann, I.E., and Kravanja, Z. 2014. Multi-period synthesis of
609 optimally integrated biomass and bioenergy supply network. *Comput. Chem. Eng.* **66**:
610 57–70. doi:10.1016/j.compchemeng.2014.02.020.
- 611 Dansereau, L.P., El-Halwagi, M., Mansoornejad, B., and Stuart, P. 2014. Framework for
612 margins-based planning: Forest biorefinery case study. *Comput. Chem. Eng.* **63**: 34–
613 50. doi:10.1016/j.compchemeng.2013.12.006.
- 614 Demirbas, A. 2010. *Biorefineries*. Springer London, London. Available from
615 <http://link.springer.com/10.1007/978-1-84882-721-9> [accessed 13 November 2015].
- 616 E. de Jong, Higson, A., Walsh, P., and Wellisch, M. 2012. *Bio-based Chemicals - Value*
617 *Added Products from Biorefineries*. EIA Bioenergy.
- 618 Ekşioğlu, S.D., Acharya, A., Leightley, L.E., and Arora, S. 2009. Analyzing the design and
619 management of biomass-to-biorefinery supply chain. *Comput. Ind. Eng.* **57**(4): 1342–
620 1352. doi:10.1016/j.cie.2009.07.003.

- 621 Elia, J.A., and Floudas, C.A. 2014. Energy Supply Chain Optimization of Hybrid Feedstock
622 Processes: A Review. *Annu. Rev. Chem. Biomol. Eng.* **5**(1): 147–179.
623 doi:10.1146/annurev-chembioeng-060713-040425.
- 624 Fahd, S., Fiorentino, G., Mellino, S., and Ulgiati, S. 2011. Cropping bioenergy and
625 biomaterials in marginal land: The added value of the biorefinery concept. *Energy*.
626 doi:10.1016/j.energy.2011.08.023.
- 627 Feng, S., Yuan, Z., Leitch, M., and Xu, C.C. 2014. Hydrothermal liquefaction of barks into
628 bio-crude – Effects of species and ash content/composition. *Fuel* **116**: 214–220.
629 doi:10.1016/j.fuel.2013.07.096.
- 630 Feng, S., Yuan, Z., Leitch, M., and Xu, C.C. 2015. Adhesives formulated from bark bio-
631 crude and phenol formaldehyde resole. *Ind. Crops Prod.* **76**: 258–268.
632 doi:10.1016/j.indcrop.2015.06.056.
- 633 Ferdosian, F., Yuan, Z., Anderson, M., and Xu, C. (Charles). 2014. Synthesis of lignin-based
634 epoxy resins: optimization of reaction parameters using response surface
635 methodology. *RSC Adv.* **4**(60): 31745. doi:10.1039/C4RA03978E.
- 636 Ferdosian, F., Yuan, Z., Anderson, M., and Xu, C. (Charles). 2015. Sustainable lignin-based
637 epoxy resins cured with aromatic and aliphatic amine curing agents: Curing kinetics
638 and thermal properties. *Thermochim. Acta* **618**: 48–55.
639 doi:10.1016/j.tca.2015.09.012.
- 640 FIBRE. 2016. Available from <http://www.fibrenetwork.org/> [accessed 21 July 2016].
- 641 Garcia, D.J., and You, F. 2015. Supply chain design and optimization: Challenges and
642 opportunities. *Comput. Chem. Eng.* **81**: 153–170.
643 doi:10.1016/j.compchemeng.2015.03.015.

- 644 Ghatak, H.R. 2011. Biorefineries from the perspective of sustainability: Feedstocks, products,
645 and processes. *Renew. Sustain. Energy Rev.* **15**(8): 4042–4052.
646 doi:10.1016/j.rser.2011.07.034.
- 647 Gold, S., and Seuring, S. 2011. Supply chain and logistics issues of bio-energy production. *J.*
648 *Clean. Prod.* **19**(1): 32–42. doi:10.1016/j.jclepro.2010.08.009.
- 649 Green, B.N., Johnson, C.D., and Adams, A. 2001. Writing narrative literature reviews for
650 peer-reviewed journals: secrets of the trade. *J. Sports Chiropr. Rehabil.* **15**(1): 5–19.
- 651 Hamel, J. 2016. Strategic directions and interest of FPInnovations. FPInnovations.
- 652 Holladay, J.E., Bozell, J.J., White, J.F., and Johnson, D. 2007. Top value-added chemicals
653 from biomass. DOE Rep. PNNL **16983**. Available from
654 <https://www.eere.energy.gov/bioenergy/pdfs/pnnl-16983.pdf> [accessed 28 February
655 2016].
- 656 Huang, S. 2014. Reductive Depolymerization of Kraft Lignin for Chemicals and Fuels Using
657 Formic Acid as a In- Situ Hydrogen Source. Western University. Available from
658 ir.lib.uwo.ca/cgi/viewcontent.cgi?article=3911&context=etd [accessed 20 April
659 2016].
- 660 Huang, S., Mahmood, N., Tymchyshyn, M., Yuan, Z., and Xu, C. (Charles). 2014. Reductive
661 de-polymerization of kraft lignin for chemicals and fuels using formic acid as an in-
662 situ hydrogen source. *Bioresour. Technol.* **171**: 95–102.
663 doi:10.1016/j.biortech.2014.08.045.
- 664 Hughes, S., R., Gibbons, W., R., Moser, B., R., and Rich, J., O. 2013. Sustainable
665 Multipurpose Biorefineries for Third-Generation Biofuels and Value-Added Co-
666 Products. *In Biofuels - Economy, Environment and Sustainability. Edited by Z. Fang.*
667 *InTech*. Available from <http://www.intechopen.com/books/biofuels-economy->

- 668 environment-and-sustainability/sustainable-multipurpose-biorefineries-for-third-
669 generation-biofuels-and-value-added-co-products [accessed 10 April 2016].
- 670 Hurley, S., Li, H., and Xu, C. (Charles). 2010. Effects of impregnated metal ions on air/CO₂-
671 gasification of woody biomass. *Bioresour. Technol.* **101**(23): 9301–9307.
672 doi:10.1016/j.biortech.2010.06.123.
- 673 Hurley, S., Xu, C. (Charles), Preto, F., Shao, Y., Li, H., Wang, J., and Tourigny, G. 2012.
674 Catalytic gasification of woody biomass in an air-blown fluidized-bed reactor using
675 Canadian limonite iron ore as the bed material. *Fuel* **91**(1): 170–176.
676 doi:10.1016/j.fuel.2011.07.016.
- 677 Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A., and Malamakis, A. 2010. Waste
678 biomass-to-energy supply chain management: A critical synthesis. *Waste Manag.*
679 **30**(10): 1860–1870. doi:10.1016/j.wasman.2010.02.030.
- 680 Iqbal, H.M.N., Kyazze, G., and Keshavarz, T. 2013. Advances in the valorization of
681 lignocellulosic materials by biotechnology: an overview. *BioResources* **8**(2): 3157–
682 3176.
- 683 Isikgor, F.H., and Becer, C.R. 2015. Lignocellulosic biomass: a sustainable platform for the
684 production of bio-based chemicals and polymers. *Polym Chem* **6**(25): 4497–4559.
685 doi:10.1039/C5PY00263J.
- 686 Johnson, D.M., Jenkins, T.L., and Zhang, F. 2012. Methods for optimally locating a forest
687 biomass-to-biofuel facility. *Biofuels* **3**(4): 489–503. doi:10.4155/bfs.12.34.
- 688 Kim, J., Realff, M.J., Lee, J.H., Whittaker, C., and Furtner, L. 2011. Design of biomass
689 processing network for biofuel production using an MILP model. *Biomass Bioenergy*
690 **35**(2): 853–871. doi:10.1016/j.biombioe.2010.11.008.

- 691 Kocoloski, M., Michael Griffin, W., and Scott Matthews, H. 2011. Impacts of facility size
692 and location decisions on ethanol production cost. *Energy Policy* **39**(1): 47–56.
693 doi:10.1016/j.enpol.2010.09.003.
- 694 Kokossis, A.C., Tsakalova, M., and Pyrgakis, K. 2015. Design of integrated biorefineries.
695 *Comput. Chem. Eng.* **81**: 40–56. doi:10.1016/j.compchemeng.2015.05.021.
- 696 Kong, J., Rönnqvist, M., and Frisk, M. 2012. Modeling an integrated market for sawlogs,
697 pulpwood, and forest bioenergy. *Can. J. For. Res.* **42**(2): 315–332. doi:10.1139/x11-
698 175.
- 699 Kong, J., Rönnqvist, M., and Frisk, M. 2013. Using mixed integer programming models to
700 synchronously determine production levels and market prices in an integrated market
701 for roundwood and forest biomass. *Ann. Oper. Res.* doi:10.1007/s10479-013-1450-0.
- 702 Kurian, J.K., Nair, G.R., Hussain, A., and Raghavan, G.S.V. 2013. Feedstocks, logistics and
703 pre-treatment processes for sustainable lignocellulosic biorefineries: A comprehensive
704 review. *Renew. Sustain. Energy Rev.* **25**: 205–219. doi:10.1016/j.rser.2013.04.019.
- 705 Laurichesse, S., and Avérous, L. 2014. Chemical modification of lignins: Towards biobased
706 polymers. *Prog. Polym. Sci.* **39**(7): 1266–1290.
707 doi:10.1016/j.progpolymsci.2013.11.004.
- 708 Leduc, S., Schwab, D., Dotzauer, E., Schmid, E., and Obersteiner, M. 2008. Optimal location
709 of wood gasification plants for methanol production with heat recovery. *Int. J. Energy*
710 *Res.* **32**(12): 1080–1091. doi:10.1002/er.1446.
- 711 Li, H., Hurley, S., and Xu, C. (Charles). 2011. Liquefactions of peat in supercritical water
712 with a novel iron catalyst. *Fuel* **90**(1): 412–420. doi:10.1016/j.fuel.2010.09.004.
- 713 Mafakheri, F., and Nasiri, F. 2014. Modeling of biomass-to-energy supply chain operations:
714 Applications, challenges and research directions. *Energy Policy* **67**: 116–126.
715 doi:10.1016/j.enpol.2013.11.071.

- 716 Mahmood, N., Yuan, Z., Schmidt, J., and (Charles) Xu, C. 2013. Production of polyols via
717 direct hydrolysis of kraft lignin: Effect of process parameters. *Bioresour. Technol.*
718 **139**: 13–20. doi:10.1016/j.biortech.2013.03.199.
- 719 Mahmood, N., Yuan, Z., Schmidt, J., and Xu, C. (Charles). 2015. Preparation of bio-based
720 rigid polyurethane foam using hydrolytically depolymerized Kraft lignin via direct
721 replacement or oxypropylation. *Eur. Polym. J.* **68**: 1–9.
722 doi:10.1016/j.eurpolymj.2015.04.030.
- 723 Mansoornejad, B. 2012. Design for flexibility in the forest biorefinery supply chain. École
724 Polytechnique de Montréal. Available from <http://publications.polymtl.ca/833/>
725 [accessed 20 October 2015].
- 726 Marvin, W.A., Schmidt, L.D., and Daoutidis, P. 2013. Biorefinery Location and Technology
727 Selection Through Supply Chain Optimization. *Ind. Eng. Chem. Res.* **52**(9): 3192–
728 3208. doi:10.1021/ie3010463.
- 729 Menon, V., and Rao, M. 2012. Trends in bioconversion of lignocellulose: Biofuels, platform
730 chemicals & biorefinery concept. *Prog. Energy Combust. Sci.* **38**(4): 522–550.
731 doi:10.1016/j.pecs.2012.02.002.
- 732 Mesfun, S., and Toffolo, A. 2015. Integrating the processes of a Kraft pulp and paper mill
733 and its supply chain. *Energy Convers. Manag.* **103**: 300–310.
734 doi:10.1016/j.enconman.2015.06.063.
- 735 Moore, J.H., and Weatherford, L.R. 2001. Decision Modeling with Microsoft Excel. *In* 6th
736 edition. Prentice Hall, New Jersey.
- 737 Moshkelani, M., Marinova, M., Perrier, M., and Paris, J. 2013. The forest biorefinery and its
738 implementation in the pulp and paper industry: Energy overview. *Appl. Therm. Eng.*
739 **50**(2): 1427–1436. doi:10.1016/j.applthermaleng.2011.12.038.

- 740 Natarajan, K., Leduc, S., Pelkonen, P., Tomppo, E., and Dotzauer, E. 2012. Optimal
741 Locations for Methanol and CHP Production in Eastern Finland. *BioEnergy Res.* **5**(2):
742 412–423. doi:10.1007/s12155-011-9152-4.
- 743 Natarajan, K., Leduc, S., Pelkonen, P., Tomppo, E., and Dotzauer, E. 2014. Optimal locations
744 for second generation Fischer Tropsch biodiesel production in Finland. *Renew.*
745 *Energy* **62**: 319–330. doi:10.1016/j.renene.2013.07.013.
- 746 Nazari, L., Yuan, Z., Souzanchi, S., Ray, M.B., and Xu, C. (Charles). 2015. Hydrothermal
747 liquefaction of woody biomass in hot-compressed water: Catalyst screening and
748 comprehensive characterization of bio-crude oils. *Fuel* **162**: 74–83.
749 doi:10.1016/j.fuel.2015.08.055.
- 750 Novaes, E., Kirst, M., Chiang, V., Winter-Sederoff, H., and Sederoff, R. 2010. Lignin and
751 Biomass: A Negative Correlation for Wood Formation and Lignin Content in Trees.
752 *PLANT Physiol.* **154**(2): 555–561. doi:10.1104/pp.110.161281.
- 753 Palander, T.S., and Voutilainen, J.J. 2013. Modelling fuel terminals for supplying a combined
754 heat and power (CHP) plant with forest biomass in Finland. *Biosyst. Eng.* **114**(2):
755 135–145. doi:10.1016/j.biosystemseng.2012.11.005.
- 756 Paleologou, M., Radiotis, T., Kouisni, L., Jemaa, N., Mahmood, T., Browne, T., and
757 Singbeil, D. 2011. New and emerging biorefinery technologies and products for the
758 Canadian forest industry. *J--J. Sci. Technol. For. Prod. Process.* **1**(3): 6.
- 759 Pandey, M.P., and Kim, C.S. 2011. Lignin Depolymerization and Conversion: A Review of
760 Thermochemical Methods. *Chem. Eng. Technol.* **34**(1): 29–41.
761 doi:10.1002/ceat.201000270.
- 762 Pantaleo, A.M., Giarola, S., Bauen, A., and Shah, N. 2014. Integration of biomass into urban
763 energy systems for heat and power. Part I: An MILP based spatial optimization

- 764 methodology. *Energy Convers. Manag.* **83**: 347–361.
765 doi:10.1016/j.enconman.2014.03.050.
- 766 Parker, N., Tittmann, P., Hart, Q., Nelson, R., Skog, K., Schmidt, A., Gray, E., and Jenkins,
767 B. 2010. Development of a biorefinery optimized biofuel supply curve for the
768 Western United States. *Biomass Bioenergy* **34**(11): 1597–1607.
769 doi:10.1016/j.biombioe.2010.06.007.
- 770 Petticrew, M., and Roberts, H. 2006. *Systematic reviews in the social sciences: a practical*
771 *guide*. Blackwell Pub, Malden, MA ; Oxford.
- 772 PUBLIC LAW 110–140—DEC. 19, 2007. 2007. ENERGY INDEPENDENCE AND
773 SECURITY ACT OF 2007.
- 774 Reyhanitash, E., Tymchyshyn, M., Yuan, Z., Albion, K., van Rossum, G., and Xu, C.
775 (Charles). 2014. Upgrading Fast Pyrolysis Oil via Hydrodeoxygenation and Thermal
776 Treatment: Effects of Catalytic Glycerol Pretreatment. *Energy Fuels* **28**(2): 1132–
777 1138. doi:10.1021/ef402227m.
- 778 Santibañez-Aguilar, J.E., Rivera-Toledo, M., Flores-Tlacuahuac, A., and Ponce-Ortega, J.M.
779 2015. A mixed-integer dynamic optimization approach for the optimal planning of
780 distributed biorefineries. *Comput. Chem. Eng.* **80**: 37–62.
781 doi:10.1016/j.compchemeng.2015.05.008.
- 782 Scott, J.A., Ho, W., and Dey, P.K. 2012. A review of multi-criteria decision-making methods
783 for bioenergy systems. *Energy* **42**(1): 146–156. doi:10.1016/j.energy.2012.03.074.
- 784 Shabani, N., Akhtari, S., and Sowlati, T. 2013. Value chain optimization of forest biomass for
785 bioenergy production: A review. *Renew. Sustain. Energy Rev.* **23**: 299–311.
786 doi:10.1016/j.rser.2013.03.005.

- 787 Shahi, S., and Pulkki, R. 2013. Supply Chain Network Optimization of the Canadian Forest
788 Products Industry: A Critical Review. *Am. J. Ind. Bus. Manag.* **03**(07): 631–643.
789 doi:10.4236/ajibm.2013.37073.
- 790 Shapiro, J.F. 2001. Modeling the Supply Chain. *In* 2nd edition. Pacific Grove: Thompson
791 Learning, Massachusetts Institute of Technology.
- 792 Sharma, B., Ingalls, R.G., Jones, C.L., and Khanchi, A. 2013. Biomass supply chain design
793 and analysis: Basis, overview, modeling, challenges, and future. *Renew. Sustain.*
794 *Energy Rev.* **24**: 608–627. doi:10.1016/j.rser.2013.03.049.
- 795 Shen, D., Jin, W., Hu, J., Xiao, R., and Luo, K. 2015. An overview on fast pyrolysis of the
796 main constituents in lignocellulosic biomass to valued-added chemicals: Structures,
797 pathways and interactions. *Renew. Sustain. Energy Rev.* **51**: 761–774.
798 doi:10.1016/j.rser.2015.06.054.
- 799 Sjöström, E. 1993. Wood chemistry: fundamentals and applications. *In* 2nd edition.
800 Academic Press, Inc, San Diego.
- 801 Srirangan, K., Akawi, L., Moo-Young, M., and Chou, C.P. 2012. Towards sustainable
802 production of clean energy carriers from biomass resources. *Appl. Energy* **100**: 172–
803 186. doi:10.1016/j.apenergy.2012.05.012.
- 804 Stadtler, H. 2005. Supply chain management and advanced planning—basics, overview and
805 challenges. *Eur. J. Oper. Res.* **163**(3): 575–588. doi:10.1016/j.ejor.2004.03.001.
- 806 Sukumara, S., Faulkner, W., Amundson, J., Badurdeen, F., and Seay, J. 2014. A
807 multidisciplinary decision support tool for evaluating multiple biorefinery conversion
808 technologies and supply chain performance. *Clean Technol. Environ. Policy* **16**(6):
809 1027–1044. doi:10.1007/s10098-013-0703-6.

- 810 Thiffault, E., Lorente, M., Murray, J., and Fritsche, U. 2014. Ecological sustainability of
811 wood bioenergy feedstock supply chains: Local, national and international policy
812 perspectives. *EIA*.
- 813 Tittmann, P.W., Parker, N.C., Hart, Q.J., and Jenkins, B.M. 2010. A spatially explicit techno-
814 economic model of bioenergy and biofuels production in California. *J. Transp. Geogr.*
815 **18**(6): 715–728. doi:10.1016/j.jtrangeo.2010.06.005.
- 816 Toka, A., Iakovou, E., and Vlachos, D. 2010. Biomass supply chain management for energy
817 polygeneration systems. *In* Proceedings of the 1st Olympus International Conference
818 on Supply Chains. Greece. pp. 1–2. Available from
819 http://www.teicm.gr/logistics/images/logisticsdocs/icsc2010/fullabstracts/1_1_ICSC2
820 [010_066_Toka_et_al.pdf](http://www.teicm.gr/logistics/images/logisticsdocs/icsc2010/fullabstracts/1_1_ICSC2) [accessed 20 November 2015].
- 821 Tong, K., Gleeson, M.J., Rong, G., and You, F. 2014. Optimal design of advanced drop-in
822 hydrocarbon biofuel supply chain integrating with existing petroleum refineries under
823 uncertainty. *Biomass Bioenergy* **60**: 108–120. doi:10.1016/j.biombioe.2013.10.023.
- 824 Tymchyshyn, M., and Xu, C. (Charles). 2010. Liquefaction of bio-mass in hot-compressed
825 water for the production of phenolic compounds. *Bioresour. Technol.* **101**(7): 2483–
826 2490. doi:10.1016/j.biortech.2009.11.091.
- 827 Velazquez-Marti, B., and Fernandez-Gonzalez, E. 2010. Mathematical algorithms to locate
828 factories to transform biomass in bioenergy focused on logistic network construction.
829 *Renew. Energy* **35**(9): 2136–2142. doi:10.1016/j.renene.2010.02.011.
- 830 Wang, M., Leitch, M., and (Charles) Xu, C. 2009. Synthesis of phenol–formaldehyde resol
831 resins using organosolv pine lignins. *Eur. Polym. J.* **45**(12): 3380–3388.
832 doi:10.1016/j.eurpolymj.2009.10.003.

- 833 Wang, M., Yuan, Z., Cheng, S., Leitch, M., and Xu, C.C. 2010. Synthesis of novolac-type
834 phenolic resins using glucose as the substitute for formaldehyde. *J. Appl. Polym. Sci.*:
835 n/a–n/a. doi:10.1002/app.32240.
- 836 Werpy, T. 2009. BIO-World conference in Biotechnology and Bioprocessing. Montreal.
- 837 Williams, C.L., Westover, T.L., Emerson, R.M., Tumuluru, J.S., and Li, C. 2016. Sources of
838 Biomass Feedstock Variability and the Potential Impact on Biofuels Production.
839 *BioEnergy Res.* **9**(1): 1–14. doi:10.1007/s12155-015-9694-y.
- 840 Yang, Y., Gilbert, A., and Xu, C. (Charles). 2009a. Production of bio-crude from forestry
841 waste by hydro-liquefaction in sub-/super-critical methanol. *AIChE J.* **55**(3): 807–
842 819. doi:10.1002/aic.11701.
- 843 Yang, Y., Gilbert, A., and Xu, C. (Charles). 2009b. Hydrodeoxygenation of bio-crude in
844 supercritical hexane with sulfided CoMo and CoMoP catalysts supported on MgO: A
845 model compound study using phenol. *Appl. Catal. Gen.* **360**(2): 242–249.
846 doi:10.1016/j.apcata.2009.03.027.
- 847 Yuan, Z., Cheng, S., Leitch, M., and Xu, C. (Charles). 2010. Hydrolytic degradation of
848 alkaline lignin in hot-compressed water and ethanol. *Bioresour. Technol.* **101**(23):
849 9308–9313. doi:10.1016/j.biortech.2010.06.140.
- 850 Yuan, Z., Xu, C. (Charles), Cheng, S., and Leitch, M. 2011. Catalytic conversion of glucose
851 to 5-hydroxymethyl furfural using inexpensive co-catalysts and solvents. *Carbohydr.*
852 *Res.* **346**(13): 2019–2023. doi:10.1016/j.carres.2011.06.007.
- 853 Yuan, Z., Zhang, Y., and Xu, C. (Charles). 2014. Synthesis and thermomechanical property
854 study of Novolac phenol-hydroxymethyl furfural (PHMF) resin. *RSC Adv.* **4**(60):
855 31829. doi:10.1039/C4RA04458D.

- 856 Yue, D., You, F., and Snyder, S.W. 2014. Biomass-to-bioenergy and biofuel supply chain
857 optimization: Overview, key issues and challenges. *Comput. Chem. Eng.* **66**: 36–56.
858 doi:10.1016/j.compchemeng.2013.11.016.
- 859 Zhang, L., Champagne, P., and (Charles) Xu, C. 2011a. Bio-crude production from secondary
860 pulp/paper-mill sludge and waste newspaper via co-liquefaction in hot-compressed
861 water. *Energy* **36**(4): 2142–2150. doi:10.1016/j.energy.2010.05.029.
- 862 Zhang, L., Champagne, P., and (Charles) Xu, C. 2011b. Supercritical water gasification of an
863 aqueous by-product from biomass hydrothermal liquefaction with novel Ru modified
864 Ni catalysts. *Bioresour. Technol.* **102**(17): 8279–8287.
865 doi:10.1016/j.biortech.2011.06.051.
- 866 Zhang, L., Champagne, P., and Xu, C. (Charles). 2011c. Screening of supported transition
867 metal catalysts for hydrogen production from glucose via catalytic supercritical water
868 gasification. *Int. J. Hydrog. Energy* **36**(16): 9591–9601.
869 doi:10.1016/j.ijhydene.2011.05.077.
- 870 Zhang, L., Xu, C. (Charles), and Champagne, P. 2010a. Energy recovery from secondary
871 pulp/paper-mill sludge and sewage sludge with supercritical water treatment☆.
872 *Bioresour. Technol.* **101**(8): 2713–2721. doi:10.1016/j.biortech.2009.11.106.
- 873 Zhang, L., Xu, C. (Charles), and Champagne, P. 2010b. Overview of recent advances in
874 thermo-chemical conversion of biomass. *Energy Convers. Manag.* **51**(5): 969–982.
875 doi:10.1016/j.enconman.2009.11.038.
- 876 Zhang, L., Xu, C. (Charles), and Champagne, P. 2012. Activity and stability of a novel Ru
877 modified Ni catalyst for hydrogen generation by supercritical water gasification of
878 glucose. *Fuel* **96**: 541–545. doi:10.1016/j.fuel.2012.01.066.

- 879 Zhang, Y., Hu, G., and Brown, R.C. 2014. Integrated supply chain design for commodity
880 chemicals production via woody biomass fast pyrolysis and upgrading. *Bioresour.*
881 *Technol.* **157**: 28–36. doi:10.1016/j.biortech.2014.01.049.
- 882 Zhang, Y., and Wright, M.M. 2014. Product Selection and Supply Chain Optimization for
883 Fast Pyrolysis and Biorefinery System. *Ind. Eng. Chem. Res.* **53**(51): 19987–19999.
884 doi:10.1021/ie503487d.
- 885 Zhang, Y., Yuan, Z., and Xu, C.C. 2015. Engineering biomass into formaldehyde-free
886 phenolic resin for composite materials. *AIChE J.* **61**(4): 1275–1283.
887 doi:10.1002/aic.14716.
- 888
- 889

Figure 1. Potential value-added biochemicals of a lignocellulosic biorefinery.

896

897

898 Figure 2. Papers reviewed percentage by journal (a), by year (b), and by country (c). The

899 review includes publications up to October 6, 2015.

900

901

902

903

904 Figure 3. Final product of the FBSC economic optimization from the 66 reviewed papers.

Draft

1 Table 1. Summary of papers regarding thermochemical technologies for new bio-based products from lignin and forest residues.

Conversion technologies	Raw material	Final product	Reference
Co-catalysts and solvents	Glucose	5-hydroxymethyl furfural	Yuan et al. (2011)
Co-liquefaction in hot-compressed water	Secondary pulp/paper-mill sludge	Bio-crude	Zhang et al. (2011a)
Delignification	Bio-phenolic compounds from lignin/forestry residuals (pine sawdust)	Phenolic resins and adhesives	Cheng et al. (2013)
Depolymerization	Hydrolysis lignin	Polyurethane foams/resins	Mahmood et al. (2015)
	Kraft lignin	De-polymerized lignin	Huang et al. (2014)
		Lignin-based epoxy resins	Ferdosian et al. (2015)
Depolymerization in supercritical acetone	Kraft lignin	Epoxy resin	Ferdosian et al. (2014)
Direct hydrolysis	Kraft lignin	Polyols	Mahmood et al. (2013)
Direct liquefaction	Eastern white pine sawdust	Bio-oil Bio-based Phenolic Resol Resins	Cheng et al. (2010; 2011)
	Sawdust, cornstalks, pure lignin and pure cellulose as references	Phenol-formaldehyde resins	Tymchyshyn and Xu (2010)
Fast Pyrolysis	Hardwood sawdust	Pyrolysis oil	Reyhanitash et al. (2014)
Gasification	Pine sawdust	Combustible gas	Hurley et al. (2010; 2012)
Glucose as the replacement of formaldehyde	Glucose	Novolac-Type Phenolic Resins	Wang et al. (2010)
Hydro-Liquefaction in Sub-Super-Critical Methanol	Woody biomass (birch powder)	Bio-crude	Yang et al. (2009a)
Hydrodeoxygenation	Bio-crude	Oily products	Yang et al. (2009b)
Hydrolytic degradation in hot-compressed water	Alkali lignin	Oligomers	Yuan et al. (2010)
Hydrothermal degradation		Bio-phenolic compounds	Cheng et al. (2012a)

2
3
4
5

6 Table 1: Continued.

Conversion technologies	Raw material	Final product	Reference
Hydrothermal liquefaction	Birchwood sawdust	Bio-crude	Nazari et al. (2015)
	Eastern white pine sawdust	Methylolated bio-oil-PF resol resins	Cheng et al. (2012b)
Liquefaction	Bark (white pine, white spruce and white birch)	Bio-crude	Feng et al. (2014)
	White birch bark and white spruce bark	BPF adhesives	Feng et al. (2015)
One pot synthesis process	Kraft lignin	Formaldehyde-free phenolic resin	Zhang et al. (2015)
Organosolv extraction		Phenol-formaldehyde resol resins	Wang et al. (2009)
Phenol-5-hydroxymethyl furfural resins synthesized by reacting phenol with 5-hydroxymethyl furfural	Glucose	Fibre-glass reinforced plastic (FRP)	Yuan et al. (2014)
Supercritical water gasification	Glucose	H ₂	Zhang et al. (2012)
			Zhang et al. (2011c)
	Pulp/paper mill sludge, sewage sludges (primary, secondary, and digested)	Bioenergy	Zhang et al. (2010b)
	Sludge (secondary pulp/paper-mill)	H ₂	Zhang et al. (2011b)

Table 2. Summary of recent BSCD papers for bioenergy and biochemicals production.

Reference	Mathematical model	Model objective	Main findings
Zhang et al. (2014)	Mixed Integer Linear Programming (MILP)	Maximizing profit for commodity chemicals production via woody biomass fast pyrolysis and hydro processing pathways.	For a case study of Minnesota, U.S., the model demonstrated that distributed biomass chipping facilities are more profitable than roadside chipping, rich biomass sites are preferable locations for building a biorefinery, also that biomass availability and facility capital costs are the most significant variables affecting the project profitability.
Camero et al. (2015)	Multi-period MILP model	Optimize the BSCD of forest residues for the production of bioenergy.	The model recommended the installation of small biomass boilers coupled with steam turbines for electricity production and pyrolysis plants to supply the needs of Williams Lake timber supply area, in British Columbia, Canada.
Čuček et al. (2014)	MILP	Optimally integrate regional biomass and bioenergy supply network including production processes from different sources of biomass producing first, second and third generation biofuels.	It is feasible to produce second and third generation biofuels. Biomass and waste, especially switchgrass and algae, were found to be promising raw materials for producing biofuels. Biorefinery supply networks could reveal significant unburdening capabilities of GHG emissions.
Tong et al. (2014)	Multi-period MILP model	Optimizing the BSCD for an advanced drop-in hydrocarbon bio-fuel BSC, integrating with existing petroleum refineries under uncertainty.	Their model demonstrates, through a case study of Illinois, that advanced hydrocarbon biofuel BSC integrated with existing petroleum refinery infrastructure significantly reduces capital cost and total annualized cost, when compared to traditional biofuel BSCs.

Table 3. Summary of the 10 papers addressing bioenergy, biochemicals and biomaterials.

Reference	Research objectives	Feedstock	Target Products	Main findings
Zhang et al. (2014)	See Table 2	Forest residues.	Commodity chemicals	See Table 2
Kokossis et al. (2015)	Developing a systems approach for the design of integrated biorefineries, finding the most profitable biorefinery portfolio.	Wheat straw, rice; poplar and birch.	37 chemical compounds, 20 intermediates, and 17 final products.	Total site integration was found to offer savings of up to 88% when compared with the non-integrated case. The final products selected were xylonic acid, polyamide ₂ , polyester, polyamide ₃ , lignin-based castor oil, polyurethane coating, and resins.
Mesfun and Toffolo (2015)	Integration of a pulp and paper mill and a wood-pellet plant that share a heat and power plant.	Pulp wood, roundwood sawdust and wood chips.	Heat, power, pulp, lumber and wood pellets.	The integrated cases studied performed better economically than the standalone ones in terms of investment opportunity.
Santibañez-Aguilar et al. (2015)	Optimal planning of a distributed biorefinery system, accounting for the time dependence of the involved variables and parameters.	Wood chips, sugar cane, sorghum grain, sweet sorghum and corn grain.	Bioethanol and specialty chemicals.	BSCs based on biomass conversion are seriously affected by the availability of biomass resources over the time.
Kong et al. (2012)	To develop an optimization model to integrate the roundwood and forest biomass value chains in the initial stage of the FBSCs. Minimizing costs of procurement, chipping, inventory, and transportation.	Sawlogs, pulpwood, and forest residues, and wood chips and bark.	Heat, pulp and wood products.	In an integrated market there may be competition between heat generation and pulp because pulpwood can be used as raw material in both.

Table 3: Continued.

Reference	Research objectives	Feedstock	Target Products	Main findings
Kong et al. (2013)	Improvements the model published in 2012 in order to address log-term planning. They presented a new approach that can jointly choose areas and define price levels for different assortments at the chosen supply points of the BSC in the long term planning.	Sawlogs, pulpwood, forest residues, wood chips and bark.	Heat, pulp and wood products.	With their model different equilibrium prices for roundwood and forest biomass can be generated, and possible unprofitable supply points can be excluded.
Sukumara et al. (2014)	A region-specific optimization model which links various aspects of the biofuel supply chain, such as feedstock source location, upstream and downstream logistics, as well as thermochemical and bio-chemical processing.	Corn stover and forest residues.	Ethanol, electricity and chemicals.	The model was proved to be the basis for a decision support tool that can guide investors and policy makers in making critical assessments on a local level in any particular region of interest.
Dansereau et al. (2014)	Integrating BSC planning and framework to optimize a superstructure that would ultimately assist decision makers to create BSC policies that can readily adjust to market changes.	Recycles paper, logs, and chips.	Newsprint products, lignin products, furfural, ethanol and heat.	By applying key concepts of the margins-based framework a company could increase its performance and robustness through BSC planning.
Zhang and Wright (2014)	Determinate the optimal plant sizes, locations, and product distributions for an integrated fast pyrolysis biorefinery BSC.	Forest residues.	Hydrogen, liquid fuels, commodity chemicals, and lignin.	Liquid fuel prices influence the annualized profit more then the commodity chemical price.
Čuček et al. (2014)	See Table 2	Corn grains, wood chips municipal solid waste, corn stover, organic manure and timber.	Heat, electricity, Ethanol, Corn-food, digestate boards, and distillers dried grains with solubles.	See Table 2