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Controlling Moisture Content and Truck Configuration to Optimise Biomass Supply Chains in Ireland

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Highlights

- A linear programming model that optimises wood biomass supply in Ireland.
- It uses MC to determine harvesting, chipping, storage and transportation costs.
- It analyses two supply chain scenarios and two truck configurations.
- Low wood MC increases supply cost due to longer transport distances.
- Optimal truck loads can be achieved by controlling wood MC.

Abstract

In the coming years, Ireland will continue to face an increasing demand for wood biomass as a renewable source of energy. This will result in strained supply/demand scenarios, which will call for new planning and logistics systems capable of optimizing the efficient use of the biomass resources. In this study, a linear programming tool was developed which includes moisture content (MC) as a driving factor for the cost optimisation of two supply chains that use short wood and whole trees from thinnings as material feedstock. The tool was designed and implemented to analyse the impact of moisture content and truck configurations (5-axle and 6-axle trucks) on supply chain costs and spatial distribution of the supply materials. The results indicate that the inclusion of wood chips from whole trees reduces the costs of wood energy supply in comparison with only producing wood chips from short wood to satisfy the demand, with 9.8% and 10.2% cost reduction when transported with 5-axle and 6-axle trucks, respectively. Constraining the MC of the wood chips delivered to the power plant increases both transport and overall supply chain costs, due, firstly to an increase in the haulage distance and secondly, to the number of counties providing the biomass material. In terms of truck configuration, the use of 6-axle trucks resulted in a 14.8% reduction in the number of truckloads and a 12.3% reduction in haulage costs in comparison to the use of 5-axle trucks across the MC scenarios analysed.

Key words: biomass supply chain, moisture content, logistics planning, truck configuration, payload efficiency.

1. Introduction

Ireland currently imports 90% of its energy needs and is very vulnerable to supply disruptions as well price changes [1]. To foster the use of renewable energies, Ireland has set a target for renewable energy sources of 16% by 2020. This goal must be met through an increase of 10% in the transport sector, 12% in the heat sector and 40% in the electricity sector (projected to reach by 2014 5.5%, 7.7% and 31% respectively) [2].

Industrial biomass energy (with wood as the major source) accounted for 69% of all thermal renewable energy used in 2011, which corresponds to 2.9% of all thermal energy used in Ireland [3]. Forestry is the largest biomass resource with over 744,000 hectares which equates to 10.6% of Ireland's land area, and further 17% expansion of forest cover is planned by 2030 [4]. Half of the estate's forests are less than 25 years old, with 53% of the forests being managed by Coillte (a commercial semi state company) and 47% managed by private owners [5].

The use of wood biomass in Ireland is dominated by the forest products sector (for heating and electricity generation), with 36% of the round wood harvested used for energy generation in 2012 [6]. The Irish government has planned that all three peat power generation stations to be co-firing with 30% biomass. One of power stations, Edenderry Power has increased the use of wood biomass for co-firing, displacing around 283,375 MWh from peat by 2011, and is on target for 2015 [7]. In order to achieve this 30% co-firing target peat power stations will require an increased amount of wood biomass [8].

The use of wood biomass energy by commercial and domestic users has risen considerably in the last years. It is forecasted that by 2020, the demand for biomass for energy in the Republic of Ireland will be 53 MGJ, with forest biomass delivering about 9 MGJ [9]. It is also forecasted a potential of wood for energy of 23.58 Mm^3 from 2011 to 2008, with a maximum 1.81Mm^3 to be produced in 2027, and mostly coming from Sitka spruce stands [10]. This situation will result in strained supply/demand scenarios. If demand for round wood is to be met by 2020, the balance of supply is likely to comprise of imported biomass, or it will require a significant investment in the sectorial supply chain, either way this will increase the competition for wood fibre [8].

Under this situation it is important that wood biomass resources are used as efficiently and as cost effectively as possible. Supply chain planning in the forest product sector encompasses a wide range of decisions, from strategic to operational [11], and decision support tools can help with the quite often complex planning of wood supply. Optimisation and simulations models can be used to gain insight into the logistics of biomass supply chains [12].

Several studies have been performed to improve the efficiency of biomass supply chains. One of the first studies on biomass supply optimisation was carried out by Eriksson & Bjoerheden (1989) in Sweden. Their study dealt with one power station and six areas supplying four biomass products (sawmill residues, logging residues, wood chips and tree sections. The aim was to satisfy the demand at the plant at minimum cost for a period of one year. With the use of linear programming (LP) they analysed different supply scenarios: chipping at roadside or at the plant, and transporting direct from to the plant or via terminals [13]. They concluded that transportation costs constitute the most essential part of the total supply costs, and that contrary to practice the best scenario was to comminute (chipping) at the forests with direct haulage to heating plants instead of using terminals.

Where to locate power plants, and how to supply forest biomass to each plant is a problem that is commonly approached through location-allocation modelling, where the global objective was to minimize the total transport cost, typically expressed as the product of demand and distance [14]. The use of geographical information systems (GIS) supports analysis of spatial relationship between locations of forests, plants and transport infrastructure. GIS for biomass supply chains provides spatial analysis, network modelling, geographical overlay and visualisation [15]. In 1996 a GIS-based biomass model called BRAVO was developed to assist the estimating the cost for supplying wood fuel to any one of the 12 coal-fired power plants located in Tennessee USA. The platform in BRAVO, based on GIS provides and efficient transport network analysis, thus enabling accurate estimates of hauling distances and related costs [16].

A more recent study in Denmark presented a GIS-based method to determine the least costly strategies to allocate forest wood chips to energy plants in Denmark. The GIS used a cost-weighted distance to wood chip resources and the annual demand as decision parameters [15]. The model allocated each supply of wood chips to plants along the least-cost paths in terms of travel time, until the demand of each plant is met or the chip source is exhausted. Resource areas are mapped on a national scale and the cumulative and total costs of supply for each plant are calculated [40]. The study suggested that allocation analysis with a network-based GIS is a suitable method to express the costs connected with matching local demand and supply, although allocation in the GIS system does not optimise after overall least costs, which results in a non-optimal supply of plants which have less access to resources [15].

In New Zealand, a simulation model was developed to compare different biomass supply chains. Biomass products consisted of loose residues and wood chips from three different forest sites, and delivered under seven supply scenarios based on a combination of forwarding, storage, chipping and truck haulage. Results indicated that the most sensitive parameters in the simulation were the MC, material density and machinery data. They authors concluded that the best supply method was the simplest as each time the biomass is handled, extra costs are added. For this study, the cheapest method meant direct haulage of loose residues to the bioenergy conversion plant where the material is chipped [17] .

In 2004 Gunnarsson et al. developed a mixed integer decision support system with the aim of minimising forwarding, chipping, storing and transportation costs of supplying from different forests and sawmills to various heating plants. One of the decision variables included in the model was whether or not to acquire residues from forests and sawmills that are not owned by the supplying company. Monthly plans for forwarding, storage and chipping were also determined. Different scenarios were tested based on storage restrictions, increased demand, chipping capacity and including new terminals [18].

The supply optimisation through the use of terminals was investigated by Kanzian et al. [19]. In Austria wood energy constant supply is required through the year especially in winter when conditions often make mountainous regions inaccessible. The authors aimed to develop a regional fuel wood supply network that included the optimal use of terminals by testing a number of different scenarios based on demand, upgrading of energy plants and inclusion of harvesting residues. All the studies mentioned above have concluded that direct supply (without the use of intermediate terminals) is the most efficient and economical way to supply fuels to heating and power plants. Although the use of terminals can improve the quality of the biomass by minimising the MC and therefore increasing the energy content, does not pay off the cost of making them part of the supply chain [19].

A mixed integer linear programming (MILP) model on the forest fuel supply network at national scale in Austria was designed by Rauch and Gronalt [21]. The model includes decisions on transport modes (road, rail and ship), number of terminals and their spatial arrangement. Scenarios are formulated to study the impact of rising energy costs and route optimisation. Railway had a minor share in all scenarios because the initial transport is always done by trucks and the total transport distances are relatively short within Austria. The impacts of rising energy costs on procurement sources, transport mix and procurement costs were evaluated. Their results show a 20% increase of energy costs resulting in a procurement cost increase of 7%, and an increasing share of domestic waterway transportation.

In Ireland, how the adoption of Irish policies related to the 30% co-firing target for the three peat power stations impact on other industries demanding wood resources was studied. A linear programming based transportation problem included 18 mills, 3 panel board plants, and the three peat power stations. The aim was to minimise transportation costs. Three scenarios were analysed for two years 2015 and 2030. Global optimisation for both sectors is important, but prioritising for the board and energy sector are equally important. Results indicated that transportation makes up roughly one third of the delivered cost of forest biomass, and that physical planning and market intervention (allocating biomass to the correct destination) could be just as effective as market subvention through incentives [22].

Moisture content is a key attribute of wood biomass, the reduction of the amount of water in wood reduces transportation costs (more wood and less water can be delivered per load) and increases combustion efficiency as less energy is required during combustion to evaporate water [23]. The wood equilibrium moisture content, CO_2 emissions from the logistic operations, and the cost of delivering wood biomass to an energy plant for 20 years in Canada were investigated. Mobini et al [24] developed a discrete event simulation model applied to 18 land units, under three harvesting systems based on the percentage of biomass available. Results showed due to different biomass availability, the demand at the plant could not be satisfied on certain years, it also recommended the inclusion of other types of biomass that are close to the plan like agricultural residues.

Acuna et al. [25] developed a non-spatial linear programming decision support system called BIOPLAN. This model applied in Finland does not use terminals, so storing of the biomass material occurs at the roadside. BIOPLAN uses drying (MC) curves as the driving factor for the optimisation of supply chain costs. The authors investigated the effect of MC on storage, chipping and transportation costs of biomass material delivered to the energy plant under different MC constraints, supply chain and biomass covering scenarios. Geographical Information Systems (GIS) can be useful tools for mapping the availability of biomass fuel resources per county, demand location and average transportation distances from each county to the plants [25]. A extended review of different approaches to wood biomass supply optimisation can be found in (Rönnqvist, 2003; Troncoso and Garrido, 2005; and Wolfsmayr and Rauch, 2014) [26] .

Minimising transportation costs is considered an essential aspect on supply chain optimisation [29] and can be responsible for 25 % to 40% of the supply chain costs (Audy and Rönnqvist). Road transportation is the main method for distributing wood to the processing plants, and this will remain as the most important mode of transport in Ireland, constituting a substantial part of the industry's raw material cost, and having a major influence on the sector's overall economic performance and competitiveness [31]. The transport of wood from the forest to the mills is carried out by trucks of different makes and models. The difference is usually given by the number of axles, axle spacing, weight of the truck, and the engine position in relation to the front axle. All European countries impose haulage regulations related to the restriction on dimensions and weight of the trucks. The weight restriction is more complex due to the relationship between number of axles and the distance between them and how this changes the design gross vehicle weight (D.G.V.W.).

Ireland sets a maximum of 42,000 kg for 5-axle trucks (now proposed to be reduced to 40,000 kg), and 46,000 kg for articulated trucks with 6 axles [32]. Regulation on the trucks weight and dimensions highlights the challenge truck operator’s face when loading enough material on a truck and trailer of fixed dimensions. Haulage contractors incur in opportunity costs when carrying less than the legal maximum weight [33]. In the case of wood biomass (chips and bundles) low bulk density can decrease the productivity in transport by having loads reaching the maximum legal dimensions (volume) of the truck and trailer before exceeding the legal maximum weight.

The interactions between parameters such as wood moisture content (MC), dry matter, solid and bulk density and truck payload constraints are complex and need to be properly evaluated in order to deliver the material cheaply and efficiently [34]. Taking previous studies as a reference point, a spatial linear programming-based decision support tool was developed to conduct an investigation into the effect of biomass MC and truck configuration on supply chain costs.

2. Materials and methods

2.1 Site description

Located 60 km west of Dublin, Edenderry Power plant is Ireland's first large scale independent power producer in operation since 2000. It produces 120MW of electricity, which supplies around 3% of Ireland's national requirement [35]. This peat power station is co-firing at 22%, displacing around 283,375 MWh from peat with biomass by 2011[7], and currently working to increase the volume of wood biomass used as feedstock for its electricity generation process [10].

2.2 Supply chains used for the analysis

The analysis considered two supply chain scenarios taking as a reference previous trials carried out in Ireland as part of the Forest Energy Programme [36]:

Supply chain I (SCI): Thinnings producing a standard short wood (3 m) assortment, with a minimum top diameter of 7 cm. Mechanical harvesting produces delimbed stems, leaving branches and any stem material less than 7 cm in diameters and 3 m length to usually form a brush mat on which the harvester and forwarder drive. Chipping is carried out at the forest roadside by tractor or truck-drawn machines, which operate while stationary on the forest road, and are fed by a crane fixed to the tractor or truck. Woodchips are then directly transported to the plant using walking floor trucks (Figure 1).

*Supply chain II (SCII): W*hole trees from thinnings produced through manual harvesting. In this case, trees are felled without delimbing or crosscutting, and a terrain chipper is used to chip the whole tree at the stump. The whole tree operation corresponds to a row thinning only with no selection between rows. Chipping is carried out by a whole tree terrain chipper Silvatec™. A chip forwarder loads the chips onto walking floor trucks which deliver the wood chips to the power plant (Figure 1).

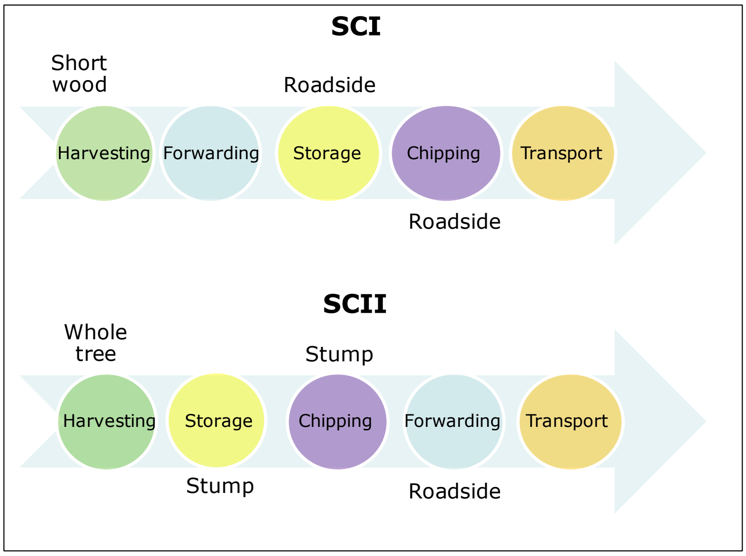

Figure 1: Supply chains analysed in the study.

2.3 Parameters of the model

The parameters used in this study (Table 1) were obtained from different sources. The harvesting, forwarding and chipping costs are fixed and differ on both supply chains, the values are based on field data from the Forest Energy Programme. Results from this programme also provided basic density, bulk density and bulk-solid volume conversion factor data [36]. The net calorific value (NCV) for Sitka spruce was derived from European standards for biofuels [37]. Transportation cost are the industry norm defined by the Irish Road Haulage Association [38], and average truck's volume and weight capacities were gathered in field studies carried out by the authors in Ireland.

Storage costs in the model are based on the assumption that there have been costs associated with harvesting and transporting the material to roadside and that these costs have been paid for at the time of harvest. Thus, storage costs are then the interest charge on the harvesting and transport to roadside costs since the wood owner incurs a delay due to storage in being reimbursed for these [25]. An annual interest rate of 4.7% was used for the analysis based in Irish standards for short term projects (less than 10 years) [39]. In addition, woody biomass loss due to storage was assumed to be 0.059 kg/m^3 per year based on studies under Irish conditions [40].

Table 1: Parameters and conversion factors.

Parameters and conversion factors	SCI	SCII
Net Calorific Value at 0% MC (GJ/t)	19.10	19.20
Basic density (kg/m^3)	377	377
Bulk density (kg/m^3)	275.86	287.38
Bulk/solid volume conversion factor	2.90	2.90
Truck maximum legal payload 5 axle (kg)	23,000	23,000
Truck maximum loose volume capacity (m^3)	95	95
Truck maximum legal payload 6 axle (kg)	27,000	27,000
Truck maximum loose volume capacity (m^3)	95	95
Material loss rate (kg m-^{3} year ^{1})	0.059	0.059
Interest rate %/month	0.39	0.39

2.4 Drying curves

The study of storage methods and drying times in Ireland have been studied by Murphy at al. [23]. They developed a model that predicts daily moisture changes during drying periods on off-forest storage using daily climate information. In-forest seasoning of Sitka spruce under Irish weather conditions has been investigated by Kofman & Kent [41], but monthly data during the two year planning period of the model was not available. Therefore, in-forest drying information for the model was based on a drying model developed by Sikanen et al. [43] (Figure 2).

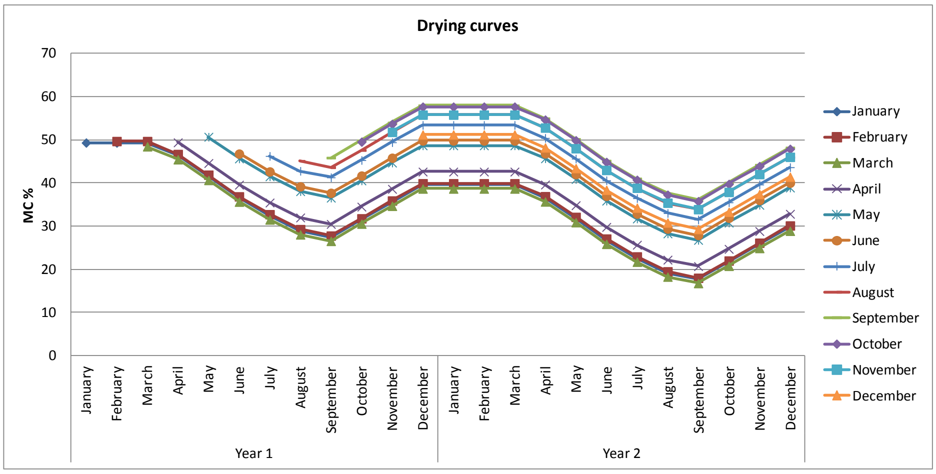

Figure 2: MC of biomass felled at different months and stored throughout the two year planning period [43].

2.5 Scenarios studied

Three scenarios based on moisture content constraints were selected in this study:

- In scenario 1 the power plant accepts material at any MC percentage (i.e. MC is unconstrained).
- In scenario 2 the material arriving at the power plant must meet a MC range between 30% and 45%.
- In scenario 3 an even tighter constraint is imposed on the MC. In this case the material arriving at the power plant must meet a MC range between 30% and 40%. A scenario where the moisture content of all the biomass material is constrained to have less than 40% MC was considered but then discarded as 40% is the minimum MC% at which the model provides a feasible solution.

Under the three MC scenarios, the analysis was conducted for short wood only (SCI), and for a combination of short wood and whole trees (SCI+SCII). The whole trees supply chain (SCII) was not analysed by itself as the available biomass produced in Ireland is not sufficient to satisfy the energy demand at the plant with this material only. In addition, for each scenario and supply chain the use of different truck configurations was analysed. The truck configurations considered in this study were both articulated box trailer with different number of axles and design gross vehicle weights 5 axles with 42,000 kg, and 6 axles with 46,000 kg.

2.6 Description of the model

The aim of the tactical and spatial optimisation model developed was to determine the optimal wood biomass supply that satisfies the energy demand at the power plant. The model considers a 2-year planning horizon where decisions on the volumes of wood to be harvested are made on a monthly basis (24 months). Storage of biomass materials (short wood and whole trees) at the roadside is allowed for a period of up to 24 months (from January year 1 to December year 2). It is assumed that the woodchips produced from these materials are consumed during the same period (month) they arrive at the power plant, and therefore, there are no costs associated with the storage of wood chips at the energy plant or terminal. In addition, the energy content of the wood chips being supplied from the forests must meet power plant's monthly energy demand (GJ) in year 2.

The model displays the results in a series of matrices including among others:

- Decision variables on tonnes and corresponding solid volume of biomass material to be harvested in each period.
- Loose volume (lv) of wood chips produced at the roadside in each period.
- Number of truck loads delivered to the power plant.
- Energy content of wood chips in gigajoules (GJ) arriving at the power plant.
- Harvesting, forwarding, chipping, storage, and transportation cost.

2.7 Mathematical model

The supply chain optimisation model was developed using linear programming, and it includes the sets, parameters, and variables used in the mathematical formulation of the model, which are presented in Table 2:

Table 2: Sets, parameters, and variables used in the mathematical formulation of the model.

Term	**Definition**
Set	
$i, j = periods$	$i \in I = \{1 \ldots 24\}, j \in J = \{13 \ldots 24\}$
$c = counties$	$c \in C = \{1 \ldots 26\}$
Parameters	
α, β	Conversion factors from m^3 solid to m^3 loose for whole trees and short wood, respectively
$EC_{i,j,c}^{sw}$, $EC_{i,j,c}^{wt}$	Energy content for chips produced in period j and county c from short wood and whole trees harvested in period i, respectively
$MC_{i,j,c}^{sw}$, $MC_{i,j,c}^{wt}$	Moisture content of chips produced in period j and county c from short wood and whole trees harvested in period i, respectively
$HC_{i,c}^{sw}, HC_{i,c}^{wt}$	Harvesting and extraction cost (€/m^3 solid) for short wood and whole trees, respectively, harvested in period i, at county c
$STC_{i,j,c}^{sw}, STC_{i,j,c}^{wt}$	Storage cost (€/m^3 solid) for short wood and whole trees, respectively, stored at the roadside or stump from period i to j (i≤j) at county c
$CHC_{i,j,c}^{sw}, CHC_{i,j,c}^{wt}$	Chipping cost (€/m^3 solid) for short wood and whole trees harvested in period i and chipped at the roadside or stump in period j at county c
$TRC_{i,j,c}^{sw}, TRC_{i,j,c}^{wt}$	Transportation cost (€/m^3) for short wood and whole trees chips (loose volume), harvested in period i and transported to the energy plant in period j from county c
$CAPC_c$	Supply capacity (m3) of short wood and whole trees in county c for the 2-year planning horizon

Variables	
$X_{i,j,c}$	Solid volume of short wood harvested in county c and period i, and stored at the roadside until period j for chipping at the roadside
$Y_{i,j,c}$	Solid volume of whole trees harvested in county c and period i, and stored at the roadside until period j for chipping at the roadside
$X'_{i,j,c}$	$X_{i,j,c} * X_{i,j} * \alpha$ = Loose volume of chips from short wood harvested in county c and period i, and stored at the roadside until period j for chipping
$Y'_{i,j,c}$	$Y_{i,j,c} * \beta\beta Z_{i,j} * \alpha$ = Loose volume of chips from whole trees harvested in period i and county c, and stored at the roadside until period j for chipping

2.7.1.Objective function (FO)

The objective function of the model minimises total supply chain costs (€) including harvesting, storage, chipping and transportation (Equation 1).

$$FO = \sum_{i,j,c} X_{i,j,c} * \left(HC_{i,c}^{sw} + STC_{i,j,c}^{sw} + CHC_{i,j,c}^{sw}\right) + \sum_{i,j,c} X_{i,j,c}^{'} * TRC_{i,j,c}^{sw} + \sum_{i,j,c} Y_{i,j,c} * \left(HC_{i,c}^{wt} + STC_{i,j,c}^{wt} + CHC_{i,j,c}^{wt}\right) + \sum_{i,j,c} Y_{i,j}^{'} * TRC_{i,j,c}^{wt} \tag{1}$$

2.7.2.Constraints

Power plant's energy demand (GJ)

The power plant demands approximately 1,518,000 GJ per year from woody biomass (Table 3). Equation 2 ensures that the monthly energy demand at the power plant (GJ) in year 2 is met by the wood chips supplied from all the forests (counties).

$$\sum_{i\leq j,c} X'_{i,j,c} * EC_{i,j,c}^{sw} + \sum_{i\leq j,c} Y'_{i,j,c} * EC_{i,j,c}^{wt} + \sum_{i\leq j,c} \geq ED_j \qquad \forall j \in J \tag{2}$$

Table 3: Power plant's monthly demand (GJ).

Month	Demanded biomass (GJ)	Month	Demanded biomass (GJ)
January	130,561	July	142,127
February	99,484	August	69,131
March	110,980	September	175,806
April	139,201	October	101,663
May	216,332	November	111,442
June	133,726	December	87,611
		Total	**1,518,063**

Minimum and maximum moisture content (MC%) of chips arriving at the power plant

This constraint ensures that the woodchips that arrive at the power plant meet the specified minimum and maximum MC (Equation 3).

$$MinMC_j \leq \sum_{i \leq j,c} X'_{i,j,c} * MC^{sw}_{i,j,c} + \sum_{i \leq j,c} Y'_{i,j,c} * MC^{wt}_{i,j,c} \leq MaxMC_j \qquad \forall j \in J \tag{3}$$

Even production of short wood and whole trees throughout the year.

An even volume of short wood and whole trees is produced in years 1 and 2. This operational constraint allows for continuous work for harvesting and haulage contractors (Equation 4 and Equation 5).

$$\textstyle\sum_{j \geq i,c} X_{i,j,c} = \sum_{j \geq i,c} X_{i+1,j,c} \qquad \forall i \in \{1 \dots 11, 13 \dots 23\} \tag{4}$$

$$\textstyle\sum_{j \geq i,c} Y_{i,j,c} = \sum_{j \geq i,c} Y_{i+1,j,c} \qquad \forall i \in \{1 \dots 11, 13 \dots 23\} \tag{5}$$

Supply capacity from counties (m^3).

This constraint ensures that the biomass supplied to the plant is lower than the maximum potential supply capacity of each county (Equation 6). Based on the Irish Round wood Forecast [10], Table 4 shows the potential harvesting volume and percentage contribution of each county to the total available supply for the two year planning period. In Ireland, most of this supply (95%) corresponds to short wood, with the remaining 5% corresponding to whole trees.

$$\textstyle\sum_{i \leq j,j} X_{i,j,c} + \sum_{i \leq j,j} Y_{i,j,c} = CAPC_c \qquad \forall c \tag{6}$$

Table 4: Potential harvesting supply available from each county forecasted during the planning period, and average distance to the plant.

County	Potential supply (m^3)	Potential supply (%)	Avg. distance to the plant (km)	County	Potential supply (m^3)	Potential supply (%)	Avg. distance to the plant (km))
Louth	879	0.16	96.7	Waterford	20,799	3.86	150.0
Monaghan	1,662	0.31	145.0	Limerick	21,447	3.98	153.0
Meath	1,919	0.36	52.6	Wicklow	22,332	4.14	83.5
Dublin	3,835	0.71	67.6	Kilkenny	23,079	4.28	84.75
Longford	4,281	0.79	79.0	Roscommon	26,177	4.85	124.0
Carlow	5,039	0.93	56.4	Leitrim	28,107	5.21	134.0
Laois	5,506	1.02	46.6	Mayo	29,496	5.47	215.0
Kildare	5,506	1.02	22.2	Donegal	31,111	5.77	212.0
Westmeath	9,637	1.79	48.3	Galway	35,334	6.55	159.0
Wexford	10,010	1.86	141.0	Tipperary	36,219	6.72	139.0
Cavan	11,609	2.15	110.0	Cork	51,003	9.46	210.0
Offaly	16,874	3.13	53.2	Clare	52,841	9.80	198.0
Sligo	19,885	3.69	168.0	Kerry	64,749	12.01	247.0

2.8 Implementation of the model

The linear programming (LP) model was implemented using the What'sBest® solver package for MS-Excel. Once the tables and solver engine were setup, a Visual Basic program was written to execute the model. Shortest routes from the centroid of each county to the energy plant were determined using the Network Analyst extension of ArcGIS 10.1® and included in the optimization model. Network Analyst uses the Dijkstra algorithm to find the least-cost paths based on distance, time or weighted cost. It uses the topological representation of the road network as arcs and nodes. Arcs hold attributes such as the road segment length and other attributes and connect the road segments. For each resource location (county), this tool identifies the nearest node of the road network and computes the distance from the resource location to the nearest node. Using the centroid of each county as the pickup location are only possible to model with approximation as there is limited availability of detailed forest and forest roads maps for the private sector. Roundtrip distances were used assuming that trucks drive fully loaded to the destination (power plant) and return empty to the supply point (forest). More applications of the network analyst tool can be found in other studies [15,44].

3. Results and Discussions

3.1 Variation of MC

The MC of the biomass materials after storage varied between scenarios. Scenario 1 (unconstrained) presented the highest variation, with short wood having a minimum of 40% and maximum of 50% MC in SCI. In the case of SCI+SCII, the minimum and maximum values were 42% and 52% for short wood and 37% and 48% for whole trees. There was not much variation in MC after analysing short wood in SCI and SCI+SCII under scenario 2 (MC 30-45%) and scenario 3 (MC 30-40%). Minimum and maximum MC% for short wood was 42% and 45% in Scenario 2, and 38% and 40% in Scenario 3. Whole trees presented a higher MC variation, with a minimum of 38% and a maximum of 45% for Scenario 2, and a minimum of 36% and a maximum of 40% for Scenario 3. The minimum MC in all the scenarios was reached when the material was delivered to the power plant during the summer months (Figure 3).

This results builds on existing research [25] where under an unconstrained scenario wood biomass presented a much higher MC variation than on the MC constrained scenarios; with logging residues having overall a lower MC compared to whole trees and stem wood. The lowers harvesting cost of whole trees in this study allows for longer storage times, therefore MC tends to be lower.

A more general approach to determining the MC of wood biomass is taken by Mobini et al. [24], in this case it was estimated that for a cut block starting from the felling operation it takes 20 days on average to deliver the harvested material to the power plant. They assumed that 20 days is long enough and after 20 days the wood would reach an equilibrium MC. An increase on MC leads to a higher forest fuel demand in terms of the supplied volume, increases the number of shipments needed and the volume of ash to be deposited and the end of the conversion process [45]. It increases the weight of the transported material and so do the costs. This study results agreed with Talbot and Suadican [46] in that MC is the most important controllable factor in determining transport efficiency.

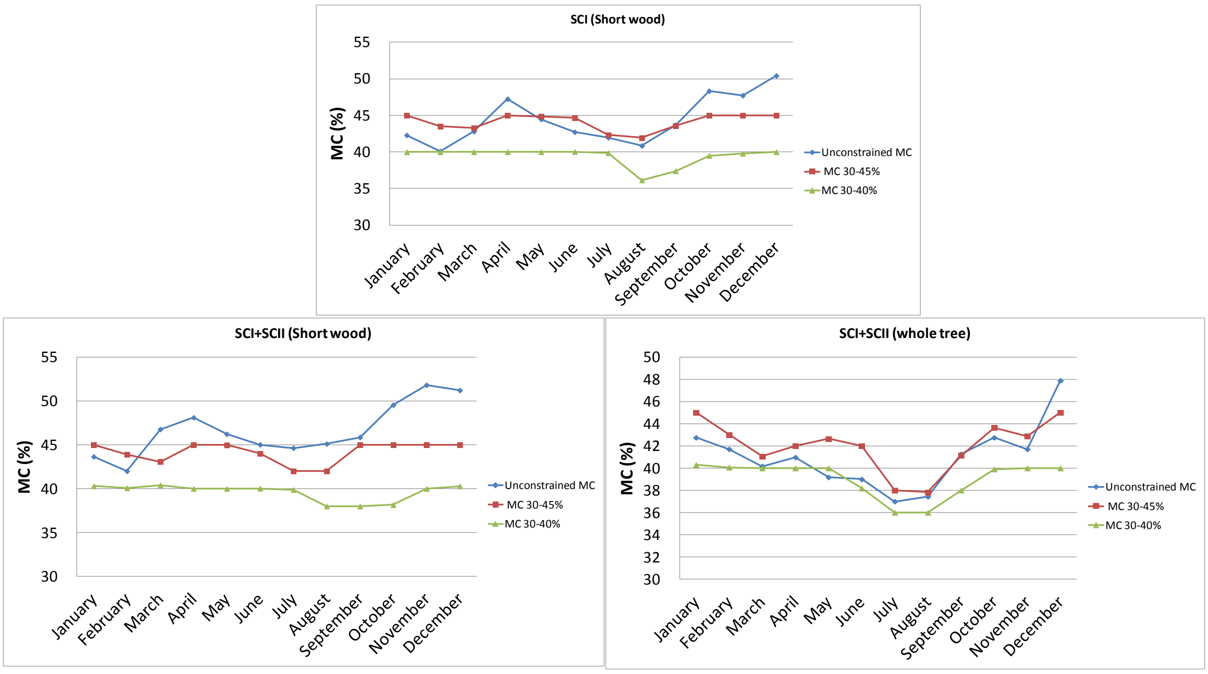

Figure 3: MC changes under different scenarios.

3.2 *Effect of MC on supply chain costs*

There were no major differences in supply chain costs on both SCI and SCI+SCII analysed under Scenarios 1 and 2. This is because the volume of wood chips supplied to the power plant remained almost the same in these two scenarios. In Scenario 3, there was an overall increase on the supply chain cost costs (3.8% and 6.4% in the case of SCI and SCI+SCII, respectively) in comparison to Scenarios 1 and 2. Transportation costs contributed 90% to this increase in SCI despite a small decrease on harvesting and chipping costs. On the other hand, harvesting and transportation costs were the major contributors to the supply chain cost increase in SCI+SCII (48.8% and 42% respectively) as they required much fossil fuel. This coincides with Wolfsmayr and Rauch [28] in that transportation costs are still crucial for economic sufficiency since they represent a great amount of the total delivered costs. In terms of the truck configuration, average savings of 12.30% and 12.28% were obtained for SCI and SCI+SCII, respectively, when using 6-axle trucks under the three MC scenarios (Figure 4).

Overall, lower supply costs were obtained for SCI+SCII in comparison with SCI. These savings result from the inclusion of whole trees as part of the supply chain, whose higher chipping costs are extensively offset by their cheaper harvesting costs, making SCI+SCII more cost effective than SCI only. On average, transportation costs were 9.8% and 10.2% higher when wood chips were transported with 5-axle and 6-axle trucks, respectively.

According to Dornburg and Faaij [47] the influences of logistics on the total costs increases with the scale of the plant, due to increasing the supplying areas therefore having higher transportation distances. Therefore, both the yield of biomass per unit area and the location of the biomass have an impact also when determining the optimum size of a power plant [48]. Follow up studies should compare the supply costs between the other two peat power stations in Ireland. This also depends on the technology used, gasification has a lower power cost than direct combustion making it the most economic technology, so technology selection cannot be separated from an analysis of feedstock cost [49].

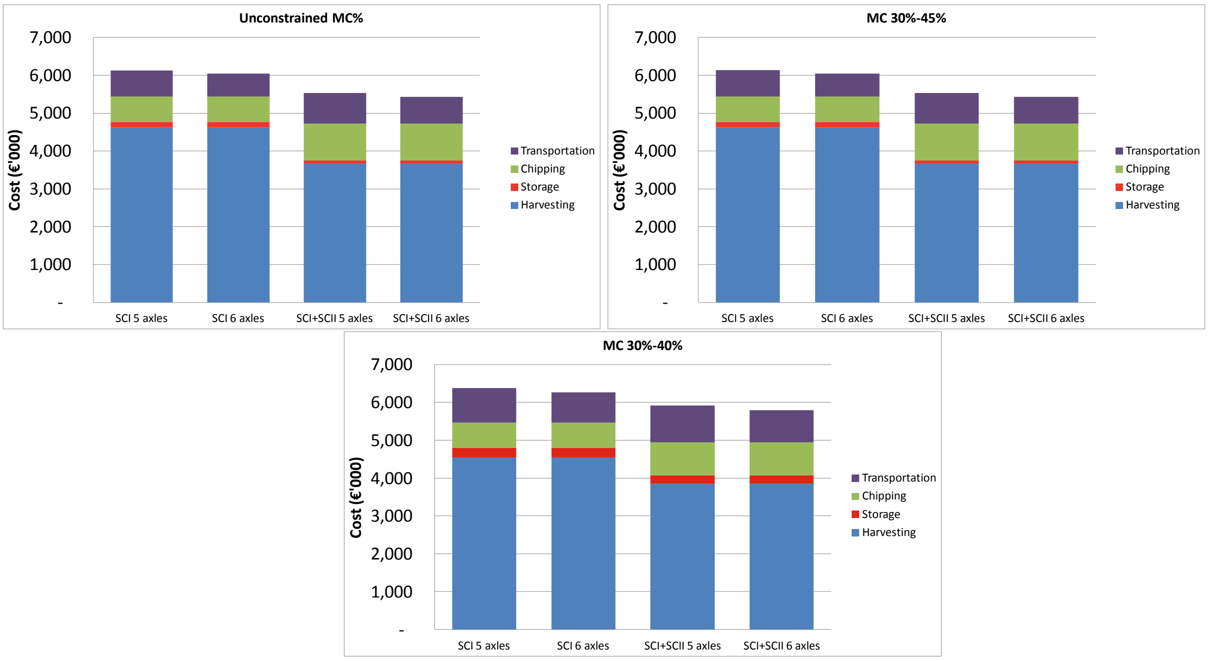

Figure 4: Costs by supply chain and truck configuration under different MC scenarios.

3.3 Effect of MC range on supply distribution

The harvest volume of short wood and whole trees required to satisfy the energy demand at the power plant varied in the planning period across the three scenarios analysed. In SCI under Scenarios 1 and 2, the volume of short wood harvested in years 1 and 2, was 48.5% and 51.5%, respectively, while in Scenario 3, 91.9% of the material was harvested in year 1, and a much lower remaining volume (8.1%) was harvested in year 2. In the case of SCI+SCII under Scenarios 1 and 2, the demand at the power plant was met by harvesting 53.3% of short wood in year 1 and 46.7% in year 2, whereas for whole trees the majority of the volume (58%) was harvested in year 2 and 42% of the volume was harvested in year 1. This situation changed dramatically in Scenario 3 where 100% of the short wood volume and 59.9% of whole trees volume were harvested in year 1, allowing a much bigger volume of material being stored for longer periods.

In terms of the total contribution in SCI+SCII the highest supply was short wood, which is explained by the bigger availability of short wood as biomass material (an average of 512,369 m^3 for the two years of planning). Short wood accounted for 76.9% in Scenario 1, 77.2% in Scenario 2, and 83.2% in Scenario 3, whereas whole trees accounted for the remaining supply volume (23.1% in Scenario 1, 22.8% in Scenario 2, and only 16.8% in Scenario 3), with a much lower availability of this material (an average of 26,967 m^3 for the two years of planning).

These results clearly show that the volume of short wood and whole trees that need to be harvested to satisfy the demand at the power plant may be sensitive to constraints on MC. This is quite evident when comparing Scenarios 2 and 3, where a 5% rise in the upper limit of the MC in Scenario 3 resulted in a bigger proportion of the materials (especially short wood) being harvested in year 1 and longer periods of storage in order to overcome the MC constraint.

Figure 5 shows the volume of short wood and whole trees harvested and storage time by supply chain type (SCI and SCI+SCII) and scenario. In SCI and Scenario 1, storage time ranged between 2 and 12 months, with the highest volume being stored for 7 months (16.1%). In Scenario 2, short wood was stored for a period that ranged between 2 to 20 months, with the highest volume being stored for up to 10 months (21.9%). A higher MC constraint (Scenario 3) resulted in longer storage periods (8 to 16 months) with the highest volume being stored for 12 months (44.8%). In SCI+SCII the storage of short wood and whole tree varies across the three scenarios. Short wood was stored for a maximum period of 12, 21, and 15 months in Scenarios 1, 2, and 3, respectively, while whole trees were stored for a maximum period of up to 16 months in scenarios 1 and 3, and for up to 20 months in scenario 2.

Wood biomass products have losses during storage, these can have positive effects (MC losses) and/or negative effects (dry matter loose). Reducing the storage times in the forest, at the roadside and at the mill yard showed tremendously reduced costs. The expense of storage time was due to value losses (fibre deterioration) and interest rate [50]. On the other hand, for Acuna et al. [25] although the volume distribution of the biomass materials was quite sensitive to the storage period, no major differences were obtained in terms of the supply chain costs per m^3 harvested. Section 3.1 in this study shows the changes in MC when storage times increased, and section 3.2 shows how low is the contribution of storage costs to the overall supply chain cost under the different scenarios. With a material loss rate of 0.059 kg $m\text{-}^3$ year ^{1} based on Irish studies [40], the overall value losses due to fibre deterioration were minimum with approximately less than 0.5%.

Different piling, covering and handling methods can have an effect on the MC changes during the storing periods. It was assumed in this study that the wood biomass was uncovered, and the comparison of different storage methods were not analysed. However, it is worth to mention some studies, one dealing with storage at heating plants, where it was concluded that the best way to store biomass for minimal fuel losses was under roof and with as low initial moisture content and large particle size distribution as possible [51]. Another scenario is to pile the wood in an open area along the forest road. The effects on this drying process through covering the wood piles and partial debarking of stems proved to be an effective method to reduce moisture [52].

In an Irish scenario it is important also to pay attention to the stacking method, wind and sun exposure. Due to abrasion by wind, branch stubs and sun exposure over time, the paper used to cover the piles did not last for more than a few months, with the authors recommending paper covering to be applied in a depot where round wood is stored for shorter time periods [41]. The benefits of increased combustion efficiency and price and reduced transportation costs due to storage must be weighed against increased handling costs (e.g., harvesting machines having to return to the forest after drying to chip logs, or intermediate transport to an off-forest storage yard) [23].

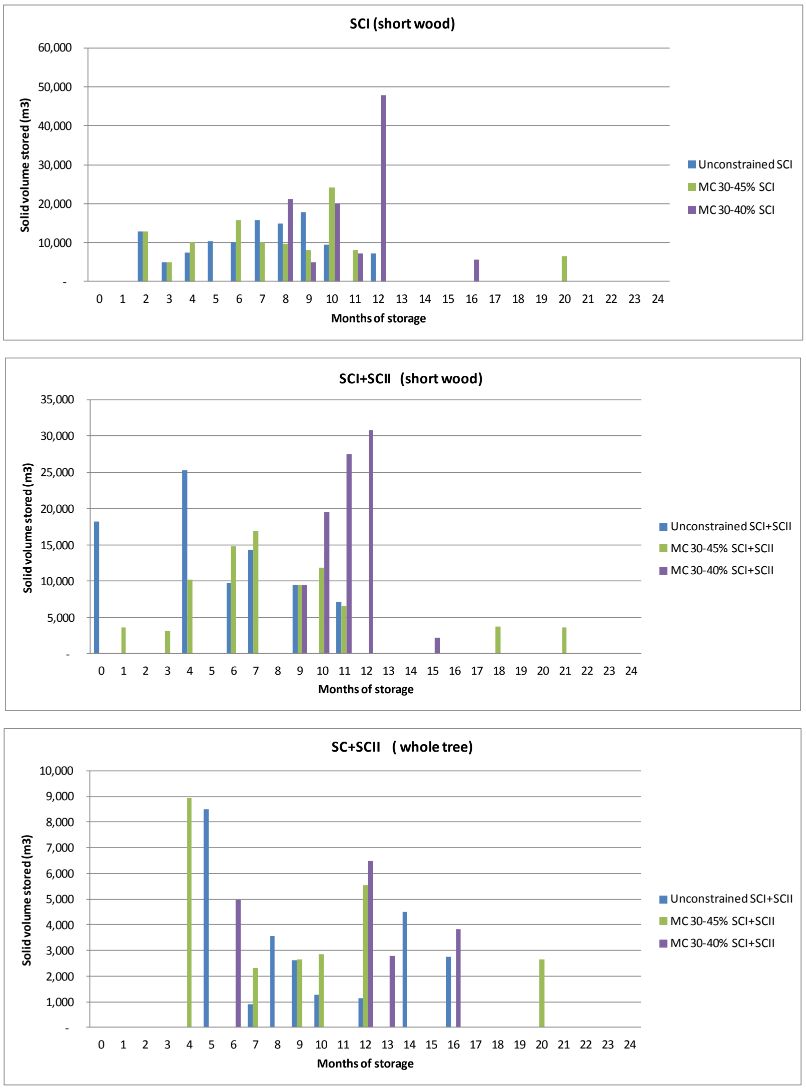

Figure 5: Volumes of short wood and whole trees stored during the 2-year planning horizon.

Figure 6 shows the spatial distribution of the supply by scenario and supply chain. In the case of Scenarios 1 and 2 applied to SCI, the total volume of wood chips demanded by the power plant was supplied by 50% (13 out of 26) of the counties. The three major suppliers were Kilkenny (10th closest to the plant), Wicklow (11th closest to the plant), and Offaly (5th closest to the plant) which supplied 19.8%, 19.2%, and 14.5% of the total volume, respectively. In Scenario 3, short wood biomass was supplied from a bigger number of counties (21 out of 26), and only the five counties with the longest transportation distance to the energy plant were excluded from the solution: Clare, Cork, Donegal, Mayo, Kerry. The major suppliers were Leitrim (10.0% supply and 14th closest to the plant), Roscommon (9.9% supply and 13th closest to the plant), and Kilkenny (9.8% supply and 10th closest to the plant).

In the case of Scenarios 1 and 2 applied to SCI+SCII, the demand at the power plant was satisfied with wood chips coming from 46% (12 out of 26) of the counties. Wood chips were produced mainly from short wood (> 98% of the total volume), and the major suppliers were Wicklow (19.4%), Offaly (14.6%) and Kilkenny (11.8%). In Scenario 3, short wood biomass was supplied from a bigger number of counties (20 out of 26), with the exception of the six counties with the longest transportation distance to the energy plant. As in the case of Scenarios 1 and 2, whole trees represented less than 2% of the total supply.

The increasing constraint of the wood MC resulted in the model assigning biomass from farther distances in other to satisfy the demand. This result agrees with Möller model [15], fo their study each single supply batch was allocated to the nearest energy plant, and when the resources in the vicinity of a plant were used, the model allowed for transport from more remote forests. In a scenario where supply increases, unattractive forest locations were left unallocated, which is an unrealistic situation. The type of biomass product plays a role also in how the supply is satisfied, in Freppaz et al. [53] for plants with lower thermal demands (less than 13MW), the capacity of each plant was satisfied trough the use of biomass coming from parcels where harvesting was cheaper. For thermal demands greater than 13 MW, the biomass coming from both from harvesting and from waste of local production activities was not able to feed the overall demand of the plants. In this study wood chips from short wood are the most supplied product even though its harvesting costs are considerably higher than producing wood chips from whole trees. This is due to Irish forests producing 95% of thinnings through short wood and only 5% through whole tree methods.

The analysis of the energy requirements and greenhouse gas emissions associated with the supply chains analysed are out of the scope of this study. Nevertheless Murphy et al. [54] identified and evaluated the energy demand and green house gas emissions related to the production of different wood biomass products from Sitka Spruce. The scenarios studied included clearfell and thinning producing round wood, pulpwood, and in some cases including logging residues bundling and stump harvesting. Results showed that transportation is the most energy intensive stage in the life cycle, accounting for 70-78% of the overall energy requirements. Harvesting and forwarding is the second most energy intensive stage 19-24%. Using the gross calorific value of conifers 19.2 GJ/odt the energy ratios for the production of wood chip and shredded bundles, shredded bundle production had the highest energy ratio, followed by stumps and finally wood chips. When employing mass allocation, the production of 1 GJ contained in biomass requires 37.1-40.1 MJ (or 0,0371 - 0.0401 GJ). When employing economic allocation 30.3 - 35.3 MJ are attributed to 1GJ of wood chip [54]

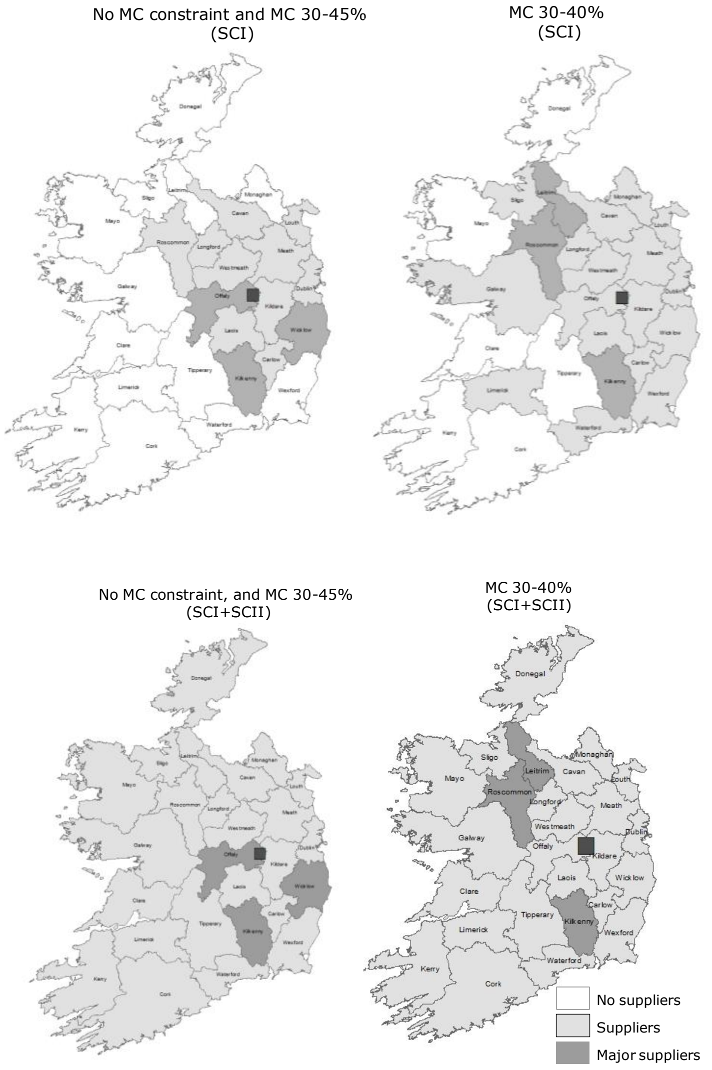

Figure 6: Spatial distribution of biomass supply by scenario and MC constraints.

These results show that as the MC constraint is tightened, the energy demand needs to be satisfied with a combination of wood chips coming from closer counties as well as with material from counties located at a longer distance from the power plant, all of which results in increased overall transport costs. Thus, the effect of a reduced total transport distance that may result from a reduced number of truckloads and transport of drier wood chips is extensively dominated by the effect of moving material from further supply points (forests). The overall effect is observed in Figure 7. In Scenario 3 (MC 30-40%) the total transport distance for 5-axle and 6-axle trucks was on average 21.72% and 21.00% longer than in Scenarios 1 and 2, whereas the transport cost was 21.03% and 21.00% more expensive than in Scenarios 1 and 2..

The impact of time dependent costs on the total costs decreases with increasing transportation distance [55]. Some authors consider that transport costs for longer distances could be kept low if the transport mode is changed, from road to rail and waterway. Shifting the transportation from trucks to trains and ships would make the supply less dependent on distance and they are more environmentally friendly [56,57]. Truck transport of biomass is generally applied for relatively short distances (<100km), train transport is favourable for overland distances exceeding 100 km and ship transport has the highest time dependent costs and therefore, using the waterway is only economic over long distances, exceeding 800 km [58]. The average transportation distance in this study for SCI was 85 km, while the average transportation distance in SCI+SCII was 121 km, and in addition forest areas are geographically disperse, making truck transportation the most important mode of timber transport in Ireland, forming having a major influence on the sector's overall economic performance and competitiveness [59].

Other factors like physical conditions of the biomass material (chipped, unchipped and baled), MC or plant size influence the economical transport distance and this cannot be fixed in general [60,61].It was found by comparing road transport costs for loose material, chips and bundles that at all distance (10-50km) of truck transportation, bundles were the cheapest and loose material (wood chips) the most expensive alternative [62].

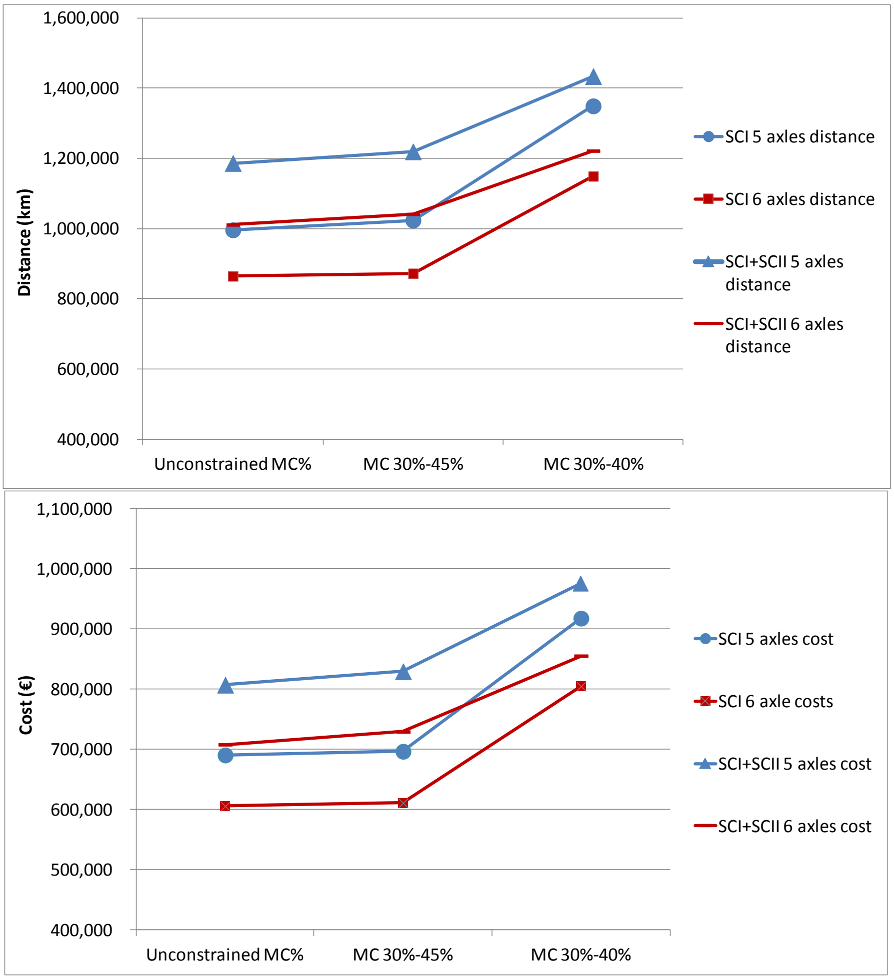

Figure 7: Total transport distance and cost by scenario and truck configuration.

3.4 *Effect of MC on number of truckloads and gross vehicle weight (GVW)*

Figure 8 shows the number of truckloads by MC scenario, with counties sorted by travel distance to the power plant. An extra 4,000 kg can be carried by 6-axle trucks which results in average 14.8% fewer truckloads, 14.8% less travelled kilometres and 12.3% less transport cost in comparison with 5-axle trucks. Most of the truckloads come from a mix of counties that are closer to the plant and with a high available supply, confirming the results presented in Figures 6 and 7. As the need for dryer material increases in year 2, the demand is satisfied by supplying wood chips from counties that are located further away from the power plant, with a one way average and maximum transport distance of 122.9 km and 247 km, respectively.

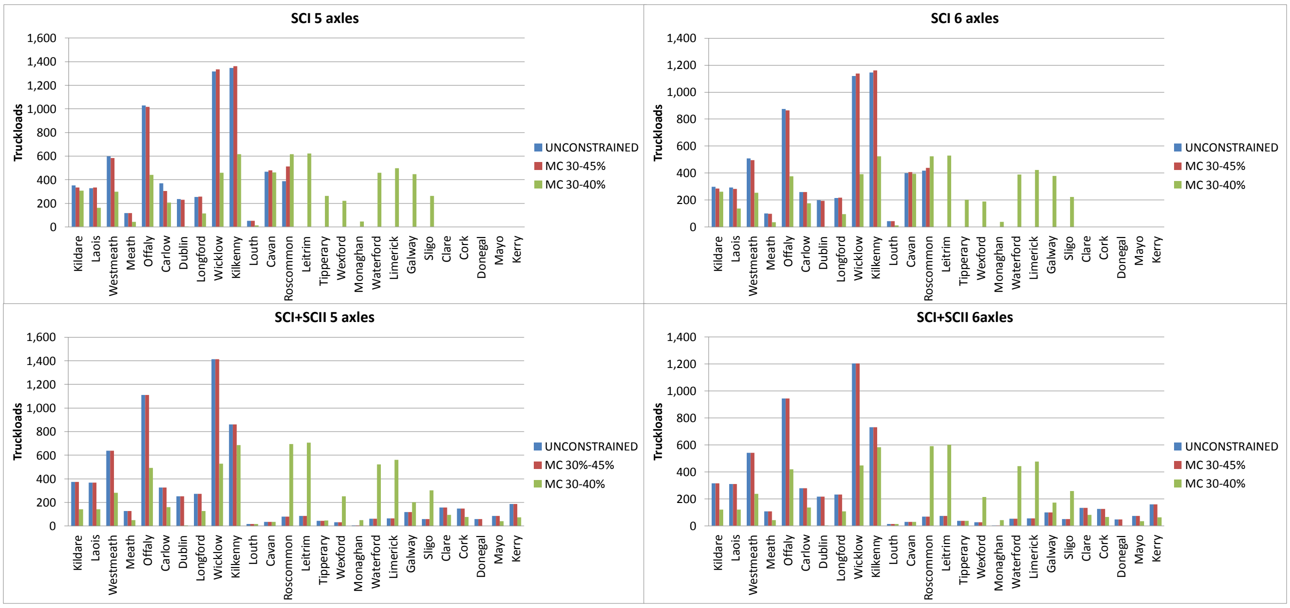

Figure 8: Truckloads per supply chain and MC% scenarios

Figure 9 shows how fully loaded 5-axle and 6-axle trucks are able to meet their legal gross vehicle weight when transporting biomass with different MC. In Ireland the legal GVW of 5-axle and 6-axle trucks is 42,000 kg and 46,000 kg, respectively. Loading the trucks at their maximum volume capacity (95 m^3) has different implications depending on the MC of the material being carried. The use of 5-axle trucks increases the chances of exceeding the legal weight limit, which in the worst case can represent an excess of 6,400 kg (winter months). This excess is much lower in the case of 6-axle trucks which may exceed the legal weight limit only by 2,400 kg. This situation reveals the convenience of using 6-axle trucks to optimise payload and meet legal weight limits. In Ireland, legal weight limits are monitored at weigh bridges, and overloaded trucks incur in penalties, normally of a financial nature, or can result in haulage contractors being banned from delivering materials for a specified period of time.

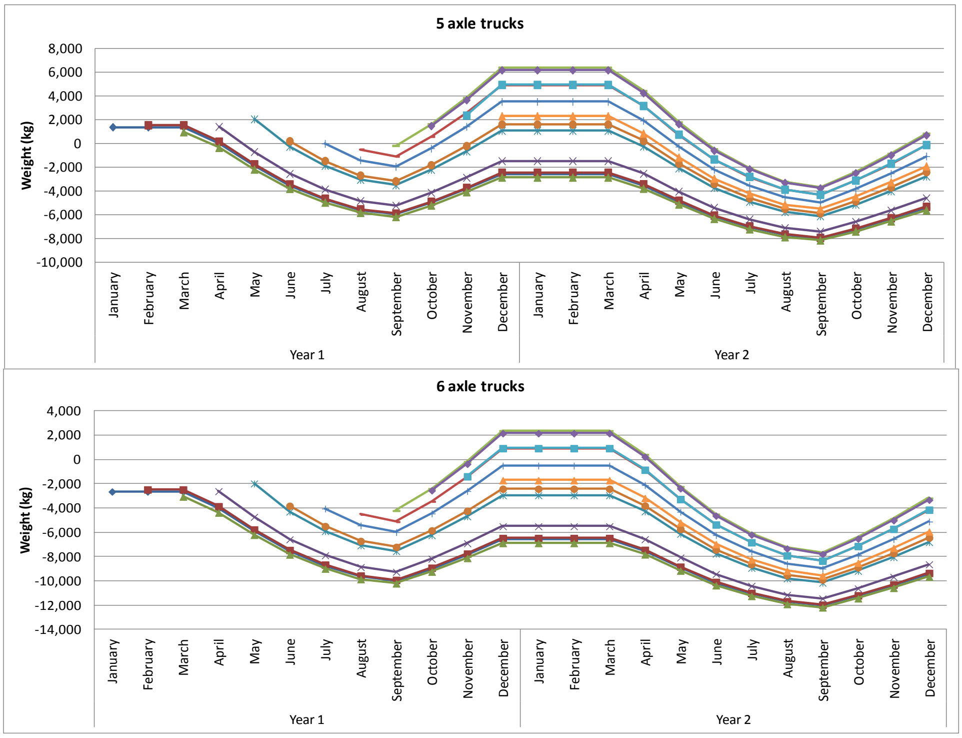

Figure 9: Weight excess in GVW by truck configuration and time of the year.

On the contrary, fully loaded trucks with material at low MC are not able to reach the maximum legal weight limit due to volume constraints. During the summer months, 5-axle and 6-axle trucks have a maximum weight underutilization of 8,170 kg, and 12,170 kg, respectively, in relation to their legal weight limit. The maximum load weight limit is reached before exceeding the maximum volume capacity when wood chips contain a MC of 50% for 5-axle trucks, and 58% MC for 6-axle trucks. On the other extreme, transporting wood chips at 30% MC results in trucks that maximise volume capacity but whose payloads are lower than the legal weight limit. The full volume and weight capacities are maximised, when materials are moved at 45% MC (54% in the case of 6-axle trucks). From a energy perspective, the most preferred situation occurs when the MC of the load is lower than or equal to the optimum MC that maximises payload without exceeding truck's volume (Table 5).

According to Wolfsmayr and Rauch [28] it is possible to overcome the supply chain costs by increasing the transportation density and the energy density. Therefore, pelletising, and in recent times torrefaction of biomass gain in importance for supplying power plant from far-off sources. Hamelinck et al. [58] illustrated several international biomass supply chains, including various forest residues as well as other sources originating in Europe and South America. It concluded that The efficiency of bioenergy transport chains may be improved when drying and/or densification (like methanol synthesis or pelletising) are applied, with the latter being only cost efficient at larger scales.

This study deals with the same type of truck (articulated truck trailers) but with different number of axles, therefore different GVW capacities. But in Talbot and Suadicani [46] it was compared two types of truck configurations, 2 containers on a rigid truck with draw bar, and a bulk trailer (articulated truck with a full tri-axled walking floor trailer), transporting wood chips. It was observed that due to higher payloads, the bulk trailer system was economically preferable, especially with increasing distances. In contrast, trucks with drawbar trailers allowed for better accessibility on forest road. Increasing the bulk density of the load towards the maximum payload (legal restrictions for truck) was recommended by applying mechanical force (e.g. the ejector of belt conveyer can increase the load density). It was stated that raising and dropping the front end of a container increased the bulk density over 5%.

Table 5: Variation on weight and volume of 5 and 6 axle trucks loaded at different MC.

	Trucks with 5 axles						**Trucks with 6 axles**					
MC%	Load vol. (m^3)	Load weight (kg)	Dry weight (kg)	NCV GJ/t	% Volume	% Weight	Load vol. (m^3)	Load weight (kg)	Dry weight (kg)	NCV GJ/t	% Volume	% Weight
0	95	12,350	12,350	236	100%	53.70%	95	12,350	12,350	236	100%	45.74%
5	95	13,000	12,350	234	100%	56.52%	95	13,000	12,350	234	100%	48.15%
10	95	13,722	12,350	233	100%	59.66%	95	13,722	12,350	233	100%	50.82%
15	95	14,529	12,350	231	100%	63.17%	95	14,529	12,350	231	100%	53.81%
20	95	15,438	12,350	228	100%	67.12%	95	15,438	12,350	228	100%	57.18%
25	95	16,467	12,350	226	100%	71.59%	95	16,467	12,350	226	100%	60.99%
30	95	17,643	12,350	223	100%	76.71%	95	17,643	12,350	223	100%	65.34%
35	95	19,000	12,350	220	100%	82.61%	95	19,000	12,350	220	100%	70.37%
40	95	20,583	12,350	216	100%	89.49%	95	20,583	12,350	216	100%	76.23%
45	95	22,455	12,350	211	100%	97.63%	95	22,455	12,350	211	100%	83.16%
50	88.45	23,000	10,350	192	93.11%	100%	95	24,700	12,350	206	100%	91.48%
55	79.60	23,000	10,350	167	83.80%	100%	93.47	27,000	12,147	196	98.35%	100%

4. Conclusions

Ireland will continue to face an increasing demand for wood biomass as a renewable source of energy in strained supply/demand scenarios, which will call for new planning and logistics systems capable of optimizing the efficient supply of good quality forest fuels to energy plants. In this paper we have presented a tactical linear-based optimisation model to minimize biomass supply chain costs based on truck configuration and moisture content of the materials (short wood and whole trees) used as feedstock. Biomass supply chains are complex by nature and are characterised by a number of operational factors and quality aspects associated with the feedstock materials being supplied to energy plants. Logistics planners have to take these considerations into account when optimising fuel procurement and energy production at the energy plants simultaneously. These considerations necessarily entail an understanding of the implications related to the storage of biomass materials at the roadside, including the positive effect on transport costs and efficiency at the energy plants, as well as the negative impact on chipping and storage costs associated with the capital that is bound to the storages. Thus, the combined impact and trade-offs associated with all these factors on supply chain costs are only possible to investigate and analyse with the use of optimisation systems and decision support tools, and their application is critical to improve the decision making process in order to deliver biomass materials to energy plants in a cost-effective way.

The analysis conducted in this study show the benefits of optimising the control of moisture content when planning the logistics of biomass supply chains. An optimised control of the MC can provide valuable information on which forest areas to harvest as well as when and how much volume to harvest and chip, and for how long to store the wood at the road side. In terms of transportation, it provides information on the number of truckloads to deliver the biomass, the energy content of each truckload, and how to maximise the payload of different truck configurations within legal weight and volume restrictions.

It is evident from our results that both supply chain costs and distribution of the volumes by type of material (short wood and whole trees) are sensitive to constraints on MC. As a result of a more restrained MC scenario, the highest supply chain costs were obtained in Scenario 3 and were explained mainly by a rise in transport costs. In addition, overall supply costs were lower for SCI+SCII in comparison with SCI. These savings resulted from the inclusion of whole trees as part of the supply chain, and whose reduced harvesting costs made SCI+SCII more cost effective than SCI only. In terms of the truck configuration, average savings of 12.30% and 12.28% were obtained for SCI and SCI+SCII, respectively, when using 6-axle trucks under the three MC scenarios.

MC also had an impact on the proportion of the materials being supplied to the energy plant. This is quite evident when comparing Scenarios 2 and 3, where a 5% rise in the upper limit of the MC in Scenario 3 resulted in a bigger proportion of the materials (especially short wood) being harvested in year 1 and longer periods of storage in order to overcome the MC constraint. The spatial distribution of the supply is also affected by a reduction in the MC range as the energy demand has to be satisfied with materials that are allocated at a longer distance from the energy plant, which results in increased overall transport costs.

Acknowledgement

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