COMPARATIVE ANALYSIS OF WOOD PELLET PARAMETERS:

CANADIAN CASE STUDY

by:

Dmitry Tarasov

A Master's Thesis Submitted in
Partial Fulfillment of the Requirements for the
Degree of Master of Science in Forestry

Natural Resources Management Faculty
Lakehead University
Thunder Bay, Ontario
August 16th, 2013

Abstract

Canada is one of the world leaders in wood pellet production and export, however, domestic consumption is extremely low. In addition there is no national standard in Canada for wood pellets. The Canadian government announced that it will increase wood pellet usage as an alternative to coal and natural gas. Wood pellets when compared to natural gas and coal, is an environmental friendly, energy-intensive and easily transported alternative.

An independent comparative analysis of prime class (residential) wood pellets was performed in this study. We tested eight producers from five Canadian provinces (BC, ON, MB, NS and QC). The measurements of pellet quality characteristics (i.e., calorific value, moisture content, ash content, durability, bulk density, fines amount, compressive strength, fixed carbon and volatile organic compounds) were analysed.

We carried out a statistical analysis of our results with the intent of finding interdependences between parameters. The analysis results show that average values of tested parameters are matching European and North American standards. Significant correlations between several parameters were found. It was also noted that there is a significant correlation between compressive resistance and pellet durability. Therefore, it was found that it is possible to use the compressive resistance test for rapid determination of pellet quality. A linear regression model for predicting mechanical durability was also developed.

According to the comparative analysis it will be possible to set parameters equal to other countries for future national standard development in Canada. This will give an opportunity to increase domestic consumption and bring biomass energy through micro-

generating and heating projects to geographically isolated areas and to small forest communities as an alternative and easily accessible energy source.

Acknowledgment

I wish to express my deep gratitude to Dr. Mathew Leitch, Dr. Chander Shahi and Dr. Reino Pulkki for their guidance and great support during my studies. I also wish to thank PhD students Patrick Gauthier and Scott Miller for their invaluable help and assistance. I would like to thank all companies, which contribute in this research and make this work possible. Also, I would like to thank Natural Resources Management Faculty staff and administration.

My special thanks are to my friends (almost relatives) in Saint-Petersburg, Russia: Pasha, Kolyan, Ksu and Panteleechka. Also, I would like to say thank to people, who became my friends here in Thunder Bay: Andrei, Anastasia Lavrenenko-Vihodchenko (also is known as Tetya Nastya), Sasha, Lesha, Nastya, Misha, Nadia, Anton, Leanne and Vlad.

Finally, I want to thank all my family for great support during my life in whole: my mom and Victor Ur'evich, my brother and sister, my father, and grandmothers Irina and Galina.

Special thank to my late grandfather Boris Besprosvanniy, who is always on my mind.

Table of contents

List of figures

List of tables

Introduction

According to the International Energy Agency, in 2009 wood energy comprised only 4% of Canada's total primary energy supply (TPES) (UNECE/FAO, 2009), while at the same time Canada was one of the world leaders in pellet production (competition with Sweden, Germany, USA and Russia.). The capacity of wood pellet production plants has grown from 300,000 t in 1997 to 3 million t in 2013 (Bradley, 2010; Murray, 2013). This growth is due in part to the European Union's renewable energy promotion policy, as 90 % of the total Canadian pellet production is exported overseas while domestic use is extremely low. Today pellet plants are present in almost all provinces of Canada, excluding the territories. However, a majority of pellet production capacity is located in Western Canada (British Columbia and Alberta). The Canadian government is promoting the use of clean energy from various sources. For example, according to an Ontario government report, the province of Ontario will be completely coal free by 2030 removing 12% of the total installed energy production in Ontario that is currently generated by coal (Ministry of Energy of Canada, 2010). Feed-in-tariff (FIT) programs were also introduced in Ontario in September 2009, which is meant to provide long-term contracts for stable, attractively priced energy generated using renewable resources (Ministry of Energy of Canada, 2010). The micro-FIT program (10 kW or less) prices for energy generated from biomass are 13.8 ¢/kWh for a 20 year contact term. The provinces Alberta, Manitoba and British Columbia have announced they will develop renewable energy micro-generation and heating projects (IEA, 2010).

With governments promoting bioenergy incentives it can be seen that domestic consumption will increase, particularly when considering the already strong export

market that has created a large pellet production base in Canada. With an increase in pellet consumption it will be necessary to develop a Canadian national wood pellet standard, which does not exist currently (Melin, 2011). The objective of this research was to examine the major characteristics/parameters of wood pellets produced by eight different companies from five Canadian provinces (Ontario, British Columbia, Manitoba, Nova Scotia and Quebec). We examined first class granules, which are also known as residential pellets, typically used in boilers with a capacity less than 1 MW or residential pellet stoves. Usually, residential boilers have a capacity from 15 kW to 500 kW; however, in the case where less than 15 kW is required it is more profitable to use a pellet stove. Comparative analysis of the results will display the influence of a certain raw-material characteristic or manufacturing practice option on the final product parameters. Interdependence and statistical analysis of pellet parameters will be organized in a manner that will be used to provide recommendations for the development of the Canadian pellet standard. These recommendations will be based on statistical analysis as well as comparative analysis with EU and Pellet Fuel Institute (PFI) standards. We hope that these recommendations will promote domestic use of wood pellets and give an opportunity to bring biomass energy through micro-generating and heating projects to geographically isolated areas.

1. Literature review

1.1 Raw Material Attributes and Resources

Canada has 10 percent of the world's forests. There are a few predominant tree species in Canada: spruce (53.2 %), poplar (11.6 %) and pine (9.3 %) (Natural Resources Canada, 2011). Annually, less than 1 percent of Canada's forests are harvested (Natural Resources Canada, 2011).

Different species display different thermal and mechanical properties. In Canada the average calorific value of softwoods is 21.18 MJ/kg and for hardwoods it is 19.35 MJ/kg (Kryla, 1984). Table 1 presents Canada's eight forest regions with their predominant tree species and the calorific values of these species.

Table 1. Calorific value of predominant Canadian tree species (Natural Resources Canada, 2013; Kryla, 1984; Singh and Kostecky, 1986; Singh and Kostecky, 1986; Stanton and Bourchier, 2012; Kelsey et al., 1979).

Forest region	Location	Predominant tree species	Calorific value	
			Stem (wood/bark)	Branch(wood/bark)
Acadian	Maritimes (Nova Scotia, Prince Edward Island and New Brunswick)	red spruce	-/20.07	-/-
		balsam fir	20.04/21.72	20.57/-
		yellow birch	19.77/21.40	20.74/20.94
		balsam poplar	17.7/19.46	19.10/-
Boreal	Northern Canada (northern British Columbia and the southern Yukon)	white spruce	19.01/19.83	21.14/-
		black spruce	18.78/19.47	20.67/-
		balsam fir	20.04/21.72	20.57/-
		jack pine	19.40/21.21	19.20/21.95
		white birch	18.82/23.98	21.11/21.50
		trembling aspen	19.35/19.62	20.41/20.83
		tamarack	18.78/19.49	21.46/-
		willow	19.66/18.93	19.89/-
		balsam poplar	17.7/19.46	19.10/-
Carolinian (Deciduous)	Southwestern Ontario	beech	-/17.77	-/-
		Maple	18.96/19.60	20.62/20.40
		hickory	19.33/17.53	18.89/17.60
		Oak	18.12/18.33	18.09/18.44
Coast	British Columbia	western red cedar	19.65/-	20.54/20.16
		western hemlock	20.13/21.62	20.62/23.13
		Sitka spruce	19.79/-	20.49/-
		Douglas-fir	20.25/23.96	20.30/25.23
Columbia	British Columbia	Douglas-fir	20.25/23.96	20.30/25.23
		western red cedar	19.65/20.16	20.54/20.16
		western hemlock	20.13/21.62	20.62/23.13
Great Lakes–St Lawrence	Central Canada (from southeastern Manitoba to the Gaspé Peninsula)	red pine	-/21.10	-/-
		red maple	19.62/17.79	19.41/18.61
		red oak	18.12/18.33	18.09/18.44
		eastern white pine	21.01/22.4	21.36/22.51
		eastern hemlock	-/20.68	-/-
		yellow birch	19.77/21.40	20.74/20.94
Montane	British Columbia and Alberta	Douglas-fir	20.25/23.96	20.30/25.23
		lodgepole pine	20.00/23.7	21.80/20.64
		ponderosa pine	20.82/22.01	-/21.99
		trembling aspen	19.35/19.62	20.41/20.83
Subalpine	British Columbia and Western Alberta	Engelmann spruce	18.84/20.54	21.11/22.37
		subalpine fir	-/-	-/-
		lodgepole pine	20.00/21.82	22.64/22.34

It can see that bark has a higher calorific value than wood. At the same time bark shows much higher ash content than wood. According to (Hakkila,1989) average ash content of stem bark is 2.97%, while stem wood displays 0.3±0.1% ash content for softwoods and

0.5±0.3% for hardwoods. For every 1% increase in ash content there is an associated decrease in the calorific value by 0.2 MJ/kg (Cassida *et al.,* 2005). Branch wood can show slightly higher ash content, because of reaction wood content and a lower proportion of wood to bark (Hosegood, 2010).

According to Penner *et al.* (1997), British Columbia has the largest amount of above ground biomass per hectare and Saskatchewan has the lowest amount. Penner *et al.* (1997) defines biomass as "the oven-dry weight in t/ha of various biological components of an ecosystem". Table 2 present biomass amount estimations in tonnes per hectare in every Canadian province:

Table 2. Average biomass amount (ODt) estimation (Penner et al., 1997).

Province/Territory	Softwood (ODt/ha)	Mixed wood (ODt/ha)	Hardwood (ODt/ha)	Unclassified (ODt/ha)
Newfoundland	52	76	84	80
Nova Scotia	71	70	83	–
Prince Edward Island	73	83	99	–
New Brunswick	87	87	90	16
Quebec	59	89	105	43
Ontario	83	85	101	84
Manitoba	46	74	72	–
Saskatchewan	35	67	89	–
Alberta	82	92	68	–
British Columbia	169	111	80	55
Yukon Territory	76	60	60	–
Northwest Territories	62	48	55	–
Canada	101	81	88	28

It is more economical to use sawdust and shavings rather than round wood for pellet production due to prime costs. According to the Collins English Dictionary (2010) "prime cost is that part of the cost of a commodity deriving from the labour and materials directly utilized in its manufacture". However, the severe drop in lumber production due to the economic downturn in the industry essentially wiped out surpluses of mill residue by 2009. In 2009 the estimated production of mill residues was under 11 million oven-dry

tonnes (ODt), or 61% of market demand for mill residue in 2004 (Bradley, 2010). More detailed data about Canada surplus mill residues is presented in Table 3.

Table 3. Canada Surplus Mill Residues (Bradley, 2010).

Province	2004 (ODt)				2009 (ODt)
	Production	Consumption	Export	Surplus	Production
BC	6,554	4,338	350	1,815	3,841
Alberta	2,406	1,924	0	481	1,985
Saskatchewan	580	416	0	164	0
Manitoba	225	212	0	13	0
Ontario	2,602	2,480	1	121	1,056
Quebec	6,669	6,400	169	100	3,171
New Brunswick	1,373	1,223	150	0	657
Nova Scotia	601	588	0	13	182
PEI	24	23	0	0	0
Nfld & Lab.	195	166	0	30	0
Total	**21,229**	**17,770**	**670**	**2,737**	**10,892**

1.2. Pellet Production process

The classical wood pellet manufacturing process is presented in Figure 1 and consists of the following stages (Kofman, 2010):

- reception and sawdust storage;
- drying and possibly intermediate storage again;
- screening for mechanical impurities;
- hammer-milling;
- pellet pressing;
- cooling action;
- screening of fines;
- packaging.

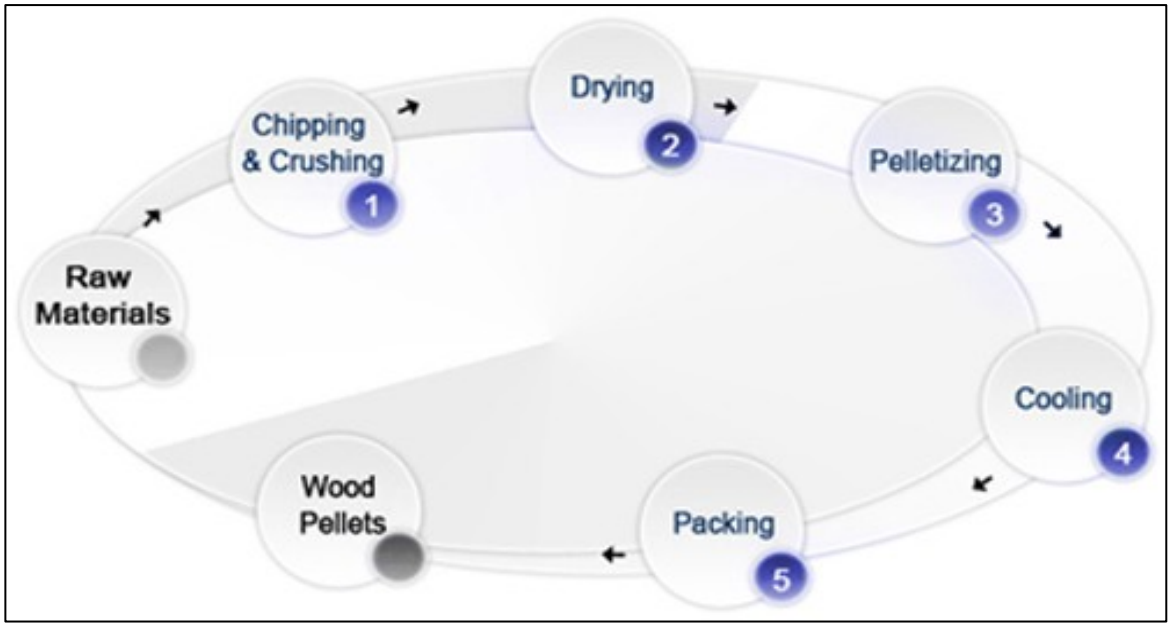

Figure 1. Pellet manufacturing process (Alpha Timber Ltd, 2013).

1.3. Raw material reception

After reception the raw-material is weighed and samples are taken for moisture content testing. It is important to separate wet and dry raw-material, as dry material cannot be stored outdoors in comparison to wet material (Kofman, 2010).

1.4. Grinding

The number of grinding stages depends on biomass type and size. If, for example, pellets are produced from round-wood or from lumber operations surplus, then there are two stages of grinding. The first stage is named the “coarse grinding stage” where the material is run through a “chipper” where the raw wood is reduced to chips similar to those found from a pulp wood chipper. Next, raw material has to be screened to avoid any impurities, i.e. stones, plastic and metal (Kofman, 2010). Following this stage the chips then enter the “fine grinding stage” where the chips go through a hammer mill to reduce the

particles to the required size. Usually, pelleting requires biomass that is ground to particles that are no more than 3 mm in size (Ciolkosz, 2009).

In the case of small-particle raw-material it is possible to skip the "coarse grinding" stage and skip to the "fine grinding" phase.

1.5. Drying

The finely ground material then moves to a drying stage. For woody raw-material the moisture content for pelletization is required to be around 15% according to Ciolkosz (2009). However, Liu and Lu (2000) reported that the ideal raw-material moisture content is approximately 8%. Moreover, wood waste with the moisture content more than 15% usually cannot be pressed properly (Tarasov, 2009). There are a few types of dryers: drum-type, belt (flatbed) drier (Kofman, 2010), tube bundle drier and the low-temperature drier (Louis, 2011). Dryers can be based on direct or indirect drying techniques, or both can be used. The direct drying method is based on hot air being applied to the raw-material, while indirect or contact drying works by heat being supplied by a heat exchanger through the metal walls (Mujumdar, 2011). Dryers also display different operating temperatures. Drum-type drier operating temperature may be between 300°C and 600°C (Louis, 2011; Worley, 2011). A belt-type operating temperature is comparatively low at 90°C to 110°C. In both cases indirect and direct methods can be used (Louis, 2011). In tube bundle driers the indirect method is used and the operation temperature is around 90°C, which minimizes organic emissions (Louis, 2011). Low-temperature dryers are based on indirect drying technology and operating temperature ranges between 50°C and 100°C (Louis, 2011). The choice of dryers is determined by the type of raw materials (wood chips, sawdust), quality requirements and the source of

thermal energy received. For instance, if the heat source is low-quality, such as a hot-water heater running at 70°C to 100°C, then a low-temperature belt-type dryer is the best option (Hein, 2011).

It is important to mention that the belt-dryer is quite universal and could be used for any type of raw material, however, traditionally belt dryers are used for saw-dust drying (Louis, 2011). On the other hand, if a producer has a high-quality heat source, such as flue-gas from suspension burners or grate-fired systems, then it is more advisable to use drum dryers based on the direct drying method (Hein, 2011). During pellet production the drying process is the most power-consuming aspect of production. It amounts to around 28% of pellet production prime costs (Alligno Maschinenexport GmbH, 2006). The indirect method of drying is more energy efficient than the direct method, although the cost of the indirect dryers is higher (Aebiom, 2007).

1.6. Pellet pressing

Usually, before pressing raw-materials are warmed up to 120°-130°C using dry steam. This action makes the lignin more plastic and it helps to bond raw material particles together (Kofman, 2010). Cylindrical and flat matrixes are used to form pellets in pellet press-machines (Figure 2).

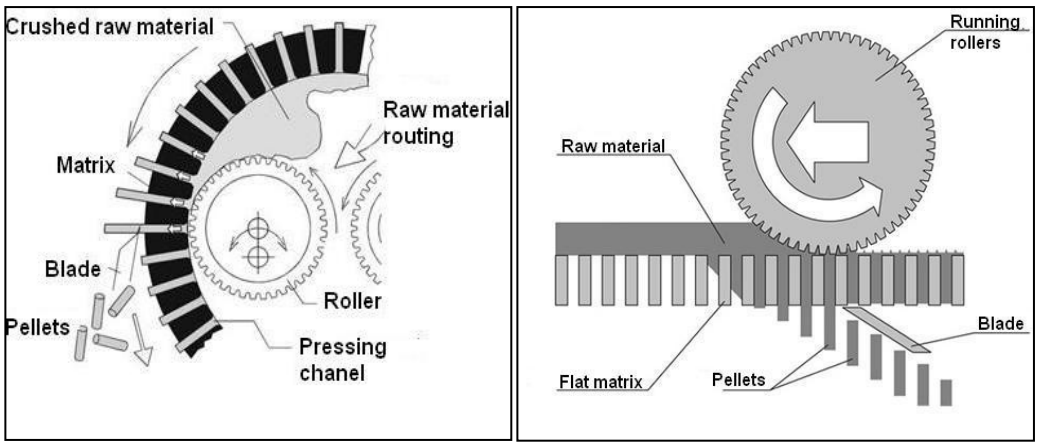

Figure 2. Pellet press with cylindrical (left) and flat matrix (right) (Pellets Partner Group, 2006).

Currently, both press types used in pellet production work on an identical principle. Running rollers create raw material deformation on a matrix, and through apertures in a matrix the raw materials are press through, which are then cut off by blades. The most important difference is in cleaning and changing matrixes and rollers. Flat matrixes in any service condition can be cleaned by drilling and polishing up at any location where deterioration is present. At the end of the production run vegetable oil is added to lubricate the last pellets. This addition is made, as it will be easier to start the press next time and avoid the last pellets becoming stuck in the matrix (Kofman, 2010).

1.7. Cooling and packaging

Following the pressing process pellets are very hot (80° - 130°C) and fairly soft (Louis, 2011; Ciolkosz, 2009). Usually pellets are cooled by blowing air over them (Ciolkosz, 2009), which also reduces moisture content of the final product (Kofman, 2010). However, during storage pellets can absorb moisture from the surrounding air (Kofman, 2010). After cooling is complete, pellets may be packed in bags of differing volumes or transported in bulk (Louis, 2011).

1.8. Additives supplement

According to the EU standards, additives that improve fuel quality, decrease emissions or boost burning efficiency can make up to a maximum of 2% of the total mass of the wood pellet (European Pellet Council, 2011). The most commonly used additives are lignosulphonate, starch, dolomite, corn or potato flour and some vegetable oils (Obernberger and Thek, 2010). These binding agents or additives also affect the production economics of the final product.

Lignosulphonate is a water-soluble anionic polyelectrolyte polymer obtained as a by-product of the wood sulfite pulping process (Lebo *et al*., 2001). Lignosulphonates are used in animal feed and have been considered as the most effective and popular binding agents for wood pellets. Normally 1 to 3% of lignosulphonates are used for effective binding of wood pellets (Tumuluru *et al.,* 2010). Starch is formed from two polymers, amylose a linear polysaccharide and amylopectin a large highly branched polysaccharide, and is obtained in various shapes and granular sizes when cereals or tubes are separated into protein and fiber components (Stahl *et al.,* 2012). The shapes and granular sizes of the starch affect its distribution in the wood material and consequently affect the pellet abrasion (Stahl *et al*., 2012). Other additives, like vegetable oil or dolomite, are added for better lubrication during the pellet production process (Kofman, 2010).

Binding agents are usually added to the production process either just before the core matrix-pressing phase in the pilot-scale pelletizing machine (Kuokkanen *et al*., 2009), or as a continuous flow of raw material on a collector screw (Kuokkanen *et al*., 2011).

The binding agents also affect power consumption and water usage during the wood pellet production process. Maize starch and lignosulphonate have been found to be better additives for reduced power consumption per unit of wood pellet output as compared to the other additives (Kuokkanen *et al.,* 2011). With no additives, the specific energy consumption for poplar wood pellet production was found to be 138 kWh/ODt (Mediavilla *et al.,* 2012). The specific energy consumption value significantly decreased to 79 kWh per dry tonne by adding 2.5% maize starch, to 128 kWh/ODt by adding 2.5% lignosulphonate, and to 106 kWh per dry tonne by adding 5% lignosulphonate (Mediavilla *et al.,* 2012). The lower specific energy consumption of using starch as an additive is due to the lubricating ability of starch during the production process. Water is added to the raw material before the pelletization process in order to obtain an optimum MC% of 6-8% (Kofman, 2010). The use of additives affects the amount of water required in the wood pellet production process. For example, the use of dolomite as an additive increases water consumption significantly, whereas wheat starch does not have much effect on water usage (BIOMASA Association, 2011). In case of dolomite supplement (0.5%) starch water consumption increases during pellet production approximately to 1%, while in case wheat starch (0.5%) additive water consumption remains same as reference sample (BIOMASA Association, 2011).

2. Wood pellet production development

Wood pellet production in Canada started in the mid 1990's. Production capacity and volume growth has exponential increased over the last 10 years (Figure 3).

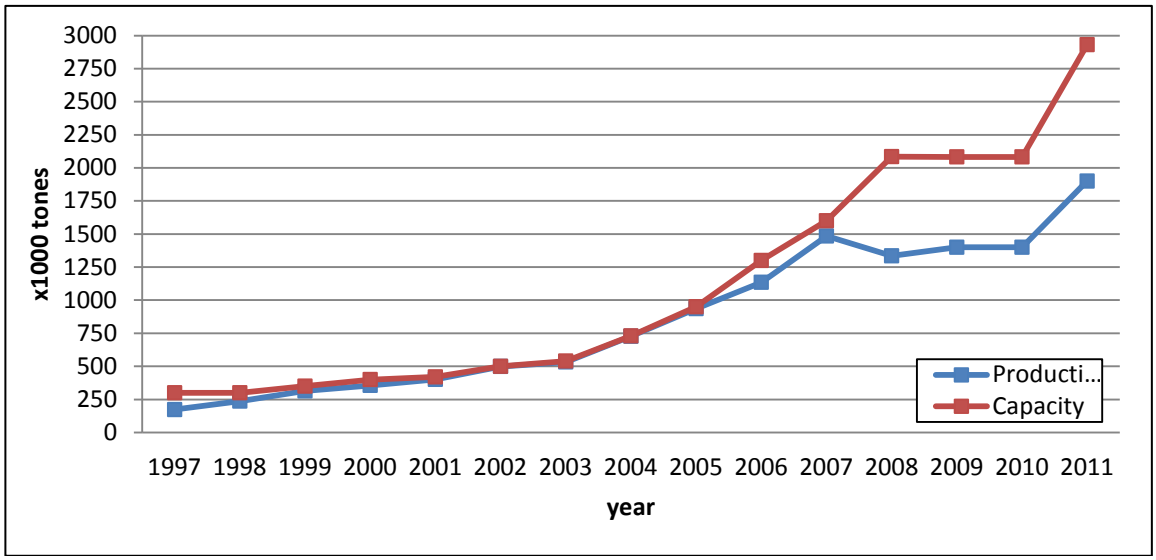

Figure 3. Wood pellet production/capacity in Canada 1997-2010 (Bradley, 2010; Swaan, 2008; Dessureault, 2011; Murray, 2011; Murray. 2013).

Figure 3 displays that until 2007 production plants were working at almost full capacity. In 2010 Canadian wood pellet plants operates at around 65% of their full capacity hence, producing approximately 1.3 million t (Wood Pellet Association of Canada, 2013).

Installed annual capacity is around 3 million tonnes, however, real production failed to rise due to a lack of mill residues, competition from other countries and lower market demand in the last few years. In particular in 2008, the housing crisis in the USA caused a dip in the demand of forest products from Canada. As 80% of Canadian forest products are exported to the USA, low demand resulted in fewer shifts or even mill shut downs in many cases (Bradley, 2010). The UNECE/FAO (2009) stated "the severe downturn in softwood sawn wood markets has had a domino effect on pellet producers and bioenergy plants in Canada". The reduction in sawmill lumber production from 2007 to 2008 was 19,151,000 metre^3 and the resulting mill residue reduction was 4,503,000 ODt (Bradley, 2010). Of course, all mill residue does not go to pellet production; if you were to assume that 5% of all mill residue went to pellet plants this equates to 236,500 tonnes of pellets

and production in 2008 could have therefore been approximately 1.6 million tonnes. This partly explains why real pellet production and installed capacity split in 2008.

The Canadian Wood Pellet Association reports that there are 38 pellet plants (Murray, 2013) wood pellet plants in Canada. According to the report of the Canada Wood Pellet Association 64% of production is concentrated in western Canada (Murray, 2012).Eastern provinces produce only 29% of all production in Canada. Mill numbers are greater in the east, but the west's production capacity is much larger. There are 22 plants in the east and 16 in the west with total installed capacities of 1,042,00 t and 1,889,000 t per year and , respectively (Murray, 2012). It is surprising that there are currently no large or even medium size producers in Ontario, however, large pellet projects are currently at the construction stage. For example Rentech Inc. out of California has recently purchased a plant in Atikokan and Wawa, Ontario to produce wood pellets for export markets with a planned production of 360,000 and 125,000 tonnes, respectively (Rentech Inc., 2013).

2.1. Domestic consumption

Canadian domestic pellet consumption sits at just 5% to 7% of production (roughly 100,000 tonnes) (Jamieson, 2010). Figure 4 below presents domestic wood pellet consumption in Canada.

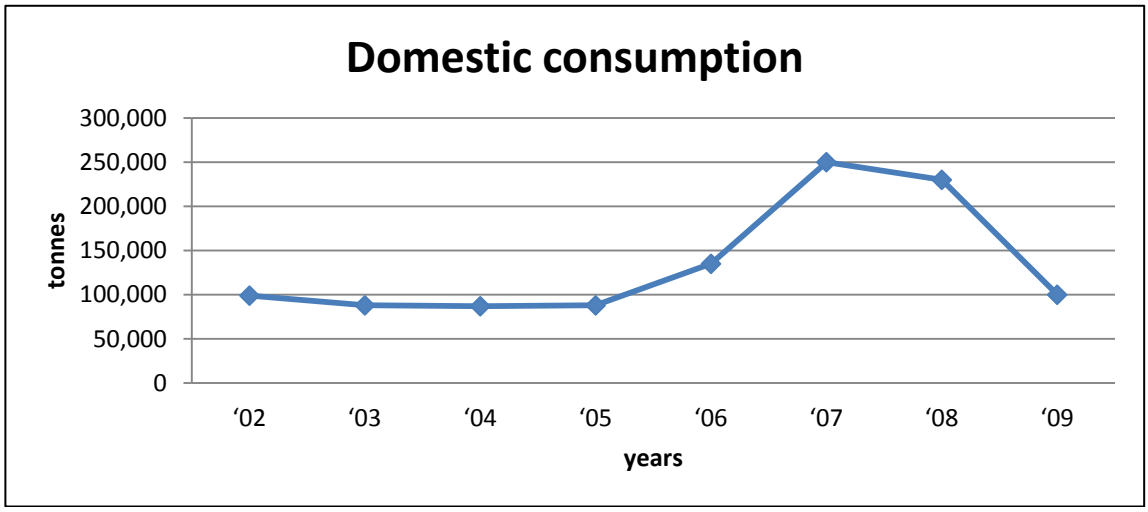

Figure 4. Wood pellet domestic consumption in Canada 2002-2009 (Bradley, 2010).

As can be seen from this figure the consumption peaked at the same time as production peaked in 2007 (see Figure 3 for production). This market is expected to grow, but slowly since there are few government policies or incentives promoting pellet use in Canada. Ontario Power Generation is planning to use 2 million tonnes of pellets annually by 2015, with most all of this supply coming from Northwestern Ontario (Junginger *et al.*, 2011). However, contracts were sighed only for 90,000 tonnes per year. According to research by the Pembina Institute (2011) 2 million tonnes of wood pellets could produce 3.4 billion kilowatt hours of electricity per year — sufficient to power approximately 285,000 homes in Ontario.

As a heating fuel for household usage pellets are popular in New Brunswick and Nova Scotia and unpopular in Saskatchewan and Alberta (Statistics Canada, 2010). Table 4 presents a comparison between the main types of heating fuels used by households.

Table 4. Type of main heating fuels used by households in 2007 (Statistics Canada, 2010).

Province	Electricity	Oil	Wood and wood pellets	Natural gas	Propane
Newfoundland and Labrador	61	F	16	F	F
Prince Edward Island	F	F	F	F	F
Nova Scotia	29	F	20	F	F
New Brunswick	59	F	23	F	F
Quebec	77	4	9	4	F
Ontario	19	68	3	68	2
Manitoba	39	56	3	56	F
Saskatchewan	16	80	F	80	F
Alberta	12	88	F	88	F
British Columbia	33	56	4	56	F

*F- too unreliable to be published

2.2. Export

Canada is a pellet export world-leader with competition for this title coming from Sweden, Germany, USA and Russia. The production of pellets in Sweden and Germany are mostly for domestic use. For example, in 2008 Swedish pellet production was 1.5 million tonnes and consumption was 1.85 million tonnes (Hiegl and Janssen, 2009), while Germany in 2008 produced 1.46 million tonnes and consumed 0.9 million tonnes (Hiegl and Janssen, 2009). Canada pellet producers are extremely export oriented. They are working in a similar manner as Russian producers where around 90% of pellets are exported to the EU. It is indicative that Canadian pellet exports to the USA were 0 in 2009, which may be "due to the impact of the Biomass Crop Assistance Program in the USA giving USA pellet producers a $50/tonne cost advantage over Canadian plants. This advantage, combined with a strong Canadian dollar, left Canadian producers uncompetitive, and consequently they lost the USA market" (Bradley, 2010).

Export numbers are difficult to get an exact value on, for example, according to the last presentation of the Wood Pellet Association of Canada's overseas exports in 2010 there

was 1.5 million tonnes exported of which 1.35 million went to the EU (Murray, 2011). However, according to Eurostat (Eurostat, 2012) Canadian wood pellet imports by the EU from Canada was only 983,065 tonnes. Discrepancies in export data are also seen in the 2009 data where the Canadian Bioenergy Association stated wood pellet exports to Europe at 1.2 million tonnes, while according to Eurostat (Eurostat, 2012) data wood pellet imports by the EU from Canada were only 520,200 tonnes. Figure 5 displays wood pellet export numbers from Canada in 2010.

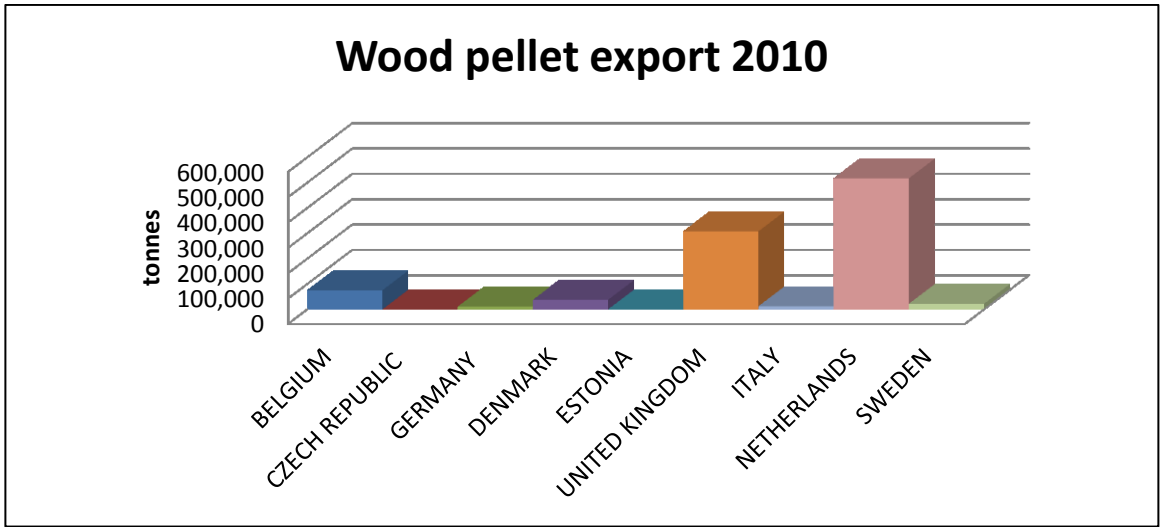

Figure 5. Wood pellet export from Canada by country of destination in 2010 (Eurostat, 2012).

As we can see from this figure a major portion of Canadian pellets go to the Netherlands and UK. This could be explained in part due to a large sea-port in Rotterdam, where a majority of Canadian vessels arrive.

3. Wood pellet characteristics/parameters

Major parameters, which affect pellet quality, are:

- Moisture content
- Heating value
- Durability
- Particular pellet density
- Ash melting point
- Bulk density
- Ash content
- Pellet size
- Chemical composition (binding agent use)

These parameters are usually measured for standards compliance. There are two main pellet standards: North American, which was developed by the Pellet Fuel Institute (PFI) and the European Union standard (CEN/TS prEN 14961-1), which was introduced in 2010. Of course, there are a lot of other national standards, like DINplus in Germany and SS181720 in Sweden, however, prEN 14961-1 is being used as the pan-European standard. A description of each of these parameters and their influence on pellet quality is provided.

3.1. Moisture content

Moisture content (MC %) is given as a percentage of the original sample mass (oven dry condition) and it has a strong influence on other pellet characteristics. Moisture affects heating value, combustion efficiency and temperature, pellet durability, and bulk density (Hansen *et al*., 2009; Wilson, 2010; Obernberger and Thek, 2010; Samuelsson *et al.,* 2010; Tabil *et al*., 2011).Moisture content also has an effect on the production cost and the production process itself.

Figure 6 displays how moisture affects the production cost.

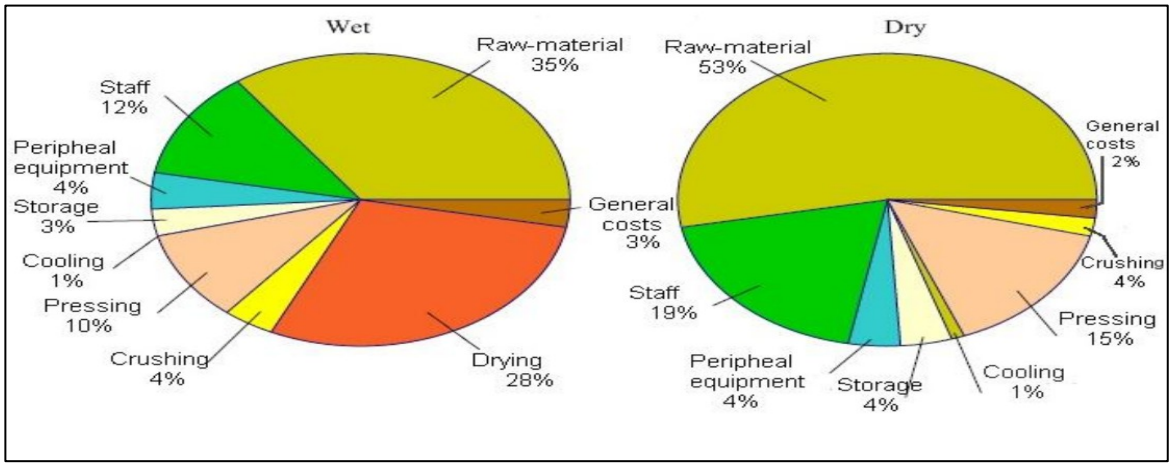

Figure 6. Percentage distributions of costs in the production of pellets using wet and dry raw-materials (ALLIGNO Mashinenexport GmbH, 2006).

As we can see with dry raw-materials 53% of the total production cost is for the raw-material; while with wet raw-material only 35% of total production cost is for raw-material as drying consumes 28% of the total production cost.

When combined, the wet raw-material costs more to get it to a dry state than the dry raw-material costs (63% versus 53% for dry raw-material). For sawdust drying, it is necessary to utilize 1 MW of energy per tonne of evaporated moisture. Also, if MC% exceeds 15% there is a danger of biological decomposition of the pellet (Hansen *et al*., 2009).

Different additives require different amounts of moisture in the raw material in order to bind the material effectively (Mediavilla *et al.,* 2012; Kuokkanen *et al.,* 2011). The use of starch as a binding agent requires the raw material MC% is between 12.5% and 13.0%, whereas lignosulphonate requires the raw material MC% is between 9.0% and 10.5% for the pelletization process (Mediavilla *et al*., 2012). When additives are used for making wood pellets, these decrease the final MC% of the wood pellet. For example, wood pellets made of a standard raw material (with 9.3% MC) and 1% or 2% lignosulphonate

(with 8% MC) mixture will result in a final pellet MC% of 5.9% (Kuokkanen *et al.*, 2011).

However, when the lignosuphonate dosage is increased to 2.5%, 5% and 7% it does not result in a significant effect on the final MC% of the wood pellet (Mediavilla *et al.,* 2012). In another example where 5% potato peel residue (with 77.8% MC) and dry raw material (with 3.3% MC) are mixed together, the resulting wood pellets have a 2.9% MC (Kuokkanen *et al.,* 2011).

The use of starch significantly reduces the final wood pellet MC%. For example, Stahl *et al.* (2012) found that when raw material (with 12.1% MC) was mixed with 1% wheat starch, and the same amount of oxidized corn-starch, the final pellet MC% was 7.6%. Increasing concentrations of wheat and corn-starch further reduces the pellet MC% (Stahl *et al.,* 2012). Interestingly, if lignosulphonate and corn-starch are added at the same time (1% of lignosuphonate and 1%, 2%, 3% or 4% of maize starch) to the raw material the final wood pellet MC% decreases only by 0.5% (Mediavilla *et al.,* 2012).

From the above-mentioned literature, it is clear that the addition of starch has a higher impact in reducing the final wood pellet MC% when compared to lignosulphonate. However, too much starch will make the final product extremely dry, which will affect pellet durability. As was mentioned previously the final MC% of the wood pellet is very important, as it affects not only the calorific value, but also durability and abrasion of the product (Hansen *et al.*, 2009; Wilson, 2010).

According to the European standard (ENplus), the MC% has to be 10% or less (Obernberger and Thek, 2010); according to the PFI standard this parameter should be less than or equal to 8% (Pellet Fuel Institute, 2010).

3.2. Heating value

The heating value or calorific value of biomass is defined as the energy amount per unit of mass or volume released from complete combustion (Obernberger and Thek, 2010). Heating value is the most important pellet characteristic as it defines customer value. The more heating value, the more energy from the same amount of product can be produced and, consequently, there is less expense for the customer. There are two types of heating value: high heating value (HHV) and low heating value (LHV) (Obernberger and Thek, 2010). The difference between these two types of heating value is very important. LHV determines the maximum amount of heat excluding heat of vaporization, while HHV includes this part of heat, which could be returned back using special systems (e.g., condensation boiler). These two heating values can be calculated from the following equations. The equation below [1] gives HHV (Gaur and Reed, 1998):

$$HHV(\text{in kJ/g}) = 0.3491C+1.1783H-0.1034O-0.0211A+0.1005S-0.0151N \quad [1]$$

(C- mass fraction of carbon, H-hydrogen, O- oxygen, A – ash, S- sulphur, N-nitrogen)

As we can see from this equation, increasing carbon, hydrogen and sulphur concentration increases HHV, but if nitrogen or oxygen goes up, HHV decreases. Different species of wood contain different amounts of nitrogen, for example, nitrogen content of red spruce wood will be two times as high compared to balsam fir wood (Young *et al*., 1965). Bark also contains more nitrogen than wood itself (Schowalter and Morrell, 2002); as a result, it is better to use de-barked raw materials. Softwoods have a higher heating value than hardwoods per mass due to softwoods containing extractives that themselves produce high heating values (Baker, 1983). Also, softwoods display higher lignin content compare

to hardwoods. Lignin content of softwoods is 25-30% and hardwoods lignin content is 18-25%. Lignin content positively affects calorific value (Blunk and Jenkins, 2000).

In Canada average calorific values of softwoods and hardwoods are 21.18 MJ/kg and 19.35 MJ/kg, respectively (Kryla, 1984). The more detailed information about calorific value of different species is presented in the "Raw material reception" chapter.

It is important to mention that the difference between the theoretical calculation of HHV and experimental results range from 0.21 % to 3.57 % (Gaur and Reed, 1998).

LHV can be calculated using equation (2) (Boundy *et al*., 2011):

$$LHV = HHV * (1 - M/100) - 2.447 * M/100 \quad [2]$$

(M- Moisture content)

As we can see from equation (2) and Figure 7, heating value has a strong linear dependence on moisture content (Ciolkosz, 2010). Also, heating value depends on the particular wood's density, in other words how much mass is contained in each unit volume. The maximal single pellet density, which was observed, is 1,901 kg/m^3 (Wu *et al*., 2011). However, with this high density wood elements are very tightly packed, which aggravates access of oxygen and, consequently, the burning process is degraded. However, it has been noted, that "dense particles show a longer burnout time" (Obernberger and Thek, 2004).

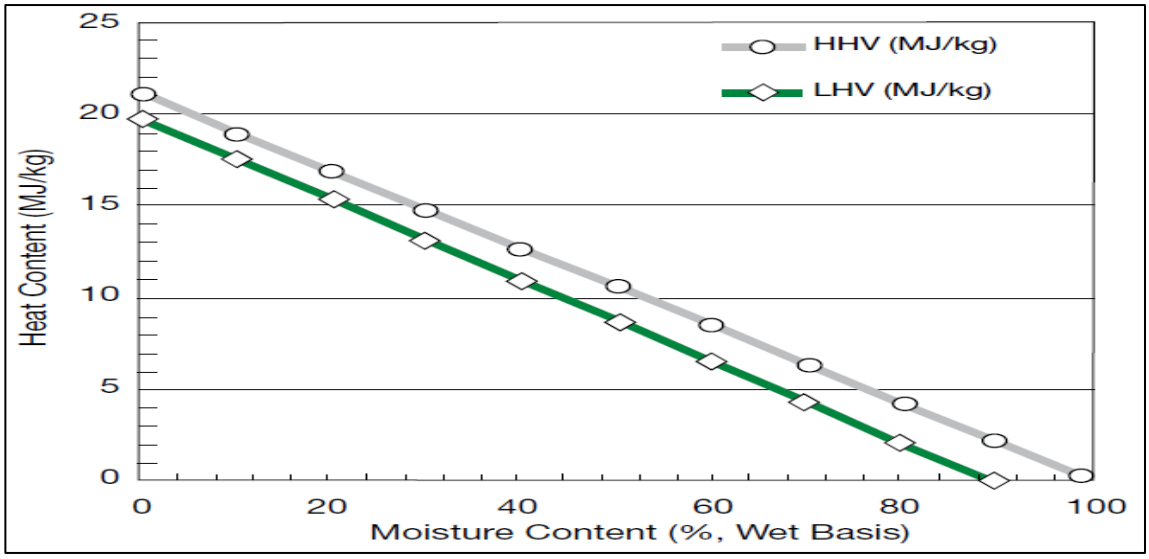

Figure 7. HHV and LHV dependence on moisture content (Ciolkosz, 2010).

Cypress produces the highest heating value at 22.96 MJ/kg, while the lowest heating value was found in Chaparall at 18.61 MJ/kg (Gaur and Reed, 1998). In the PFI standard, a minimum pellet heating value is not mentioned (Pellet Fuel Institute, 2010), however, according to the EU standard this parameter has to be ≥16.5 MJ/kg (Obernberger and Thek, 2010).

The calorific value of pellet depends on raw-material composition. Pellets made from nonresinous raw-material shows heating values from 18.6 to 19.8 MJ/kg. In case of resiniferous species gross calorific values will be from 20.0 to 22.5 MJ/kg. Pellets made from bark of nonresinous and resinous species yields from 18.6 to 19.8 MJ/kg and from 20.4 to 25.1 MJ/kg respectively (Resch, H, 1989)).

The presence of lignin, which is naturally in woody biomass, also increases the heating value of woody biomass (Demirbas, 2001). Bark has higher lignin content than the woody component of a tree and therefore displays a higher heating value (Lehtikangas, 2001).

The additives lignosulphonate, potato flour and potato peel residue do not significantly impact the calorific value of wood pellets (Kuokkanen *et al.,* 2011). However, a 0.5% concentration of motor oil and vegetable oil increases calorific values while 0.5% corn-starch as an additive decreases calorific values by about 0.5 MJ/kg (Nosek *et al.,* 2011). In addition, particulate emissions during the burning of softwood pellets are lower than for hardwood pellets (Houck, 2009). For example, under a normal burn rate (1.01 kg/h) the particulate emission rate of softwoods was measured at 0.60 g/h, and the particulate emission factor is 0.59 g/kg; in the case of hardwood pellets, the particulate emission rate and emission factor were 2.34 g/h and 2.32 g/kg, respectively (Houck, 2009).

3.3. Pellet durability and strength

It is important to understand the difference between durability and strength. The PFI defines durability as the ability of pellets to resist destruction caused by shipping and handling (Pellet Fuel Institute, 2010). Kaliyan and Morey (2009) define durability as abrasion resistance, and strength as compressive resistance and impact resistance. There are a few different methods for abrasion resistance measurements: Tumbler test, Dural test, Holmen test and Lingo test (Oveisi-Fordiie, 2011). For our measurements the Lingo test was used. During this test "pellets are subjected to shocks caused by an air stream that induces the particles to collide against each other and the walls of equipment" (Oveisi-Fordiie, 2011). A compressive resistance test simulates the load of the pellets own weight during storage, while impact resistance simulates the impact forces affecting granules when pellets are dropped on a rigid surface or onto one another (Wilson, 2010). Compressive resistance is the maximum collapse load, which a pellet can sustain before breaking (Kaliyan and Morey, 2009). Some researchers consider durability and strength

as one parameter referred to as durability and defined as how well a product can resist external forces after a sustained period of time (Oveisi-Fordiie, 2011). According to Rumpf (1962), five factors describe the binding forces between particles, which are also responsible for final product strength. These five factors are:

- Solid bridges form as a consequence of the temperature gradient at densification and during the cooling process. According to Manickam (2006) solid bridges play an important role in the final strength of the product;
- Attractive forces between fractions and especially van der Waals forces (Wilson, 2010), work only if particles are close to each other (Samuelsson *et al.,* 2012). There is an inverse relationship between attractive forces and particle size (Kaliyan and Morey, 2006);
- Interfacial forces "result from surface tension and capillary forces between the liquid and particles" (Samuelsson *et al.,* 2012). However, links created by interfacial forces and capillary pressure pass away after pellet dehydration;
- Mechanical interlocking forces can recalcitrate against tearing forces formed during recovery after pressing (Grey, 1968); and
- Adhesive and cohesive forces, are largely affected by interfacial forces and capillary pressure (Wilson, 2010). Adhesive forces are the attraction between molecules of the same subject matter, while cohesive forces are the attraction of molecules of different types (Samuelsson *et al.,* 2012).

According to Rumpf (1962) granule strength is determined by pellet strength, which is affected by the strength of the bonds within the pellet and pore volume in the granule. Pellet durability is affected by factors such as MC%, raw-material chemical composition,

particles size distribution, binders and additives. One of the most important factors is the MC%. Research has shown that MC%, within a range, works as a binding agent, which has also led to research relating to the ideal MC% for wood pellets. Li and Liu (2000) reported that high quality pellets could be produced when the raw-material MC% is between 6 % and 12 %. Subsequently they mentioned that the ideal raw-material MC is around 8 % (Li and Liu, 2000). Water is known to affect the development of interfacial and capillary pressures (Wilson, 2010). When insufficient moisture is available the funicular state will not fully develop. The funicular state is characterized by the filling of all voids with liquid (Wilson, 2010). Too much moisture will produce a negative effect on the particles agglomeration due to the non-compressible nature of water (Wilson, 2010).

It is known that lignin acts as an adhesive (Mancera, 2011). High lignin content leads to more durable pellets and increased abrasion resistance (Obernberger and Thek, 2010). Interestingly, Novaes *et al. (2010*) mentioned in their research that there was a negative correlation between lignin content and biomass growth. The above-ground wood volume is negatively correlated with syringyl/guaiacyl lignin units ratio (S/G ratio), r=0.59 (Novaes *et al.,* 2010). They suggest, that "improved growth rate could result in a reduction in lignin content", which will produce higher yields for biomass fuel production. In addition, some pellet producers are utilizing different binding agents, for example starches and lignosulphonate, for pellet quality improvement. Stahl *et al.* (2012) found that the addition of starch additives increased wood pellet mechanical durability. The addition of 2.8% oxidized corn starch had the best overall effect among all the starches, with the mechanical durability index increasing from 93.6% (native wood) to 98.1% (Stahl *et al.*, 2012).

The addition of lignosulphonate resulted in a mechanical durability value of 98.0% compared to 95.9% when the same amount of maize starch was added (Mediavilla *et al.,* 2012). Interestingly the combination of lignosulphonate and maize starch did not improve the mechanical durability at any of the combinations tested, in fact they were all lower than the additives at all concentrations tested independently (Mediavilla *et al*., 2012) (see Table 5).

Table 5. Particle density and mechanical durability of poplar pellets using different additives, with specific pelletization surface area of 5.6 cm^2/kW (Mediavilla et al., 2012).

Additive	MC (%)	Particle density (kg/m^3)	Mechanical durability (%)
LS 2.5%	9.9	960	98.0
MS 2.5%	9.9	970	95.9
LS 5%	8.5	1080	98.8
MS 5%	9.8	960	97.3
LS 7%	9.5	1060	98.4
MS 7%	9.0	1000	96.4
MS 0.95% + LS 1.05%	6.3	1070	93.2
MS 1.94% + LS 1.06%	8.4	1030	95.6
MS 2.94% + LS 1.06%	8.0	1100	97.1
MS 3.93% + LS 1.07%	7.2	1130	97.1

(LS: Lignosuphonate, MS: Maize Starch)

Particle size is another important criterion, which predetermines pellet durability and strength parameters (Wilson, 2010). "Hammer mill screen sizes of either 3.2 mm or 3.2 to 4.0 mm (4.0 mm on top, 3.2 mm on bottom) produced the highest quality pellets." (Wilson, 2010).

Finer-grained feedstock increases pellet durability and strength. Research has shown that the best quality pellets are produced with a combination of particle sizes due to increased inter-particle connections (mechanical interlocking) and the isolation of inter-particle spaces (attractive, adhesive and cohesive forces) (Oveisi-Fordiie, 2011). According to the European standards, the durability of high-class pellets should be equal to or greater than 97.5% (Obernberger and Thek, 2010), while the PFI standard sets this parameter at equal

to or greater than 96.5% (Pellet Fuel Institute , 2010). There currently is no standard value for compressive resistance of pellets.

3.4. Particular density

Particle density is the ratio of the sample mass and its volume including pore volume (Temmermana *et al.,* 2006). Single pellet density is variable and depends on the wood pellet production pressure settings and wood species. These strength parameters are particularly important for storage and transportation of wood pellets over long distances, as it is important to minimize dust and fracture formation during storage and transportation. Pellets with higher single pellet density also have a longer burnout time (Obernberger and Thek, 2010).

Nosek (2011) found that using additives (such as motor oil, cornstarch, sodium carbonate, urea, vegetable oil and dolomite) at a concentration of 0.5% decreased wood pellet particle density. The strongest effect on decreasing wood pellet particle density was found when corn-starch and dolomite were used as an additive (Nosek *et al*., 2011).

A minimum pellet density does not exist in the prEN 14961-2 and PFI standards (Obernberger and Thek, 2010; Pellet Fuel Institute , 2010). However, according to the German and Austrian standards, single pellet density should be between 1000 and 1400kg/m^3 (Hahn, 2004).

3.5. Bulk density

Bulk density of pellets is the mass of a portion of a solid fuel divided by the volume of the container that is filled by that portion under specified conditions (Obernberger and

Thek, 2010). The most influential factor for bulk density is raw-material MC%, which displays a negative correlation (Larsson *et al.*, 2008).

Bulk density affects transport and storage expenses (Tabil *et al.,* 2011). It is logical that lower bulk density will result in higher transport costs. Pellets with higher bulk density have higher energy density, and consequently lower transportation and storage cost in case of equal pellet volumes (Obernberger and Thek, 2010). Also, bulk density increases with higher single pellet density (Obernberger and Thek, 2010).

Tabil *et al*. (2011) and Samuelsseon (2012) reported an inverse negative relationship between MC% and bulk density. Raw materials with a larger particle size and higher MC% reduce bulk density of the product, while higher process temperatures and pressures increase bulk density (Tumuluru *et al*., 2010).

A straight-line relationship should exist between single pellet density and bulk density (Thek and Obernberg, 2010.). However, according to Wu's (2011) research, 6 mm pellets (average particle density of 1,764 kg/m^3) compared to 8 mm pellets (average particle density of 1,687 kg/m^3) display a lower average bulk density of 609 kg/m^3 compared to 621 kg/m^3, respectively. The author explains this seemingly reversed result as material and technology differences (Wu, 2011). According to the European standard, bulk density should be equal to or greater than 600 kg/m^3 (Obernberger and Thek, 2010). Bulk density of softwood pellets increases by 20-25 kg/m^3 with the addition of 5% bark as the additive (Filbakk *et al.,* 2011). This is due to bark containing 8-10 times the concentration of metals, such as aluminum, iron and sodium than is found in stem wood (Obernberger, 2005). Other additives, such as lignosulphonate and different types of

starch decrease the moisture content of a wood pellet, thereby increasing the bulk density of the product.

The PFI standard is more specific for this parameter where bulk density of residential pellets should be 640-736 kg/m^3 (Obernberger and Thek, 2010; Pellet Fuel Institute , 2010).

As was mentioned previously, softwood pellets display higher heating value per unit mass than hardwood pellets; hence under similar conditions, the same mass of softwood pellets will give more energy than hardwoods.

3.6. Ash content

Ash content is interpreted in percent as the weight of ash in relation to fuel weight. It is a significant parameter for all users of pellets, as high ash content will decrease stove efficiency, potentially degrade internal metal components of the stove and the stove will require cleaning more often (Obernberger and Thek, 2010). It is easy to see from Equation (1) (Gaur and Reed, 1998), that ash content also displays a negative effect on the heating value.

Hartman and Herranen (2005) reported that there is a direct dependence between ash content increases and dust emissions (Figure 8).

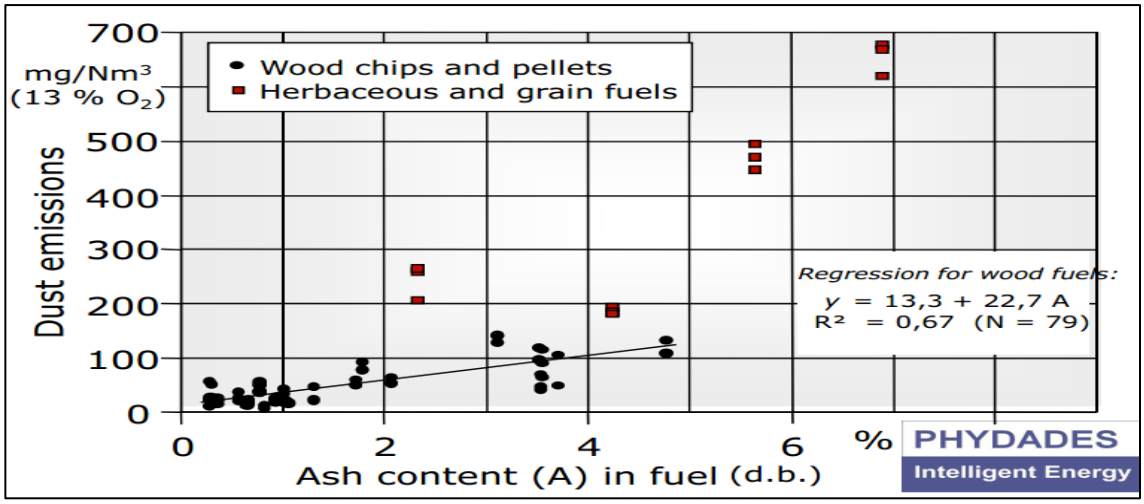

Figure 8. Influence of the ash content on dust emissions (Hartman and Herranen, 2005).

Different species have different ash contents. According to Gaur and Reed (1998), ash content in wood ranges from 0.1 % (White Pine) to 2.2% (Western Hemlock) in softwoods and from 0.2% (Tan Oak) to 2.98% (Mango) in hardwoods. Generally softwoods have lower ash content than hardwoods with the average ash contents being 0.71% and 0.91%, respectively (Gaur and Reed, 1998). However, ash content of pellets can be higher than the ash content of the raw material, due to external factors, such as different impurities and additives (such as bark and sand) which increase ash content (Hansen *et al*., 2009).

According to the EU standard, premium class pellet ash content should be 0.7% or less (Thek and Obernberg, 2010), while PFI standards define this parameter to be equal to or less than 1% (Pellet Fuel Institute, 2010). If a producer adds a large amount of bark during pellet production, therefore increasing ash content above the 1% level, these pellet mixtures are classified not as A (prime) class pellets, but as A2 and B-class (Hansen *et al*., 2009). Kuokkanen (2011) found that a supplement of 1% potato flour does not affect ash content, however a 2% concentration of the same additive increased ash content from

0.5% (native wood) to 0.6%. A 0.5% and 3% addition of dolomite also increased the ash content as compared to the reference sample (BIOMASA Association, 2011). When lignosulphonate was used at concentrations of 1% and 2%, wood pellet ash content increased from 0.5% (native wood) to 0.6% and 0.8%, respectively (Kuokkanen *et al.,* 2011). However, a 0.5% addition of wheat starch significantly reduced ash formation two times (BIOMASA Association, 2011).

Ash produced from the burning of wood pellets is currently being seen as a "potential forest fertilizer and soil conditioning agent" (Kuokkanen *et al*., 2011). Studies are currently ongoing and if pellet ash displays encouraging results as a fertilizer it will increase opportunities for large burning systems such as CHP to sell off an otherwise waste product from the combustion of pellets.

In addition, wood ash could be used as a filling matter in the construction of flexible pavements for roads and highways (Ban and Ramli, 2011). Moreover, wood waste ash is useful in building construction. It was found that it could be used as a partial cement replacement matter during structural grade concrete and self-compacting concrete manufacturing (Ban and Ramli, 2011).

3.7. Ash melting temperature

Ash melting point is defined as the temperature which ash starts to melt or soften (Force Tecnology, 2013). Ash melting point for high-quality pellets should be 1200-1300°C (Hansen *et al*., 2009). At lower values it is possible for slagging and/or sediment formation (Hansen *et al*., 2009). Slagging is defined as heavy deposition of fly-ash onto the kiln interior (Pitelka, 2007), while the degree of sintering is the strength of the

deposits (Ohman *et al.,* 2004). Werther (2000) postulated that ash-melting point has an inverse relationship with alkali content.

Ash melting point is affected by the chemical composition of the biomass used for making wood pellets. For example as concentrations of calcium and magnesium in the biomass increase, or the concentrations of potassium and sodium in the biomass decrease, the ash melting point of the wood pellet decreases (Werther, 2000; Paulrud, 2004; Obernberger and Thek, 2010). High concentrations of chlorine, potassium and sodium also enhance the likelihood of corrosion to the inner components of the stove or boiler system (Hahn, 2004).According to the EU standard, the ash melting point has to be greater than 1200°C (Bernhardt *et al.,* 2009).

More specifically, ash fusion temperature depends on phosphorous, sodium, magnesium, manganese and potassium (Filbakk *et al.,* 2011). For example, as previously mentioned high potassium and sodium content reduce the ash-melting temperature. However, elements like calcium and magnesium improve the ash fusion point (Paulrud *et al.,* 2001; Hahn, 2004). It is also important to take into account K, Cl and S content as those metals form chlorides, which can cause accelerated corrosion of equipment during combustion (Biedermann and Obernberger, 2011).

According to Filbakk (2011) ash-melting point of pure wood pellets (scots pine) is 1230°C, however, with a 5% bark additive the ash-melting point significantly increases to 1567°C (Filbakk *et al.*, 2011). According to this research it is possible to include up to 10% bark in a pellet and meet EU and PFI standards. Bark also contains large concentrations of silicium (Si) for protection (Biedermann and Obernberger, 2011). The concentration of Si is approximately 150mg/kg in stem wood while it can be as high as

2,000mg/kg in softwood bark and 10,000mg/kg in hardwood bark (Biedermann and Obernberger, 2011). Si forms potassium silicates at high temperatures, which reduces the combustion efficiency of wood pellets (Paulrud *et al.,* 2001; Baxter *et al.,* 1998). Nosek (2011) found that 0.5% dolomite as an additive significantly increased the ash melting point from 1200°C (native pellets) to approximately 1500°C, while other additives did not show any significant effect on ash melting point. However, ash melting point was significantly impacted when bark was used as an additive.

It is important to mention that there is no ash-melting point mentioned in the PFI standard (Pellet Fuel Institute, 2010), however, according EU standards prime-class pellets require an ash-melting point ≥1200°C and for first-class pellets equal to or greater than 1100°C (Obernberger and Thek, 2010)

3.8. Volatile organic compounds (VOC) and chemical composition

The term volatile organic compound was defined by Health Canada as "all chemicals containing carbon and hydrogen with the organic compounds having boiling points roughly in the range of 50° to 250°C" (Minister of Public Works and Government Services Canada, 2001). The higher the VOC's and CO emissions the more inefficient the fuel combustion is (Wakelin and Beauchemin, 2008).

There are other volatile hydrocarbon vapours produced by pellet stoves, besides methane, such as ethene, ethyne, chlorethane, vinyl chloride propene, propyne and benzene (Olsson, 2003;Preto, 2005). According to Preto (2005) the most common VOCs are the so-called BTEX compounds (benzene, toluene, ethylbenzene and xylenes). In addition, Preto (2005) mentioned that the following pellet characteristics have an influence on VOC emissions:

- low moisture results in low VOC emissions;
- increasing burn rate results in lower VOC emissions; and
- VOC emissions during hardwood pellet burning are much lower than from softwood pellet burning.

Moreover, several researchers have reported that VOC's were emitted from pellets during storage. Compared to new pellets, three-week-old pellets displayed emission values of pentanal and hexanal that were more than 28-times and 8-times that of new pellets, respectively (Arshadi and Gref, 2005).

The PFI standard defines an acceptable maximum level of chloride as 300 ppm. In the EU standard chloride is accepted up to 200 ppm, plus there are maximum levels mentioned for some heavy metals like zinc, nickel, and mercury (Thek and Obernberg, 2010.). Table 6 presents the amount of other gases measured by Hansen *et al.* (2009), which were emitted during wood pellet combustion.

Table 6. Gases emitted during pellet combustion (Hansen et al., 2009).

Name	Emitted amount
CO_2	0.108 g/MJ
SO_2	0 g/MJ
CO	50-3000 Mg/MJ*
NO_x	130-300 Mg/MJ

*depending on boiler type

There are several parameters, which could assure low VOC emissions, such as high temperature, high air surplus and long retention time. However, these condition "are the main reasons for the creation of nitrous oxides (NOx)" (Hansen *et al*., 2009).

As it was mentioned previously, biomass combustion behaviour depends on percentage composition of C, H, N and O. However, other element contents are affecting wood pellet quality.

For example, an increased amount of K during combustion causes higher aerosol formation and particulate emissions (Obernberger and Thek, 2004). In addition, a high content of Cl can also cause corrosion problems to internal components of the burning system (Obernberger and Thek, 2004).

3.9. Emissions Formation

Wood fuel is considered a renewable energy source and can help decrease the earth's atmospheric CO_2 concentration levels, if it replaces fossil fuels for energy production (BW McCloy Associates Inc, 2009). Greenhouse gas emissions during wood pellet production and combustion are much lower compared to burning fossil fuels (Bates, 1995; Bates and Henry, 2009). However, wood pellets cannot be considered as a CO_2 neutral energy source (Roth, 2006). The carbon emissions for wood pellets, is higher than for wood chips because of the additional energy consumed in wood pellet production stages, such as drying, pelletizing, etc. (Roth, 2006). The amount of CO_2 emissions varies from 30kg/MWh to 106kg/MWh, and depends on the biomass species used, its source and the method of drying and pellet production (Bates and Henry, 2009). The use of additives in wood pellets has also been found to further increase greenhouse gas emissions. For example, lignosulphonate addition significantly increases sulphur content (Kuokkanen *et al*., 2011), resulting in increased SO_x emissions (Hahn, 2004; Lehtikangas, 2002). Although, the addition of corn-starch (0.3% and 0.5%) and dolomite (0.1%) decreases SO_x emissions from 6mg/m³ to 4mg/m³, these additives significantly increase carbon monoxide (CO) emissions (Nosek *et al.,* 2011).

Pellets without additives emit approximately 250mg/m³ of CO emissions, while pellets with 0.3% corn starch as an additive emit approximately 550 mg/m³ of CO, and with 0.5% of dolomite as an additive emit approximately 700mg/m³ of CO (Nosek *et al.,* 2011). However, no significant influence on NO_x emissions has been found (Nosek *et al*., 2011; Kuokkanen *et al.,* 2011).

The summary Table 7 below presents a brief description of parameter interdependencies and their increasing/decreasing effect on pellet quality.

3.10. Pellet size

Pellet size affects strength and bulk density. Sikanen and Vilppo (2012) found that wood pellet burning temperature decreases by 31% and flue gas temperature by 25%, as the pellet diameter increases from 5.8 mm to 13.1 mm. The use of binding agents as additives has been found to have an effect on pellet length. Stahl (2012) found that starch as an additive significantly increased wood pellet length when no cutting blade was used. For example, without the starch supplement average pellet length was 6.8 mm, but in the case of adding 0.7%, 1.1% and 2% of starch average pellet length increased to 7.3 mm, 7.5 mm and 8.2 mm, respectively (Stahl *et al.*, 2012). Also, it was noted that oxidized starch increases the pellet length more than native starch (Stahl *et al.*, 2012).

High-class pellets, according to the PFI standard are required to be between 5.84 mm and 7.25 mm in diameter, while in the EU standard diameter ranges from 6 mm to 8 mm (+/- 1 mm) (Obernberger and Thek, 2010; Pellet Fuel Institute, 2010). Length based on the PFI standard should be 38 mm (1.5 inches ± 1%) while the EU standard describes length to be 31.5 mm to 40.0 mm (Pellet Fuel Institute, 2010; Obernberger and Thek,

2010). The summary Table 7 below presents a brief description of parameter interdependencies and their increasing/decreasing effect on pellet quality.

Table 7. Summary table of wood parameter interdependencies and the EU and PFI standard values.

Parameter	Interdependencies	Effects description	prEN-14961-2[1]	PFI[19]
Moisture content	Calorific value, durability, bulk density	High amount decreases CV[1] and bulk density[2,3]; negative effect on durability if MC is 12% and over (no influence 6-12%)[4]	≤10%	≤8%
Calorific value	Moisture content, particular density, C,H and N content, ash amount	Shows negative correlation with MC[1]; Positive correlation with pellet compactness (longer burnout time)[1]. High N content species negatively affect CV[5]	≤ 16.5 MJ/kg	N/A
Mechanical durability	Moisture content, particular density, fines, particle size distribution, binding agents usage	Positive effect as a result of fine particular size[2] and starch[6] or/and lignosulphonate additives[7]. Low lignin content[1] of raw-material has negative effect	≥ 97.5%	≥ 96.5%
Particular density	Calorific value, mechanical durability, fines, bulk density	Positive effect on burnout time and bulk density[1]	N/A. According to DIN plus[15] (Germany) 1000-1400 kg/m³	
Bulk density	Moisture content, particular density	The way to increase is to decrease MC[8, 9], raise particular density[1] and use fine-grinded raw-material[10]. Bark supplement positively affect this parameter [11].	≥600kg/m³	≥640kg/m³
Ash content	Dust emissions, calorific value, content of minerals (sand and etc.)	Presence of bark[12, 13] and impurities raises ash content[1]. Additives, like dolomite [14] and lignosulfonate[7] raises ash content, but addition of wheat starch significantly reduced ash formation[14] Softwood species display decreased ash content compared to hardwoods[5].	≤0.7%	≤1.0%
Ash melting point	Content of Mg, P, Ca, K and Na	High content of Mg, Ca and P raises ash melting temperature[15]; 0.5% dolomite as an additive[16] or 5% bark as an additive increases ash melting temperature. High content of K and Na decreases ash melting point[15], which leads to high corrosion and slagging tendencies[3, 17]	Should be stated	N/A
S and Cl content	Additives usage	Lignosulphnate as an additive increases S content[7] and SOx emissions[15, 18]; Cl raising corrosion probability[15]	S≤0.03% Cl≤0.02%	Cl≤ 300 ppm.

Sources: [1]Obernberger and Thek, 2010; [2]Wilson, 2010,[3]Hansen *et al.,* 2009; [4]Li and Liu, 2000; [5]Gaur and Reed, 1998; [6]Stahl *et al.,* 2012; [7]Kuokkanen *et al.,* 2011 [8]Tabil, 2011; [9]Samuelsseon, 2012; [10]Tumuluru *et al*., 2010 [1]Filbakk *et al.,* 2011; [12]Paulrud *et al.,* 2001; [13]Baxter *et al.,* 1998; [14]BIOMASA Association, 2011; [15]Hanh, 2004; [16]Nosek *et al.,* 2011; [17]Öhman *et al*., 2004; [18]Lehtikangas, 2002; [19]Pellet Fuel Institute, 2010.

4. Pellet utilization

There are three types of pellet-burners: pellet stoves, boilers and furnaces (AEA, 2012). A wood pellet stove is sized for residential settings, while a wood pellet boiler is for larger commercial needs (Biomass Energy Resource Center, 2007). Moreover, there are some other distinctions between stoves and boilers "in the degree of automation and fuel storage and handling, based on the different needs of residential and commercial users (Biomass Energy Resource Center, 2007)".

Pellet residential burners have a hopper with 20-60 kg fuel capacity and screw auger, which automatically move pellets from the hopper to the combustion chamber (NRC, 2002; CMHC, 2008). A detailed diagram of pellet stove is presented below (Fig.9)

Pellet stoves have to be filled from daily to weekly depending on usage. In the case of a boiler or furnace a hopper may need to be loaded daily or loading could be automatic (AEA, 2012). In the case of a pellet stove the ash pan should be cleaned out weekly and in the case of boilers the tubes need to be cleaned monthly also (AEA, 2012).

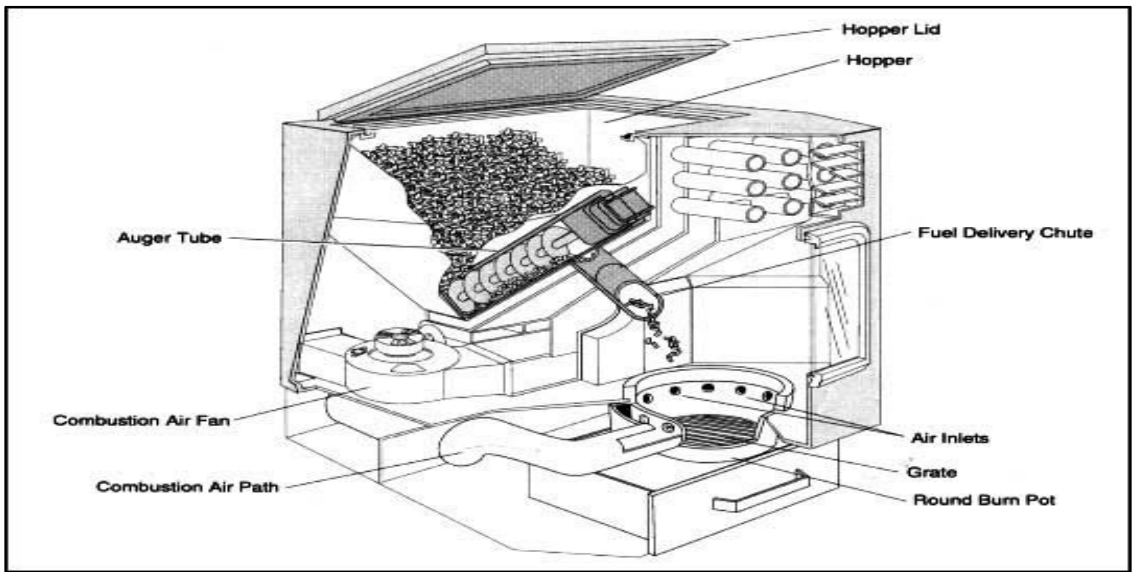

Figure 9. Wood pellet stove diagram (Alternative Heating Solutions, 2010).

Present-day pellet stoves, furnaces and boilers precisely regulate fuel supply and combustion air leading to a clean burn and high efficiency ratings of 78 percent to 82 percent (Persson *et al.*, 2005; Focus on Energy, 2007). Table 8 presents advantages and disadvantages of pellet stoves compared to natural wood burners (NRC, 2002; AEA, 2012).

Table 8. Advantages and disadvantages of wood pellet stoves compared to natural wood burners ((NRC, 2002; AEA, 2012).

Advantages	Disadvantages
• Automatic filling operation. One hopper load could be enough for 24 hours of operation. • Fire starts via ignition button. • Less ash than with a log fire. • Lower risk of chimney fires and accidental fires. • Could be controlled with a wall thermostat. • Less smoke emissions compare to advanced wood stoves.	• Pellet price is higher than firewood cost. • Need electricity to operate auger motors and fans. • It is impossible to use any other wood fuel instead of pellets.

In the case of wood pellet boilers and furnaces there are also some advantages and disadvantages compared to oil or propane appliances (Table 9).

Table 9. Advantages and disadvantages of boilers and furnaces compared to oil or propane appliances (AEA, 2012).

Advantages	Disadvantages
• Cost efficiency, a unit of heat produced by pellet burning will have lower price than heat produced by oil or propane. • Lower GHG emissions compare to oil or propane. • No danger and damage to the environment in case of pellets leaking or spilling.	• Pellet appliances are more expensive than oil or propane appliances. • Regular ash removing and cleaning needed.

As it was mentioned above wood pellet stoves operate at lower emissions than firewood stoves (NRC, 2002). Table 10 presents more detailed data on the emissions from a wood stove compared to a pellet stove.

Table 10. Emissions of CO_2, CO, OGC and NO_2 during wood stove and pellet stove operation (Bafver et al., 2011).

Case	CO_2 (%)	CO*	OGC*	NO_2*
Wood stove 1	5.2	1600	150	110
Wood stove 2	8.8	1900	210	82
Wood stove 3	6.7	1400	200	74
Wood stove 4	5.2	1200	140	81
Wood stove 5	6.2	1900	170	77
Wood stove 6	8.7	1300	220	85
Pellet stove 1	3.1	92	4	68
Pellet stove 2	5.6	200	7	71
Pellet stove 3	8.0	180	2	83

* mg pollutant per megajoule fuel

It is easy to see from the table above that modern wood stoves display much higher emissions of carbon dioxide (CO_2), carbon monoxide (CO), organic gaseous carbon (OGC) and nitrogen oxides (NO_2) emissions during operation compared to pellet stoves.

5. Materials and Methods

5.1. Study area

In the end of 2012 there were 38 operational pellet plants in Canada with a total capacity of 2,931,00 tonnes per year (Murray, 2012). Pellet plants function in almost every Canadian province or territory, except for Saskatchewan and the Northwest Territories (Bradley and Bradburn, 2012). We have contacted eight pellet producers from five provinces (British Columbia, Manitoba, Nova Scotia, Ontario and Quebec), who sent us 2 bags (40 lbs each) of their residential pellets.

We cannot publish real names of these companies therefore in the text they are referred to as Companies 1 through 8.

5.2. Pellet Parameter Tests

5.2.1. Visual evaluation of pellet quality

High-quality pellets normally have even and shiny surfaces without any longitudinal fractures. The smooth surface indicates that the pressing process was conducted under the right temperature and the lignin agglutinated pellets properly. Pellet color is not a quality criterion, although color can help define raw material type and additives used, and it is not possible to judge pellet quality from color. Therefore visual evaluation involves looking at a representative sample of pellets and examining if there are longitudinal fractures or any other surface defects.

5.2.2. Moisture content

Moisture content analysis followed the ASTM standard, Standard Test Method for Moisture Analysis of Particulate Wood Fuels (ASTM E871-82, 2006). This testing method covers the determination of total moisture on a weight basis in the sample analysis of a particular wood fuel (ASTM E871-82, 2006). Moisture content was therefore determined based on initial sample weight minus the final oven dry sample weight and then divided by the oven dry sample weight, which is then multiplied by 100 to give a percent moisture content (oven dry basis). All samples were tested under identical conditions (temperature, atmosphere and equipment).

Non-porous, open metal trays were used as weighing and drying containers. A minimum volume in the containers was 32.18 cm^3 (ASTM E871-82, 2006). The temperature in the drying oven was set at 103±1°C (ASTM E871-82, 2006).

Measurements of each sample group were made in several steps (ASTM E871-82, 2006):

- A dry sample container was placed for 30 min at 103±1°C in the oven and then cooled to room temperature. The container was weighed to the nearest 0.01 g on a 4-ptn Mettler Balance and the container weight was recorded as *W*c.
- A sample (50 g minimum weight) was placed in the container. The sample and the container were weighted to the nearest 0.01 g, and this weight was recorded as initial weight *W*i.
- The sample and the container were placed in the oven for 16 h at 103±1°C.
- The sample and the container were removed from the oven and cooled to room temperature. The sample and the container were weighed on the scales to the nearest 0.01 g, and the weight was recorded.
- The sample and the container were returned to the oven at 103±1°C for 2 hours; step 3 was repeated.
- Step 3 was repeated until the total weight variations were less than 0.2 %. The final weight was recorded as *W*f.

Moisture percentage was calculated using equation (3) (ASTM E871-82, 2006):

$$MC = [(Wi - Wf)/(Wf)] * 100 \quad [3]$$

Where,
MC= moisture in analysis sample, %
*W*c = container weight, g
*W*i = initial green weight, g*W*f = final oven dry weight, g

Three samples from each producer were measured and the average result was recorded as the final moisture content for that producer.

5.2.3. Bulk density measurement

Bulk density measurement was made according to ASTM Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels (ASTM E 873-82, 2006). This testing method covers the procedure for the determination of bulk density (or bulk specific weight) of densified particulate biomass fuels (ASTM E 873-82, 2006).

An empty container (1 cubic foot) weight was measured and recorded using an electronic scale. The next step was to fill the measuring box precisely up to the brim where pellets were evenly distributed and consistently packed in the container. The container was dropped five times from the height of 150 mm on a non-resilient surface to allow settling (ASTM E 873-82, 2006). After additional pellets were added following the drops, any pellets over the top edge were brushed off so the top was even and level with the rim of the container. Then the container full of pellets was weighted and the total weight was recorded. Bulk density was calculated according to equation (4) (ASTM E 873-82, 2006):

$$\textit{Bulk density } (g/cm^3) = \textit{(weight of box and sample) - (weight of box)/ (volume of box)} \quad [4]$$

The final result was converted from g/cm^3 to kg/m^3.

5.2.4. Mechanical Durability and Fines amount

Mechanical durability and fines amount were determined according to the Austrian Standard EN 15210-1: Determination of the Mechanical Durability of Pellets and Briquettes (Austrian Standards Institute, 2009). The test samples are exposed to a controlled forced air mixing of the pellets against each other and the walls of a specially

designed grated test chamber. Durability is calculated using the mass of the remaining sample following the test run and the mass of the separated abraded and fines broken particles (Austrian Standards Institute, 2009). For these tests a Lingo-Tester EX II durability and fines tester was used.

5.2.5. Mechanical Durability

A sample weighing 1,500 g was taken from each pellet producer. All samples were filtered through a 3.15 mm wire screen sieve before the durability test (Austrian Standards Institute, 2009). Each sample was then divided into three portions of 100±0.5 g each. Each portion was weighed on the scale to the nearest 0.01 g, and the weight was recorded.

During the test the Lingo-Tester tumbled samples at the rate of 50 ± 2 rotations per minute, for a total of 500 rotations per test. After the durability test the samples were weighted and the results were recorded.

Mechanical durability of each sample was calculated using equation (5) (Austrian Standards Institute, 2009):

$$D_U = (m_a/m_e)*100 \quad [5]$$

Where,
D_U - mechanical durability, %
m_a - the weight of pellets after Lingo-Tester operation, g
m_e - the weight of pellets before Lingo-Tester operation, g

The final durability of each producer was presented as the average value of three samples. The final results were rounded to the second decimal place. In Table 11 repeatability and reproducibility limit values are presented.

Table 11. Repeatability and reproducibility limits.

Mechanical durability	**The maximum discrepancy between test results**	
	Repeatability limit,%	**Reproducibility limit,%**
≥97.5%	0.4	0.8
< 97.5%	2	3

Repeatability limit is the result of two consecutive measurements of pellets produced by the same producer. Measurements have to be made in the same lab, by the same lab technician, on the same equipment. Reproducibility limit is the average value of two consecutive measurements made in two different laboratories (Austrian Standards Institute, 2009).

5.2.6. Fines amount

Bulk samples weighting 1,000 g were taken from each producer. Each sample was evenly divided into three portions 300± 50 g each (Holmen, 2011). Samples were placed in the Lingo-Tester and the "Fine Material Amount" regime was selected in the Lingo-Tester menu. In this regime blower motor start to circulate pellets for 30 sec and automatically stopped.

After this operation, samples were weighted again. The fine material amount was calculated with equations (6) and (7) (Holmen, 2011):

$$F_a = mE - mA \qquad [6]$$

Followed by:

$$F = (F_a/mE)*100 \quad [7]$$

Where,
F = Fine material amount, g
F_a = weight of fines, g
mE = weight of pellets before cycle, g
mA = weight of pellets after cycle, g

5.2.7. Ash content, Volatile Organic Compounds (VOC) and Fixed Carbon amount

VOC and fixed carbon amount are not standardized and differ from tree species to tree species. These parameters were measured in the Forest Soils Laboratory of Lakehead University, using a TGA-601 Thermogravimetric Analyzer. This analyzer measures weight loss as a function of temperature. This analyzer allows 19 samples to be examined at the same time. Sample weight before the experiment starts and during all aspects of the experiment was controlled and monitored. The percentage weight loss is reported at the end of the experiment (LECO, 2001).

Sample preparation operations include the following steps (LECO, 2001):

- samples are first ground in a large Wiley mill (this mill prepares materials for analysis with minimal moisture loss) and after that in a small Wiley mill (40 mesh); the samples should be stored in air-resistant bags or tubs;
- samples should be dried for 48 hours at 65°C temperature, and the weights before and after drying are recorded;

According to this method: for determination of moisture content, the samples were heated up to 107°C for 2 h (under normal atmospheric conditions); for determination of volatile compounds content the samples were heated up to 950°C for 7 min (in a nitrogen atmosphere); and for determination of ash content, samples were heated up to 575°C for 2 h (in a pure oxygen atmosphere) (LECO, 2001). The fixed carbon value was determined by subtracting the moisture content, volatile organic compounds and ash content from 100, leaving the fixed carbon value (Klass, 1998).

5.2.8. Calorific value

Calorific value was measured according to ASTM E 711-87: Standard Test Method for Gross Calorific Value of Refuse-derived Fuel by the Bomb Calorimeter (ASTM E711-87, 2004). This test method covers the determination of the gross calorific value of a prepared sample of solid form of refuse-derived fuel by the bomb calorimeter (ASTM E 711-87, 2004). According to this method, calorific value is determined by burning a weighed sample in an oxygen bomb calorimeter under controlled conditions (ASTM E 711-87, 2004).

In this research a PARR 6200 oxygen bomb calorimeter and PARR 6510 water handling system were used. Before measurements, pellets were ground up (2 mm mesh) using a Willey-Mill. The sample was pressed using a Parr Pellet press resulting in a test sample pellet weighing between 0.8-1.2 g. The samples were weighed and recorded (weight to be inputted into the bomb calorimeter prior to testing). The pellet sample was then placed in the specimen container and then loaded onto the holder where a fuse wire is attached to the holder and is touching the pellet (making sure the fuse does not touch other parts of

the assembly). The bomb, with the sample and holder assembly inside, was very firmly closed and filled with Oxygen to 450 psi. After filling with Oxygen, the bomb was placed into a pail with 2 l of distilled water at 22-23°C. Next, the bucket with the bomb inside was placed into the calorimeter chamber. Once the bomb is in place, the unit lid is shut and the weight is input into the software prior to firing the run. Once the burn is complete the calorimeter calculates the gross heat of combustion using equation (8) (Parr Instrument Co., 2007):

$$H_c = \frac{(W*T)-e1-e2-e3}{m} \quad [8]$$

Where,
H_c - gross heat of combustion, MJ/kg
T - observed temperature rise, °C
W - energy equivalent of the calorimeter and bomb bucket combination being used, MJ/°C
e_1 - heat produced by the burning of the nitrogen portion of the air trapped in the bomb to form nitric, MJ
e_2 - heat producing by the formation of sulphuric acid from the reaction of sulphur dioxide, water and oxygen, MJ
e_3 - heat produced by the fuse wire and cotton thread, MJ
m - mass of the sample, kg

The final calorific value for each producer is presented as an arithmetic mean value of five measurements.

5.2.9. Particular pellet density

This parameter is not standardized for wood pellets by the Pellet Fuel Institute or prEn 14961-2 (Pellet Fuel Institute, 2010; Thek and Obernberg, 2010). However, this parameter was specified for briquettes in the CEN technical specifications for biofuels (Alakangas, 2005). Also, according to the standards DIN 51731 (Germany) and ONORM M7135 (Austria) particular pellet density is a quality indicator for pellets and briquettes.

There is a group of methods presented in the CEN technical specifications for biofuels for particle density determination named "CEN/TS 15150 Solid Biofuels - Methods for the determination of particle density" (Alakangas, 2005).

For our measurements, a water displacement method was used for calculating pellet volume. In this method, the mass of a displaced liquid agent was determined following the method of Rabier *et al.* (2006) where distilled water was used as liquid agent. Prior to the displacement procedure the single pellet weight was determined on an electronic scale and recorded.

A glass container was filled with water and placed on a balance platform. The weight of the filled container tared so the balance read zero prior to the sample being immersed. A pellet sample was immersed in the water using a long needle and the mass of the sample immersed in the water was recorded (the value on the balance in g equals the volume of the sample in cm^3).

The particle density (p_μ) was calculated using equation (9) (Rabier, 2006):

$$p_\mu = (m_u / m_{w.dis}) * p_w \quad [9]$$

Where,
p_w - density of liquid at a given temperature, g/cm^3
m_u - pellet weight in the air, g
$m_{w.dis}$ - weight of liquid displaced by the sample, g

Five random samples from each producer were tested and the average result was presented as the final particle density for this producer.

5.2.10. Dimensions measurement

The diameter and length of pellets in mm were determined using electronic callipers. Twenty samples from each producer were randomly selected. The final dimension reported is the average value of the 20 measured pellets.

5.2.11. Compressive resistance (pellet strength)

This parameter is not defined by any standard. Pellet mechanical strength is defined as the force necessary for sample disruption (Kakitis *et al*., 2011). For a pellet strength test, the diametrical compression method was used. During these measurements, a single pellet was placed between the two flat and parallel plates (Salas-Bringas *et al.,* 2010; Wilson, 2010) of a Tinius Olsen universal wood testing machine compression testing tool with the top plate applying pressure to the sample in the perpendicular direction. The top plate compressed the pellet at the speed of 0.5 mm min^{-1} and the force increased until the pellet structure failed (Kakitis *et al*., 2011). The compression level was set at 4 mm at which time the software stopped the test. In other words, when the top plate moved down 4 mm, the experiment automatically stopped. The maximum force during deformation was registered as the compression strength. The experiment set up is presented in Figure 10.

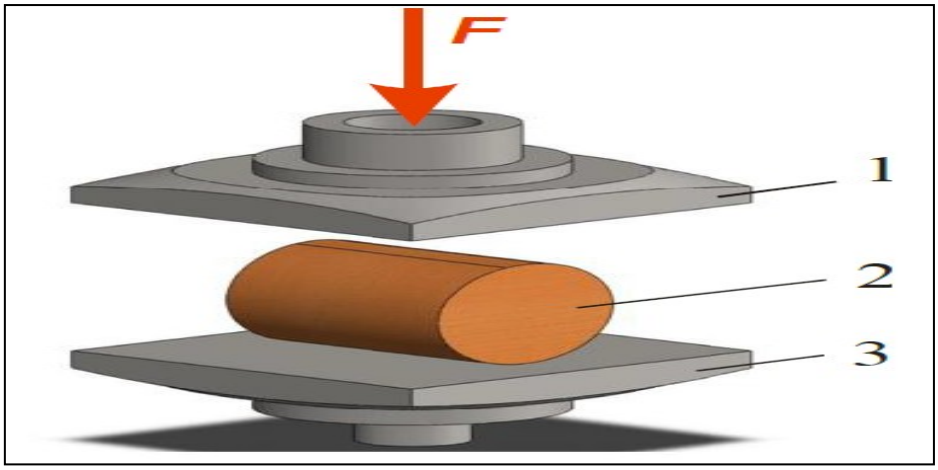

Figure 10. Compressive strength test. 1-compression plate, 2- sample, 3- support plate with F being the load applied (Kakitis et al., 2011).

Fifteen samples from each producer were randomly selected. The final result for each producer is presented as the average value of 15 measured pellets.

5.2.12. Statistical Analysis

For statistical analysis R software was used. Correlation dependency calculations were made using the *cor (x,y)* function (Revelle, 2013). P-values were calculated via the *cor.test (x,y)* function (Coghlan, 2013). Linear models were made up by applying the *lm (x~y)* function (The R Stats Package Documentation , 2013). For diagrams Microsoft Excel 2007 software was used.

6. Results

Since the EN group of standards are being enforced overseas, our national standards should be withdrawn or adapted to meet the EN-standards according to Alakangas (2009). However, some parameters such as single pellet density are not specified by the

prEN 14961-2 standards. Hence it is important to compare our results of pellets from Canadian producers with other European and North American standards.

We measured 12 different parameters, including parameters, which are not included in any of the present standards, such as compressive strength, fixed carbon amount and percentage of volatile organic compounds. These measurements were made to allow an augmented analysis of parameter interdependences. The average values of measurements in comparison with EU and North American pellet standards are shown in Table 12. The EU and North American pellet standards used for comparison include:

- EU Standard prEN 14961-2
- U.S. standard Pellet Fuel Institute Standard
- Austrian Standard ONORM M7135
- Swedish Standard SS 187120
- German Standard DIN 51731/DIN plus
- Italian Standard CTI-R 04/5

Table 14 displays parameter correlations obtained using R software. It can be seen that the grand mean of each parameter matches the prEN 14961-2 and PFI standard recommendations. However, a few producers displayed qualitatively unsatisfactory results for some parameters. The analysis of these results is presented here and discussed in the "Discussion" chapter.

Bulk density for all producers was above the lowest standards value (EU at 600 kg/m^3) with the highest value being recorded for Producer No.1 with a bulk density of 701.3 kg/m^3. The average for all the Canadian producers tested was 690.5 kg/m^3. All

producers were well within all of the allowable standard moisture contents of below 8% to 12%.; the Canadian producers averaged 4.56% with a low of 3.76% and high of 6.08%. All pellets tested matched the PFI standards for durability (96.5%), however, one Producer (96.53%) did not meet the EU standard value of 97.5%. All producers' values for fines percent fell within the allowable values for all standards with an average of 0.06% while standards range from less than 0.5% (PFI standard) up to less than 1.0% (EU standard). All single pellet density values were above 1,200 kg/m^3, while the standards require single pellet density to be greater than 1,000 kg/m^3, with one standard (DIN plus) having an upper limit of 1,400 kg/m^3. Volatile Organic Compounds (VOC) and Fixed Carbon are two measures that are not in the standards but were measured and were consistent between producers with a VOC average of 85.06% (range between 83.9 and 86.8) and Fixed Carbon average of 9.88% (range between 8.52% and 11.51%). Ash content (%) was an average of 0.48% for all eight producers, which is below all standards for top quality pellets which range from 0.5% to a high of 1.5%. All producers meet the DIN plus standard of 1.5% or less, all producer but No. 7 meet the EU standard of less than 0.7%, and all meet the PFI standard of 0.5% or less except Producer No. 2 (0.52%), 7 (1.05%) and 8 (0.53%). Of the three producers that do not meet the PFI standard, No. 2 and 8 are very close to the standard being off less than 0.03%. All pellets meet EU standards for lower calorific values. The standards state pellets need to have a value higher than 16.5 MJ/kg for the EU standard, 18.5 MJ/kg for the PFI standard. The average value of high heating value (gross heating value) for all producers in this study was 20.12 MJ/kg with a low of 19.42 MJ/kg by Producer No. 8 and a high of 20.64 MJ/kg by Producer No. 5. On the basis of Equation (2), the net calorific value (lower calorific value) was calculated (Boundy *et al.,* 2011). The lowest net calorific value was

shown by ProducerProducerProducer No. 2 (18.28 MJ/kg) and the highest by Producer No. 5 (19.77 MJ/kg). The average net calorific value was 19.09 MJ/kg. Producer 2 and 8 do not match PFI recommendations for this parameter. All pellet producers fell within the standards for pellet length and diameter. Length ranges from 3.15 mm up to less than 50 mm and diameter ranges from 5.84 mm up to 10 mm.. Tested pellets shows average length of 19.9 mm and diameter 6.4 mm. The last parameter measured was Stress, which is not a standard measure but one that can represent durability of pellets. In this study, samples displaying durability values meeting PFI and EU standards, display a stress value greater than 70 MPa. The average stress value across all eight producers was 93.2 MPa with a low of 66.4 MPa and a high of 112.4 MPa.

Table 12 present average values of measured parameters and Table 13 presents correlation dependences. As we have a small data set, it is possible to increase the level of significance up to 10% (Noymer, 2008).

Linear models were developed and are presented below (Equations 10-12). Linear model 1 (equation 10) displays mechanical durability prediction based on fines amount and moisture content. Linear model 2 (equation 11) displays how it is possible to predict durability values using bulk density and compressive resistance (stress) parameters. Bulk density is possible to predict according to linear model 3 (equation 12). On the basis of this model bulk density could be predicted by moisture content and particular (single) pellet density.

Tables 14-16 are present standard errors, t-values and probability for a null hypothesis for linear models 1, 2 and 3, respectively. Also, for each linear model the coefficient of determination (Adjusted R-squared) is presented. For acceptable models, the coefficient

of determination should be higher than 0.5; in the case of well-fit models the R-squared value should be 0.8 or higher (De Veaux *et al*., 2005).

Table 12. Average values of wood pellet parameters for eight producers in comparison with European and North-American Standards.

Producer №	Bulk Density (kg/m^3)	Moisture Content (%)	Durability (%)	Fines Amount (%)	Single Pellet Density (kg/m^3)	VOC (%)	Fixed Carbon (%)	Ash Content (%)	HHV[1] (MJ/kg)	LHV[2] (MJ/kg)	Length (mm)	Diameter (mm)	Stress (MPa)
1	701.3	4.44	97.51	0.063	1277.23	84.9	10.1	0.45	20.54	19.52	22.34	6.39	108.5
2	665.3	6.08	99.06	0.061	1274.45	83.8	9.54	0.52	19.62	18.28	20.36	6.38	95.6
3	698.1	4.01	96.53	0.07	1283.79	86.8	8.83	0.32	19.83	18.94	24.55	6.05	66.4
4	677.9	4.77	98.17	0.067	1245.83	85.4	9.46	0.35	20.25	19.17	17.26	6.52	90.7
5	699.2	3.76	97.01	0.066	1272.61	84.4	11.51	0.29	20.64	19.77	13.96	6.56	92.1
6	696.8	4.06	98.08	0.062	1251.6	85.4	10.22	0.31	20.25	19.33	21.58	6.53	78.8
7	692.8	4.83	98.67	0.055	1286.78	85.5	8.52	1.05	20.41	19.31	20.20	6.35	100.6
8	692.6	4.6	99.28	0.037	1272.28	83.9	10.9	0.53	19.42	18.41	19.01	6.48	112.4
Average	**690.5**	**4.56**	**98.02**	**0.06**	**1270.57**	**85.06**	**9.88**	**0.48**	**20.12**	**19.09**	**19.9**	**6.4**	**93.2**
EU	≥600	≤10	≥97.5	≤1.0	N/A	N/A	N/A	≤0.7		≥16.5	3.15-40	6±1	N/A
PFI	≥640	≤8	≥96.5	≤0.5	N/A	N/A	N/A	≤1.0	≥18.5*		≤38**	5.84-7.25	N/A
M7135	N/A	≤12	N/A	≤1.0	≥1000	N/A	N/A	≤0.5	≥18.0		≤100	4-20	N/A
SS187120	≥600	≤10	N/A	≤0.8	N/A	N/A	N/A	≤0.7	≥16.9		N/A	≤4	N/A
DIN plus	N/A	<12	N/A	N/A	1000-1400	N/A	N/A	<1.5	17.5-19.5		<50	4-10	N/A
CTI-R	620-720	≤10	≥97.7	N/A	N/A	N/A	N/A	≤0.7	≥16.9		N/A	6 or 8	N/A

*recommended value; ** the weight percent of all pellets exceeding the specified length should be ≤ 1% (PFI, 2010)

[1] High heating value (gross calorific value); Measured using bomb calorimeter

[2] Low heating value (net calorific value); Calculated on the basis of Equation 2.

Table 13. Correlations and significance level for all parameters for all eight producers tested.

	Bulk Density	Moisture Content	Durability	Fines Amount	Single Density	LHV	VOC	Fixed Carbon	Ash Content	Length	Diameter
Bulk Density											
Moisture Content	-0.886**										
Durability	-0.577	0.715**									
Fines Amount	0.01	-0.224	-0.753**								
Single Density	0.256	0.062	-0.134	-0.154							
LHV	0.646*	-0.692*	-0.625*	0.488	-0.093						
VOC	0.403	-0.469	-0.630*	0.544	0.089	0.343					
Fixed Carbon	0.266	-0.36	-0.027	-0.257	-0.26	0.19	-0.631*				
Ash Content	-0.107	0.419	0.530	-0.462	0.517	-0.128	-0.049	-0.499			
Length	0.144	0.0714	-0.132	0.109	0.315	-0.271	0.543	-0.603	0.082		
Diameter	-0.102	-0.018	0.387	-0.262	-0.637*	0.25	-0.639*	0.671*	-0.128	-0.745**	
Stress	-0.083	0.357	0.618*	-0.699*	0.158	-0.132	-0.711**	0.324	0.469	-0.325	0.448

**correlation is significant at 95% level (p-value<0.05)

*correlation is significant at 90% level (p-value<0.1)

Linear model 1:

$$Durability=\beta_1*Fines\ amount+\beta_2*MC \quad [10]$$

Table 14. Standard deviation, t-values and p-value coefficients for linear model 1.

Coefficients	Regression estimate β_1	Std. Error	t value	Pr(>|t|)
Fines	-58.4516	14.7133	-3.973	0.0106 **
MC	0.7745	0.2116	3.660	0.0146 **

*** is significant at 99% level (p-value 0)
** is significant at 95% level (p-value<0.05)
Adjusted R-squared: 0.8357; Regression model p-value: 0.004715

Linear model 2:

$$Durability=\beta_1*Bulk\ density+\beta_2*Stress \quad [11]$$

Table 15. Standard deviation, t-values and p-value coefficients for linear model 2.

Coefficients	Regression estimate β_1	Std. Error	t value	Pr(>|t|)
Bulk density	-0.04117	0.02032	-2.027	0.098548 *
Stress	0.03700	0.01682	2.200	0.079126 *

***is significant on 99 % level (p-value 0)
** is significant on 95% level (p-value<0.05)
* is significant on 90% level (p-value<0.1)
Adjusted R-squared: 0.5256; Regression model p-value: 0.06685

Linear model 3:

$$Bulk\ density=\beta_1*MC+\beta 2*Single\ pellet\ density \quad [12]$$

Table 16. Standard deviation, t-values and p-value coefficients for linear model 3.

Coefficients	Regression estimate β_1	Std. Error	t value	Pr(>|t|)
MC	-15.6815	2.6470	-5.924	0.00195***
Single pellet density	0.2699	0.1316	2.050	0.09561 *

*** is significant on 99 % level (p-value <0.001)
** is significant on 95% level (p-value<0.05)
* is significant on 90% level (p-value<0.1)
Adjusted R-squared: 0.8369; Regression model p-value: 0.004629

It is easy to see from Table 13 that bulk density displays a strong negative correlation coefficient (-0.886) with moisture content. Moisture content is positively correlated with durability (0.715) and negatively correlated with low calorific value (-0.692). Mechanical durability is negatively interrelated with fines amount (-0.753) and with low heating value (-0.625). The fines amount parameter demonstrates negative dependence with compressive resistance (-0.699). Single pellet density shows a negative correlation with pellet diameter (-0.637). Fixed carbon amount is negatively correlated with volatile matter (-0.631). A direct correlation was mentioned between fixed carbon and pellet diameter (0.671). Volatile organic compounds VOC display an negative correlation with the diameter value (-0.639) and with compressive resistance (-0.711). There is a strong negative correlation between pellet length and diameter (-0.745). These interdependences are elaborated on in the "Discussion" chapter. The Figures 11 to 14 below present bulk density, moisture content, ash content and low calorific values and compare them to EU and PFI standards. As can be clearly seen in Figure 11 all producers meet or exceed the EU and PFI standards for bulk density.

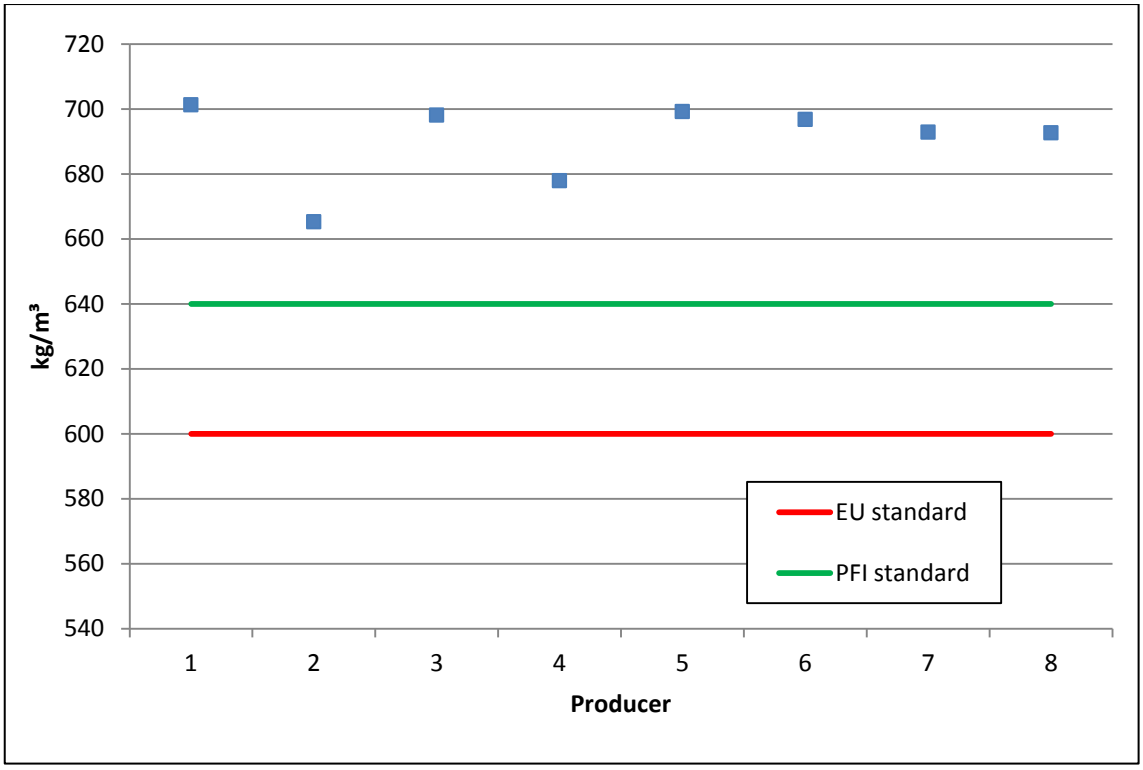

Figure 11. Bulk density values compare to EU and PFI standards.

Similar to bulk density results, the moisture content of all eight producers were found to be within the EU and PFI standard values (Figure 12). Ash content for all producers except Producer No. 7 met the requirements of the EU and PFI standards (Figure 13). Producer No. 7 did not meet either the EU or PFI ash content standards, however, was very close to meeting the PFI standard at 1.05% where the standard cut off is 1.0%. Figure 15 displays that all producers meet the EU standards for LHV, however, Producer No. 2 and No. 8 do not meet the PFI standards for this parameter.

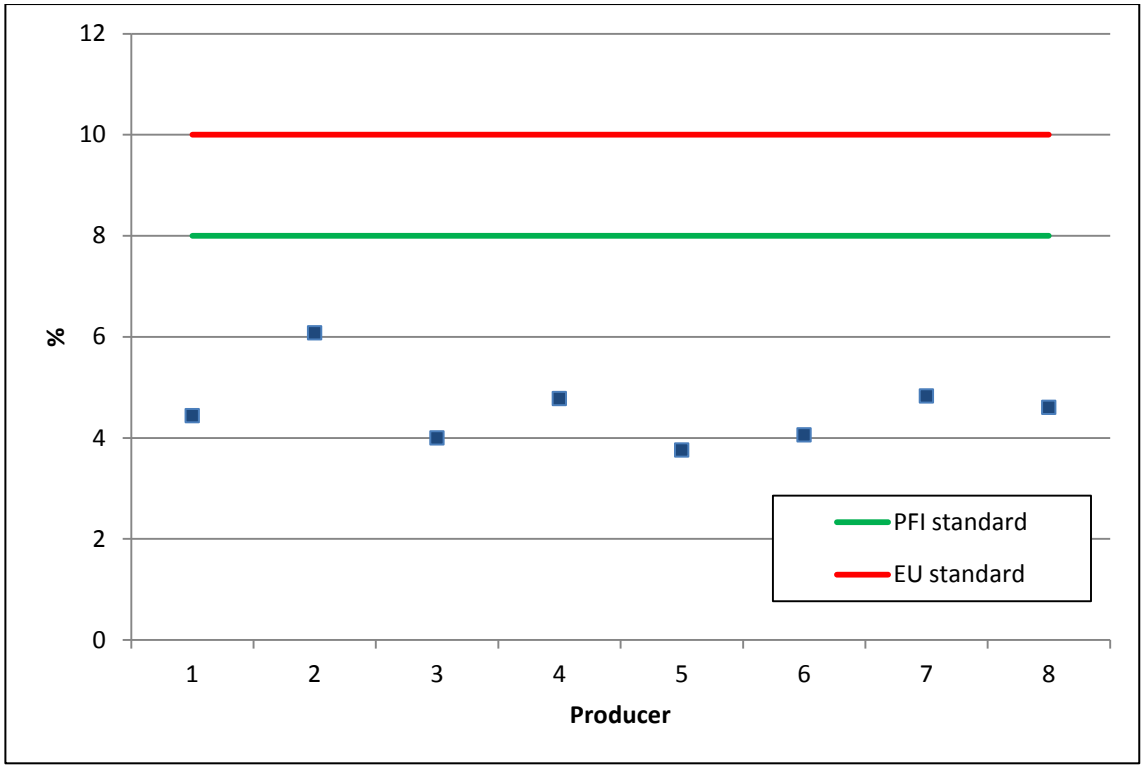

Figure 12. Moisture content values compare to EU and PFI standards.

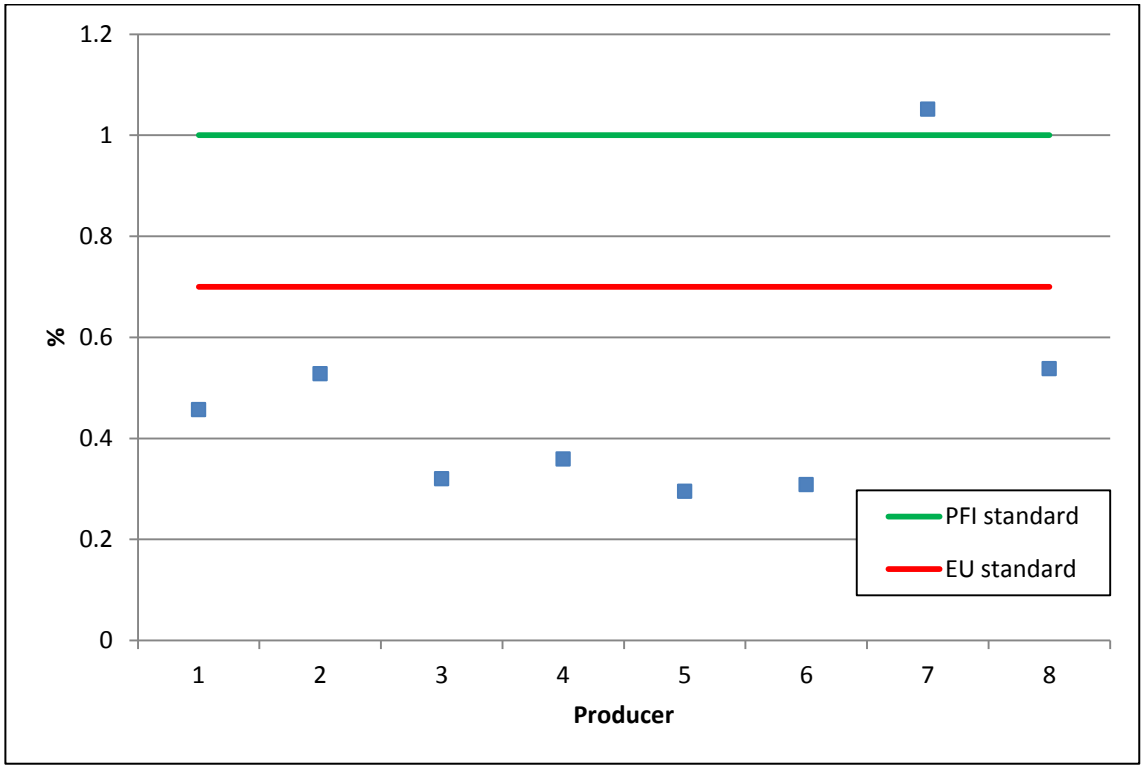

Figure 13. Ash content values compare to EU and PFI standards.

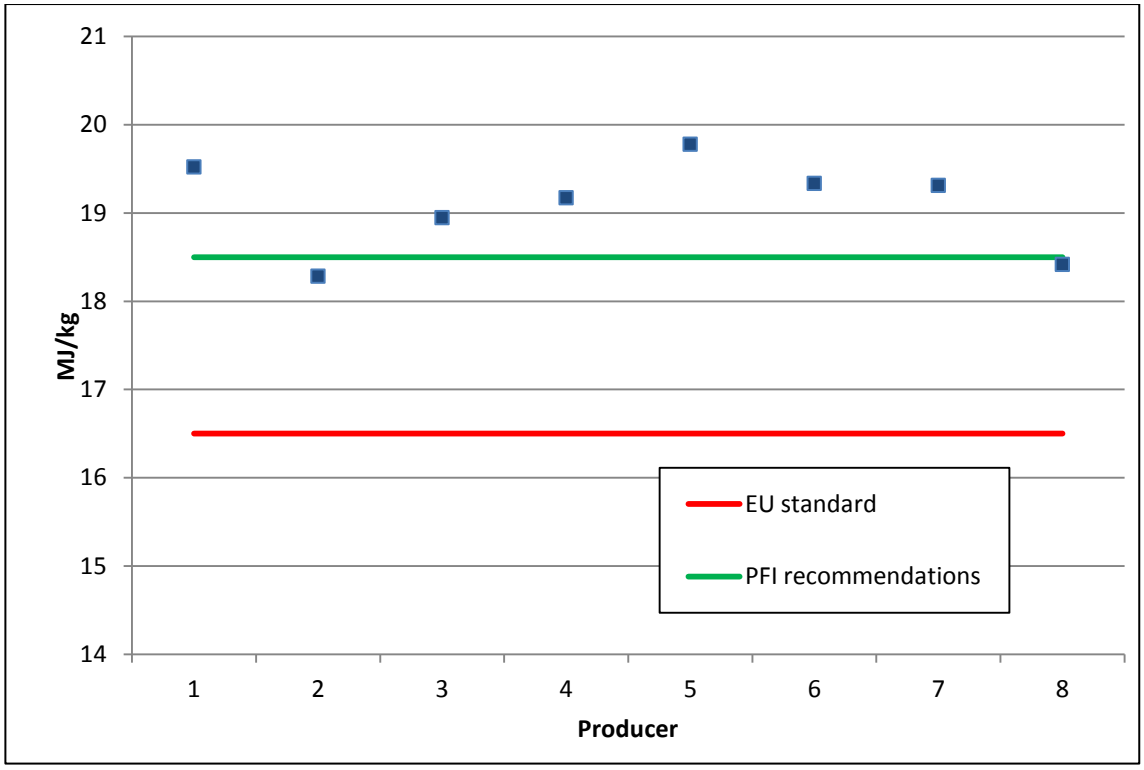

Figure 14. Low heating values (net calorific value) compare to EU and PFI standards.

Box-plot diagrams were used as they allow estimation of outliers and display the value range. The distance between different parts of the box-plot (lower quartile (Q1), median (Q2), upper quartile (Q3)) allow the researcher to determine the degree of incidence (dispersion) and asymmetry; they also show outliers. Box-plot diagrams of tested parameters are presented in Figures 15 to 21.

Figure 15 presents the box-plot graph for calorific values (HHV) which were made based on five measurements per sample. We can see from Figure 15 that all samples match all standards. Producer No. 5 (19.77 MJ/kg) and Producer No. 2 (18.28 MJ/kg) show the highest and lowest calorific values, respectively. However, Producer No. 5 is showing the highest value range (3.515), while the lowest range was displayed by Producer No. 4 (1.01).

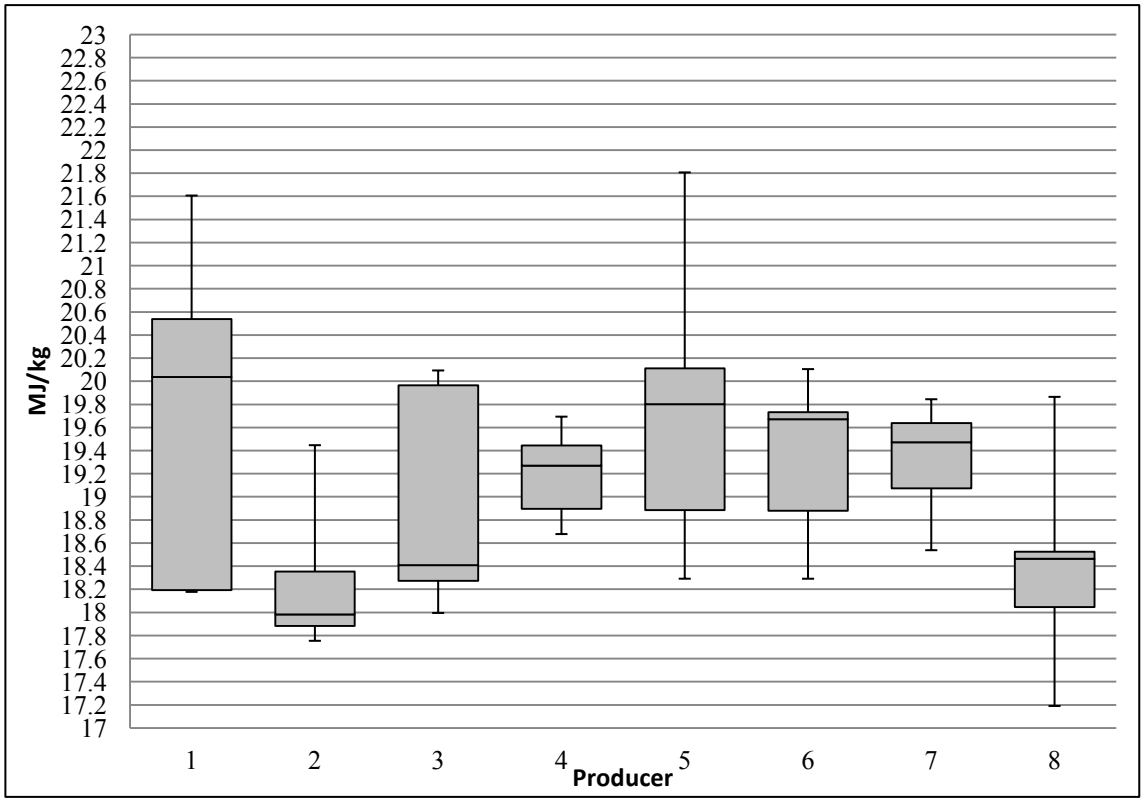

Figure 15. Low calorific value (MJ/kg) box-plot diagram for all eight producers.

Figure 16 displays the box-plot graph for mechanical durability. All samples match the PFI standard recommendations with Producer No. 3 and Producer No. 5 not matching the prEN 14961-2 standard. Also, it is interesting to mention that Producers No. 1, No. 3 and No. 5 did not match the Italian (CTI-R) standard. The best and worst durability results were found for Producer No. 8 (99.28%) and Producer No. 3 (96.53%), respectively. The box-plot figure is made on the basis of three measurements. The box plot clearly displays that all the samples have a small-range distribution. The highest range was displayed by Producer No. 3 (1.288), while the lowest range was shown by Producer No. 8 (0.121).

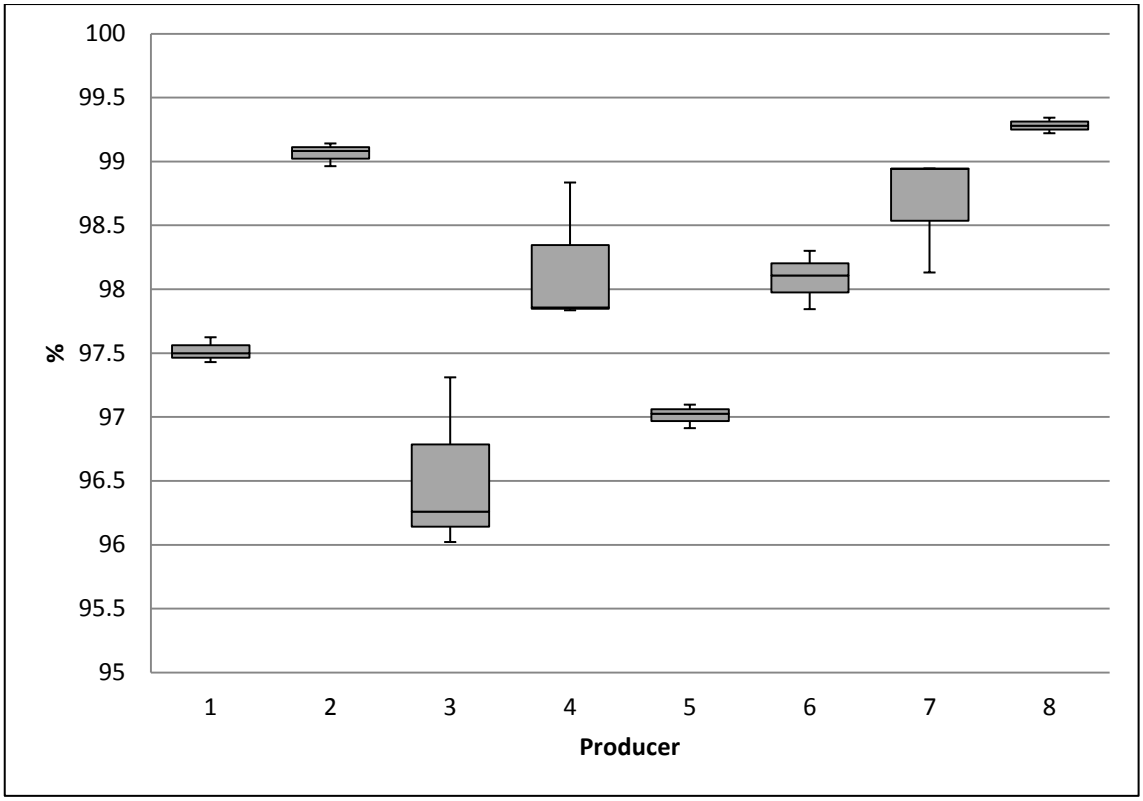

Figure 16. Mechanical durability (%) box-plot diagram for all eight producers.

Figure 17 displays the box-plot graph for fines amount. All samples match all of the standards. The lowest amount of fines was showed by pellets made by Producer No. 8 (0.037%), whereas the highest amount of fines was found by pellets manufactured by Producer No. 3 (0.07%). The box-plot diagram is made on the basis of three experiments. The narrowest range in data was found for Producer No. 1 (0.0029105) and the widest range was found for Producer No. 7 (R=0.022182).

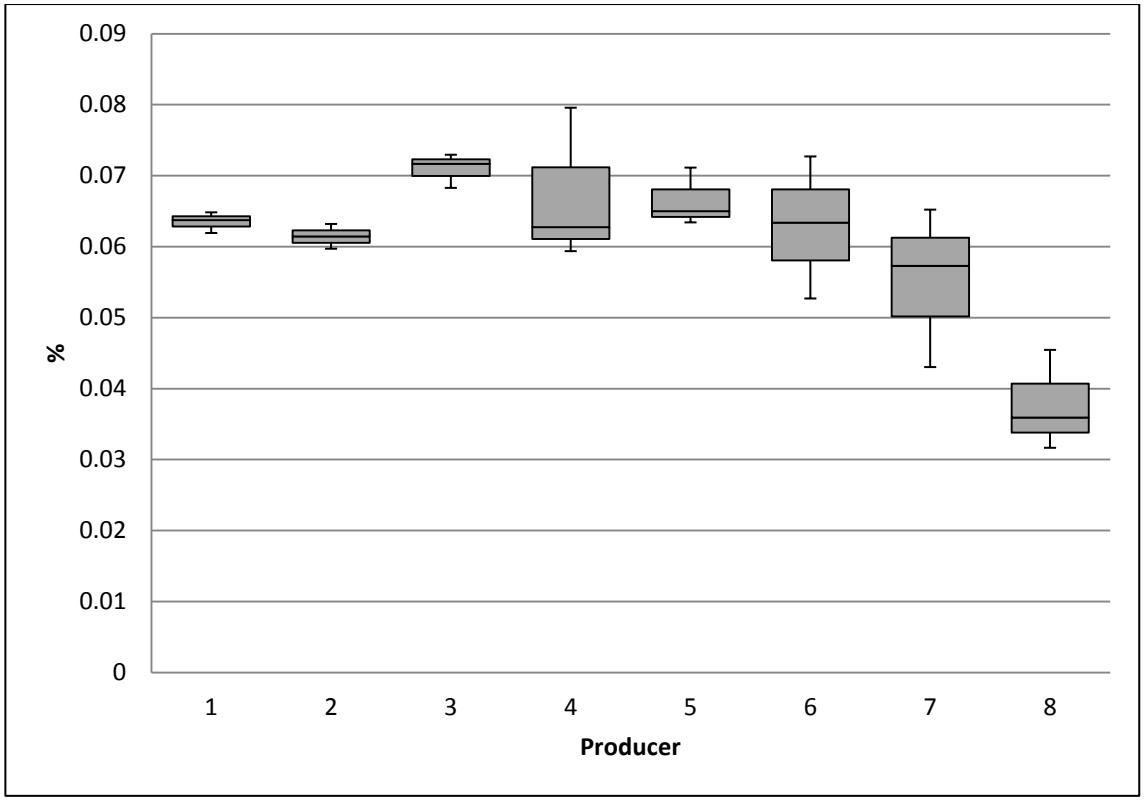

Figure 17. Fines amount (%) box-plot diagram for all eight producers.

Figure 18 displays the box-plot graphs for single pellet density. All samples display a high single pellet density value. As was mentioned in Table 1, there is no recommendation for this parameter in the prEN 14961-2 or PFI standards. Therefore, we decided to compare our results with the Austrian (ONORM M7135) and German (DIN plus) standards. All our samples matched regulatory requirements for both standards. These box-plots are made on the basis of three measurements. The highest and the lowest average value of the single pellet density were displayed by Producer No. 7 (1,286 kg/m^3) and Producer 4 (1,245 kg/m^3), respectively. The lowest range was shown by Producer No. 8 (2.7), and the highest range was displayed by Producer No. 6 (57.4).

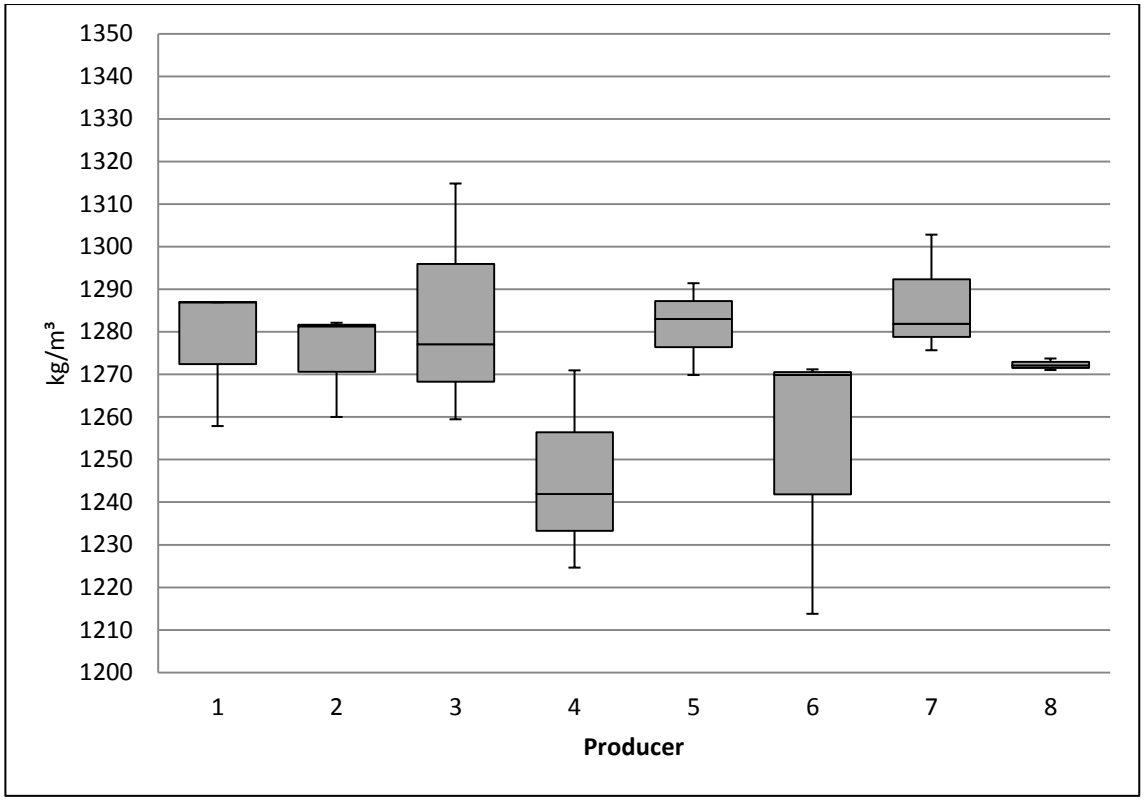

Figure 18. Single pellet density (kg/m^3) box-plot diagram for all eight producers.

All samples match standards by length and by diameter. An exception is the Swedish recommendations for the pellet diameter. These box-plots (Figures 19 and 20) are made on the basis of 10 experiments. On average, pellets from Producer No. 3 were the longest, while pellets from Producer 5 were the shortest. In regards to diameter, samples made by Producer No. 5 and Producer 6 are displaying the largest average diameter. The smallest average diameter was displayed by Producer No. 3. The highest and lowest measured range during length measurements was displayed by Producer No. 8 (23.5) and Producer No. 4 (4.87). Maximum value range measured during diameter measurements was displayed by Producer No. 3 (R=0.56) and the lowest range was displayed by Producer No. 8 (R=0.12).

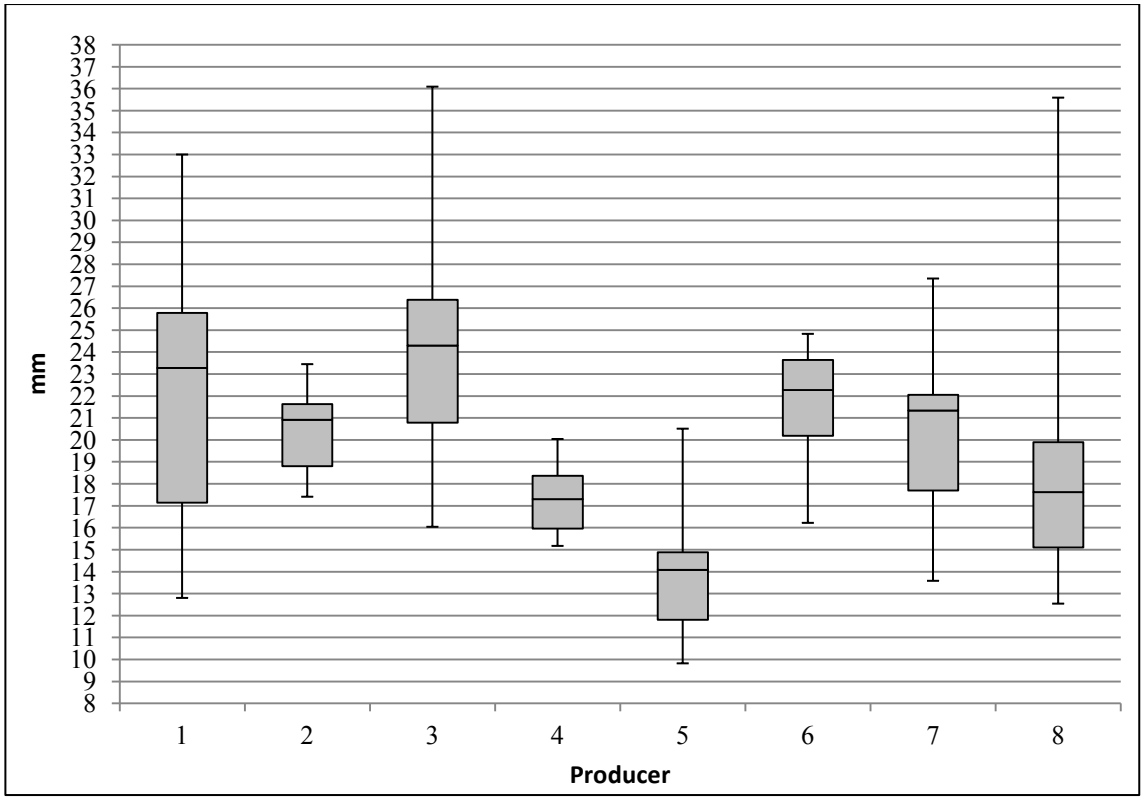

Figure 19. Length (mm) box-plot diagram for all eight producers.

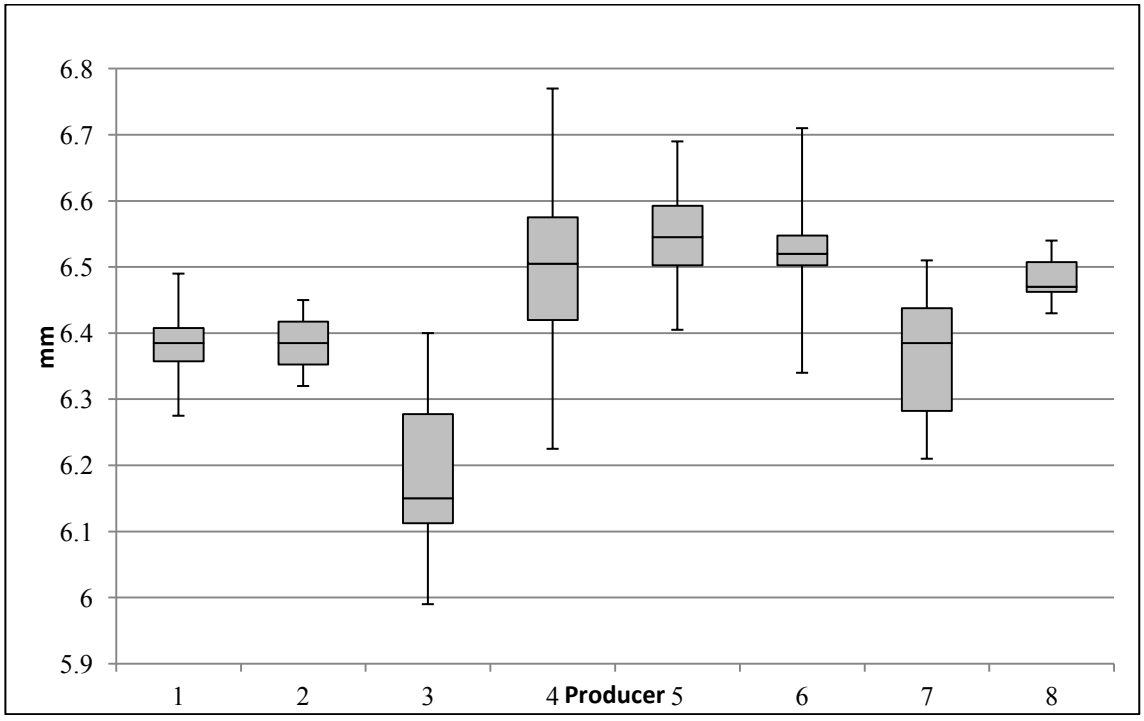

Figure 20. Diameter (mm) box-plot diagram for all eight producers.

There are no recommendations for the compressive resistance parameter. It is easy to see from Figure 21 that the lowest and highest average compressive resistance values were found for pellets produced by Producer No. 3 and Producer No. 8, respectively. These box-plots are based on 15 measurements. All samples are showing a wide value range. The widest range was showed by samples from the Producer No. 4 (62.42) and the narrowest range is displayed by Producer No. 6 (37.65). It is interesting to mention that the same Producers (No.3 and No. 8) are displaying the lowest and the highest average durability values, respectively. Therefore, it can be assumed that there is dependence between mechanical durability and compressive resistance. This assumption was confirmed by correlation analysis.

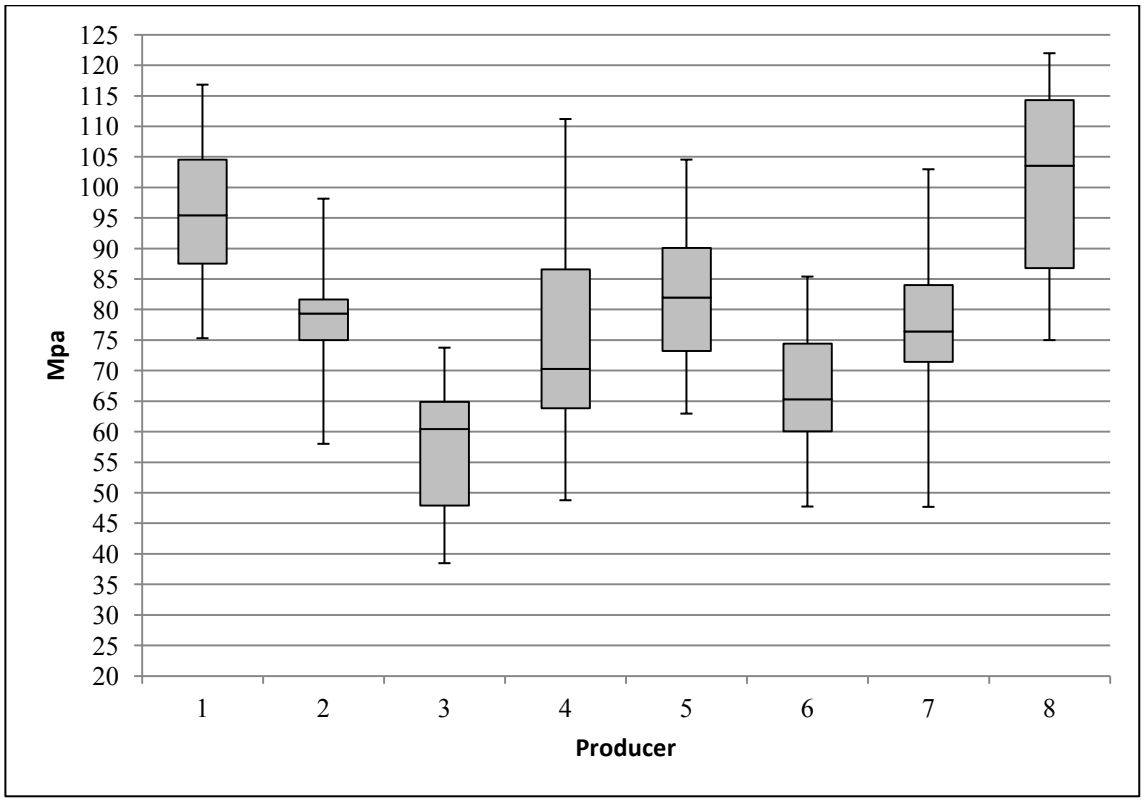

Figure 21. Compressive resistance stress (MPa) box-plot diagram for all eight producers.

7. Discussion

As can be seen from Table 12 the average values for all eight producers of measured parameters match all standards recommendations. However, some pellets produced by individual producer are not compliant with the standards for a few parameters. In this chapter I will discuss each measured parameter and their correlation dependence with the results, and with results presented by other researchers.

7.1. Bulk density

Our measured samples displayed high average bulk density values of 690.5 kg/m^3, with a range of 665.3 to 701.3 kg/m^3. According to Lehtikangas (2001) the average bulk density of nine pellet samples produced from a mixture of Norway spruce and Scots pine was 646.1 kg/m^3. Obernberger and Thek (2004) reported that bulk density of measured samples ranged from 520 kg/m^3 to 640 kg/m^3. Our samples displayed average bulk density values of 690.5 kg/m^3, which is higher than values, presented in the literature and meet all standards compared to.

Bulk density depends on several factors. It can be seen in Table 13 that bulk density displays a strong negative correlation with moisture content (-0.886). Tabil (2011) and Samuelsseon (2012) also reported a negative relationship between moisture content and bulk density. Also, pellets made from different species display different bulk density values (Wilson, 2010). According to Wilson (2010) pellets made from maple and red oak display the highest bulk density values at 751 kg/m^3 and 795 kg/m^3, respectively. Pellets produced from Douglas-fir and Lodgepole pine display a slightly lower bulk density value of 734 kg/m^3 and 620 kg/m^3, respectively (Wilson, 2010). Lehtikangas

(2001) postulated that bulk density is positively affected by particular pellet density. This statement was confirmed in the present study. However, analysis in the current study displays only a weak positive correlation (0.256), which could, in part, be explained by different manufacturing techniques and different raw material used for pellet production. As was explained above different species produce different pellet bulk density (Wilson, 2010). At the same time additive supplements affect both bulk density and particular pellet density. Mediavilla *et al.* (2012) postulated that maize starch and lignosulfonate supplements positively affect particular pellet density. Nosek *et al.* (2011) found that corn-starch and dolomite as additives decrease wood pellet particular density. Filbak *et al.* (2011) mentioned that the bulk density of softwood pellets increases by 20–25 kg/m^3 with the addition of 5% bark as an additive. So, it could be suggested that different manufacturing conditions and raw materials could affect the correlation between these parameters.

According to our research wood pellet bulk density could be predicted using the linear regression model presented by equation (12).As we can see from Table 16 the coefficient of determination of this model is quite high (Adjusted R-squared: 0.8369).

7.2. Moisture content

Measured samples displayed low average moisture content of 4.56%. Stahl *et al.* (2004) reported the average moisture content of pellet samples produced by five different Swedish manufactures at 6.85%.

Moisture content is one of the most important pellet parameters, as it affects durability, bulk density and calorific values (Hansen *et al.,* 2009; Wilson, 2010; Obernberger and Thek, 2010; Samuelsson *et al.,* 2010; Tabil *et al.,* 2011).

Our measurements and correlation analysis confirms these interdependences. Correlation dependence with the bulk density parameter was discussed above. According to our measurements and calculations, moisture content displays a strong negative correlation with net calorific value (-0.692). It can be seen in the Lower Heating Value Equation (2) (Boundy *et al.,* 2011), that moisture content is the main factor affecting net calorific value (Obernberger and Thek, 2010). The effect of moisture content on the heating value can be attributed to the C=C, C=H and C-C bonds containing more energy than O-H bonds (Lestander and Rhen, 2005). Consequently, lower levels of O-H bonds (lower humidity) produce higher heating values (Gillespie *et al.,* 2013).

Moreover, we found that moisture content shows a positive correlation with durability (R^2=0.715). This finding has been confirmed by Obernberger and Thek (2010), however, they postulated that beyond 10% moisture content durability decreases rapidly.

Li and Liu (2000) reported that high quality pellets could be produced when the rawmaterial MC% is between 6 % and 12 %. Liu and Liu (2000) postulated that equilibrium moisture content is close to 8%, as at this MC pellets do not tend to absorb water from the surrounding environment. In the current study the highest MC was 6.08%, however, this sample displayed a high durability value of 99.06%. Wilson

(2010) mentioned that the effect of moisture on the densification process is not well understood.

7.3. Durability, compressive resistance and particle pellet density

As was presented in the "Results" chapter, durability levels of measured samples were quite high ranging from 96.53% to 99.28%. Wilson (2010) reported that the average durability of pellets, produced from different species, ranged from 87.24% to 95.04%. Temmerman *et al.* (2006) reported mechanical durability values for 11 samples with a range from 91.2% to 99.3%.

It was postulated by several researchers that durability depends on moisture content, particle size distribution, chemical composition, binder supplement, particle pellet density and lignin content (Obernberger and Thek, 2010; Wilson, 2010; Mancera, 2011; Oveisi-Fordiie, 2011).

According to our results durability displays a positive correlation with moisture content and this fact was described in the previous chapter. In addition, interdependence with compressive resistance (stress) was found. Negative correlations with bulk density could be explained as cases of indirect dependence. As this parameter displays a negative correlation with moisture content, consequently there is an effect on mechanical durability as well. Obernberger and Thek (2010) concluded that there is an interrelationship between particle density and wood pellet durability. We did not find a strong enough correlation to confirm this fact, however, logically this interdependence has to exist and is likely stronger for pellets produced under the same conditions and from the same raw material. Temmerman *et al.* (2006) mentioned that there is no

relation between mechanical durability and particle density for pellets made from different raw material, produced by different equipment and under variable conditions. Moreover, we can see from other research that additive supplements or MC% levels have a stronger effect on mechanical durability than on the compactness factor (Mediavilla *et al.,* 2012).

Filbak *et al.* (2010) noted that durability displays a strong negative correlation with the fines amount (-0.753) and that high durability occurred when the amount of fines was reduced. This statement is confirmed by linear regression model 1 (equation 10).

This model fits perfectly for mechanical durability prediction, as is shows a very high coefficient of determination according to table 14 (Adjusted R-squared: 0.8357).
A positive correlation between mechanical durability and ash content was found, which has also been reported by Lehtikangas (2001) and Gillespie *et al.* (2013). Ash content displays a positive correlation with lignin content, which indicates the effect on durability is indirect (Lehtikangas, 2001).

Moreover, our analysis displayed that particular pellet density and compressive resistance (stress) show a positive correlation with ash content. This result could also be explained by ash content having a positive correlation with lignin and durability (Lehtikangas, 2001). Consequently, the ash content effect on single pellet density and compressive resistance is indirect.

A positive correlation was shown between durability and compressive resistance or stress (r= 0.618). Theoretically, there should be a strong positive correlation between pellet density and yield load (or stress), as was displayed by Salas-Bringas *et al*. (2010).

However, in the same research it was mentioned that pellets are losing ductility with increasing density. Consequently, higher density pellets can become brittle in nature (Salas-Bringas *et al.,* 2010). Their measurements were conducted on pellets with single pellet densities ranging from 950 kg/m³ to 1,100 kg/m³, while in the current study the lowest single pellet density was 1,245 kg/m³. This could explain the absence of a correlation between single pellet density and compressive strength.
According to our results we can assume that it is possible to define pellet durability using the compressive resistance test. These statements are supported by linear regression model 2 (equation 11).

This model also fits for mechanical durability forecast. This model does not show a very high coefficient of determination compare to linear model 1. The coefficient of determination of linear regression model 2 is 0.5256. However, this model could be useful for a quick approximate mechanical durability prediction, in case of Ligno-Tester absence.

We suggest that if the average value of the pellet compressive resistance test is 70-75 MPa then the pellet qualifies as a high-quality pellet with an equivalent durability value of 97.5% or higher, meeting the prEN 14961-2 standard. This value does imply a premium class pellet produced in compliance with manufacturing standards and does not relate to lower class pellets. Kaliyan and Morey (2009) postulated that the compressive resistance test could be used for "a quick measure of the quality of pellets as soon as the pellets are produced from the pellet mill and aids in adjusting the pelleting process to improve pellet quality".

Therefore, it is possible to assume that if the average compressive resistance test value is higher than 70 MPa, the pellet will meet or exceed the durability requirement of EU and PFI standards.

Particular pellet density of measured samples ranged from 1,245 kg/m^3 to 1,286 kg/m^3. Obernberger and Thek (2004) mentioned in their research, that particular pellet density of tested samples ranged from 1,003 kg/m^3 to 1,300 kg/m^3. According to prEN 14961-2 particular pellet density is not a standardized parameter (Obernberger and Thek, 2010). However, it affects bulk density, heat conductivity, burning time and mechanical durability (Rabier *et al*., 2006, Obernberger and Thek, 2010).

7.4. Calorific value

All measured samples displayed relatively high calorific values. Through the use of the bomb calorimeter the gross heating value was measured (see Table 12), but on the basis of equation (2), we calculated net calorific value (lower calorific value). Correlation analysis was conducted using net calorific value data. This is a more accurate measure of energy content; during combustion moisture is evaporating and this process requires energy (Telmo and Lousada, 2011). However, we would like to compare our study with other research using the gross heating value parameter, as net calorific value is highly affected by moisture content (Boundy *et al*., 2011).

According to Telmo and Lousada (2011) the average high (gross) heating value of 17 tested samples was 19.62 MJ/kg. Our average gross heating value was 20.12 MJ/kg for pellets tested from the eight producers.

Theoretically, calorific value is negatively affected by moisture and ash content (Gaur and Reed, 1998; Chaiyaomporn and Chavalparit, 2010; Boundy *et al*., 2011). Additionally, if pellets are made of nitrogen fixing raw material it will negatively affect calorific value (Gaur and Reed, 1998).

The interdependence with moisture content was discussed in the previous chapter. Our analysis displays weak negative correlation dependence with ash content. Obernberg and Thek (2010) postulated that ash content and nitrogen have a minor effect on net calorific value. Monti *et al.* (2008) postulated that a 1% increase in ash content leads to a 0.2 MJ/kg gross heating value decrease in the case of energy crops.

In our case almost all samples display low ash and high-energy content. The exception is for pellets provided by Producer No. 7, which display quite high ash content and high calorific value (1.05% and 20.41 MJ/kg, respectively). This could be explained by bark supplement during pellet production, as bark increases both calorific value and ash content (Kryla, 1984; Hansen *et al.,* 2009).

The positive correlation between calorific value and bulk density was mentioned. It could be explained by the fact that higher bulk density produces higher energy density (Obernberger and Thek, 2010). It is documented by the following equation (13) *(Obernberger and Thek, 2010)*:

$$P_e = NCV * P_b \qquad [13]$$

Where,
Pe- energy density (MJ/m^3)
NCV- net calorific value (MJ/kg wet basis)
Pb- bulk density (kg/m^3 wet basis)

We can see that the energy density directly depends on the net calorific value. Consequently, an interrelationship between calorific value and bulk density is indirect.

High energy content leads to fewer deliveries and less storage space requirements (Hansen *et al.,* 2009; Obernberger and Thek, 2010). Therefore, high energy density is very important from the economical point of view for pellet producers and retailers (Obernberger and Thek, 2010).

We mentioned a positive correlation with fixed carbon and volatile organic compounds (R^2 of 0.19 and 0.34, respectively). These interdependencies have been reported previously. According to Obernberger and Thek (2004) the amount of volatile matter influences the thermal decomposition and combustion behaviour of solid fuels. Chaiyaomporn and Orathai (2010) mentioned that pellets with high volatile matter and fixed carbon content combust easily, however, those pellets will produce more smoke. Pereira *et al*. (2012) postulated that fixed carbon content directly related to heating value. Moreover, we can see from equation (1) that carbon content has a major effect on higher heating value (Gaur and Reed, 1998), consequently, it also affects net calorific value.

7.5. Pellet dimensions

Measured samples displayed a wide variation in length. Obernberger and Thek (2004) mentioned pellet length ranges from 8.6 mm to 29.6 mm. This wide range could be explained by current pellet production technologies not carefully controlling this parameter. Cutting knives are used to cut pellets before they get too long but other control systems do not exist (Sikanen and Vilppo, 2012). Diameter range is much

tighter in dimensions than length. Pellet diameter varies from 5.9 mm to 10.2 mm (Obernberger and Thek, 2004). However, most tested pellet diameter values are 6 mm or 8 mm (Obernberger and Thek, 2004).

The ratio of length/diameter is important as a single long pellet can block the feeding system in a pellet stove (Obernberger and Thek, 2004). According to the Austrian standard this ratio should be less than 5:1 (Hanh, 2004).

8. Conclusion

Pellets from all of the eight pellet producers tested were very high quality pellets. Average values of tested parameters are matching pan-European standards (prEN 14961-2) and Pellet Fuel Institute standards (USA). However, few producers did not match certain parameters in the standards. Pellets from Producer No. 3 are below the EU standard for mechanical durability, while pellets from Producer No. 7 had an ash content that exceeds the standards and does not match either the EU or PFI standards. This could be a result of additives or bark supplements during pellet manufacturing.

The average moisture content of measured samples is 4.56%, which is quite low when compared to other research. For example, the average moisture content of Swedish pellets was found to be 6.85% (Stahl, 2004). According to our correlation analysis moisture content has a significant effect on bulk density, heating value and mechanical durability. These correlations have also been noted by other researchers (Hansen *et al.,* 2009; Obernberger and Thek, 2010; Samuelsson *et al.,* 2010; Wilson, 2010; Tabil *et al.,* 2011). The average bulk density value is high and is equal to 690.5 kg/m^3. Lehtikangas (2001) reported the average bulk density of nine pellet samples produced from a mixture of Norway spruce and Scots pine at 646.1 kg/m^3. We were unable to find a strong

correlation between bulk density and particular pellet density. However, Lehtikangas (2001) mentioned that this correlation exists. This contradiction could be a result of different production conditions and raw-materials of tested samples.

Several samples are showing mechanical durability values over 99%, however, the average of this parameter is 98.02%. In the literature it has been postulated that there is a correlation between durability and particular pellet density (Obernberger and Thek, 2010), however, we did not find a correlation between these parameters. This could be explained by the fact that tested samples were made from different raw-materials and under different production conditions. However, a significant correlation was noted between durability and the compressive resistance parameters. Regression models for mechanical durability prediction were developed.

Average heating value of tested samples is high at 20.12 MJ/kg. Other papers reporting about lower average calorific values of 19.62 MJ/kg (Telmo and Lousada, 2011). According to the literature, calorific values should be negatively affected by moisture and ash content (Gaur and Reed, 1998; Chaiyaomporn and Chavalparit, 2010; Boundy *et al*., 2011). Our analysis displays a strong negative correlation with moisture content and a weak negative correlation with ash content. It could be explained by the minor effect of ash content on the heating value parameter (Monti *et al.,* 2008; Obernberg and Thek, 2010).

9. References

Abreu H., Nascimento A. and Maria M. (1999). Lignin structure and wood properties. Wood and Fiber Science 31(4) : 426-433 pp.

AEA. (2012). Residential Wood Pellet Heating: A Practical Guide for Homeowners. Canada, NWT: Arctcic Energy Alliance., 52 pp.

Aebiom. (2007). Pellets for small-scale domestic heating systems. Brussels: Aebiom, 17 pp.

Alakangas. (2005). CEN Technical Specification for Solid biofuels Fuel Specification and Classes and Fuel Quality Assurance. Jyväskylä, Finland: VTT, Technical Research Centre of Finland, 9 pp.

Alligno Maschinenexport GmbH. (2006). Practical guidance for pellets production management. Moskow: Alligno Maschinenexport GmbH., 18 pp.

Alpha Timber Ltd. (2013). Pelletizing Process of the Wood Pellet Plant. Retrieved May 28, 2013, from http://alphatimber.biz/wood_pellet.html

Alternative Heating Solutions. (2010). Are Wood Pellet Stoves The Right Choice? Retrieved June 05, 2013, from Alternative Heating Solutions: http://www.alternative-heating.com/wood-pellet-stoves.html

Arshadi M.and Gref R. (2005). Emission of volitile organic compounds from softwood pellets during storage. Forest Product journal 55(12): 132-135 pp.

ASTM E 873-82. (2006). Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels. West Conshohocken, USA: American Society for Testing and Materials, 2 pp.

ASTM E711-87. (2004). Standard Test Method for Grosss Calorific Value of Refuse-Derived Fuel by the Bomb Calorimeter. West Conshohocken: American Society for Testing and Materials (ASTM), 8 pp.

ASTM E871-82. (2006). Standard Test Method for Moisture Analysis of Particulate Wood Fuels. West Conshohocken, USA: American Society for Testing and Materials, 2 pp.

Austrian Standards Institute. (2009). BS EN 15210-1:2009 Determination of the mechanical durability of pellets and briquettes- Part1: Pellets. Wien: Austrian Standards Institute, 14 pp.

Bafver L., Leckner B., Tullin C.and Berntsen M. (2011). Particle emissions from pellets stoves and modern and old-type wood stoves. Biomass and Bioenergy 35: 3648-3655 pp.

Baker A. (1983). Wood fuel properties and fuel products from woods. Fuelwood Management and Utilization Seminar. East Lansing, Mich, USA, Michigan State University: 14-25 pp.

Bates J. (1995). Full Fuel Cycle Atmospheric Emissions and Global Warming Impacts from UK. Stationery Office Books, 39 pp.

Bates J.and Henry S. (2009). Carbon factor for wood fuels for the supplier obligation. Oxfordshire: AEA Technology, 23 pp.

Baxter L., Miles T.R., Miles T.R.Jr.,Jenkins B.M., Milne T., Dayton D., Bryers R.W. and Oden L.L. (1998). The behavior of inorganic material in biomass-fired power boilers:field and laboratory experiences. Fuel Processing Technology journal 54 (1-3): 47-78 pp.

Beauchemin A. and Tamprier M. (2008). Emissions from wood-fired combustion equipment. British Columbia, Canada : Ministry of Environment BC, 81 pp.

Biedermann F. and Obernberger I. (2011). Ash-related problems during biomass combustion and possibilites for a sustainble ash utilization. BIOS Bioenergiesysteme GmbH, Graz, Austria, 8 pp.

BIOMASA Association. (2011). The effect of additives for production costs and parameters of wood pellets. BIOMASA Association, Slovenia, 6 pp.

Biomass Energy Resource Center. (2007). Wood Pellet Heating Guidebook . Boston: Massachusetts Division of Energy Resources, 26 pp.

Blunk S.L. and Jenkins B.M. (2000). Combustion properties of lignin residue from lignocellulose fermentation. Davis, CA: University of California, 16 pp.

Boundy B., Diegel S., Wright L. and Davis S.(2011). Biomass energy data book:Edition 4. Tennessee: U.S. Department of Energy, 254 pp.

Bradley D. and Bradburn K. (2012). Economic Impact of Bioenergy in Canada-2011. Ottawa: Canadian Bioenergy Association, 26 pp.

Bradley D. (2010). Canada Report on Bioenergy 2010. Ottawa, Natural Resources Canada, 57 pp.

BW McCloy Associates Inc. (2009). NWT Wood Pellet Pre-feasibility Analysis. Vancouver, British Columbia: FPInnovations , Forintek Division, 25 pp.

Chaiyaomporn K. and Chavalparit O. (2010). Fuel Pellets Production from Biodiesel Waste. Environment Asia 3(1): 103-110 pp.

Cheah C. and Ramli M. (2011). The implementation of wood waste ash as a partial cement replacement material in the production of structural grade concrete and mortar: An overview. Resources, Conservation and Recycling vol.55(7): 669-685 pp.

Ciolkosz D. (2010). Characteristics of Biomass as a Heating Fuel. The Pennsylvania State University, 4 pp.

CMHC. (2008). Guide to Residential Wood Heating. Canada: Canada Mortgage and Housing Corporation, 82 pp.

Coghlan A. (2013). A Little Book of R For Multivariate Analysis. Cambridge: Wellcome Trust Sanger Institute, 47 pp.

Collins English Dictionary. (2010). Collins English Dictionary - Complete & Unabridged 10th Edition. HarperCollins Publishers, 1920 pp.

Dessureault D. (2011). Canada biofuel annual 2011. Global Agriculture Information Network, 37 pp.

De Veaux R., Velleman P. and Bock D. (2005). Stats: Data and Models. Washington: Pearson Education Inc., 743 pp.

European Pellet Council. (2011). Handbook for the certification of wood pellets for heating purposes. European Pellet Council, Brussels, Belgium, 41 pp.

Eurostat. (2012). Retrieved June 3, 2013, from Eurostat: http://epp.eurostat.ec.europa.eu

Filbakk T., Jirjis R., Nurmi J and Hoiboa O. (2011). The effect of bark content on quality parameters of Scots pine (Pinus sylvestris L.) pellets. Biomass and Bioenergy journal 33(8): 3342–3349 pp.

Focus on Energy. (2007). Pellet Fuel for Commercial and Residential Heating Applications. Wisconsin : Wisconsin Focus on Energy, 2 pp.

Gaur S. and Reed T.. (1998). Thermal Data for Natural and Synthetic Fuels. New York: Marcel Dekker Inc., 259 pp.

Gillespie et al. (2013). Prediction of quality parameters of biomass pellets from proximate and ultimate analysis. Fuel , In press.

Grey W.A. (1968). Compaction after Deposition. In: The Packing of Solid Particles. New York: Marcel Dekker Inc: 89-107 pp.

Hakkila P. (1989) Utilisation of Residual Forest Biomass. (568 pp) Springer series in Wood Science -Springer Verlag, Berlin, 568 pp.

Hansen M., Rosentoft Jein A., Hayes S. and Bateman P. (2009). English Handbook for Wood Pellet Combustion. Pellets Atlas: Munich, 86 pp.

Hartman H. and Herranen M. (2005). Physical and mechanical fuel properties-significance and standard determination methods. The PHYDADES Action, 21 pp.

Hein T. (2011). Choosing a Dryer. The Canadian Biomass Magazine, 2 pp.

Hiegl W., Janssen R. (2009). Pellet market overivew report: Europe. Pellet Atlas. WIP Renewable Energies, 31 pp.

Holmen. (2011). Lingo-Tester User Manual. Holmen Inc., 8 pp.

Hosegood S. (2010). Fuel characteristics of Northwestern Ontario tree species and their components. Thunder Bay: Lakehead University, 131 pp.

Houck J., Clark J. and Christensen T. (2009). Evaluation of hardwood vs. softwood pellets. OMNI Environmental Services Inc. Portland, 4 pp.

IEA. (2010). Canada review 2009. International Energy Agency Bioenergy: Paris, 266 pp.

Jamieson S. (2010). One home at a time. Canadian Biomass Journal, March-April. Retrieved May 3, 2013, from Canadian Biomass Journal: http://www.canadianbiomassmagazine.ca/content/view/1674/136/

Junginger H.M., Jonker J.G.G., Faaij A., Cocchi M., Hektor B., Hess R., Heinimö J., Hennig C., Kranzl L., Marchal D., Matzenberger J., Nikolaisen L., Pelkmans L., Rosillo-Calle F., Schouwenberg P., Trømborg E., Walter A. (2011). Summary,synthesis and conclusions from IEA Bioenergy Task 40 country reports on international bioenergy trade. IEA Bioenergy: Utrecht, 25 pp.

Kaķītis A., Nulle A. and Ancans D. (2011). Mechanical properties of composite biomass briquettes. In: Proceedings of the 8th International Scientific and Practical Conference. Volume 1 (pp. 175-183). Rēzekne: Rēzeknes Augstskola. 20-22 June 2011.

Kaliyan N. and Vance Morey R. (2009). Factors affecting strength and durability of densified biomass products. Biomass and Bioenergy 33(3): 337-359 pp.

Kelsey R., Shafizadeh F., and P. Lowery D.P. (1979). Heat Content of Bark, Twigs, and Foliage of Nine Species of Western Conifers. United States Department of Agriculture Forest Service: Ogden, 9 pp.

Klass D. (1998). Biomass for renewable energy, fuels and chemicals. San Diego, CA: Academic Press Limited, 651 pp.

Kofman P. (2010). The production of wood pellets. Processing/Products №10, 6 pp.

Kryla J. (1984). Determination pf available heat of combustion data for canadian wood species. Ottawa: Forintek Canada Corp., 89 pp.

Kuokkanen M., Kuokkanen T., and Pohjonen V. (2009). The development steps in eco-efficient pellet production and technology. EnePro conference . Oulu: University of Oulu, 36-40 pp.

Kuokkanen M., Vilppo T., Kuokkanen T., Stoor T. and J. Niinimaki (2011). Additives in wood pellets. BioResources journal 4(6): 4331-4355 pp.

Larsson S.H., Thyrel M., Geladi P. and Lestander T.A. (2008). High quality biofuel pellet production from pre-compacted low density raw materials. Bioresource Technology 99: 7176-7182 pp.

Lebo S.E. Jr., Gargulak J.D. and McNally T.J. (2001). Lignin. In Kirk-Othmer Encyclopedia of Chemical echnology. Jonh Wiley & Sonc Inc., 1021 pp.

LECO Corporation (2001). TGA-601 Thermogravimetric Analyzer Instruction Manual. LECO Corporation, USA, 204 pp.

Lehtikangas P. (2002). Quality Properties of Fuel Pellets from Forest Biomass . Uppsala, Sweden: The Swedish University of Agricultural Sciences, 84 pp.

Lehtikangas P. (2001). Quality Properties of Fuel Pellets from Forest Biomass . Biomass and Bioenergy 20: 351–360 pp.

Lestander T.A. and Rhen C. (2005). Multivariate NIR spectroscopy models for moisture, ash and calorific content in biofuels using bi-orthogonal partial least squares regression. Analyst 130: 1182-1189 pp.

Li Y. and Liu H. (2000). High-pressure densiication of wood residues to form an upgraded fuel. Biomass and Bioenergy 19(3): 177-186 pp.

Lope T.1, Phani A.1 and Mahdi K. (2011). In Biomass Feedstock Pre-Processing:Densification (In E. b. Bernardes, Biofuel's Engineering Process Technology (pp. 439-464): InTech., 742 pp.

Louis J.N. (2011). Pellet industry: A driving force for the Karelian Region. Oulu: University of Oulu, 18 pp.

Mancera C. (2011). The effect of lignin as a natural adhesive on the physico-chemical properties of Vitis Vinefera fiberboards. BioResources Journal 6(3): 2851-2860 pp.

Manickam I., Dr. Ravindran D. and Dr. Subramanian P. (2006). Biomass densification methods and mechanisms. Cogeneration and Distributed Generation Journal 21(4): 33-45 pp.

Mediavilla I. Esteban L. S. and Fernandez M. J. (2012). Optimisationof pelletisation conditions for poplar energy crop. Fuel Processing Technology Journal vol.104: 7–15 pp.

Melin S. (2011). Quality certification and standards for solid biofuels. Biomass Pelletization Workshop. Wood Pellet Association of Canada: Ottawa, 28 pp.

Ministry of Energy of Canada. (2010). Ontario`s long-term energy plan. Ministry of Energy of Canada: Ottawa, 37 pp.

Minister of Public Works and Government Services Canada. (2001). The enviromentally responsible construction and renovation handbook. Minister of Public Works and Government Services Canada, 178 pp.

Monti et al. . (2008). Mineral composition and ash content of six major energy crops. Biomass and Bioenergy 32: 216-223 pp.

Mujumdar A.S. (2011). Drying Technology - An Overview. Singapore: National University of Singapore, 134 pp.

Murray G. (2011). Canadian Wood Pellet Update. PFI Annual Conference (pp. 1-27). Ponte Vedra Beach, Florida: Wood Pellet Association of Canada.

Murray G. (2012). Canada's Wood Pellet Industry Status Quo and Outlook. 12th Pellets Industry Forum (pp. 1-22). Berlin: Wood Pellet Association of Canada.

Murray G. (2013). Ontatio Fuel Opportunities. Presentation for Ontario Ministry of Energy (pp. 1-16). Toronto, Ontario: Wood Pellet Association of Canada.

Natural Resources Canada. (2011). Forests. Ottawa, ON, Canada. Retrieved from http://www.nrcan.gc.ca/statistics-facts/forests/897

Natural Resources Canada. (2013). Forest regions. Canada. Retrieved from: http://cfs.nrcan.gc.ca/pages/125

Nosek R. and Jandacka J. (2011). Increasing the melting temperature of ash by adding diferent types of additives into wood pellets. Zilina: Care Tech University of Zilina, 19 pp.

Novaes E., Kirst M, Chiang V., Winter-Sederoff H. and Sederoff R. (2010). Lignin and Biomass: A Negative Correlation for Wood Formation and Lignin Content in Trees. Plant Physiology 154 (2): 555-561 pp.

Noymer. (2008). Alpha, Significance Level of Test. In P. J. Lavrakas, Encyclopedia of Survey Research Methods (p. 18). Thousands Oaks, California: SAGE Publications Inc.

NRC. (2002). A Guide to Residential Wood Heating. Ottawa: Natural Resources Canada, 82 pp.

Obernberger I., Brunner T. and Barnthaler G. (2006). Chemical properties of solid biofuels -signicance and impact. Biomass and Bioenergy 30: 973-982 pp.

Obernberger I.and Thek G. (2004). Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass and Bioenergy journal 27(6): 653-669 pp.

Ohman M. Boman C. Hedman H. Nordin A. and D. Boström (2004). Slagging tendencies of wood pellet ash during combustion in residential pellet burners. Biomass and Bioenergy journal 27(6): 585-596 pp.

Olsson M. (2003). Wood pellets as low-emitting residental biofuel. Chalmers University of Technology: Göteborg, 70 pp.

Oveisi-Fordiie E. (2011). Durability of wood pellets. Vancouver: The University of British Columbia, 134 pp.

Parr Instrument Co. (2007). Operating Instruction Manual- 6200 Oxygen Bomb Calorimeter. Moline, IL: Parr Instruments Company, 10 pp.

Paulrud S. (2004). Upgraded Biofuels - Effects of quality on processing, handling characteristics,combustion and ash melting", Doctoral dissertation. Umea, Sweden: Swedish University of Agricultural Sciences, 53 pp.

Paulrud S., Nilsson C. and Ohman M. (2001). Reed canary-grass ash. Fuel Journal 80(10): 1391-1398 pp.

Pellet Fuel Institute. (2010). Pellet Fuels Institute Standard Specification for Residential/Commercial Densified Fuel. Arlington, USA: Pellet Fuel Institute, 9 pp.

Pellets Partner Group. (2006). Press and matrix. Retrieved May 29, 2013, from Portal Pellet.ru: http://www.pellets.ru/op-module_show/id-370/oborud.html

Pembina Institute. (2011). Biomass sustainability analysis summary report. Toronto: Pembina Institute, 16 pp.

Penner M., Power K., Muhairwe C., Tellier R. and Wang Y. (1997). Canada's Forest Biomass Resources: Deriving Estimates from Canada's Forest Inventory. Victoria, British Columbia: Canadian Forest Service, 33 pp.

Pereira B., Oliveira A., Carvalho A., Carneiro A., Santos L. and Vital B. (2012). Quality of Wood and Charcoal from Eucalyptus Clones . International Journal of Forestry Research vol. 2012: 1-8 pp.

Persson T., Nordlander S. and Rönnelid M. (2005). Electrical savings by use of wood pellet stoves and solar heating systems in electrically heated single-family houses. Energy and Buildings 37: 920–929 pp.

Pitelka. (2007). Glossary of Ceramic Terminology. Retrieved June 3, 2013, from http://iweb.tntech.edu/wpitelka/syllabi- handouts/handouts/glossary_of_ceramic_terminology.htm

Preto F. (2005). Emissions from residental wood combustion. IEA Task 32, International Energy Agency, 35 pp.

Rabier F., Temmerman M., Bohm T., Hartmann H., Jensen P.D., Rathbauer J., Carrasco J. and Fernández M. (2006). Particle density determination of pellets and briquettes. Biomass and Bioenergy 30(11): 954-963 pp.

Rentech Inc. (2013). Wood pellets. Retrieved July 29, 2013, from Rentech Inc.: http://www.rentechinc.com/wood-pellets.php

Resch, H., 1989, Fuel from Wood Residues; a Profit Center for Mills, Forest Industries, 8 pp.

Revelle W. (2013, May 20). Using R for psychological research. Retrieved July 9, 2013, from Personality Project:http://www.personality-project.org/R/r.guide.html#corr.test

Roth E. (2006). What can we expect from wood pellets? Leonardo ENERGY, Paris, France, 5 pp.

Rumpf H. (1962). The Strength of Granules and Agglomerates. In W. Knepper, From Agglomeration. New York: 379-418 pp.

Salas-Bringas C., Filbakk T., Skjevrak G, Lekang O.L., Høibø O.A. and Schüller R.B. (2010). Compression rheology and physical quality of wood pellets pre-handled with four different conditions. Annual Transactions of the Nordic Rheology Society 18: 87-93 pp.

Samuelsson R., Larsson S., Thyrel M. and Lestander T. (2012). Moisture content and storage ime influence the binding mechanisms in biofuel wood pellets. Applied Energy Journal vol. 99: 109-115 pp.

Schowalter T. and Morrell J. (2002). Nutritional quality of douglas-fir wood: effect of vertical and horizontal position on nutrient levels. Wood and Fiber Science Journal 34 (1): 158-164 pp.

Sikanen L. and Vilppo T. (2012). Small scale pilot combustion experiments with wood pellets he effect of pellet lenght. The open renewable energy journal 5: 1-6 pp.

Singh T. and Kostecky M. (1986). Calorific value variations in components 10 Canadian tree species. Canadian Journal of Forest Research 16(6): 1378-1381 pp.

Stahl M., Berghel J., Frodeson S., Granström K., and R. Renström (2012). Efects on Pellet properties and energy use when starch is added in the wood-fuel pelletizing process. Energy Fuels Journal 26(3): 1937–1945 pp.

Stanton C.R. and Bourchier R.J. (2012). The Canadian Encyclopedia: Forest Regions. Canada. Retrieved from http://www.thecanadianencyclopedia.com/articles/forest-regions

Statistics Canada. (2010). Households and the Environment: Energy Use. Ottawa: Statistics Canada. Retrieved June 15, 2013, from Statistics Canada: http://www.statcan.gc.ca/pub/11-526-s/2010001/t002-eng.htm

Stahl M., Granström K., Berghel J. and R. Renström (2004). Industrial processes for biomass drying and their effects on the quality properties of wood pellets. Biomass and Bioenergy 27 (6) : 621–628 pp.

Swaan J. (2008). European wood pellet import: The Canadain Influence. Wood Pellet Association of Canada, 22 pp.

Tarasov D. (2009). Wood pellets markets in Russia. Lappeenranta: Lappeenranta University of Technology, 61 pp.

Telmo and Lousada. (2011). Heating values of wood pellets from different species. Biomass and Bioenergy 35: 2634 -2639 pp.

Temmerman M., Rabier F., Jensen P. D., Hartmann H., and Böhm T. (2006). Comparative study of durability test methods for pellets and briquettes. Biomass and Bioenergy journal 30(11): 964–972 pp.

The R Stats Package Documentation (2013). Fitting Linear Models. Retrieved July 9, 2013, from http://127.0.0.1:25338/library/stats/html/lm.html

Tumuluru J. S., Wright C., Hess J. R. and Kenney K. (2010). A review on biomass densification technologies for energy application. Biofules, Bioproducts and Biorefining journal, vol.5: 683-707 pp.

UNECE/FAO. (2009). Forest Products Annual Market Review, 2008- 2009. New York, Geneva: United Nations, 188 pp.

Werther J.. (2000). Combustion of agricultural residues. Progress in Energy and Combustion Science 27(1): 1-27 pp.

Wilson T. (2010). Factors afecting pellets durability. University Park, Pa, USA: Department of Agricultural and Biological Engineering, The Pensylvania State University, 81 pp.

Wood Pellet Association of Canada. (2013). Canadian wood pellet production, Retrieved August 8, 2013, from http://www.pellet.org/production/production

Worley M. (2011). Biomass drying technology update. BioPro and Expo MarketPlace (pp.1-36). Atlanta, GA: Harris Group Inc.

Wu M., Schott D.and Lodewijks G. (2011). Physical properties of solid biomass. Bioenergy journal 35(5): 2097-2098 pp.

Young H., Carpenter P. and Altenberger R. (1965). Preliminary tables of some chemical elements in seven tree species in Maine. Aspen: Utah State University., 92 pp.

Appendix A

Tables of parameters values

Table A 1 Bulk density and moisture content measurements

Sample	Bulk density (kg/m^3)	Moisture content (%)
1	701.3	4.44
2	665.3	6.08
3	698.13	4
4	677.94	4.779
5	699.22	3.76
6	696.8	4.06
7	692.89	4.83
8	692.68	4.6045

Table A 2 Mechanical durability measurements

Sample	Test run No. (%)		
	1	2	3
1	97.42951	97.6238	97.4995
2	99.08321	98.96301	99.14077
3	96.25972	96.02114	97.31001
4	97.83498	97.85793	98.83501
5	97.02612	96.91239	97.09637
6	98.10663	97.84388	98.30017
7	98.94064	98.13075	98.94485
8	99.22062	99.34237	99.28108

Table A 3 Fines amount measurements

Sample	Test run No. (%)		
	1	2	3
1	0.0619195	0.06376	0.06483
2	0.059701	0.06142	0.06319
3	0.072946	0.068276	0.071652
4	0.079569	0.062759	0.05936
5	0.06341287	0.064987	0.07113
6	0.072702	0.05269	0.06339
7	0.057309	0.043028	0.06521
8	0.03165559	0.03594	0.04545

Table A 4 Single pellet density measurements

Sample	Test run # (kg/m^3)		
	1	2	3
1	1286.923	1286.909	1257.867
2	1281.25	1282.118	1260.01
3	1277.108	1314.815	1259.452
4	1270.946	1224.627	1241.923
5	1283.02	1291.404	1243.429
6	1213.778	1271.183	1269.848
7	1275.667	1302.807	1281.884
8	1272.093	1273.729	1271.021

Table A 5 Volatile organic compounds, fixed carbon amount and ash content measurements

Sample	Volatile organic compounds (%)	Fixed carbon amount (%)	Ash content (%)
1	84.995	10.1082	0.4568
2	83.845	9.54715	0.52785
3	86.85	8.83	0.32
4	85.4	9.46195	0.35905
5	84.43	11.51485	0.29515
6	85.41	10.2216	0.3084
7	85.595	8.5235	1.0515
8	83.955	10.9026	0.5379

Table A 6 Gross heating value measurements

Sample	Test run No. (MJ/kg)				
	1	2	3	4	5
1	22.7244	21.0802	20.6203	19.1354	19.1525
2	19.3047	19.1992	20.8639	19.0615	19.7003
3	21.0323	19.1369	20.8997	18.8467	19.2779
4	20.5422	20.3587	19.9679	20.6818	19.7378
5	19.7187	20.6701	19.1015	20.992	22.7545
6	19.7822	19.1687	20.6701	21.0591	20.6064
7	20.9755	20.7593	20.5834	20.1649	19.603
8	19.536	20.9416	18.1377	19.473	19.0344

Table A 7 Pellet length measurements

Sample	Test run No. (mm.)									
	1	2	3	4	5	6	7	8	9	10
1	12.8	15.87	33	23.88	20.81	22.67	27.74	26.22	24.5	15.92
2	18.58	23.45	20.69	17.98	21.92	21.14	17.41	21.78	19.49	21.17
3	16.3	16.04	25.42	23.43	33.04	26.7	19.9	24.08	36.09	24.53
4	18.54	17.82	20.04	18.94	17.39	15.17	15.8	15.27	17.21	16.46
5	20.51	11.26	13.55	16.76	13.45	14.62	14.79	9.82	14.91	9.99
6	24.83	22.79	16.22	21.75	23.85	18.16	23.01	20.95	24.32	19.94
7	21.67	17.43	15.72	22.07	13.58	22.71	22.01	18.49	21.01	27.35
8	14.24	17.43	12.54	16.5	14.64	17.81	35.59	22.53	20.4	18.41

Table A 8 Pellet diameter measurements

Sample	Test run No. (mm.)									
	1	2	3	4	5	6	7	8	9	10
1	6.38	6.35	6.4	6.41	6.49	6.31	6.44	6.35	6.38	6.39
2	6.43	6.41	6.36	6.41	6.36	6.33	6.3	6.45	6.42	6.35
3	6.11	6.28	6.36	6.14	6.11	6.12	6.16	6.4	6.27	5.84
4	6.56	6.38	6.27	6.77	6.58	6.75	6.4	6.52	6.48	6.49
5	6.6	6.57	6.54	6.55	6.51	6.48	6.5	6.69	6.68	6.5
6	6.71	6.53	6.54	6.51	6.5	6.48	6.51	6.48	6.57	6.55
7	6.41	6.36	6.44	6.35	6.19	6.11	6.26	6.45	6.43	6.51
8	6.47	6.42	6.47	6.46	6.51	6.54	6.5	6.47	6.53	6.43

Table A 9 Compressive resistance measurements

Run No. (MPa)	Sample No.							
	1	2	3	4	5	6	7	8
1	116.41	93.1	57.44	103.01	92.19	78.23	86.44	96.28
2	129.02	97.52	54.17	105.35	105.06	65.62	98.08	89.2
3	107.63	104.17	81.01	63.82	83.04	77.64	71.41	86.87
4	117.14	90.97	57.2	82.28	112.58	77.58	100.43	86.79
5	99.36	97.81	57.98	78.45	80.63	60.07	77.33	128.55
6	94.43	93.98	71.59	76.08	73.19	71.46	108.38	129.56
7	127.64	75.02	74.22	111.82	104.02	62.87	100.51	123.44
9	113.49	99.55	69.88	84.88	79.59	88.02	107.13	133.77
10	118.29	96.37	83.18	76.56	92.7	95.51	126.69	121.66
11	87.5	97.6	47.89	92.65	114.78	73.35	125.42	100.91
12	107.31	86.82	78.79	100.27	83.82	74.63	99.91	114.7
13	100.05	83.64	71.05	126.24	84.27	80.86	97.25	123.63
14	111.4	95	74.43	79.3	92.96	97.72	100.16	129.91
15	102.66	115.16	61.68	95.58	85.73	85.53	93.03	106.39